FINAL REPORT

6/30/2011

Full data for all device tests conducted by the Working Group is available for download at:
ftp://twg:freeforall@ftp.novatel.ca

Contents

1. Introduction 6

2. Organization and Functioning of the WG and TWG 7

2.1 Organization of the WG and TWG 7
2.2 Participation in the TWG 9
2.3 Work Plan 9
2.4 Functioning of the TWG 12
2.5 Overview of the Testing Process 12
2.6 Anonymity of Testing Results 14
2.7 Abstract of Sub-Team Report Summaries 14
2.7.1 Aviation 15
2.7.2 Cellular 16
2.7.3 General Location and Navigation 17
2.7.4 High Precision, Timing and Networks 21
2.7.5 Space-based Receivers 24

3. Sub-Team Reports 27

3.1 Aviation Sub-Team 27
Executive Summary 27
3.1.1 Work Plan Item 1: Establish Pertinent Analytical and Test Methodologies and Assumptions Underlying the Test Regime 28
3.1.2 Work Plan Item 2: Select the Categories of Receivers and Receivers to be Tested 31
3.1.3 Work Plan Item 3: Develop Operational Scenarios 32
3.1.4 Work Plan Item 4: Establish the Methodology for Analyzing Test Results 37
3.1.5 Work Plan Item 5: Derive the Test Conditions Based on the Established Operational Scenarios 39
3.1.6 Work Plan Item 6: Write the Test Plan and Procedures 40
3.1.7 Work Plan Item 7: Identify and Engage Appropriate Neutral Test Facility(ies) for the Testing Portion of the Work Plan 42
3.1.8 Work Plan Item 8: Perform Testing 42
3.1.9 Work Plan item 9: Analyze Test Results Based on Established Methodology 45
3.1.10 Work Plan Item 10: Assess Operational Scenarios Using Analytics and Test Results 47
3.1.11 Work Plan Item 11: Assess Whether any Mitigation Measures are Feasible and Appropriate 50

3.2 Cellular Sub-Team 54
3.2.1 Work Plan Item 1: Establish Pertinent Analytical and Test Methodologies and Assumptions Underlying the Test Regime 55
3.2.2 Work Plan Item 2: Select the Categories of Receivers and Receivers to be Tested 60
3.2.3 Work Plan Item 3: Develop Operational Scenarios 63
3.2.4 Work Plan Item 4: Establish the Methodology for Analyzing Test Results 64
3.2.5 Work Plan Item 5: Derive the Test Conditions Based on the Established Operational Scenarios 64
3.2.6 Work Plan Item 6: Write the Test Plan and Procedures 64
3.2.7 Work Plan Item 7: Identify and Engage Appropriate Neutral Test Facility(ies) for the Testing Portion of the Work Plan 72
3.2.8 Work Plan Item 8: Performance Testing 73
3.2.9 Work Plan item 9: Analyze Test Results Based on Established Methodology 75
Figure 3.2.3 CDF of Final of Passing Blocker Levels across All Devices and Test Suites for the lower 10MHz 79
3.2.10 Conclusions regarding L Band Interference Impact to Cellular GPS Receivers 113
3.2.11 Work Plan Item 10: Assess Operational Scenarios Using Analytics and Test Results 117
3.2.12 Work Plan item 11: Prevention and Mitigation Measures 117
3.2.13 Summary of Live Sky Testing by LightSquared and TechnoCom Wireless 120

3.3 General Location / Navigation Sub-Team 122
3.3.0 Executive Summary 122
3.3.1 Establish Pertinent Analytical and Test Methodologies and Assumptions Underlying the Test Regime 129
3.3.2 Work Plan Item 2: Select the Categories of Receivers and Receivers to be Tested 130
3.3.3 Work Plan Item 3: Develop Operational Scenarios 132

3.3.4 Work Plan Item 4: Establish the Methodology for Analyzing Test Results.....133
3.3.5 Work Plan Item 5: Derive the Test Conditions Based on the Established Operational Scenarios 133
3.3.6 Work Plan Item 6: Write the Test Plan and Procedures 133
Combined Sub-Team Perspective.....133
3.3.7 Work Plan Item 7: Identify and Engage Appropriate Neutral Test Facility(ies) for the Testing Portion of the Work Plan.....133
3.3.8 Work Plan Item 8: Perform Testing.....134
3.3.9 Work Plan Item 9: Analyze Test Results Based on Established Methodology 136
3.3.10 Work Plan Item 10: Assess Operational Scenarios Using Analytics and Test Results.....167
3.3.11 Work Plan Item 11: Assess Whether any Mitigation Measures Are Feasible and Appropriate 176
3.4 High Precision, Timing, and Networks Sub-Team.....180

1. Executive Summary.....180
1.1 GPS Community Positions 180
1.2 LightSquared Positions.....181

2. Introduction and Background 183

3. Test Methodologies and Assumptions 186
3.1 Background Assumptions 186
3.2 LightSquared Rollout Plan 186
3.3 Harmful Interference 187
3.3.1 Introduction.....187
3.3.2 Coverage Measure.....187
3.3.3 Accuracy Measure.....188
3.4 Resulting Test Methodologies and Rationale 188
3.5 High Precision Receivers 191
3.5.1 Wide Bandwidths and Filters.....191
3.5.2 L1 and L2 GPS Frequencies.....195
3.5.3 Carrier Phase Navigation 196

4. Receivers Tested.....198
4.1. Anechoic Chamber 198
4.2. Live Sky.....199
4.3. Laboratory 199

5. Operational Scenarios 200
5.1. Key Performance Requirements.....200
5.1.1 Availability.....200
5.1.2 Accuracy.....200
5.1.3 Commercial Integrity.....200
5.2. Operational Scenarios 201
5.2.1 Agriculture 201
5.2.2 Construction – Heavy and Civil Engineering.....202
5.2.3 Professional Services: Land Surveying, Architecture, Engineering 203
5.2.4 Public Administration: Federal, State, and Local Government.....204
5.2.5 Utilities (Electric, Gas and Water), Energy, Mining, Oil & Natural Gas 206
5.2.6 Transportation: Road and Rail.....207
5.2.7 Networks, Monitoring and Scientific.....208
5.2.8 GPS Precision Timing.....211

6. Methodology for Analyzing Test Results.....212
6.1 Susceptibility.....213
6.2 Propagation Model.....213
6.3 Area of Impact 214
6.4Manufacturing and Temperature Variability 214

7. Test Conditions.....215
7.1 Anechoic Chamber 215
7.2 Live Sky.....216
7.3 Laboratory 216

8. Test Plans.....217

8.1 Anechoic Chamber 217
8.2 Live Sky 217
8.3 Laboratory 217

9. Test Facilities 218
9.1 Anechoic Chamber 218
9.2 Live Sky 220
9.3 Laboratory 221

10. Testing 222
10.1 Anechoic Chamber 222
10.1.1 Physical Test Structure 222
10.1.2 Receivers Tested 223
10.1.3 LightSquared LTE Signals 223
10.1.4 Setup and Calibration of LightSquared LTE Signals 224
10.1.5 Setup and Calibration of GPS Signals 227
10.1.6 Setup and Calibration of the Timing Equipment 227
10.1.7 Interference Among Receivers 228
10.1.8 Test Automation 228
10.2 Live Sky 229
10.2.1 Trimble Live Sky Testing 229
10.2.2 Deere Live Sky Testing 237
10.3 Laboratory 239

11. Test Results Analysis 240
11.1 Anechoic Chamber 240
11.1.1 Tests Executed 240
11.1.2 Data Processing 241
11.1.3 High Precision Receivers - Conclusions 242
11.1.4 Timing Receivers - Conclusions 244
11.1.5 PCTEL Antenna – Conclusions 246
11.1.6 OmniSTAR and StarFire - Conclusions 247
11.2 Live Sky 248
11.2.1 Trimble Summary 248
11.2.2 Deere Summary 250
11.2.3 Verizon Wireless Summary 252
11.2.4 NOAA/NGS Summary 253
11.2.5 CORS Summary 253
11.2.6 Sprint Nextel Summary 253
11.2.7 Topcon Summary 254
11.2.8 Live Sky Conclusions 254
11.3 Laboratory 255
11.4 Coverage Effects 257
11.5 Intermodulation Effects (IM3) 269

12. Effects on Operational Scenarios 274
12.1 Key Performance Indicators 274
12.2 Antenna and Power Assumptions 275
12.3 Agricultural Operational Scenario 276
12.4 Other Operational Scenarios 279
12.5 Networks 283
12.5.1 Decimeter Networks 283
12.5.2 Centimeter Networks 285

13. Potential Mitigations 287
13.1 Interference Mechanisms 287
13.2 Mitigation Conditions 288
13.3 GPS Receiver Mitigation Analysis for Proposed Rollout 289
13.3.1 High Precision and Network Receivers 289
13.3.2 Augmented Receivers 289
13.3.3 Timing Receivers 290
13.4 GPS Receiver Mitigation for an Upper Band Only Rollout 291
13.5 Mitigation of GPS Receivers for a Lower Band Only Rollout 292
13.6 Other Mitigation Possibilities 295

14. Glossary.....296
3.5 Space Based Receivers.....300
3.5.0 Executive Summary.....300
3.5.1 Work Plan Item 1: Establish Pertinent Analytical and Test Methodologies and Assumptions Underlying the Test Regime 302
3.5.2 Work Plan Item 2: Select the Categories of Receivers and Receivers to be Tested 302
3.5.3 Work Plan Item 3: Develop Operational Scenarios.....303
3.5.4 Work Plan Item 4: Establish the Methodology for Analyzing Test Results.....304
3.5.5 Work Plan Item 5: Derive the Test Conditions Based on the Established Operational Scenarios 304
3.5.6 Work Plan Item 6: Write the Test Plan and Procedures 304
3.5.7 Work Plan Item 7: Identify and Engage Appropriate Neutral Test Facility(ies) for the Testing Portion of the Work Plan.....305
3.5.8 Work Plan Item 8: Perform Testing.....306
3.5.9 Work Plan item 9: Analyze Test Results Based on Established Methodology.....306
3.5.10 Work Plan Item 10: Assess Operational Scenarios Using Analytics and Test Results.....308
3.5.11 Work Plan Item 11: Assess Whether any Mitigation Measures are Feasible and Appropriate 315

1. Introduction

This is the final report of the Working Group (WG) that was formed to study the GPS overload/desensitization issue as described by the Federal Communications Commission (FCC) in DA 11-133. On February 25, 2011, LightSquared and the United States Global Positioning System Industry Council (USGIC) submitted a Work Plan to the Federal Communications Commission (FCC) outlining the intended actions and governance of the WG to study fully the potential for overload interference/desensitization to GPS receivers, systems, and networks. Progress reports were filed with the FCC on March 15, April 15, 2011, and May 16, 2011 (with the latter progress report supplemented on May 23, 2011). LightSquared, along with the non-governmental members of the GPS Technical Working Group (TWG) hereby submit this report which has been approved by the Co-Chairs of the WG[1].

The February 25, 2011 Work Plan stated that the TWG would include representatives from a broad cross-section of constituencies using the positioning, navigation, and timing (PNT) information broadcast by GPS/GNSS/augmentations/L-band systems. These applications include, but are not limited to: public safety; aviation (commercial, business, and general); electric power and utilities; engineering and construction; environmental protection; law enforcement and legal services; maritime and waterways; transportation (most modes); agriculture; surveying, mapping, and land management; weather, scientific, and space; precision timing, consumer devices, and cellular handsets. Also to be included were constituencies using augmentation systems to include space-based such as: Wide Area Augmentation System (WAAS); but also Ground-based Augmentation Systems (GBAS); Nationwide Differential GPS System (NDGPS); Continuously Operating Reference Stations (CORS); Global Differential GPS (GDGPS); International GNSS service (IGS); wide–area differential GPS corrections service using satellite broadcast techniques; and commercial virtual reference stations providing high-accuracy, real-time kinematic (RTK) GNSS positioning for wider areas. Candidate constituencies use the following types of GPS receivers, systems, and networks consisting of single frequency receivers; multi-frequency GPS receivers; multi-frequency GNSS receivers; and may include one or more augmentation(s) and corrections streams.

The TWG identified seven categories of receivers that are representative of the non-military use of GPS in the United States: aviation, cellular, general location/navigation, high precision, timing, networks, and space-based receivers. Each category includes augmented and unaugmented devices. GPS receivers used in public safety applications were included in the general location/navigation category, as were commercial and maritime safety of life at

[1] This Report was prepared with technical input from U.S. Government employees and contractors, but does not necessarily represent their views.

sea (SOLA)[2]receivers. GPS receivers used in science (other than those exclusively used in space applications) were included in the high precision category.

The TWG created seven sub-teams, each focused on one of these categories. Each sub-team had active participation from representatives of LightSquared and the GPS community. These sub-teams were responsible for identifying interference criteria, determining device selection and prioritization criteria, defining operational scenarios, listing testing conditions and developing test plan procedures, identifying appropriate test facilities, participating in the testing, analyzing test data against operational scenarios, and considering and addressing potential mitigation as appropriate based on observed interference effects.

In each receiver category, devices were selected for assessment such that they represent an appropriate range of manufacturers and uses. The sub-teams prioritized devices for testing by criteria, including criticality of use, such as safety-of-life and public safety; the size of embedded user base; operational and economic dependency on positioning, navigation, and timing information; the availability of suitable test devices; and other category-specific factors.

2. Organization and Functioning of the WG and TWG

2.1 Organization of the WG and TWG

The WG was comprised of (1) two Co-Chairs, (2) a Technical Working Group ("TWG") and (3) Advisors, with roles as follows:

Co-Chairs

The WG was co-chaired by designated representatives of LightSquared and the USGIC. The co-chair from the USGIC was Charles R. Trimble, Chairman of the USGIC. The co-chair from LightSquared was Jeffrey Carlisle, LightSquared Executive Vice President of Regulatory Affairs and Public Policy.

The Co-Chairs were responsible for reviewing and approving the results of the WG, and providing direction for the WG based on input received from its members. All matters within the responsibility of the WG generally required the approval of both Co-Chairs (with the exception of two members each of the TWG, the appointment of technical observers of the testing process, and the selection of Advisors as discussed below). The Co-Chairs were also responsible for preparing the monthly status reports to be filed by the WG.

Technical Working Group (TWG)

The TWG was comprised of GPS industry experts and provided guidance and recommendations for the WG on critical elements of the interference study. Members of

[2] "Receivers built to meet IMO Resolution MSC.112(73) and IEC 61108-1 Ed.2 for SOLAS (Safety of Life at Sea) carriage requirements

the TWG were selected to bring strong technical and/or use-case expertise to the working group and represent a diversity of receiver categories and installed user groups.

The TWG was responsible for defining and recommending:

- Pertinent analytical and test methodologies and assumptions underlying the test regime;
- Neutral test facilities, field test sites, independent laboratories, and objective third parties for laboratory and field testing of the work plan;
- Which receivers, systems, networks are to be tested;
- Analysis of the test results pursuant to agreed-upon methodologies;
- Operational scenarios that represent the installed GPS base
- Test results criteria for interpreting the dataset for operational impact; and
- Mitigation strategies, if feasible, "to prevent harmful interference to GPS" installed operations.

  These elements were subsequently incorporated into the specific work plan elements defined by the WG.

Each of the Co-Chairs appointed two members of the TWG. The remaining TWG participants were selected by agreement of the two Co-Chairs.

Advisors

Advisors represented the full range of stakeholders and other affected entities, including interested manufacturers, user groups, and experts in the GPS field. The number of Advisors in the WG was not limited.

Advisors were encouraged to provide feedback to the TWG and Co-Chairs on the WG's Work Plan and receivers to be tested. Advisors assisted the TWG and Co-Chairs by providing specific technical expertise and identification of specific use case scenarios that should be considered.

Sub-Teams

The TWG created the following seven sub-teams, each focused on one of the categories of receivers identified as representative of non-military GPS use in the United States. The seven sub-teams are as follows:

- Aviation
- Cellular
- General Location/Navigation
- High-Precision
- Timing
- Networks
- Space

The sub-teams were responsible for determining device selection and prioritization criteria, defining operational scenarios, listing testing conditions and developing test plan procedures, identifying appropriate test facilities, participating in the testing, analyzing

test data against operational scenarios, and considering and addressing potential mitigation as appropriate based on observed interference effects.

2.2 Participation in the TWG

According to the Work Plan, "the TWG will be comprised of GPS industry experts and will provide guidance and recommendations for the WG on critical elements of the interference study. It is expected that the TWG will be made up of individuals numbering 14-20 who will bring strong technical and/or use case expertise to the working group and represent a diversity of receiver categories and installed user groups." In the end, the Working Group roster (see Appendix W.1 to this Report) included 113 participants from LightSquared; GPS/GNSS equipment and chipset manufacturers; aerospace/aviation companies, wireless providers; engineering firms; civil (including public safety), commercial, and scientific GPS user communities; local and federal government agencies; and academia. Participants included the two WG co-chairs – Jeffrey Carlisle LightSquared and Charles R. Trimble from the USGIC; the four information facilitators for the TWG – Ann Ciganer and F. Michael Swiek from the USGIC, and Martin Harriman and Geoffrey Stearn from LightSquared; [39] TWG members; [61] advisors; and 7 registered observers. No representative from the FCC participated in the WG or TWG.

The size of the Working Group was clearly larger than initially anticipated, however the co-chairs felt that the importance of fostering the greatest level of participation among a wide degree of stakeholders outweighed any concerns about the actual size of the WG.

2.3 Work Plan

The WG structure and working methods were developed to achieve the following outcomes:

- Collection of a representative, accurate dataset (sufficient to allow evaluation of operational impacts) within the timeframe set out by the Commission
- Creation of a transparent, inclusive process
- Determination of operational impacts on installed GPS users
- Identification of mitigation techniques that aim to "prevent harmful interference to GPS"[3]
- Recommendations

To achieve these objectives, the WG established the 11 elements of the February 25, 2011 Work Plan. These elements are:

[3] See SAT-MOD-020101118-00239, Order and Authorization, DA 11-133, para. 41.

1. **Establish pertinent analytical and test methodologies and assumptions underlying the test regime**

   The TWG will establish underlying definitions, including:

   - Defining harmful interference criteria at the GPS/GNSS/Augmentations/L-band receiver, including what constitutes harmful interference in terms of receiver parameters with reference to relevant international standards, immediate effects, and effects that may persist over time, such as receiver desensitization.

   - Identifying relevant information regarding the broadband terrestrial radiation, including power levels, bandwidth, modulation, antenna pattern, and other technical characteristics that govern the signal(s) to be emitted; average and peak transmit equivalent isotropic radiated power (EIRP) for base stations and handsets; modulation, including cycle and multiple access schemes, for both base stations and handsets which are planned to operate in the 1626.5 MHz-1660.5 MHz band; transmit signal envelope data over the range 1525 MHz – 1559 MHz, including channelization and allowed operating frequencies; transmit antenna gain contours both azimuth and elevation (-90° to +90° patterns); deployment plans (cities to be covered, transmit sites per city and, if known, site locations in each city covered);

   - Identifying and agreeing upon interference analysis assumptions; choosing assumptions suitable for interference testing and analysis, including those for the signal propagation path loss, receiver antenna gain, and other assumptions that would affect power transfer from transmitter to receiver; use of receiver signal quality metrics such as C/N0; and agreement on baseline noise floor;

   - Evaluating potential test methodologies for accomplishing the work for which the WG has been formed, consistent with the key tenets outlined earlier in this work plan. Specifically, the test methodology that is adopted must be objective, transparent, and reproducible. The TWG will also recommend appropriate operational assumptions that are key to the implementation of the test plan. This task will begin upon the completion of the TWG formation.

2. **Select the categories of receivers and receivers to be tested**

   The TWG, with input from the Advisors, will recommend to the Co-Chairs the specific receivers, systems, networks that should be tested by the TWG. The TWG will ensure that the receivers, systems, and networks tested are representative of the broad range of installed GPS/GNSS/Augmentation/L-band applications, to the extent practical. Categories will include safety-of-life and public safety services, including Federal, state, and local government use of GPS. This task will begin upon the completion of the TWG formation.

3. **Develop operational scenarios**

   Identify and define operational scenarios in urban and other areas to facilitate a better understanding of the potential impact of LightSquared's Ancillary Terrestrial Component (ATC) base stations and mobile handsets on GPS receiver desensitization

characteristic. Identify conditions under which the receivers will be used, including both their physical situations, receiver dynamics, and types and strengths of the signals that they are expected to receive at the antenna front end. Scenarios will be identified and developed by the TWG with input from the Advisors. This task will begin upon the completion of the TWG formation.

4. **Establish the methodology for analyzing test results**

   The TWG will establish methodologies under which the test results will be evaluated. These methodologies are important in understanding and interpreting test results.

5. **Derive the test conditions based on the established operational scenarios**

6. **Write the test plan and procedures**

   Write the plan to conduct testing that ensures conditions previously established will be observed, result in comprehensive data, and be reproducible.

7. **Identify and engage appropriate neutral test facility(ies) for the testing portion of the work plan**

   It is anticipated that some or all receivers, systems and networks that are laboratory tested will also be tested in a field environment. It is agreed that field testing cannot substitute for laboratory testing as it cannot replicate all conditions and is not repeatable. However, field testing has the advantage of avoiding assumptions about propagation models.

   The TWG will recommend testing facilities, field test sites, independent laboratories, and objective third parties that are able to conduct the testing according to the adopted test methodologies and tenets described in this work plan. It is expected that several test facilities/chambers and test sites will be engaged in the testing process in order to evaluate a meaningful number of receivers. The selection of the test facilities, field test sites, independent laboratories, and objective third parties will require the concurrence of Co-Chairs.

8. **Perform testing**

   Have independent laboratories perform laboratory testing according to the work plan with participation and technical observation by TWG members or relevant Advisors, who are not to interfere with or otherwise delay the testing process. Each Co-Chair will appoint one or more TWG members or Advisors as technical observers.

   All testing conducted in the field environment will be performed by an objective third-party selected jointly by the Co-Chairs with participation and technical observation by TWG members or relevant Advisors, who are not to interfere with or otherwise delay the testing process. Each Co-Chair will appoint one or more TWG members or Advisors as technical observers.

   LightSquared has already begun inquiring about the availability of test facilities, but no selection will occur until the TWG has been formed.

9. **Analyze test results based on established methodology**

   Using the methodology established earlier in the work plan, analyze the results to determine the proposed terrestrial signal transmissions effect on GPS operations.

10. **Assess operational scenarios using analytics and test results**

    The TWG will analyze the test results in the context of the operational scenarios in order to assess the practical impact of receiver desensitization/overload conditions on the installed user base. This will allow for the identification of areas of concern. This task will begin after test results have been evaluated and scenarios identified and defined.

11. **Assess whether any mitigation measures are feasible and appropriate**

    The TWG will identify mitigation options, if feasible, including LightSquared design considerations, types of components, transmit power, and/or operational frequency modifications that, along with the OOBE restrictions previously agreed to between LightSquared and the USGIC, will prevent receiver desensitization/overload from occurring in installed GPS operations. Any mitigation recommendations mutually acceptable to the Co-Chairs will be provided to the Commission in LightSquared's final report which is due on June 15, 2011.

2.4 Functioning of the TWG

The TWG held its first meeting on March 3, 2011 in Arlington, VA and via a conference bridge for those members who were unable to attend in person. The TWG met at least weekly thereafter, including in-person and teleconference-only sessions, to monitor and review sub-team progress; to address matters of general applicability across-sub-teams; and to prepare the monthly progress reports for March, April, and May. The TWG held a two-day meeting in Arlington, VA on June 1 and 2 to consider the preliminary sub-team reports on Work Plan Item Nos. 9-11, and to organize the preparation of the June 15 Report.

Each of the sub-teams also held multiple meetings and teleconferences (in some cases more than 20) over the course of the WG. During these meetings, the sub-teams developed their lists of devices to be tested and assessed; identified appropriate test facilities; developed and revised test plans and procedures (including, in several cases, procedures for anonymization of the devices tested for reporting purposes as discussed in Section 2.6 below).

2.5 Overview of the Testing Process

Under the monitoring of the TWG, the seven category sub-teams met separately to focus specifically on their individual areas of responsibility. Over 130 types of receivers were

laboratory tested under the supervision of the seven sub-teams, with several of the teams testing multiple units of the same type of device to account for process variation.[4]

Tests directly developed by the TWG were conducted by six independent testing laboratories using four anechoic chambers and two conducted testing environments for the cellular, general location/navigation, high-precision, timing, and network sub-teams. The TWG agreed to accept testing being performed in parallel by the FAA/ RTCA for aviation and associated augmentation receivers, and by the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) for space-based receivers, in lieu of separate TWG testing.

Testing in all cases was conducted using laboratory transmission equipment to emulate the signal in the manner in which LightSquared intends to operate in the field. Testing was performed in the 1525-1559 MHz (downlink) and the 1626.5-1660.5 MHz (uplink) bands (for some receiver categories), and actual GPS/GNSS/augmentation/L-band receivers were tested. Lab equipment was also used to simulate the GPS satellite constellation in various configurations.

Testing commenced in March 2011 (with the space sub-team), and was concluded on June 14, 2011, when testing of the final device from the cellular sub-team was completed.

All teams tested the three phases of LightSquared's planned spectrum deployment – one involving LightSquared's operation of a 5 MHz LTE channel centered on 1552.7 MHz (Phase 0); one involving LightSquared's operation of two 5 MHz LTE channels centered on 1552.7 MHz and 1528.8 MHz (Phase 1), and one involving LightSquared's operation of two 10 MHz LTE channels centered on 1550.2 MHz and 1531.0 MHz (Phase 2). Teams included additional potential spectrum deployment scenarios either as part of their initial testing plan, or as subsequently modified. All seven sub-teams developed test plans and test procedures to test operational scenarios against these transmission phases using parameters provided by LightSquared.[5] For teams that had not included a test of the lower 10 MHz downlink channel on a stand-alone basis, LightSquared subsequently encouraged teams to add that as a test case and consideration as a potential mitigation technique.

Test data taken by the facilities selected by the sub-teams (or by Zeta Associates and JPL in the cases of the aviation and space sub-teams, respectively) were analyzed and assessed by each sub-team against identified operational scenarios as set forth in Item Nos. 9 and 10 of the Work Plan.

---

[4] Several of the sub-teams and/or TWG members tested receivers during two weeks of "live-sky" testing that LightSquared and the cellular sub-team organized in Las Vegas, NV during the last two weeks of May 2011. The live-sky tests, while recognized to be potentially useful and illustrative in terms of improving understanding of the propagation effects of LightSquared's proposed transmission system, were not conducted under the same rigorous controls as the conducted and chamber tests called for in the sub-team test plans, and involved only a subset of device types tested by the cellular, high-precision, and general location/navigation sub-teams. The live-sky testing and the results presented to the TWG are addressed in Appendix Ito this Report (and the Attachments thereto).

[5] Appendix B to this Report contains the LightSquared base station and user equipment transmission characteristics (including antenna patterns), parameters, and deployment phases.

2.6 Anonymity of Testing Results

In order to encourage the broadest representation of devices in the testing process, the TWG agreed on a device anonymity mechanism to ensure that test results produced in the report for several of the sub-teams would accurately reflect the results of tests for each device analyzed in those sub-teams' testing processes, but would not publicly associate specific results with specific devices. In tests conducted by the cellular, general location/navigation, high-precision, timing, and network sub-teams, random number codes were assigned to the devices/receivers tested by that sub-team prior to testing. This rendered the results of the tests anonymous. Each supplier of a device/receiver to a sub-team practicing anonymity was informed of the code(s) assigned to hardware it supplied. LightSquared was also provided the code numbers for all devices tested, as were some sub-team leaders, and each agreed to treat the information confidentially (executing confidentiality agreements, when requested).

The TWG agreed that should the FCC require the device code key, LightSquared would provide the list to the Commission under cover of a request for confidential treatment. The complete list of devices tested by the TWG sub-teams is included as Appendix D.1 to this Report.

The National Public Safety Telecommunications Council (NPSTC) submitted comments to the TWG report to its information facilitators, requesting that these comments be included in the WG's final report, which are attached as Appendix N.1. The comments deal specifically with public safety use cases pertaining to three of the sub-teams: Cellular, General Location/Navigation and Timing. It noted that these sub-teams have not had the opportunity to review this document prior to the filing of this report.

2.7 Abstract of Sub-Team Report Summaries

This is the final report of the Working Group (WG) that was formed to study the GPS overload/desensitization issue pursuant to *LightSquared Subsidiary LLC*, DA 11-133 (Int'l. Bur. released January 26, 2011)."LightSquared, along with the non-governmental members of the GPS Technical Working Group (TWG) hereby submit this report which has been approved by the Co-Chairs of the WG.

The TWG identified seven categories of receivers that are representative of the non-military use of GPS in the United States: aviation, cellular, general location/navigation, high precision, timing, networks, and space-based receivers. In each receiver category, devices were selected for assessment such that they represent an appropriate range of manufacturers and uses. The sub-teams prioritized devices for testing by criteria, including criticality of use, such as safety-of-life and public safety; the size of embedded user base; operational and economic dependency on positioning, navigation, and timing information; the availability of suitable test devices; and other category-specific factors.

A brief abstract of Sub-Team report summaries of the findings of each sub-team follows:

2.7.1 Aviation

2.7.1.1 Executive Summary

The Aviation Sub-team used an approach which the Aviation members characterize as "analytical" and LightSquared characterizes as "theoretical," together with results of receiver testing, to analyze the potential for interference to airborne GPS receivers. The analysis defines interference based on existing FAA Technical Standard Orders (TSOs) for certification of such equipment, along with an additional "safety margin" of 6 dB consistent with domestic and international spectrum management practices (see, e.g., ITU-R M.1477) and a further 6 dB reduction for initial acquisition for some operational scenarios. Although the RTCA Minimum Operational Performance Standards ("MOPS"), invoked by the TSOs, only specify the initial acquisition adjustment for in- and near-band interference,[6] a 6 dB adjustment for out-of-band interference is provided for in International Civil Aviation Organization Standards and Recommended Practices (ICAO SARPs) and is consistent with the need for higher C/N_0 for initial acquisition versus tracking as derived in RTCA/DO-235B. The aviation representatives believe it is consistent with established aviation community practices. LightSquared representatives on the sub-team disagreed with the aviation representatives as to whether to use the additional 6 dB for initial acquisition.

Based on the approach outlined above, the Aviation Sub-team concluded that all three phases of the currently proposed LightSquared deployment plan are incompatible with aviation GPS operations absent significant mitigation, and would result in a complete loss of GPS operations below 2000 feet above ground level (AGL) over a large radius from the metro deployment center. For the originally defined LightSquared spectrum deployment scenarios, GPS-based operations are expected to be unavailable over entire regions of the country at any normal operational aircraft altitude.

The Aviation Sub-team considered multiple potential mitigation options to allow the LightSquared ATC service to coexist with existing and currently proposed aviation GPS operations. The most promising involves a shift in the LightSquared ATC transmit frequency. Analysis performed by RTCA suggests that a shift to using only a lower 5 MHz channel likely would be compatible with aviation GPS operations provided that ATC transmissions are kept at or below proposed levels of 32 dBW EIRP. Compatibility of aviation GPS operations with a single lower 10 MHz channel could not be determined definitively without additional study. While not studied by RTCA, a shift in the LightSquared ATC frequency to spectrum that is not

[6] The band corresponding to the definition of "in-band and near-band" in the RTCA MOPS DO-229D excludes the center frequencies that would be occupied by ATC channels corresponding to LightSquared's initially published deployment plan.

adjacent to the GPS band could eliminate all interference concerns for aviation GPS.

The Aviation Sub-team also studied the potential for improvements in GPS receiver selectivity using new filter technology. Such improvements could not be tested because the new filter technology is not available at this time. This mitigation strategy could take many years to design, obtain FAA airworthiness certification, and install new airborne equipment in a manner consistent with FAA requirements. The aviation representatives on the sub-team believe, based on past experience with programs for modification of certified systems with safety or operational benefits that this process would take at least 8-10 years. LightSquared believes that the process could take significantly less time, in light of other instances in which the FAA has issued complicated and costly airworthiness directives to address potential unsafe conditions in far less time, the public policy importance of broadband wireless access, and the broad group of stakeholders working on this issue. Although the Aviation Sub-team has not identified a reliable cost estimate for the filter retrofit option (and cannot since no design currently exists), the aviation representatives have stated that they believe that pursuing the filter strategy will be expensive to implement.

2.7.2 Cellular

2.7.2.1 Executive Summary

To verify any effects on cellular devices, the Cellular Working Group developed test plans in accordance with industry standards to determine any impact on GPS receivers within cellular devices. These test plans are provided as part of the report Appendix C.1 and were agreed to by all parties. The testing sought to determine if any harmful interference would arise to legacy cellular devices.

The Cellular Working Group tested a limited but representative sample of cellular devices sent by four US operators (AT&T, Sprint, US Cellular, and Verizon) to determine the effects of LightSquared signals on GPS receivers embedded in these devices. 41 devices representing different models were tested in a laboratory testing environment with a smaller subset of devices selected and tested in a radiated, live sky fashion utilizing the agreed upon test plans. However, by necessity due to time constraints, the working group did not complete all tests and instead prioritized certain tests to ensure the greatest number of devices was tested with the most meaningful results.

The Cellular Subgroup has analyzed in depth test data from three independent labs, group member contributions and other expert presentations, and internal group analyses of 41 mobile devices tested in the lab. In addition, 29 mobile devices representing 8 models were tested in the field by companies in live sky tests. Enough test data was available to

demonstrate that LightSquared signals in the higher 5 MHz and 10 MHz band (1545.2 to 1555.2 MHz) caused GPS failure for a significant number of the tested devices. In contrast, the current test data and analysis to date indicates that operations in the lower bands (1526 to 1536 MHz) may be possible without harmful interference to existing cellular GPS devices.

Like other subgroups, this subgroup also notes that it could only practically sample a tiny percentage of models relative to what is installed in the field. Counteracting that was a careful selection of devices based on fielding the widest number of different GPS receiver designs and other characteristics.

Based on all the data available, upper band mitigation techniques can be further explored. For lower band (referred at points in this document as "Lower 10 MHz") operation, additional immunity to adjacent L Band signals are within grasp using existing, known filter technologies. A substantial number of legacy devices are being used today and therefore it appears that LightSquared may not be able to operate in the upper portion of the downlink band as mitigation is not possible at this time under current LightSquared deployment plans. However, filtering technology may be available to reduce susceptibility to adjacent band signals into the GPS receivers of future cellular devices. Once the necessary rejection levels have been determined, final filter specifications can be proposed or offered by vendors and evaluated for commercial timing or viability. Until these filters and other mitigation techniques are developed and implemented, it is reasonable to expect that a significant number of mobile devices would continue to be vulnerable to interference from LightSquared's upper band operations.

Originally the subgroup was to test a femtocell device at the request of one of the wireless operators. Due to agreed priority to test the mobile devices, the subgroup ran into time constraints. To resolve the issue, the subgroup considered testing the device after its final report submission and filing the test results in a supplemental report. The wireless operator providing the femtocell and technical support staff to test it has subsequently decided to not pursue testing of this device within the TWG.

2.7.3 General Location and Navigation

Note: There were significant areas within Section 3.3.4 of this Final Report (General Location and Navigation) where LightSquared and the sub-team could not reach agreement. Where different perspectives exist, they are clearly labeled as the "GPS Industry Perspective" or "LightSquared's Perspective."

2.7.3.1 Executive Summary

2.7.3.1.1 GPS Industry Perspective

The General Location/Navigation sub-team has concluded that all phases of the LightSquared deployment plan will result in widespread harmful interference to GPS signals and service and that mitigation is not possible. The team devoted considerable time and effort to studying all three deployment phases proposed by LightSquared. The Phase 1 deployment scenario, which includes both the upper and lower 5 MHz channels at a power level of +62 dBm, was studied comprehensively. Phase 1 Interference Susceptibility tests show that the majority of devices tested will be subject to harmful interference within 1.1 km of a LightSquared transmit tower. Using the FCC authorized transmit power levels, which are higher than those used in phase one, the majority of devices tested would be jammed within 3.3 km of the transmit tower. The projected impact to the Washington D.C. area (including the National Mall and Ronald Reagan Washington National Airport) is illustrated in Figure 1. Red areas show where GPS receivers will be jammed by the LightSquared proposed deployment plan, and yellow areas show the broader areas affected by the FCC authorized deployment plan.

Figure 1

Numerous conference calls and countless hours were spent studying potential mitigation strategies that might allow the proposed LightSquared service to coexist with the well established GPS user base. No stone was left unturned as the team evaluated proposals for mitigation options involving both LightSquared's transmitters and GPS receivers. Another proposed mitigation would be to permanently eliminate the upper channel and deploy only on the lower 10 MHz channel. Although LightSquared insists that this is not part of its deployment plan, this mitigation strategy was discussed at length in the General Location /Navigation sub- team. In fact, the sub- team even altered its test plan after testing had commenced in order to accommodate LightSquared's interest in this mitigation strategy. Lab testing revealed that many devices suffered from harmful interference from the lower 10 MHz channel; specifically, 20 out of 29 devices experienced harmful interference.

Several simulated filters were proposed as options for GPS receivers; however, no testing could be performed since these parts do not exist. While claiming marginal improvements in rejection of the LightSquared signals, these simulated filters did so at the expense of increased degradation of GPS signals. As a result of these efforts, the General Location/Navigation sub-team has concluded that no mitigations exist for the existing user base or for future products as long LightSquared remains in the MSS L-band. The only option for coexistence with GPS is for LightSquared to move to another frequency band.

Several "Live Sky" tests were run over the past few months, and results from one of those tests are included in the General Location/Navigation sub-team report. While the transmitter power level was only a fraction of that specified in the proposed deployment plan, these tests were very useful in confirming the necessity of a free-space propagation model to show worst-case interference effects.

2.7.3.1.2 LightSquared Perspective

Individual manufacturers participating in the General Location/Navigation sub-team did extensive laboratory tests on the potential impact of the LightSquared terrestrial network on 29 of their own devices.

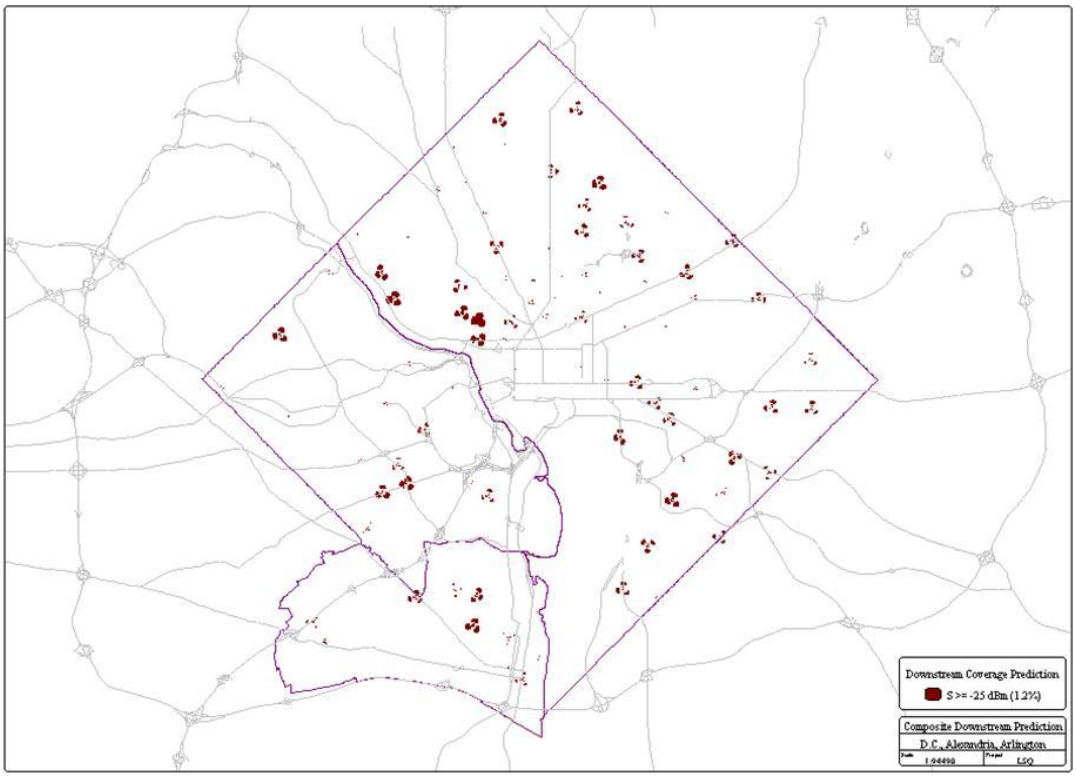
The sub-team reached consensus on the selection of devices and the methodology for testing. There was no consensus regarding the interpretation of the results or the potential for mitigation through either limiting LightSquared base stations to operation on the lower 10 MHz channel or adding filters to future devices.

The representatives of some GPS manufacturers interpret the results based on a definition of harmful interference as a 1 dB change in C/N0 and a worst-case propagation model using free space only. They concluded that no

devices passed when tested against upper channel configurations and only eight devices passed when tested against the lower 10 MHz channel configuration. They contend that the feasibility of adding filters to future devices is unproven. LightSquared strongly believes that the feasibility of adding filters to future devices has been demonstrated by experienced filter manufacturers using proven technology.

In assessing the performance of legacy devices, LightSquared interprets the results based on definition of harmful interference as a 6 dB change in C/N0 and a probabilistic propagation model. This analysis shows that 13 devices passed when tested against upper channel configurations and all 29 devices passed when tested against the lower 10 MHz channel configuration. The analysis established that all devices tested against the Lower 10 MHz channel experienced a 6 dB change in C/N0 only at signal strengths greater than -25 dBM; a signal strength which will occur only in up to 1.2% of LightSquared's service area as shown in the maps below.

WI-LOS Analysis of -25 dBm7 Signal Strength and Greater in Washington DC using morphology data collected through drive testing



[7] This model is part of the cellular RF planning tool, CelPlan

Figure 2

Korowajczuk Propagation Model Analysis of -25 dBM Signal Strength and Greater in Washington DC

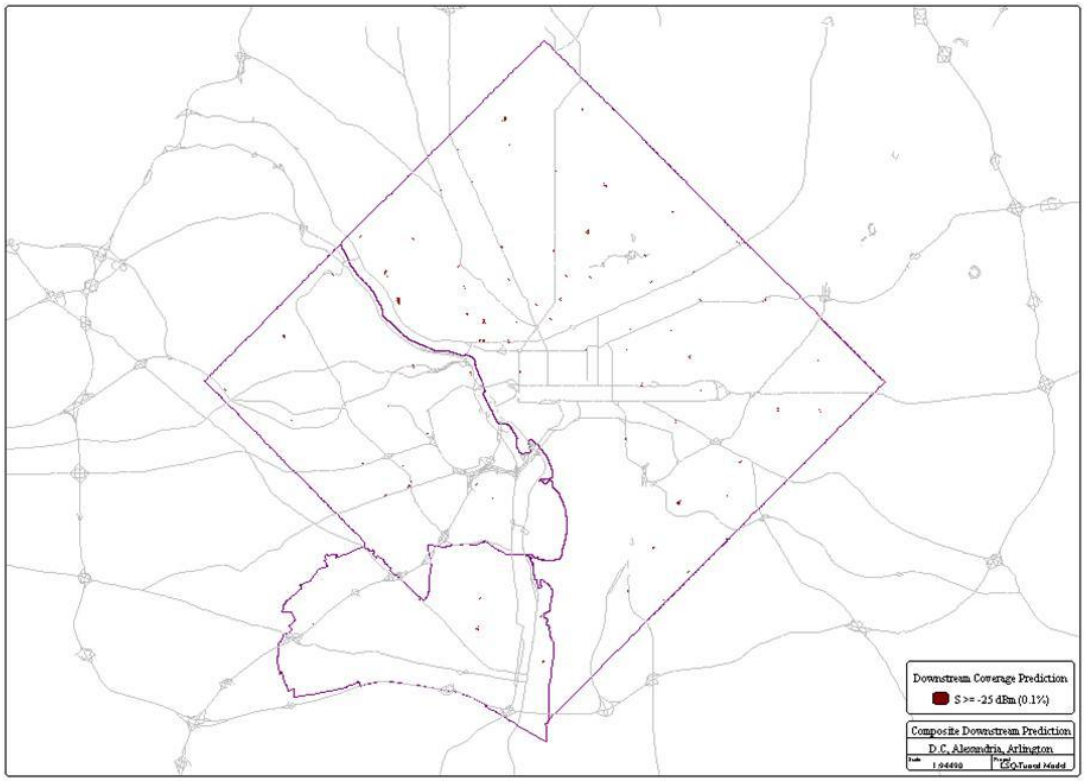


Figure 3

2.7.4 High Precision, Timing and Networks

This report summarizes the test results and presents the conclusions for the High Precision, Timing, and Network Sub-Teams. These Sub-Teams combined their efforts, as the types of testing required were compatible, and this helped meet the testing schedule.

Three types of interference studies were conducted:

- Anechoic Chamber – radiated tests in a controlled environment.
- Live Sky – radiated tests in an uncontrolled open environment.
- Laboratory – conducted tests in a controlled environment.

2.7.4.1 GPS Community Positions

These three interference studies collectively are sufficient to reach the following conclusions with respect to LightSquared interference with GPS for High Precision, Timing, and Network receivers:

1) The LightSquared Base Station 4G LTE signals harmfully interfere with High Precision, Timing, and Network GPS receivers over long ranges.
2) The LightSquared Base Station signals cause harmful co-channel interference with the FCC licensed StarFire and OmniSTAR augmentation systems.
3) LightSquared handsets, when operated close to a GPS receiver, harmfully interfere with it.
4) Current GPS receivers using other GNSS constellations such as Galileo and Compass and augmentation systems such as Wide Area Augmentation System (WAAS) with signals in the GPS L1 band will suffer harmful interference from the LightSquared signals for the same reasons as do the GPS signals[8].
5) In the lower 10 MHz channel configuration, 31 of 33 High Precision and Network GPS receivers tested experienced harmful interference within the range of power levels that would be seen inside the network (Fig 84). High precision receivers fielded today would experience harmful interference at up to 5km from a single LightSquared base station.

With respect to possible mitigations:

1) We know of nothing feasible that can be done to make currently fielded wide band High Precision, Timing, and Network receivers and augmentation systems operate properly when in the vicinity of a LightSquared base station, with respect to either GPS or augmentation systems, under LightSquared's Phase 0, 1 or 2 rollout plans, or the recently announced 10 MHz Low Band rollout plan.
2) For some currently fielded narrow band Timing receivers, mitigation may be feasible if LightSquared operations are restricted solely to the 5/10 MHz Low Band or to the 5/10 MHz High Band.
3) We know of no currently available receiver, filter, antenna or other mitigation technology that would enable the construction of future wideband High Precision, Timing, or Network GPS receivers and augmentation systems that are compatible with the Phase 0, 1, or 2 LightSquared rollout plans.
4) We believe more study is required on the feasibility of building future wideband High Precision, Network, and Timing receivers and augmentation systems that would be compatible with LightSquared terrestrial signals and which would provide the same performance as today's receivers and systems. We do not foresee any possibility that LightSquared signals near the GPS band could ever be compatible with wideband receivers.

[8] These other constellations and signals were not studied, but because their signals occupy the GPS L1 band, and the interference affects the RF front end of the receivers, they will necessarily suffer interference.

5) The most straightforward mitigation would be for LightSquared to use a different frequency band for their terrestrial network.

6) The viability of proposed future concepts to accommodate high precision GPS and MSS augmentations in the presence of interference from LightSquared terrestrial operations only in the lower 10MHz band has not been tested or validated as part of this study.

In addition to these conclusions, we note the following concerns:

1) Many users maintain their current receivers and systems for up to 15 years (and occasionally longer) to achieve an economic return on investment.

2) The use by LightSquared of power levels beyond those planned, up to the authorized FCC maximum of 72 dBm, would extend the range of interference and receiver degradation.

2.7.4.2 LightSquared Positions

The studies are sufficient to reach the following conclusions:

1) High Precision and Network GPS receivers are designed in such a way that they may receive harmful interference due to receiver overload from the LightSquared Base Station 4G LTE signals operating in an adjacent band. Timing receivers experience overload in some spectrum configurations; with almost all performing well in the presence of the lower 10 MHz channel.

2) High Precision and Network GPS receivers utilizing StarFire and OmniStar augmentation systems are designed with RF front ends to accommodate both GPS and augmentations signals. Due to this design, interference between LightSquared base station signals and the StarFire and OmniSTAR augmentation systems is possible.

3) Some GPS receivers, when a LightSquared handset is operated very close by (within 1 meter distance), may also experience receiver overload.

With respect to possible mitigations:

1) Mitigation is feasible, particularly in connection with LightSquared operation on the 10 MHz Low Band. Such mitigations could include, but not be limited to the following options:

   - Operating the MSS augmentation link close to the upper end (1559 MHz) of the MSS L-band and using a narrower bandwidth, but still common preselector for the augmentation signal and GPS. Basically, this would involve operating the augmentation link in the guard band of the preselector.

   - Operating the MSS link with a dedicated (not common) preselector, separate from the GPS preselector. This would allow the MSS augmentation link to be operated in more frequencies than immediately adjacent to 1559 MHz.

- Operate the augmentation link on a multimode (terrestrial-satellite) link that LightSquared could provide in the future. This would allow (a) operation anywhere in the L-band, including frequencies co-channel with the ATC, and (b) offer the added benefit of much higher throughputs when in terrestrial coverage.
- Operate the augmentation link on a non-L-band cellular data link. Filter the GPS signal with an improved preselector sufficient to protect it in proximity to ATC channels. Software in the application layer causes augmentation link to be switched between the existing MSS L-band link and the cellular data link.

2) Due to time constraints, the sub-teams were not able to give adequate consideration to potential receiver-side mitigation options. Such options appear to be viable, and need to be worked jointly between the GPS community and LightSquared going forward.

2.7.5 Space-based Receivers

Two different high-precision space receivers used for either Radiooccultation (RO) measurements or orbit determination/navigation were studied - a current generation receiver (IGOR) and a next generation receiver (TriG). In addition, testing was performed for two high precision GPS receivers that are representative of receivers used in the International GNSS Service (IGS) and other NASA science applications.

LightSquared notes that the next generation TriG receiver is still in development.

Conducted testing performed at NASA/JPL on four NASA GPS receivers indicated that a 1 dB degradation in carrier-to-noise density ratio (C/N_0), assuming the LightSquared signal at the output of a GPS passive receive antenna, occurred at approximately -68 dBm for one model of high precision GPS receiver and -56 dBm for another high precision receiver. For the two space-based receivers tested, 1-dB degradation to C/N_0 occurred at approximately -82 dBm for the TriG and -59 for the IGOR receiver.

LightSquared notes that these measurements were performed with dual LightSquared emissions (both the upper and lower channels). LightSquared further notes that when measured with a single LightSquared emission in the lower channel, 1-dB degradation to C/N0 occurred at approximately -63 dBm for the developmental TriG and -13 dBm for the IGOR. This shows an improvement of 19 dB for the TriG and 46 dB for the IGOR.

Aggregate interference statistics were calculated for a LightSquared base station deployment of approximately 34940 stations distributed among 139 major cities in the US and using LightSquared base station characteristics. For the RO receiver in the 800km/72° orbit (Case 1), degradation of at least 1-dB (in C/N_0) ranged from 0.4% of the time (IGOR) to 9% of the time (TriG). For the RO receiver in the 520 km/24° orbit (Case 2), degradation was less than 1 dB for both receivers since the satellite does not pass over the US. For the navigation receiver in the 400 km/72° orbit (Case 3), degradation of at least 1-dB occurred

about 3% of the time for the TriG receiver and 0% of the time for the IGOR receiver. These results assume each base station sector is transmitting 2 (5 MHz) channels at 32 dBW EIRP per channel. If base stations transmit up to their FCC authorized level of 42 dBW EIRP, then the degradation to TriG will increase to 12% of the time. In NASA's view, the interference to space-based GPS receivers used for RO would be severely disruptive to NASA's science missions based on the test and analysis conducted in the TWG. Space-based GPS receivers used for navigation and precise orbit determination would receive a lesser amount of interference, though interference would occur. Therefore, mitigation of the interference to space-based GPS receivers is necessary in NASA's view.

LightSquared notes that the peak aggregate interference levels identified by the simulations were -55.1 dBm for the COSMIC-2 satellite in a 800 km/72° inclined orbit, -88.2 dBm for the COSMIC-2 satellite in a 520 km/24° inclined orbit, and -78.1 dBm for the LEOSAT in a 400 km/72° inclined orbit.

For high-precision GPS receivers used for Earth sciences and other applications requiring precise measurements, analysis was conducted to determine the required minimum separation distance between a terrestrial high-precision GPS receiver and a single LightSquared base station where there would be a 1 dB drop in the received C/N_0. Results of the analysis showed that separation distances for the two receivers tested, assuming several different propagation models, ranged from approximately 1.5 to 4 kilometers for one receiver type to approximately 3 to 12 kilometers for the other receiver model tested. For the space based receivers, separation distances were approximately 4 km for the IGOR and 22 km for the TriG, assuming free space propagation conditions.

LightSquared notes that these measurements were performed with dual LightSquared emissions (both the upper and lower channels).

Given the ATC deployment density anticipated with the LightSquared terrestrial network, it is unlikely that such separation distances could be assured. Therefore in NASA's view, mitigation of the interference to high precision GPS receivers used for NASA's scientific purposes is necessary.

Preliminary analysis also showed that MSS handsets operating in the 1626.5-1660.5 MHz MSS band could interfere with space-based receivers at distances in excess of 200 meters during terrestrial pre-launch check-out. However, there was insufficient time to thoroughly investigate this potential interference scenario, or the possible aggregate interference effect from handsets, for either space-based receivers or high precision science receivers.

NASA is of the view that, although the TWG members worked diligently and in good faith throughout the period prescribed by the FCC, it was impossible to adequately evaluate and thoroughly investigate potential interference mitigation options for space-based and high

precision science receivers. While some limited testing[9] conducted by JPL at the request of the TWG towards the end of the TWG's work showed promise for one type of space-based receiver, there was minimal improvement for the second space-based receiver tested. In NASA's view, there was not sufficient time to adequately evaluate the effectiveness of this particular technique, or any other mitigation technique, for space-based or terrestrial high precision science receivers.

LightSquared believes that, based on the measured lower channel test results and the simulation calculations, restricting LightSquared emissions to the lower 10 MHz channel completely mitigates the current generation IGOR receiver with in excess of 40-dB margin between the peak aggregate power received and the received power level resulting in 1-dB C/N_0 degradation. LightSquared also believes that restricting operations to the lower 10 MHz channel reduces the impact on the next generation TriG receiver, but does not completely mitigate it. Additional mitigation would be required in the form of increased selectivity through front end filtering at the receiver. LightSquared believes that since the TriG receiver is still in development, it could be modified to achieve complete mitigation with minimal impact on NASA science missions.

NASA notes that one mitigation technique that would resolve interference to both space-based and terrestrial high precision GPS receivers is to relocate high power terrestrial operations to a different frequency band. However, any potential candidate bands would need a thorough evaluation that would consider, among other issues, the implications for providing terrestrial wireless services and potential impacts to in-band and adjacent band operations for incumbent systems and services.

[9] NASA was able to conduct limited testing of one potential mitigation technique, use of just the lowest 10 MHz channel by LightSquared, for the two space-based receivers but not for the high precision science receivers.

3. Sub-Team Reports

3.1 Aviation Sub-Team

The efforts of the Aviation Sub-team[10] closely paralleled those conducted concurrently by the FAA and RTCA[11]. Many members of the Aviation Sub-team also actively participated in RTCA's Special Committee 159, Working Group 6, which was also studying this issue. The analytical work focused primarily on the potential interference to an airborne GPS receiver that is minimally compliant with existing RTCA performance specifications. Laboratory testing was also conducted on a limited number of receivers. The result of RTCA's work has been published as RTCA/DO-327, "Assessment of the LightSquared Ancillary Terrestrial Component Radio Frequency Interference Impact on GNSS L1 Band Airborne Receiver Operations." The contents of this document are referenced throughout the Aviation Sub-team report.

Executive Summary

The Aviation Sub-team used an approach which the Aviation members characterize as "analytical" and LightSquared characterizes as "theoretical," together with results of receiver testing, to analyze the potential for interference to airborne GPS receivers. The analysis defines interference based on existing FAA Technical Standard Orders (TSOs) for certification of such equipment, along with an additional "safety margin" of 6 dB consistent with domestic and international spectrum management practices (see, e.g., ITU-R M.1477) and a further 6 dB reduction for initial acquisition for some operational scenarios. Although the RTCA Minimum Operational Performance Standards ("MOPS"), invoked by the TSOs, only specify the initial acquisition adjustment for in- and near-band interference,[12] a 6 dB adjustment for out-of-band interference is provided for in International Civil Aviation Organization Standards and Recommended Practices (ICAO SARPs) and is consistent with the need for higher C/N_0 for initial acquisition versus tracking as derived in RTCA/DO-235B. The aviation representatives believe it is consistent with established aviation community practices. LightSquared representatives on the sub-team disagreed with the aviation representatives as to whether to use the additional 6 dB for initial acquisition.

Based on the approach outlined above, the Aviation Sub-team concluded that all three phases of the currently proposed LightSquared deployment plan are incompatible with aviation GPS operations absent significant mitigation, and would result in a complete loss of GPS operations below 2000 feet above ground level (AGL) over a large radius from the metro deployment center. For the originally defined LightSquared spectrum deployment scenarios,

[10] Aviation Sub-team members included: LightSquared, Trimble, USGIC, FAA, Garmin, MITRE, Rockwell Collins, Zeta Associates, Boeing, Lockheed Martin, Thales, AJ Systems, United Air Lines, and Airline Pilots Association, International.

[11] RTCA is a private, not-for-profit corporation that develops consensus-based recommendations regarding communications, navigation, surveillance, and air traffic management system issues. For more information about RTCA, see http://www.rtca.org/aboutrtca.asp.

[12] The band corresponding to the definition of "in-band and near-band" in the RTCA MOPS DO-229D excludes the center frequencies that would be occupied by ATC channels corresponding to LightSquared's initially published deployment plan.

GPS-based operations are expected to be unavailable over entire regions of the country at any normal operational aircraft altitude.

The Aviation Sub-team considered multiple potential mitigation options to allow the LightSquared ATC service to coexist with existing and currently proposed aviation GPS operations. The most promising involves a shift in the LightSquared ATC transmit frequency. Analysis performed by RTCA suggests that a shift to using only a lower 5 MHz channel likely would be compatible with aviation GPS operations provided that ATC transmissions are kept at or below proposed levels of 32 dBW EIRP. Compatibility of aviation GPS operations with a single lower 10 MHz channel could not be determined definitively without additional study. While not studied by RTCA, a shift in the LightSquared ATC frequency to spectrum that is not adjacent to the GPS band could eliminate all interference concerns for aviation GPS.

The Aviation Sub-team also studied the potential for improvements in GPS receiver selectivity using new filter technology. Such improvements could not be tested because the new filter technology is not available at this time. This mitigation strategy could take many years to design, obtain FAA airworthiness certification, and install new airborne equipment in a manner consistent with FAA requirements. The aviation representatives on the sub-team believe, based on past experience with programs for modification of certified systems with safety or operational benefits, that this process would take at least 8-10 years. LightSquared believes that the process could take significantly less time, in light of other instances in which the FAA has issued complicated and costly airworthiness directives to address potential unsafe conditions in far less time, the public policy importance of broadband wireless access, and the broad group of stakeholders working on this issue. Although the Aviation Sub-team has not identified a reliable cost estimate for the filter retrofit option (and cannot since no design currently exists), the aviation representatives have stated that they believe that pursuing the filter strategy will be expensive to implement.

3.1.1 Work Plan Item 1: Establish Pertinent Analytical and Test Methodologies and Assumptions Underlying the Test Regime

Definition of Harmful Interference Criteria

In the FCC rules[13], harmful interference is defined as "interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the ITU] Radio Regulations."

For aviation GPS operations, the aviation representatives on the sub-team defined harmful interference as any unwanted signal that prevents the airborne GPS receiver from meeting all of the performance requirements specified in RTCA Minimum Operation Performance Standards (RTCA/DO-229D, DO-253C, and DO-316) as invoked by FAA Technical Standard Orders (TSOs), plus an extra 6 dB safety margin and, for applicable operational scenarios, 6 dB for initial acquisition. The Aviation Sub-team identified several key performance requirements to be assessed by test

[13] Section 2.1 of the FCC's rules, 47 CFR §2.1: No. 1.169 of the ITU Radio Regulations.

and/or analysis: initial acquisition, signal tracking and data demodulation, Wide Area Augmentation System (WAAS) message loss rate, and pseudorange measurement accuracy.

3.1.1.1 Relevant Broadband Signal Characteristics

As part of developing the testing methodology for the Aviation receivers, the following broadband network technical signal characteristics were identified:

Power Levels: The measure of power from the LightSquared base station was quoted in terms of equivalent isotropic radiated power (EIRP). Since a signal's power level varies according to the volume of data it is transmitting as well as the modulation scheme used to broadcast it, the average value was used for analytical purposes. The aggregate radio frequency interference ("RFI") analysis performed by RTCA assumed an EIRP of 32 dBW per LTE channel per sector. This limit is based on LightSquared's stated deployment plans, but is significantly lower than the maximum authorized limit of 42 dBW EIRP. The laboratory tests used emulated 5 and 10 MHz wide bandpass white noise signals from an arbitrary waveform generator. The emulated signals were transmitted through a set of filters provided by LightSquared before they were presented to the receiver under test. These filters were sufficient to ensure that the power spectral density of the emulated LightSquared base stations signals in the RNSS band (1559 – 1610 MHz), as measured at the passive antenna connector, was representative of the OOBE noise from the LightSquared base station.[14]

Bandwidth: This is the amount of spectrum that was consumed by the test signal transmitted from the LightSquared Test Transmitter. Bandwidth was quoted in megahertz (MHz) and was a value of 5 or 10 MHz to ensure true operational conditions were being simulated.

Antenna Patterns: LightSquared proposes to deploy base stations with directional antennas having a 16.8 dBi gain in the bore sight and a 3-dB beamwidth of 7.95° in elevation and 66.33° in azimuth. Typically they will have 2° electrical downtilt. The actual 3D patterns of an antenna planned to be deployed were utilized in the analyses. (See Appendix A.5) Many GPS receivers are installed with antennas that comply with RTCA/DO-301 or RTCA/DO-228 (change 1) performance standards, and those built to other standards are not expected to be more susceptible to adjacent band interference These standards do not specify antenna gain below the aircraft, so the antenna pattern model from DO-235B was utilized. (See RTCA/DO-327, section 2.2.2.1)

[14] In an actual deployment, the power spectral density of LightSquared's base station signals would be at least 125 dB below the inband level (25 dBW/MHz for a 5 MHz channel – (-100 dBW/MHz) = 125 dB). The present filter provided less rejection (65 dB in the RNSS band) but that did not affect the validity of the laboratory set up as the LightSquared signal power at the GPS receiver input was never greater than -10 dBm (-40 dBW).

3.1.1.2 Interference Analysis Assumptions

RTCA/DO-327 provides extensive documentation of the assumptions used to analyze the effects of the LightSquared system on aviation GPS operations. These assumptions can be summarized as follows:

- Since multiple ATC base stations are visible to aircraft in flight, the analysis determined the aggregate RFI levels that would be seen at the airborne GPS receiver.
- ATC base station concentrations were based on the single-city model described in DO-327 for all scenarios except for the high altitude case. For high altitude operations a representative scenario over the mid-Atlantic region of the U.S. was used. (See section 3.2.3 of DO-327 for details). Base station exclusion zones were derived from existing regulations for airport obstacle clearance surfaces.
- An ATC base station loading factor of 100 % was assumed for the aggregate RFI analysis. LightSquared's position is that an RFI reduction of 2.2 dB should be applied to the maximum calculated value due to an average base station loading factor of 60% when LightSquared's signal is aggregated over a large number of sources. The aviation representatives' position is that using a loading reduction would be acceptable only if it was enforced within an FCC authorization.
- The propagation models used in the analyses varied depending on the operational scenario. For scenarios at altitudes above 550 meters AGL, a free space path loss model was assumed. For scenarios below 550 meters AGL, a combination of probabilistic path loss models was used. The combination of models included the use of a 2-Ray model at distances below 1 km and changed to a Hata-Okamura model at longer distances. Depending on the operational scenario, transitions between models were made continuous by using either a logarithmic fit function or an Erceg/Greenstein path loss segment. Details of the propagation models can be found in Section 2.3 and appendix B of RTCA/DO-327.
- Receiver susceptibility was evaluated relative to the minimum GPS receiver selectivity mask specified in the minimum performance standards (DO-229D, DO-253C, and DO-316).[15]
- The assessment of receiver susceptibility was supplemented by measurements on 8 GPS receivers used in aviation, including both airborne and ground-based applications. This section of the TWG report summarizes and analyzes results for four airborne receivers compliant with DO-229, DO-253, or DO-316. Excerpts from the test results for DO-208 airborne receivers and ground receivers may be found in Appendix A.2.

[15] Some existing GPS receivers have been certified to TSO-C129 that invokes DO-208. Such equipment is more tolerant of adjacent band interference than DO-229D avionics, but such equipment does not provide equivalent operational capabilities (e.g., precision approach) for which a wider bandwidth receiver is required. The aviation representatives note that since 1997, the FAA has approved all manufacturers' deviation requests to use the wider DO-229 MOPS radio interference mask for TSO-C129 receivers, and most TSO-C129 receivers in operation today use the wider DO-229 mask.

3.1.1.3 Testing methodology

The methodology applied to the testing of LightSquared's impact on aviation GPS receivers was based on RTCA minimum operational performance standards (MOPS) (DO-229D, DO-253C and DO-316). MOPS provide standards for specific equipment and its component units necessary for the system to properly perform its intended function(s). The MOPS provide the information needed to understand the responses and required performance that should be expected from the device under test (DUT). Compliance with these standards is the means of assuring the equipment will perform its intended function(s) satisfactorily under all conditions normally encountered in routine aeronautical operations. The FAA invoke MOPS (or portions thereof) into Technical Standard Orders (TSOs) [16] and other nations certify avionics using harmonized certification guidance. Compliance with the TSO and the associated MOPS provides a basis for demonstrating that a system meets FAA technical requirements for certification. MOPS may be implemented by one or more regulatory documents and/or advisory documents and may be implemented in part or in total. The objective of the following tests, performed for evaluation of aviation receiver effects, is to evaluate the overload and desensitization impact of the LightSquared transmissions on the Global Navigation Satellite System (GNSS) receiver. This impact is verified by evaluating GNSS receiver performance metrics (critical to a certified aviation receiver) in the presence of LightSquared 3GPP emissions.

3.1.2 Work Plan Item 2: Select the Categories of Receivers and Receivers to be Tested

The Aviation Sub-team selected receivers based mainly on device availability – for example, those that were already owned by the FAA Technical Center. This set of receivers includes equipment that has been certified for primary navigation in instrument conditions and meet the most rigorous FAA requirements.

There are many other aviation receiver models in addition to those tested, including models by other manufacturers that are also certified to the FAA requirements for use in instrument conditions, which are not included within the tested set.

Receivers

The following FAA certified aviation receivers were used for the MOPS-based receiver testing:

[16] Although TSOs incorporate MOPS, they can also modify the MOPS depending on the type of system covered by the TSO.

- Canadian Marconi GLSSU 5024
- Garmin GNS 430W
- Garmin GNS 480
- Rockwell Collins GNLU-930 Multimode Receiver

The following receivers were also characterized to determine the point at which the LightSquared signals resulted in a 1 dB degradation in C/N_0 and complete loss of function. However, since these receivers are either ground-based or were certified to older standards, their performance under the MOPS test conditions was not evaluated.

- An RTCA DO-208 compliant airborne receiver
- Local Area Augmentation System (LAAS) Ground Facility (LGF) receiver
- Novatel G-II WAAS Ground Reference Station
- Zyfer Timing Receiver

3.1.3 Work Plan Item 3: Develop Operational Scenarios

Aviation use of GPS is not limited to navigation. It is also used to support many other safety-of-flight applications as well. These applications greatly enhance aviation safety and operational capabilities. While acknowledging the increasing importance of GPS in air navigation, LightSquared notes that most operational cases below have existing available non-GPS alternatives that rely on traditional navigational systems (*e.g.* ground-based navigational aids or instrument landing system (ILS) procedures), and that aircraft can and do operate in the National Airspace System (NAS) without the use of GPS.[17] The aviation representatives note that the United States plans to divest many of the traditional navigation systems. The following list, while not exhaustive, identifies many of the ways GPS is used within the aviation industry:

3.1.3.1 Enroute and terminal area navigation

GPS is widely used by aircraft for navigation to and from airports, both in visual and instrument conditions. For many aircraft, GPS is used as a primary means to navigate from point to point. The area navigation provided by GPS allows direct and therefore more efficient routing that is no longer predicated on the circuitous airway paths that go from one ground-based navigation station to the next In the event of an in-flight emergency, GPS systems can provide immediate navigation to the closest airport, even in areas where there are no ground-based navigation aids.

3.1.3.2 Instrument approaches and flight procedures

GPS-based approaches, both standalone and those augmented by WAAS/GBAS, allow aircraft to land safely at airports throughout the country. GPS approaches require significantly less ground infrastructure

[17] For example, in the case of Category II/III IAPs, no equivalent GPS procedures currently exist, but were analyzed to address application of GPS at similar altitudes/runway distances as further described in the RTCA report.

than those approaches utilizing ground-based navigation aids. Vertically-guided GPS approaches increase aviation safety by allowing the pilot to fly a stabilized approach to a safe landing.

3.1.3.3 Surveillance

The FAA is in the process of implementing the NextGen program, which uses airborne GPS as a foundation for a new Air Traffic Control system. Automatic Dependent Surveillance-Broadcast (ADS-B) equipment is used to broadcast GPS-derived position reports to other aircraft in the vicinity and to Air Traffic Control centers on the ground. ADS-B promises to provide increased safety, precision, capacity and capability to Air Traffic Control with a reduced cost of operation as it is not dependent on ground-based radar systems. The FAA has mandated that all aircraft operating in class A, B or C airspace be equipped with ADS-B by 2020.

3.1.3.4 Traffic Alerting and Collision Avoidance

GPS is used as an input to many traffic alerting and collision avoidance systems, including those that will be derived from ADS-B. These systems can enhance safety by providing pilots with timely alerts of potential collisions with other aircraft so that they can be avoided.

3.1.3.5 Terrain Awareness and Warning

Supplies position and altitude information to many terrain awareness systems. Such systems greatly reduce the likelihood of controlled-flight-into-terrain incidents by providing the pilot with a picture of the aircraft's position relative to the surrounding terrain and obstacles.

3.1.3.6 Cockpit Position Display

Many aircraft are equipped with electronic multi-function displays that depict the aircraft's location on a map. GPS is a primary source of position data for the these displays. They reduce pilot workload by improving situational awareness by showing the aircraft position on a map that can be overlaid with weather radar and traffic information. Such systems also help reduce runway incursions because they provide an unambiguous display of the aircraft position relative to active runways and other airport landmarks.

3.1.3.7 Low cost Attitude and Heading Reference Systems

GPS is used in conjunction with low cost inertial sensors to provide reliable, inexpensive and lightweight attitude and heading systems. These devices are used to replace spinning-mass gyroscopic instruments that have notoriously poor reliability and provide the pilot's primary means for determining attitude and heading during instrument flight.

3.1.3.8 Emergency Location and Airborne Search and Rescue

GPS is a key technology for airborne search and rescue operators. GPS allows search and rescue aircraft to fly precise pre-determined search patterns at any location, day or night, under all weather conditions. Accurate GPS position reports allow rescue personnel to quickly reach the correct location once the victim is found.

3.1.3.9 Synthetic Vision

Synthetic vision systems provide a virtual 3D image of the surrounding terrain that enhances situational awareness when flying in instrument conditions.

The Aviation Sub-team used the following five operational scenarios defined in the RTCA Radio Frequency Interference ("RFI") assessment document, RTCA/DO-235B as the basis for the analyses. While these scenarios are only focused on the navigation uses of GPS, the use cases outlined above will translate to these scenarios based on the operating altitude of the aircraft. For each of the operational scenarios, critical performance requirements from the relevant RTCA MOPS were evaluated in the presence of both LightSquared emissions (considering constraints on the deployment of base stations near airports to protect mobile satellite services) and all known other interference sources as identified in DO-235B. This section provides a brief summary of the key parameters assumed in each scenario. A complete description of these operational scenarios can be found in section 3 of RTCA/DO-327.

3.1.3.10 High Altitude En Route RFI Encounter Scenario

This scenario represented an aircraft operating in the en route portion of a flight. The aircraft is assumed to be in a high speed level flight at a representative altitude of 18,000 feet. This scenario is described in detail in section 3.2 of RTCA/DO-327.

Receiver Modes Evaluated:	GPS and WAAS tracking and data demodulation; initial (warm start) acquisition
Aircraft Antenna Height:	18,000 feet (5.49 km) mean sea level (MSL)
Base Station Antenna Height:	30 meters AGL
Radio Horizon to Base Stations:	328.2 km
LightSquared Source Concentration Model:	A multi-city regional model was used to model ATC base stations for this scenario. Details can be found in section 3.2.3 of DO-327. Mobile terminal emissions were not considered.

RFI Sources Considered:	LightSquared ATC base station emissions, GNSS intra-system (CDMA) noise, on-board installed avionics emissions; passenger cabin portable electronic device emissions.

3.1.3.11 Generic Low Altitude / Terminal Area (FAF WP) RFI Encounter Scenario

For the terminal area scenario, the aircraft was assumed to be in level flight with its GNSS antenna at an altitude typical for an aircraft established on the final approach to landing. It was based on the representative case of the final approach fix waypoint (FAF WP) on the Category I approach LAX Runway 25L (Los Angeles, CA). This scenario is described in detail in section 3.3 of RTCA/DO-327.

Receiver Modes Evaluated:	GPS and WAAS tracking and data demodulation; initial acquisition
Aircraft Antenna Height:	535.2 meters AGL
Base Station Antenna Height:	30 meters AGL
Radio Horizon to Base Stations:	118 km
Mobile Antenna Height:	1.8 meters AGL
Radio Horizon to Mobile Terminals:	101 km
LightSquared Source Concentration Model:	The single-city model described in DO-327 was used to model ATC base stations for this scenario. Mobile terminals were evaluated at densities of 100, 300, and 1000 terminals per 3.8 km^2 cell. There were no exclusion zones for base stations or mobile terminals in this scenario.
RFI Sources Considered:	LightSquared ATC base station emissions; LightSquared ATC mobile terminal emissions; GNSS intra-system (CDMA) noise; on-board installed avionics emissions; baseline aggregate RFI from other ground-based sources

3.1.3.12 Generic Category I Precision Approach RFI Encounter Scenario

For the Category I Precision Approach scenario, the aircraft was assumed to be in a stabilized descent on a 3° glide slope at the Category I decision height (DH) for the approach. This scenario is described in detail in section 3.4 of RTCA/DO-327.

Receiver Modes	GPS and WAAS tracking and data demodulation

Evaluated:	
Aircraft Antenna Height:	53.34 meters AGL
Base Station Antenna Height:	30 meters AGL
Radio Horizon to Base Stations:	52.7 km
Mobile Antenna Height:	1.8 meters AGL
Radio Horizon to Mobile Terminals:	35.7 km
LightSquared Source Concentration Model:	The single-city model described in DO-327 was used to model ATC base stations for this scenario. Mobile terminals were evaluated at densities of 100, 300, and 1000 terminals per 3.8 km^2 cell. Exclusion zones for base stations and mobile terminals are based on airport obstacle clearance surfaces.
RFI Sources Considered:	LightSquared ATC base station emissions; LightSquared ATC mobile terminal emissions; GNSS intra-system (CDMA) noise; on-board installed avionics emissions; baseline aggregate RFI from other ground-based sources

3.1.3.13 Generic Category II/III Precision Approach RFI Encounter Scenario[18]

For the Category II/III Precision Approach scenario, the aircraft was assumed to be in a stabilized descent on a 3° glide slope at the 100 foot decision height for the Category II approach. This scenario is described in detail in section 3.5 of RTCA/DO-327.

Receiver Modes Evaluated:	GPS and WAAS tracking and data demodulation
Aircraft Antenna Height:	25.94 meters AGL
Base Station Antenna Height:	30 meters AGL
Radio Horizon to Base Stations:	43.6 km
Mobile Antenna Height:	1.8 meters AGL
Radio Horizon to Mobile Terminals:	26.5 km
LightSquared Source Concentration Model:	The single-city model described in DO-327 was used to model ATC base stations for this scenario. Mobile

[18] Currently, no GPS-based procedures exist that are equivalent or substantially similar to Category II/III IAPs, however the FAA has plans to publish GBAS Cat II/Cat III procedures.

	terminals were evaluated at densities of 100, 300, and 1000 terminals per 3.8 km^2 cell. Exclusion zones for base stations and mobile terminals are based on airport obstacle clearance surfaces.
RFI Sources Considered:	LightSquared ATC base station emissions; LightSquared ATC mobile terminal emissions; GNSS intra-system (CDMA) noise; on-board installed avionics emissions; baseline aggregate RFI from other ground-based sources

3.1.3.14 Generic Surface Movement (Taxiway) Guidance RFI Encounter Scenario

This scenario represented an aircraft located on a taxiway. The aircraft was either stationary or in a slow taxi. This scenario is described in detail in section 3.6 of RTCA/DO-327.

Receiver Modes Evaluated:	GPS and WAAS tracking and data demodulation; initial acquisition
Aircraft Antenna Height:	4 meters AGL
Base Station Antenna Height:	30 meters AGL
Radio Horizon to Base Stations:	30.8 km
LightSquared Source Concentration Model:	An ATC base station concentration based on a 2.2 km tower spacing is used in this scenario. Mobile terminal emissions are not considered. Exclusion zones for base stations are based on airport obstacle clearance surfaces.
RFI Sources Considered:	LightSquared ATC base station emissions; GNSS intra-system (CDMA) noise; on-board installed avionics emissions; baseline aggregate RFI from other ground-based sources

3.1.4 Work Plan Item 4: Establish the Methodology for Analyzing Test Results

The analysis of the vulnerability of aviation GPS receivers to LightSquared signals was based primarily on calculations referenced to Fig C-1 in RTCA DO-327. This interference mask is invoked in FAA TSOs and in ICAO SARPs for stand-alone GPS equipment, as well as for equipment for GPS augmented by satellite-based and ground-based augmentation systems (SBAS/GBAS) (note that the United States SBAS is referred to as WAAS). The mask, which was first published in 1996 in the original version of RTCA DO-229, describes the maximum level of adjacent band continuous wave (CW) interference that a certified GPS receiver is required to tolerate. In this analysis, the CW mask is assumed to be applicable to broadband LTE signals in the 1525 – 1559 MHz band and also adjusted downward by 6 dB for initial acquisition. Although the MOPS only specifies the initial acquisition adjustment for

in- and near-band interference, a 6 dB adjustment for out-of-band interference is provided for in ICAO SARPs and is consistent with the need for higher C/N_0 for initial acquisition versus tracking as derived in RTCA/DO-235B. LightSquared representatives on the sub-team disagreed with the aviation representatives as to whether to use the additional 6 dB for acquisition for some of the operational scenarios.

Aggregate interference levels for the operational scenarios discussed in Section 3.1.3 were evaluated using analytical models. The aircraft antenna heights corresponding to the operational scenarios are listed below:

a) High Altitude Enroute - A/C Antenna Height 5490 m MSL
b) Low Altitude/ Terminal Area - Final Approach Fix Way Point (FAF WP) - A/C Antenna Height 535.2 m AGL
c) Category I Decision Height - A/C Antenna Height 53.34 m AGL
d) Category II Decision Height- A/C Antenna Height 25.94 m AGL
e) Surface Operations (Taxiway) - A/C Antenna Height 4 m AGL

The analytical models used for the determination of aggregate LightSquared emission levels use the source-path-receive approach. The models used are detailed in Appendix B of RTCA DO-327. The models considered both random and discrete RFI source location approaches, and detailed aggregate computations were performed for both approaches.

Probabilistic path loss models were considered for most operational scenarios under consideration (except the high Altitude Enroute scenario for which free space path loss models were used). Details regarding the different probabilistic path loss models as a function of lateral separation radii between the aircraft and the LightSquared RFI source are found in Appendix B.3.1 of RTCA DO-327.

As a function of frequency, these computed aggregate power levels for the different operational scenarios are compared against the required MOPS interference mask (Figure C-1 of DO-327). The certified aviation receiver baseline interference requirement (as reflected in Fig. C-1 of DO-327) is set 6 dB below the receiver MOPS-related environmental limit to establish a margin of safety beyond the minimum performance requirements used for device certification (ITU-R M.1477). Aggregate interference power levels in excess of this could cause an undesirable impact to a certified aviation GPS receiver.

These analyses were performed based on a maximum LightSquared base station EIRP of 32 dBW per LTE channel per sector. This limit is the power level at which LightSquared's deployment is designed. As noted elsewhere, the FCC authorization allows EIRP up to 42 dBW per sector. Since the analysis scales linearly for an additional 10 dB of LTE downlink power, linear extrapolation of the aggregate power levels seen at the LightSquared frequencies would suffice to address the impact of maximum authorized signal levels. Note that EIRP of 32 dBW is based on 100% loading of all the base stations involved in causing the interference. More typical base

station loading of 60% will result in an average EIRP of 29.8 dBW (2.2 dB reduction). Results of the aggregate analysis are provided in Section 3.1.10. The analysis also assumes LTE center frequencies that are at least 6.3 MHz from the lower edge of the 1559 – 1610 MHz band based upon LightSquared implementation plans, whereas the FCC authorization provides no constraint on center frequency beyond those required to meet applicable out-of-band emission requirements. Finally, the analysis assumes that the impact of LightSquared signals on a GPS receiver is the same as an equal power CW signal at the same center frequency. Section 3.1.8 addresses the validity of this assumption.

The aggregate interference power analysis for different operational scenarios is supplemented by laboratory tests of a limited number of FAA certified aviation receivers. Test conditions, plans and procedures are described in sections 3.1.5 and 3.1.6 of this report. Results of these tests are provided in Section 3.1.9.

3.1.5 Work Plan Item 5: Derive the Test Conditions Based on the Established Operational Scenarios

The aviation sub team also agreed upon performing conducted testing to evaluate the impact of LightSquared RFI to these receivers. The test conditions for evaluation of the impact of LightSquared RFI to certified civil aviation and ground reference station GPS receivers are based on the signal operating environment that is reflected in the DO-229D receiver MOPS. This signal operating environment represents the receiver MOPS [DO-229D] requirements for steady state tracking of the GPS L1 C/A signals.

Interference Signals with power spectral density similar to the LightSquared OFDM signals were generated using arbitrary waveform and vector signal generators and were filtered using LightSquared BTS filters (RMC1550B10M01 at 1550 MHz and RMC1531B10M01 at 1531 MHz). The aviation sub team agreed upon the methodology to generate signals that are equivalent (for the purposes of this evaluation) to the LightSquared transmissions in the lower and upper downlink bands for LightSquared deployment Phases 0, 1, and 2.

The modified MOPS test conditions are a combination of:

a) near band continuous wave interference limit as a function of frequency [RTCA DO-327, Figure C-1]
b) a wideband RFI PSD in the receiver passband that is 3 dB lower than the MOPS receiver interference limits [RTCA DO-327, Section A.1.1.1]

The MOPS test condition was modified to address the fact that the Lightsquared interference power is injected into the scenario in conjunction with existing wideband RFI already present in the GPS passband.

Evaluation of WAAS message failure rates (for WAAS capable receivers) was performed with a combination of nominal receiver MOPS interference conditions for

in-band RFI [RTCA DO-327, Section A.1.1.1] and LightSquared emission levels per the test procedures in Section A.1.3 of RTCA DO-327 .

3.1.6 Work Plan Item 6: Write the Test Plan and Procedures

Conducted emission testing was performed at Zeta Associates in Fairfax, VA following a standard MOPS based test procedure required to certify airborne receivers. Emulated interference was combined with simulated GPS and WAAS signals and fed into the receiver input port for the devices under test.

Since the LightSquared downlink scheme in the MSS band (1525 – 1559 MHz) is adjacent to GPS L1 frequency in the Aeronautical Radio Navigation Service (ARNS) band (1559 – 1610 MHz), the testing focused on the impact of LightSquared emissions on receivers that process the L1 C/A code. Note that the certification basis for airborne GPS solutions is predicated on their ability to successfully receive and process the L1 C/A GPS signal and meet receiver MOPS requirements [RTCA DO-208/DO-229/DO-253/DO-316 as applicable] under established MOPS interference conditions [RTCA DO-235].

3.1.6.1 Test Plan:

The test plan focused on evaluating:

1dB CNR degradation point for the GPS receivers in the presence of CW interferers centered at frequencies in the LightSquared downlink band.

1dB CNR degradation point for the GPS receivers in the presence of LightSquared signals.

Impact of LightSquared signals on the WAAS message loss rates (for WAAS capable airborne receivers).

Impact of LightSquared signals on the ranging accuracy of the receivers under test

The validity of the assumption that CW signals and broadband LTE signals have an equivalent effect on GPS receivers.

Additional evaluations were performed to estimate Lightsquared signal levels at which the units lost lock on the satellites.

3.1.6.2 Test Procedure:

To estimate the impact of planned LightSquared base station emissions on Wide Area Augmentation System (WAAS) reference equipment (WRE), aviation GPS receivers, and Local Area Augmentation System (LAAS) reference equipment radiofrequency interference (RFI) testing

of GPS receivers using simulated LightSquared and GPS signals was conducted at Zeta Associates.

Desired GPS Signals, anticipated in-band GPS noise and LightSquared signals were generated to faithfully represent the output of the antenna unit and cabling that is designed for each tested receiver, including the effects of antenna filtering (Fig. 2-3 of RTCA DO-301), low noise amplification and all incurred losses. For airborne receivers, the testing follows the procedures defined in RTCA DO-327, Section A.1.

MOPS test procedures are used to demonstrate that the equipment under test meets all applicable performance requirements in the presence of the anticipated interference environment and with minimum anticipated GPS signal levels. The LightSquared emissions are not part of the nominal MOPS signal environment and the baseline MOPS test procedures were modified to include the same. Equipment testing extended beyond the MOPS pass/fail criteria up to the limitations of the test setup.

Per the test plan, Carrier-to-noise ratio (CNR) degradation baseline tests (Section A.1.1 of RTCA DO-327) were conducted to determine the 1 dB degradation and loss of tracking points against LightSquared Phase 0, 1 and 2 as well as 5 MHz Low and 10 MHz Low signal configurations. Additional tests comparing narrow (CW) and wide (5 MHz) bandwidth signals were done for both the Low (1528.8 MHz) and the High (1552.7 MHz) channels. WAAS message loss tests (Section A.1.3) also were conducted but due to time constraints, only two receivers were tested for the Phase 0 LightSquared configuration.

Tests were conducted using the GPS L1 C/A signals of GPS satellites, simulated using a Nortel (Spirent) STR2760. Waveforms representative of planned LightSquared emissions were simulated using a Sony/Tektronix AWG420 arbitrary waveform generator along with an HP (Agilent) 8780A vector signal generator (VSG). The LightSquared test waveforms were also filtered using BTS transmit filters. LightSquared interferer power levels were varied from zero to levels where the MOPS based test would indicate device failure. All tests were monitored on a spectrum analyzer to ensure the simulated LightSquared emission remained consistent with expected operation as its power level was increased.

Detailed descriptions of the test procedures can be found in Appendix A of RTCA DO-327. Additional details regarding the test setup and methodology used to perform the test procedures can be found in Appendix D.1.1 – D.1.3 of RTCA DO-327.

All results were tabulated, plotted and summarized for comparison with tests by other entities.

The WAAS G-II or GUST receiver was configured to track the GPS L1 C/A signal using PRN 18.[19] The RANGE and AGCSTATS logs, which include C/N_0, code and carrier standard deviation, AGC gain and bin data, etc., were output from the receiver at a rate of 1 Hz and collected for analysis.

No testing was performed to evaluate initial acquisition performance in the presence of LightSquared signals.

3.1.7 Work Plan Item 7: Identify and Engage Appropriate Neutral Test Facility(ies) for the Testing Portion of the Work Plan

The Aviation Sub-team relied on conducted testing funded by the Federal Aviation Administration (FAA). Testing was performed at Zeta Associates Incorporated, Fairfax, Virginia. The Aviation Sub-team participated in the development of the plan for this testing.

3.1.8 Work Plan Item 8: Perform Testing

Receiver testing was performed in line with the test plan in Appendix A.1. Testing was performed to characterize the LightSquared power levels at which a 1 dB degradation in the receiver's CNR estimate was observed. Results of this test are seen in Table 3.1.1 where the receiver identities have been made anonymous. RFI power levels are referenced to the output of the passive radiator element of an active DO-301 antenna element. In the test setup used at Zeta, this is equivalent to point A in Fig 3-1 of Appendix D of RTCA DO-327. As observed in this table, this characterization was performed for multiple LightSquared signaling schemes that are consistent with the LightSquared deployment plan. Upon further discussion within the Aviation Subgroup, additional evaluations were undertaken to characterize the individual impact of the lower 5 MHz and 10 MHz LightSquared emissions.

Receiver	Phase 0	Phase 1	Phase 2	5 MHz Low	10 MHz Low
#1	-35.9	-35.9	-33.3	+3.4	-1.1
#2	-61.9	-62.5	-59.7	+3.7	-1.7
#3	-50.2	-50.0	-47.7	+2.9	-1.7
#4	-35.4	-38.2	-37.7	-1.0	-4.4

Table 3.1.1: Lightsquared Signal Powers (dBm/channel) Resulting in 1 dB Reported C/N_0 Degradation

Per line item 1 of the test plan (Appendix A.1), tests were also conducted by concentrating the power of the LightSquared signal in a CW tone at the mid

[19] Pseudorandom noise (PRN) is a GPS satellite designation.

frequency points of the Phase 1 signaling scheme. This was performed in order to evaluate an overall correction factor for CW vs. broadband intereferers vis-à-vis the GPS MOPS CW Interference curve (Fig C-1 of RTCA DO-327). Results of this test are seen in Table 3.1.2.

Receiver	1552.7 MHz LtSq RFI / CW (dB)	1528.8 MHz LtSq RFI/ CW (dB)
#1	-7.8	+0.7
#2	-11.1	+0.8
#3	-0.5	+0.6
#4	-0.9	+0.7

Table 3.1.2: Ratio of LightSquared to CW RFI powers for 1 dB reported C/N_0 Degradation

For example, receiver #1 would see a 1dB CNR degradation at 7.8 dB lesser power from the LightSquared transmitter (in the 1550.2 – 1555.2 MHz band) versus a CW signal centered at 1552.7 MHz. Effectively all receivers tested are impacted to a greater degree by the LightSquared signal at 1552.7 MHz than a CW signal of equal power located at 1552.7 MHz. The effect is reversed for the lower 5 MHz or 10 MHz channel where the tolerance for the broadband signal was approximately 0.7 dB greater than for a CWsignal.

Table 3.1.3 depicts the power levels of the LightSquared transmitters required to cause loss of track of the low power satellites used in the scenario per the MOPS requirements in DO-229D.

Receiver	Phase 0	Phase 1	Phase 2	5 MHz Low	10 MHz Low
#1	-28	-28	-24	+10*	+3
#2	-55	-56	-53	+9	+1
#3	-48	-48	-45	+10	+2
#4	-27	-34	-34	+7	+2

Table 3.1.3: Lightsquared signal powers (dBm/channel) resulting in loss of Satellite Tracking

* Receiver #1 maintained lock at +10 dBm but registered a low C/N_0

The last set of tests performed at Zeta was the WAAS message loss rate tests. A baseline run was performed to establish that the receivers under test would pass the WAAS message loss requirements in the MOPS environment. At the MOPS signal and noise levels, without the additional 1 dB degradation from LightSquared, all three

tested WAAS channels in Receiver #3 and the two tested WAAS channels in Receiver #4 passed the WAAS Message Loss tests. Table 3.1.4 lists the number of WAAS Message failures per channel and the confidence levels (as a percentage value) with which these tests were declared as PASS for Receiver #3.

Receiver	Channel 1 (errors and PASS confidence level)	Channel 2 (errors and PASS confidence level)	Channel 3 (errors and PASS confidence level)	Total of Number of WAAS Messages
#3	1 (99.1%)	5 (91.7%)	2 (99.6%)	9633

Table 3.1.4: WAAS Message Loss Test Resultsfor Receiver #3 under nominal MOPS conditions

Tests conducted in a similar fashion for Receiver #4 revealed results seen in Table 3.1.5.

Receiver	Channel 1 (errors and PASS confidence level)	Channel 2 (errors and PASS confidence level)	Total of Number of WAAS Messages
#4	1 (99.9%)	3 (98.6%)	9648

Table 3.1.5: WAAS Message Loss Test Results for Receiver #4 under nominal MOPS conditions

The next step was to perform these same tests with the LightSquared Phase 0 signal (1552.7 MHz) injected at the 1 dB degradation power levels determined during the CNR degradation tests (each receiver run separately at the appropriate level). Table 3.1.6 and Table 3.1.7 provide the results of these tests for Receivers #3 and #4 respectively.

Receiver	Channel 1 (errors and FAIL confidence level)	Channel 2 (errors and FAIL confidence level)	Channel 3 (errors and FAIL confidence level)	Total of Number of WAAS Messages
#3	22 (99.8%)	19 (98.5%)	23 (99.9%)	10799

Table 3.1.6: WAAS Message Loss Test Results for Receiver #3 at the 1 dB CNR degradation level

Receiver	Channel 1 (errors and FAIL	Channel 2 (errors and FAIL	Total of Number of WAAS

	confidence level)	confidence level)	Messages
#4	16 (90.6%)	20 (99.0%)	11025

Table 3.1.7: WAAS Message Loss Test Results for Receiver #4 at the 1dB CNR degradation level

Based on the results observed in Table 3.1.6 and 3.1.7, it is evident that a 1 dB CNR degradation is unacceptable for the certified WAAS receivers as they fail to meet the WAAS Message Loss requirements (Message Loss Rate should be < 1 in 1000 messages per DO-229D Scn.2.1.1.3.2). The methodology used to model the WAAS Message failures is based on statistically modeling the word errors as independent Bernoulli trials. Additional details of this modeling are available in Appendix D.1.5 of RTCA DO-327. Due to lack of time, the LightSquared signal level at which a word error rate pass would have been encountered was not determined.

3.1.9 Work Plan item 9: Analyze Test Results Based on Established Methodology

Test results from four certified aviations receivers yielded LightSquared emission levels at which receiver metrics such as 1dB CNR degradation and WAAS Message Loss Rates were characterized per the Receiver test plan. Results of these tests are listed in Section 3.1.8. At the modified MOPS levels, based on a sample of four GPS receivers, it is observed that the 1 dB CNR degradation due to LightSquared emissions occurs at different interferer levels for different GPS receivers This result indicates that the design and implementation of GPS airborne receivers that are MOPS compliant may vary to such an extent that their susceptibilities to LightSquared emissions for the Phase 0 deployment scheme can differ by up to 26.5 dB. The aviation representatives take the position that this variation in susceptibility is expected because the LightSquared emissions are vastly more powerful than the levels specified in the airborne receiver MOPS, the receivers are all compliant with the applicable standards, and not all tested receivers provide the same operational capability. LightSquared's position is that the variation suggests that it may be possible to redesign the most susceptible receivers to make them perform similarly to the least susceptible ones, without the development of new filtering technologies.

Based on the test results in Section 3.1.8, for 4 receivers, it is observed that there is slight difference (0-2.8 dB) across the 1 dB CNR degradation points for phases 0 and 1. Similarly, for the same 1 dB CNR degradation, variations of the order of 0.5 to 2.8 dB are observed in LightSquared power levels across Phases 1 and 2. Independent evaluation of the 1dB CNR degradation points for the lower 5 and lower 10 MHz bands were performed. Based on observed results, the receivers are more resilient to the lower 5 MHz signaling than to the lower 10 MHz signaling scheme.

The results in table 3.1.2 depict the relative CW signal vs. Broadband LightSquared signal power levels which produce the same 1dB CNR degradation as reported by the respective receiver under test. This test has been performed for each of the Phase 1 5 MHz LTE channels. From these results, it is readily observed that the relative impact of CW vs. LightSquared signals at 1552.7 MHz across receivers is in the range of -0.9 to –11.1 dB.

As a result it is not viable to produce an overall correction factor for CW vs. wideband interference at the upper LTE band. In the case of the lower LTE band, it is seen that the variation across CW and wideband LTE signals is within 1dB. This implies for the lower LTE channel that the receiver signal processing is impacted by the total power in the signal (for the 4 receivers tested) and not necessarily the power spectral density (PSD) of the LTE signaling scheme. The LightSquared position is that the 0.7 dB difference in susceptibility to broadband signals vis-à-vis CW could be added to the margin available to GPS receivers when the lower ATC channels are used. The aviation community position is that no such general assumption should be made on the basis of only 4 tested receiver models out of many dozen models currently fielded.

Results in Table 3.1.3 depict the LightSquared interferer levels at which the respective GPS units lose lock on the GPS signal. Please note that in the constellation used to simulate the minimum signal scenario, all GPS satellites were set to emulate the minimum receive GPS signal power with the exception of one satellite that was set to a higher signal power level per the test procedure in Appendix A of DO-327. As a result, it is typical to see loss of lock on a multitude of satellites at the same interferer levels resulting in subsequent loss of navigation solution at these interferer levels.

It is observed that the LightSquared signal levels at which the navigation solution is lost varies from the 1dB CNR degradation point by 2 to 10 dB for all LightSquared deployment phases. This variation reflects the fact that there is relatively little margin between the 1dB CNR degradation point and the point of loss of navigation function and is due to the fact that the nominal receiver input CNR levels for the MOPS tests are approximately in the range of 32 - 33 dB-Hz. Any further CNR degradation reduces the receiver tracking margins.

It had been hypothesized that the loss of WAAS messages beyond an acceptable threshold (1 in 1000 messages per Section 2.1.1.3.2 of DO-229D.) would be a performance limiting factor for the airborne units in the presence of LightSquared emissions. Results of WAAS message loss tests performed at Zeta support this hypothesis. Units tested for WAAS message loss rate passed the test at the nominal MOPS conditions but failed the WAAS message loss tests at the same LightSquared power levels estimated to cause a 1dB CNR degradation with I_{Ext} set to -170.5 dBm/Hz (DO-327, Appendix A.1.2.1). As a result a 1dB CNR degradation level is determined to be excessive for WAAS capable MOPS compliant airborne GPS solutions. It is noteworthy that tests could have been performed to determine the LightSquared signal power reductions required to pass the word error rate test but was not owing to lack of time and lower priority given to this test. This LightSquared signal power reduction would result in some reduction of the 20+ dB of margin currently shown by the tested receivers between the 1dB C/N_0 reduction point and the maximum tolerable interference level required by the current performance standards.

These test results and subsequent interpretations of the same are based on a sample size of 4 certified GPS receiver models, whereas the number of certified airborne GPS receiver models is expected to be larger by more than an order to magnitude. The performance variations encountered across the units that were tested could very

well be seen across the other aviation units that have not been tested. In addition variations within a given receiver model may be seen across multiple receiver samples. This would be a result of production related variations. Variations observed in these receiver test results are within receiver design and product manufacturing margins. The aviation representatives on the Sub-team believe that this margin may not be utilized towards accounting for any shortfall between the MOPS interference test limit and the aggregate interferer power levels for the different operational scenarios. Their conclusion, in part, is due to the small sample size of the units tested and the potential for a certified receiver to exhibit performance degradations within a few dB of the MOPS interference mask limits (low production/design margin). LightSquared believes that a significant margin may still exist when a much larger sample of receivers is tested.

3.1.10 Work Plan Item 10: Assess Operational Scenarios Using Analytics and Test Results

The aggregate LightSquared base station interference effect on airborne GPS receivers has been analyzed as described in RTCA DO-327 for the following scenarios:

(1) High Altitude Enroute RFI Encounter Scenario

(2) Generic Low Altitude / Terminal Area (Final Approach Fix Waypoint [FAF WP]) RFI Encounter Scenario

(3) Generic Category I Precision Approach RFI Encounter Scenario

(4) Generic Category II/III Precision Approach RFI Encounter Scenario

(5) Generic Surface Movement (Taxiway) Guidance RFI Encounter Scenario

The following table summarizes the maximum aggregate received emission levels from the LightSquared base station network. The table values are from DO-237 and presume an EIRP of 62 dBm per LTE channel per sector and an airborne antenna gain pattern from RTCA DO-235B.

Scenario		Aircraft Height (meters)	Aggregate Received Power/Channel (dBm)
1	High Altitude	5490.0 MSL	-49.6
2	Low Altitude (FAF WP)	535.3 AGL	-36.6

3	Cat I Decision Height	53.3 AGL	-38.9
4	Cat II Decision Height	25.9 AGL	-39.0
5	Surface	4 AGL	-49.5

Table 3.1.8: Aggregate Received Power per LTE Channel for Five Aviation Operational Scenarios

Note that, of the five operational scenarios identified by RTCA, the maximum aggregate interference level per LTE channel occurs for the Scenario 2, Low Altitude (FAF WP), with the aircraft at a height of 535.3 meters AGL. RTCA DO-327 recommends further investigation to determine whether higher aggregate received power levels may occur at other altitudes. Assuming an average (over the ensemble of all base stations visible to the aircraft) base station EIRP of 62 dBm per LTE channel per sector, Table 3.1.9 provides a comparison of the aggregate power seen by an airborne receiver at 535.3 meters altitude vs the interference limits (including the safety margin of 6 dB). The resulting operating margins for this operational scenario are shown for different operating center frequencies. Note that the margins would be negative for all LTE center frequencies and bandwidths if the base stations operated at the FCC authorized maximum EIRP level of 72 dBm per carrier per sector.

Center Frequency (MHz)	Carrier Bandwidth (MHz)	Maximum Received Interference level (dBm)	Interference Limit, Tracking (dBm)	Margin, Tracking (dB)
1550.2	10	-36.6	-85.6	-49.0
1552.7	5	-36.6	-92.4	-55.8
1528.8	5	-36.6	-28.2	8.4
1531.0	10	-36.6	-34.1	2.5

Table 3.1.9: Comparison of Aggregate Power Seen by Airborne GPS Receiver in the Low Altitude (535.3 meters AGL) vs Interference Limits

The aviation participants in the Aviation Sub-team note that the margins would diminish by 6 dB for initial acquisition, and further the margins for the upper LTE channels would be even less if the CW-to-broadband conversion results from Table 3.1.2 were factored in. The aviation participants note that, considering initial

acquisition, there are negative margins for all ATC channel configurations, except the lower 5 MHz.

LightSquared notes that the margins shown here would, in practice, increase by 2.2 dB owing to a typical 60% average loading of base station when considered over the ensemble of an entire city. LightSquared further notes that the 6 dB margin reduction for acquisition is subject to confirmation through additional work. Lastly, LightSquared notes that the CW-to-broadband conversion would yield an additional margin of approximately 0.7 dB for the lower ATC channels according to Table 3.1.2.

All of the deployment plans currently proposed by LightSquared (Phase 0, 1, and 2) include an upper channel at either 1552.7 or 1550.2 MHz. The results in Table 3.1.9 show that, using the definition of harmful interference in the analysis, the aggregate interference that would be experienced at 535.2 meters AGL (1756 feet AGL) vastly exceeds the levels that current GPS equipment is required to withstand – by a factor of 200,000 or more. RTCA DO-327 also states that the peak interference levels experienced by the airborne receiver will occur at an altitude somewhere between 535.2 meters and 1,000 meters AGL. Given this, a complete loss of aviation GPS operation at altitudes below 2,000 feet (609.6 meters) AGL is possible over a wide radius from cities where LightSquared plans to deploy, if such deployment includes a channel in the upper part of LightSquared's band.

Center Frequency (MHz)	Carrier Bandwidth (MHz)	Maximum Received Interference level (dBm)	Interference Limit, Tracking (dBm)	Margin, Tracking (dB)		
1550.2	10	-49.6	-85.6	-36.0		
1552.7	5	-49.6	-92.4	-42.8		
1528.8	5	-49.6	-28.2	21.4		
1531.0	10	-49.6	-34.1	15.5		

Table 3.1.10: Comparison of Aggregate Power Seen by Airborne GPS Receiver in the High Altitude Scenario (5490 m) vs Interference Limits

Table 3.1.10 shows the aggregate interference that would be seen by an airborne receiver operating at an altitude of 5490 m MSL above the Mid-Atlantic region of the U.S. As in the low altitude scenario, the signal levels generated by LightSquared base stations transmitting at 1550.2 MHz or 1552.7 MHz exceed the limit for harmful interference by more than 36 dB. Based on this analysis, GPS-based operations could be unavailable over entire regions of the country at any normal

aircraft altitude if LightSquared were to deploy with a channel in the upper part of its spectrum band.

The data and analysis indicate that the primary potential causes of aviation GPS interference from LightSquared base stations are the upper channels of the current deployment plan. RTCA DO-327 suggests that a shift to using only a lower 5 MHz channel centered at 1528.8 MHz may be compatible with aviation GPS operations provided that ATC transmissions are kept at or below 62 dBm EIRP. The lower 10 MHz channel shows compatibility with a small margin for tracking functions, but not necessarily for initial acquisition. Therefore RTCA DO-327 concludes that the use of the lower 10 MHz channel cannot be determined to be compatible with aviation GPS operations without additional study. It is important to note an increase in EIRP levels from the deployment plans of 62 dBm per channel per sector to the authorized EIRP limit of 72 dBm is not compatible with aviation GPS operations.

3.1.11 Work Plan Item 11: Assess Whether any Mitigation Measures are Feasible and Appropriate

Mitigation measures fall into two broad categories: those that would be applied to the LightSquared ATC transmissions and those that would be applied to the airborne GPS receivers and antennas. Given the long service lifetime of airborne GPS equipment and the high cost of purchase, certification and installation, any acceptable mitigation measures need to accommodate the currently installed user base. Determining the cost of modifying existing certified aircraft installations must take into account costs beyond the basic equipment, such as consideration for aircraft down time.

Section 6 of the RTCA/DO-327 report examines both categories of mitigation measures in detail. It is important to note that the analysis of GPS receiver over load potential is primarily based on an RTCA receiver selectivity mask (RTCA/DO-327, Figure C-1) which defines the maximum continuous wave (CW) interference power that the airborne receiver is required to tolerate and still satisfy the minimum performance requirements. Consensus on using the RTCA mask for this assessment was reached within RTCA SC-159 Working Group 6 and in the Aviation Sub-team, both of which included LightSquared representatives.

While the aviation receivers tested did show a 20+ dB difference between the 1 dB C/N_0 degradation point and the maximum tolerable levels required by the current performance standards, the RTCA mask is used for the following reasons:

- The RTCA masks are used to meet FAA certification requirements.
- The aviation representatives believe that the RTCA mask should be used for the following additional reasons:
    - The receivers tested failed to meet key performance requirements (WAAS message-loss-rate) in the presence of LightSquared signals that resulted in 1 dB degradation in C/N_0.
    - The receivers tested showed a wide range of susceptibility to the LightSquared signal at 1552.7 MHz. Given the small sample of

receivers, it is not expected that the test results represent the full range of susceptibility that might be found in current designs.

- The testing did not account for differences in performance due to manufacturing variability or changes in environmental conditions (most notably temperature).

The RTCA mask represents the RFI limit that aviation GPS receivers are required to withstand for FAA certification and use.

The objective of the mitigations discussed here is to make the aviation receivers compatible with the RTCA mask.

3.1.11.1 LightSquared Transmitter Mitigations

RTCA/DO-327 looked at two types of mitigation at the RFI source: shifts in the ATC transmit frequency and reductions in the ATC transmit power. (DO-327 sections 5.1 and 6.2.4)

ATC Frequency Shift

RTCA DO-327 suggests that one possible mitigation would be to eliminate the use of the upper band (1545.2-1555.2 MHz) and only transmit in the lower portion of the band (1526-1536 MHz). This mitigation takes advantage of the minimum required GPS selectivity curve that provides significantly more rejection at the lower end of the band.

Two single-channel configurations in the lower band were considered: a 5 MHz channel centered at 1528.8 MHz and a 10 MHz channel centered at 1531 MHz. The RTCA report states that the lower 5 MHz configuration might be compatible with aviation GPS operations, provided that the ATC transmit power remains below the stated LightSquared deployment plan of 32 dBW EIRP. The current authorization allows for base station transmissions of up to 42 dBW EIRP. Transmissions at 42 dBW would result in aggregate received power levels that exceed the RTCA minimum receiver selectivity mask and would therefore not be compatible with aviation GPS receivers. Accordingly, any mitigation using a single 5 MHz or 10 MHz channel in the lower L-band (below 1536 MHz) would need to be accompanied by a reduction in the current 42 dBW EIRP maximum authorized transmit power to 32 dBW EIRP. The minimum required selectivity curve provides even less rejection for the 10 MHz configuration centered at 1531 MHz. The RTCA report concludes that more study is needed to determine if restricting operations to the lower band could be an acceptable mitigation for aviation GPS operations.

The RTCA report only considered a frequency shift within the currently allocated band of 1525-1559 MHz. The aviation community believes that a frequency shift to a band that is not adjacent to the GPS L1 band could eliminate all interference effects with GPS receivers.

ATC Power Reduction

Since the fundamental ATC base station emission is the source of the primary RFI effect, reducing the EIRP might be another means of mitigation. However, the power restriction at the upper 5 MHz channel center would have to be quite stringent (~ -23 dBW EIRP max.) to make it compatible. Note that a reduction in the transmit EIRP would not be an effective mitigation if it is accompanied by an increased number of ATC base stations visible to the aircraft, because the airborne receiver is affected by the aggregate power within its line of sight. Refer to section 5.1.2 of RTCA/DO-327 for additional discussion of this mitigation option.

3.1.11.2 GPS Receiver Susceptibility Reduction

Several different mitigation techniques that might be applied to airborne GPS equipment were also evaluated. These included improved preselection, adaptive antenna processing, and improvements to receiver tracking processes. Of these techniques, improvements to preselection hold the most promise, but as of today there are no proven commercially-available solutions that could be used to substantially improve airborne receiver selectivity. Section 5.2 of RTCA/DO-301 provides an analysis of the GPS receiver mitigation option that is the basis for the summary below.

Improved Preselection

Most fielded aviation GPS receivers use separate active antennas built to RTCA/DO-301 or RTCA/DO-228 (change 1) standards. The antenna assemblies include filtering (preselection and/or postselection) but do not provide much rejection at the upper LightSquared center frequency of 1552.7 MHz. An estimated 55 dB of increased rejection at 1550.2 MHz for an upper 10 MHz channel would be required to reduce the aggregate interference received from LightSquared base station to a level below the current RTCA receiver selectivity mask.[20] This is based on a 32 dBW/carrier transmit EIRP by LightSquared base stations as currently planned. If

[20] The 55 dB estimate is based on the use of the upper 10 MHz channel.. The aviation representatives note that even greater suppression may be required due to the lack of equivalence between CW and broadband signal impact, see, e.g., Table 3.1-2.

LightSquared were to transmit at the limit of its license (42 dBW), 10 dB greater reduction would be required.

No currently available filter technologies exist that can provide this much rejection and are also suitable for incorporation into an antenna assembly. Cavity filters may be able to provide this level of selectivity, but are far too large to fit within the antenna unit on aircraft. However, new filter designs may be able to improve the level of selectivity possible in the active antenna. For example, the Aviation Sub-team evaluated a preliminary proposal from Delta Microwave, working in collaboration with an unidentified antenna manufacturer, for filters meeting this rejection requirement, while also meeting other passband requirements, such as group delay variation. The form factors vary from 9.5 x 3.5 x 2.0 inch to 9.5 x 3.5 x 1.25 inch depending on whether cavity filters or dielectric resonators are used, respectively. The proposal (see Appendix A.3) would provide significantly more rejection than existing antennas, but also requires more input power than is currently provided by fielded GPS receivers. According to the aviation representatives, the preliminary estimate of a 50 dB improvement in selectivity at 1552.7 MHz falls short of the 55 dB required for compatibility with receivers designed to the current performance standards.

LightSquared understands that Delta is interesting in bidding on developing a new DO-301 antenna that is wholly compatible with the present mechanical and electrical requirements and all applicable standards of a DO-301 antenna, while still providing the target rejection in the upper L-band.

New antenna designs with improved selectivity may provide hope for mitigations to existing airborne receiver installations. The aviation representatives believe that this is neither a currently available proven solution nor is it an inexpensive short-term solution. New standards would need to be established, equipment developed and certified to those standards, and this equipment would need to be installed by the user base, and could take many years.

The Aviation Sub-team also discussed the possibility of improving selectivity by the use of a passive inline cavity filter. This mitigation is not desirable to the aviation community because it increases the number of subassemblies that need to be securely mounted in the aircraft and may not be possible in smaller aircraft. Since this filter would be installed after the active antenna, there is still a potential for interference effects in the antenna caused by 3rd order intermodulation products of the upper and lower ATC channels.

Adaptive Antenna Processing

This technology uses multi-element antenna arrays to detect interference sources and suppress them before they reach the receiver. Such antennas are large, heavy, and expensive. Moreover they are limited in the number of interference sources that can be suppressed. It is anticipated that the hundreds of ATC base stations visible to the antenna would exceed the antenna's suppression capabilities. Given these constraints, this technology is not considered to be a suitable potential mitigation for any interference.

Improved Receiver Tracking Processes

There are currently no available technologies that can substantially improve GPS receiver carrier-phase tracking and WAAS data-demodulation. In particular, WAAS data demodulation is currently performed to within 1.5 dB of the theoretical limits. Substantial improvements to this level of performance may not be possible to achieve and would require new receivers. If new receivers are to be built then increasing receiver selectivity would be a more promising (but also unproven) solution to LightSquared ATC emissions.

3.2 Cellular Sub-Team

Executive Summary

To verify any effects on cellular devices, the Cellular Working Group developed test plans in accordance with industry standards to determine any impact on GPS receivers within cellular devices. These test plans are provided as part of the report Appendix C.1 and were agreed to by all parties. The testing sought to determine if any harmful interference would arise to legacy cellular devices.

The Cellular Working Group tested a limited but representative sample of cellular devices sent by four US operators (AT&T, Sprint, US Cellular, and Verizon) to determine the effects of LightSquared signals on GPS receivers embedded in these devices. 41 devices representing different models were tested in a laboratory testing environment with a smaller subset of devices selected and tested in a radiated, live sky fashion utilizing the agreed upon test plans. However, by necessity due to time constraints, the working group did not complete all tests and instead prioritized certain tests to ensure the greatest number of devices was tested with the most meaningful results.

The Cellular Subgroup has analyzed in depth test data from three independent labs, group member contributions and other expert presentations, and internal group analyses of 41 mobile devices tested in the lab. In addition, 29 mobile devices representing 8 models were tested in the field by companies in live sky tests. Enough test data was available to

demonstrate that LightSquared signals in the higher 5 MHz and 10 MHz band (1545.2 to 1555.2 MHz) caused GPS failure for a significant number of the tested devices. In contrast, the current test data and analysis to date indicates that operations in the lower bands (1526 to 1536 MHz) may be possible without harmful interference to existing cellular GPS devices.

Like other subgroups, this subgroup also notes that it could only practically sample a tiny percentage of models relative to what is installed in the field. Counteracting that was a careful selection of devices based on fielding the widest number of different GPS receiver designs and other characteristics.

Based on all the data available, upper band mitigation techniques can be further explored. For lower band (referred at points in this document as "Lower 10 MHz") operation, additional immunity to adjacent L Band signals are within grasp using existing, known filter technologies. A substantial number of legacy devices are being used today and therefore it appears that LightSquared may not be able to operate in the upper portion of the downlink band as mitigation is not possible at this time under current LightSquared deployment plans. However, filtering technology may be available to reduce susceptibility to adjacent band signals into the GPS receivers of future cellular devices. Once the necessary rejection levels have been determined, final filter specifications can be proposed or offered by vendors and evaluated for commercial timing or viability. Until these filters and other mitigation techniques are developed and implemented, it is reasonable to expect that a significant number of mobile devices would continue to be vulnerable to interference from LightSquared's upper band operations.

Originally the subgroup was to test a femtocell device at the request of one of the wireless operators. Due to agreed priority to test the mobile devices, the subgroup ran into time constraints. To resolve the issue, the subgroup considered testing the device after its final report submission and filing the test results in a supplemental report. The wireless operator providing the femtocell and technical support staff to test it has subsequently decided to not pursue testing of this device within the TWG.

3.2.1 Work Plan Item 1: Establish Pertinent Analytical and Test Methodologies and Assumptions Underlying the Test Regime

3.2.1.1 Definition of Harmful Interference

Harmful interference was defined as: (1) a failure to preserve the same threshold of performance expected for GPS (as defined below in GPS Failure Threshold section) and, (2) any change or degradation in the user experience (for example, an inability to obtain E911 location fixes) deemed harmful based on analysis of Key Performance Indicators (KPIs) shown below and defined in the test plan attached in Appendix C.1 defined below.

Tests conducted by the Cellular Working Group were performed in accordance with the following industry technical standards:

- 3GPP TS 34.171: Terminal Conformance Specification, Assisted Global Positioning System (A-GPS), Frequency Division Duplex (FDD)
- TIA-916: AGPS Minimum Performance for CDMA devices
- CTIA v3.1: Test Plan for Mobile Station Over the Air Performance, Section 6.12.1 GPS for CDMA Devices
- CTIA v3.1: Test Plan for Mobile Station Over the Air Performance, Section 6.12.2 GPS for GSM/UMTS Devices

The following four Key Performance Indicators (KPIs) were logged or recorded if available by industry standards compliant GPS simulators and related test equipment and test facilities and anechoic chambers:

- 2D position error
- Response time, otherwise referred to as Time to First Fix
- C/N_0 as reported by the GPS receiver (N_o as used throughout this document includes all sources of receiver noise)
- GPS Satellite ("SV") power levels
- Other metrics such as Doppler error, response time, and code phase error that underlie or directly relate to the performance metrics above

In addition to determining the threshold values of Band 24 power levels where harm is synonymous with "GPS failure" as defined in the above-referenced standards occurs. All tests were extended until any one of the following conditions (referred to as the GPS Threshold Failure Criteria) were met:

- Satellite Vehicle (SV) lock cannot be maintained simultaneously on at least 3 satellites (i.e., the fourth satellite encounters consistent loss of lock, as observed continuously over a period of time)
- The device fails to provide a GPS-based position report
- Position errors are excessive as deemed by the standard as set forth in each test based on Key Performance Indicators (KPIs) shown below and defined in the test plan attached in Appendix C.1

Each of these conditions, if met, would indicate that the Band 24 signal(s) of continuous, fixed power led to GPS failure, based on a prescribed number of successive independent trial failures.

3.2.1.2 Relevant Broadband Signal Characteristics

As part of defining the testing methodology for the Cellular receivers, the following technical signal characteristics were identified:

Power Levels: This is the measure of the actual power in Watts of the test signal from the LightSquared test base station. This power will be quoted in terms of equivalent isotropic radiated power (EIRP). The signal's power level will vary according to the information it is transmitting as well as the modulation scheme used to broadcast it. This will result in peak and average values being measured or considered for the tests.

Bandwidth: This is the amount of spectrum that will be consumed by the test signal transmitted from the LightSquared Test Transmitter. Bandwidth will be quoted in megahertz (MHz) and will typically be a value of 5 or 10 MHz to ensure that true operational conditions are being simulated. Bandwidth data will also refer to any channelization schemes applied.

Modulation: The means by which information is conveyed by a radio signal. For the purpose of the test, the LightSquared test transmitter signals will conform to 3GPP (Band 24) standards for LTE, which use Orthogonal Frequency Division Multiplexing (OFDM). The OFDM signal can be substituted with complex baseband 5 or 10 MHz bandwidth, random noise signals with appropriate baseband filtering. Furthermore, random test data will be transmitted, simulating 100% loading of the base station. The data used to modulate the upper L-band and lower L-band carriers (where both are used simultaneously) will be statistically independent.

Antenna Patterns: Antennas transmit and receive signals with a varying degree of strength and gain (amplification) in certain directions. The isotropic antenna is a theoretical antenna that transmits equally in all directions and is used when referring to power levels transmitted. LightSquared, however, will typically be using directional antennas that form a main beam in a set of defined directions in both azimuth and elevation.

3.2.1.3 Interference Analysis Assumptions

As part of the testing and analysis, a set of assumptions were defined and agreed to by the Cellular sub-team. The assumptions were:

Signal Propagation Path Loss: this is defined as the degradation in signal strength as a result of the signal traversing a distance from the LightSquared test base station. The path loss will vary for certain conditions such as ground-based clutter to include trees and buildings. For network simulation of signal path loss, a number of path loss models that predict LTE signal strength were used. These include a general bounding of the interference

signal range of values between Free Space Path Loss (FSPL), and an appropriate "clutter" model appropriate for the site locale (e.g., urban, suburban, rural) and morphology. The working group accepts a diverse range of potential models to project or predict field power levels.

Use case definition: The theoretical predictions of the power levels of LightSquared's signals (both from base stations and user equipment), at a given GPS receiver, are based on assumed scenarios involving certain representative spatial distributions of the LightSquared signal sources and heights above ground of the cellular receiver.

Receiver Antenna: Each device under test will use an antenna to receive the test signals. For laboratory testing, the antenna may differ from the antenna typically used in the field or can be substituted with direct RF connection at the antenna port (conducted test). Controlled testing and accurate measurements with a high degree of repeatability will be required in conducting the laboratory tests to derive meaningful conclusions. Field-based antennas used will be those recommended by the manufacturer to support actual use-case scenarios.

Baseline Noise Floor: All electronic equipment generates ambient noise and the atmosphere itself contains an ambient level of signal noise, generated by all radio equipment on earth as well as noise emanating from space. This baseline level must be considered in defining the tests.

3.2.1.4 Testing methodology

3.2.1.4.1 Laboratory Tests

Test plans were developed based on the CTIA v3.1, TIA-916, and 3GPP 34.171 standards, as discussed in Section 3.2.6, below. The detailed test plans are provided in Appendix C.1. While the Cellular Working Group initially developed detailed and elaborate test plans, in some cases, it was unable to complete all tests for all of the devices, or dropped by necessity test procedures (e.g. instances where automated testing exited a particular test sequence without rendering a viable verdict, or it became apparent from clear trends in the results obtained from a subset of the devices that the dropped tests would only provide redundant information). In order to test the maximum number of devices and manage three test labs simultaneously, the group established certain test priorities to ensure the greatest number of devices were tested with the most meaningful test results. Due to these time constraints, not all devices were tested under each

procedure. The objectives in selecting and defining the test plans were as follows:

- Include tests that would show performance impact at the sensitivity limits of the devices (in terms of applied GPS signal power, also referred to as SV power), such as SV levels below -150 dBm (corresponding to indoor or other obscured settings).
- Include tests that would show performance at intermediate SV levels, around -147 dBm. These would correspond to the following use cases: indoors, dense urban outdoor areas, or other areas with significant blockage of GPS signals.
- Include tests that would show performance at SV levels corresponding to nominal outdoor usage with relatively open skies (SV levels around -130 dBm).
- Limited tests were performed with variable SV levels (these tests were based on the dynamic range tests in the above-referenced standards). However, it became apparent that, as with other test suites, the results were found to be similar to the nominal use case and therefore not all devices were subjected to these tests.

3.2.1.4.2 Field (Live Sky) Tests

To supplement the information gathered from the laboratory tests, field (live sky) tests were performed in Las Vegas, NV for a period of 12 days in late May 2011. Base stations were set up in four locations in and around Las Vegas in areas ranging from urban to rural, with three sectors per site at two sites and two sectors per site at the other two. The test transmitters were similar to the LightSquared LTE base stations and antennas planned to be used for commercial deployment, except that they transmitted at a power level that was 0-3dB (for a brief period 6 dB) less (for exact power levels transmitted, please refer to daily log of power found in Appendix C.7 that is planned for commercial deployment (the transmit power settings during the live-sky testing are included in the Las Vegas test report in Appendix C.3). 15 minute on-off periods were used to allow KPI measurements without excessive change in the satellite constellation geometry between measurements. Due to time constraints, only a subset of the devices was tested in the field.

The objectives of the field tests were as follows:

- Perform a subset of the laboratory KPI tests in live sky conditions. However, due to time constraints, the test coverage was rather limited.

For example, it was not possible to evaluate the cold-start GPS location performance of the devices selected for field testing.

- Perform limited propagation measurements to: (a) ensure that "hot" sites (in terms of received power) were amply considered and used in the KPI measurements; (b) gather propagation path loss data to be used in the analysis of the laboratory tests, (c) gather both dynamic tracking and static test KPI's, including in-building results

A detailed test plan for the LightSquared field test is provided in Appendix C.3. Additional field test data maybe filed in the Supplemental report by Verizon. These field test plans are provided in Appendix C.8

3.2.2 Work Plan Item 2: Select the Categories of Receivers and Receivers to be Tested

The cellular sub-team selected GPS-enabled cellular devices with GPS receivers that were representative of the broad range of deployed devices. This device list is not exhaustive or all-inclusive, but contained a representative sample from different manufacturers and with differing GPS receiver architectures. The sub-team tested approximately 40 different devices across many popular device models.

Device selection decisions were made by four US operators (note: the Working Group subgroup asked the device suppliers to eliminate known redundancies to test the largest sample possible.) The device selection criteria employed by the operators included placing a priority on devices that represent both legacy and current equipment. The US operator's device selection was also based on availability, size of the installed base, and diversity of GPS receiver and/or RF front-end configurations. An assessment of the device universe was also made by PRTM, an outside consulting firm retained by LightSquared, which resulted in adding (and removing) several devices during the test phase. All submissions were voluntary and drawn from production units, without modification other than to enable certain devices to operate in a conducted test mode.

Listed below are the receivers used for the tests.

3.2.2.1 Receivers Tested In the Independent Test Labs

The 41 Mobile devices listed below have been tested to date and are the subject of this report:

- Apple iPhone 3S (GSM)
- Apple iPhone 4 (CDMA)
- HTC Desire 6275
- HTC A6366
- HTC ADR6200
- HTC ADR63002
- HTC ADR63003
- HTC ADR6400L
- LG Lotus Elite
- LG Rumor Touch
- LG VN250
- LG VS740
- LG VX5600
- LG VX8360
- LG VX8575
- LG VX9200
- Motorola A855
- Motorola W755
- Motorola DROID X
- Motorola VA76R
- Sony Ericsson W760
- Nokia 6350
- Nokia 6650
- Nokia E71-2
- RIM 8330C
- RIM 8530
- RIM 9350
- RIM 9630
- RIM 9650
- RIM 9800
- Samsung SPH-M900
- Samsung SCH-R330
- Samsung SCH-R630
- Samsung SCH-R880
- Samsung SCH-U310
- Samsung SCH-U350
- Samsung SCH-U640
- Samsung SCH-U750
- Samsung SCH-I500 (VZ)
- Samsung SCH-I500 (USC)
- Samsung SGH-I617

Testing focused largely on handheld devices.

3.2.2.2 Devices Tested In the Live Sky Tests by LightSquared

29 devices representing seven different models were field-tested by LightSquared in the Las Vegas field test, and are found in the Table 3.2.1 below.

Table 3.2.1 Devices Tested by LightSquared for Live Sky

Manufacturer	Phone Model	Radio Technology	Number of Devices
Apple	iPhone 4	UMTS, GSM	4
Apple	iPhone 4	CMDA	4

LG	VS740	CDMA	4
HTC	Eris	CDMA	4
HTC	Aria	UMTS, GSM	4
HTC	Thunderbolt	CDMA	4
Motorola	Driod X	CDMA	4
Samsung	SPH-M900	CDMA	1

3.2.2.3 Statement of the Wireless Operators and Subgroup Regarding Device Selection and Monitoring of the Testing Process

"The test plan for cellular devices, including the threshold for determining harmful interference, was developed with strong input from the participating cellular operators. The cellular operators also determined which devices should be tested. In several cases, as the testing progressed, the cellular operators agreed to adjust the test plan and the list of cellular devices to ensure that the testing would be as thorough and useful as possible within the given time allowed for testing. The cellular operators also reviewed testing as it occurred, and augmented some of the lab testing with testing during the Las Vegas Live Sky tests. And the cellular operators reviewed the testing results to ensure that it made sense; in some cases, additional testing was conducted to investigate potential concerns with the data results. As a result of their intensive participation in the process of developing and reviewing the tests, the participating cellular operators accept that the data presented in this report represents a thoughtful and reasonable assessment of the potential of interference from LightSquared's operations to existing cellular devices."

3.2.2.3.1 Statement by Qualcomm regarding the TWG Cellular Subgroup Testing Process

"Qualcomm has reviewed the TWG test results. Qualcomm's internal testing is more limited than the extensive scope of the TWG testing, but given that, the results are broadly consistent with testing carried out by Qualcomm so far on our own reference designs. As described in our report to the FCC, we have used a different test configuration than the one called out in the TWG test plan; however at this time we do not believe these differences influence the overall conclusion."

Qualcomm is believed to be the largest AGPS chip technology supplier in terms of US devices in the field and offers its technology in

both CDMA and UMTS mobile devices, and is the largest GPS chip set supplier in devices that were tested.

Statements of the Independent Testing Labs regarding the TWG Cellular Subgroup Test Process

In the following Appendix' (C.4.1, C.4.2 and C.4.3), all three test labs provided quality certification statements to the sponsor of these tests.

3.2.3 Work Plan Item 3: Develop Operational Scenarios

3.2.3.1 Cellular Device AGPS Use Cases

The three primary use case examples for GPS receivers in cellular telephones are: 1) E911 Location; 2) Location-Based Services and 3) Real-Time Navigation. Each of these three use cases is associated with unique signal level and propagation aspects, driven, in part, by device orientation and proximity to the user.

3.2.3.1.1 E911 Location

The FCC's accuracy and reliability requirements for automatic location information (ALI) for wireless carrier enhanced 911 (E911) service require that carriers using handset-based E911 solutions provide location information within 50 meters for 67 percent of calls and within 150 meters for 95 percent of calls. These are the historical requirements for handset based location and there are recently adopted rules, 47 CFR Part 20.18 which will reflect different standards in the coming years. Carriers are expected to deliver a location fix within 30 seconds. These performance criteria are in alignment with FCC OET 71 guidelines. During an E911 call, the cellular telephone must acquire an accurate location fix using GPS/A-GPS, in some cases utilizing other location determination systems in addition to GPS.

3.2.3.1.2 Location-Based Services

This use case provides cellular telephone users with location or distance information for use in consumer applications and services.

3.2.3.1.3 Real-Time Navigation

This use case allows the user to utilize his cellular telephone as a navigation device. The cellular telephone may be oriented such that it does not have a direct view of the sky. In addition, the cellular telephone may be situated inside a moving vehicle where the GPS signal strength is further attenuated and fading is

prevalent. The GPS receiver operates differently than the above cases since it is continuously tracking satellites versus having to acquire those satellite signals from either a partially or fully unknown state.

3.2.4 Work Plan Item 4: Establish the Methodology for Analyzing Test Results

For the laboratory tests, a key objective of the analyses was to translate the overload thresholds measured in the laboratory to prediction of impacted areas relative to existing GPS coverage. The following methodologies were used in making this prediction:

3.2.4.1 Deterministic Analysis

A deterministic analysis was performed based on calculating the received power at various distances from the base station on a radial line along the azimuth of maximum transmit antenna gain. The elevation pattern of the base station antenna was considered in these calculations, but the maximum loss relative to the transmit antenna's bore sight was capped at 20 dB. This capping is necessary because multipath clutter tends to limit the maximum antenna gain discrimination. Various analyses were performed using both free space and Walfisch-Ikegami Line-of-Sight (WILOS) propagation models to show the range of power levels likely to be received where mobile devices are prevalent.

3.2.5 Work Plan Item 5: Derive the Test Conditions Based on the Established Operational Scenarios

As mentioned above, the test conditions were as defined based on the 3GPP or 3GPP2 standards, except where the Cellular sub-team chose to make a modification to fulfill the objects of blocker susceptibility testing. Some modification was necessary as the standards do not define tests with adjacent band signals. For example, for the minimum sensitivity tests, the SV power levels were increased by 1 dB when LightSquared signals were applied, to allow a uniform method of test with a common test margin (e.g.,1 dB C/N_0) for the passing of the test in a condition where the LightSquared L Band signal is present. The details of the test plans are documented in Appendix C.1

3.2.6 Work Plan Item 6: Write the Test Plan and Procedures

These tests encompassed overload testing of cell phone-based GPS receivers in proximity to LightSquared's base stations and UEs using 3GPP Band 24. While most of the testing emulated a GPS-capable device in close proximity to LightSquared base stations, some testing time was dedicated to the emulation of overload caused by proximate LightSquared User Equipment (UE's).

3.2.6.1 Laboratory Testing

Cellular devices were tested using conducted or radiated-chamber modes, consistent with industry practice, with a small number of devices being tested using both modes. Radiated testing was the default method of test for

devices that did not come with a connector to inject signals into the GPS receiver in place of the antenna. Specifically, all CDMA 3GPP2 devices were only subjected to conducted testing. Seven UMTS 3GPP devices were subjected to radiated testing and two UMTS 3GPP devices were subjected to conducted testing. The Cellular Working Group leveraged or adopted cellular industry standards for A-GPS normally used to determine receiver conformance to standards while extending these standardized procedures to add the effect of adjacent band signal to test receiver adjacent band interference. Testing for adjacent band interference is itself a common radio test practice which has been a vital component in receiver performance evaluation for decades.

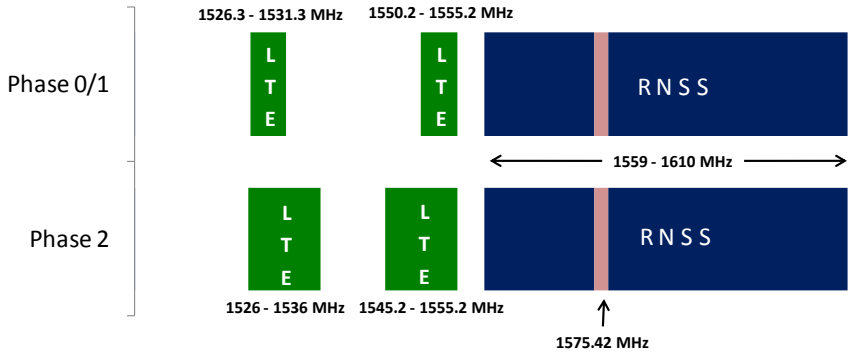
The Cellular Working group combined the A-GPS and interference desensitization standards into a new test methodology for the purpose of measuring cellular A-GPS receivers in the presence of adjacent-band interferers. Since there were no recognized test methods available, through consensus the Cellular Working Group devised seven test conditions, or test suites. The GPS receiver performance of the Cellular Working Group's test devices were evaluated against each applicable suite, which included evaluation of the receiver performance with multiple combinations of adjacent band interference signal levels and carrier frequencies.

The following standards served as a basis for the tests for both UE-based and UE- assisted AGPS devices.

3.2.6.1.1 Laboratory Testing Methodology

As previously discussed, the purpose of the test is to obtain performance results of GPS devices when exposed to both base station and mobile LightSquared LTE signals in their respective parts of the L Band. For the purpose of these tests, the LightSquared LTE signals were emulated either through the use of conducted injection of adjacent band signals into the device under test (DUT) or through radiated injection of signals and a cellular control channel carrier into a CTIA certified anechoic chamber. An anechoic chamber is a controlled environment that assures the test is performed in a setting void of external spectrum reflectance or interference that would otherwise cause instability or inconsistency in the measurement results. Devices were exposed to Band 24 signals representative of LightSquared's planned ATC base stations and UEs. Figure 3.2.1 below illustrates the location of the LightSquared downlink spectrum and its proximity to the Radio Navigation Satellite Service (RNSS) band. Additional testing was also performed utilizing the "lower-band" 1526-1536 carrier on a stand-alone basis.

Figure 3.2.1: LightSquared Downlink LTE band 24 and GPS band



In order to comply with industry standards and FCC requirements, LightSquared must control the amount of power it radiates in spectrum outside its own band. The allowable distribution of transmit power over a spectrum range is known as a spectrum mask. It is quantified in terms of power spectral density (PSD) as a function of frequency, both in-band and out-of-band relative to LightSquared's allocated channels. The tables below indicate the various requirements for the spectrum mask.

3.2.6.2 Test Procedure Summary and general approach

In essence, the testing assessed the performance of each Device Under Test (DUT) in the presence of the simulated Band 24 downlink and uplink signals. The DUTs used a simulated GPS satellite signal from a signal generator that had the ability to create a summation of received GPS signals from different satellites. The GPS received signal power settings was be set as described in the individual test cases described below. The detailed test plans were challenging to execute on a constrained schedule. The Cellular Working Group completed all device tests on the lower 10 MHz band testing thanks to the TWG extension of time. It also modified the test process (which included stopping certain upper and both band testing) to improve test flow and increase the rate of devices that could be tested while also working across three labs performing in 7x24 hour test shifts.

The original LightSquared Phase 1 spectrum plan was selected as it was able to create what was considered a worst-case in terms of overload potential. Phase 1 also has the potential to create third-order inter-modulation (IM) products in the GPS receiver at the GPS L1 frequency. In addition, Phase 1 also would, if authorized, generate the highest power density adjacent to the RNSS band. Testing was performed with 5 and 10 MHz LTE carriers separately and together to detect third-order IM products. As mentioned above, at a point midway in testing, devices were additionally tested with the lower 10 MHz channel on a standalone basis.

The following four key performance indicators (KPIs), as defined in the relevant standards, were measured and recorded:

#	Key Performance Indicator
1	2D position error
2	Response Time
3	C/N_0, as reported by the GPS
4	GPS SV power level

The tests were conducted as discussed in Section 3.2.1. The KPIs described above were recorded as functions of Band 24 power levels from zero power until any one of the conditions described in Section 3.2.1 was met. There was no pass/fail criterion in this test; logging KPIs at different blocker power levels resulted in power level readings that were subsequently interpreted. This form of testing was known as *full range testing*.

Finally, the following five constraints for the overall measurements were placed on the testing as follows:

1. When testing at blocker levels beyond the point where a defined pass/fail criterion had been met, the number of trials at each blocker level were set at a fixed number (30 for CDMA and 77 for UMTS) and the 67% and 95% (one and two sigma) values of the KPI were recorded.[5]
2. It was recommended from a procedural standpoint, that the testing for pass/fail criteria be conducted starting above levels likely to be encountered further than 20 meters from the base station blocker level (e.g. --15dBm) and then reduced to very weak blocker signal levels until a passing threshold was encountered. This was to ensure that the test system started with the minimum number of trials and then increased up to the maximum number.
3. All tests were performed separately for Band 24 signals corresponding to base station and UE.
4. Tests performed with and without Band 24 signals, for a given test environment, used exactly the same satellite constellations.

5. Because multiple test labs were utilized, some devices were selected as common objects and subjected to the same tests at different labs to confirm calibration and consistency across test sites.

3.2.6.2.1 Connectorized Device Conducted 3GPP tests

The following text highlights the tests performed by directly attaching test equipment to the DUT via an RF connector ("connectorized"). These tests were based on 3GPP TS 34.171. The tolerances to which these tests were measured are available in Table F.2.1 of TS 34.171. To determine the relative impact of the LTE signal, the tests were performed with the Band 24 blocker signal applied to the DUT at levels including zero and the maximum value where the success criterion as defined in the specification is met. Also, the following tests followed the specification with the exception that additional Band 24 signals were also applied.

AGPS Sensitivity test with Coarse Time Assistance per the 3GPP Standard

The sensitivity of the GPS receiver without interference was also tested. The following GPS Satellite levels and configurations were used:

GPS Satellite Configuration and Levels	
GPS signal for one satellite:	-141 dBm
GPS signals for remaining (7) satellites:	-146 dBm

AGPS Sensitivity test with Coarse Time Assistance at minimum, uniform SV power levels

Lower GPS Satellite power levels were used for this test as they determined, for a given DUT, the lowest set of GPS Satellite power levels at which the test will pass while maintaining the same number of satellites and relative satellite power levels per the specification. The provision applied for this particular sensitivity test was that when a blocker signal of non-zero power was applied, the minimum GPS Satellite signal power levels determined above were increased uniformly (for all GPS Satellites) by 1 dB (or a factor of 1.26).

AGPS Sensitivity Test with Coarse Time Assistance at discrete, uniform GPS Satellites power levels

This test was performed according to the 3GPP 34.171 specification with altered power levels for the seven lower-

powered GPS Satellites. Specifically, the seven low power satellites were set to levels of -135, -149, -152 dBm as opposed to -147 dBm for all satellites as called for in the standard: The 8th GPS Satellites was 5dB (or 3.16 times) above the other 7 GPS Satellites for each case.

This test was curtailed midway (that is not all devices were tested at all of the discrete levels) since it was not yielding results significantly different than the other test suites and test time optimization was sought.

AGPS Nominal Accuracy test as per standard

The GPS Satellite levels for this test were set to -130 dBm for all eight satellites. Additionally, full range testing was performed as previously described ignoring the pass/fail criteria.

AGPS Performance Test with different SV power levels

This test followed the specification with the additional exception; use of the following GPS Satellite power levels: -125, -128, -131, -134, -137, -140, -143, -146 dBm. Additionally, full range testing was performed as previously defined ignoring the pass/fail criteria.

3.2.6.2.2 Connectorized Device Conducted 3GPP2 tests

The following tests, based on the TIA-916 specification were performed against 3GPP2-compliant devices. All general requirements mentioned above also applied.

GPS Sensitivity Test as per standard

The test followed the specification with the exception of the additional Band 24 signals. Per the standard, the mobile devices were tested to capture the "Provide Location Response" or Provide Pseudo-range Measurement." To determine the relative impact of the interfering LTE signal, the above test was performed with the Band 24 blocker signal applied to the DUT at levels including zero and the maximum value where the success criterion as defined in the specification were met. Additionally, full range testing was performed as above.

GPS Sensitivity Test at minimum, uniform GPS Satellite power levels

Again, the test followed the specification with the exception of the additional Band 24 signals and the use of alternative satellite

signal levels. The measurement method did not use the GPS Satellite levels used in the standard test case; this test determined the minimum GPS Satellite signal level, with 4 Satellites visible. To determine the relative impact of the interfering signal, the above test was again performed with the Band 24 blocker signal applied to the DUT at levels including zero and the maximum value where the success criterion as defined is met.

GPS Sensitivity Test at discrete, uniform GPS Satellite power levels

The test was performed to specification at the following discrete SGPS Satellite levels: -135, -149, -152 dBm instead of the -147dBm in the standard. The testing was identical to that previously described in all other respects. The different GPS Satellite power levels were associated with different C/N_0 values, derived using a fixed N_0, comprised of thermal noise, at -174 dBm/Hz, as implied by the specification.

GPS Accuracy as per standard

The test again followed the standard with the exception of the additional Band 24 signals. The mobile devices were tested to capture the "Provide Location Response" or Provide Pseudo-range Measurement". In summary, the GPS Satellite signal levels were set to -130 dBm with C/No expected to register 44 dB/Hz. This test sets the simulator to present 8 GPS Satellites to the DUT. To determine the relative impact of the interfering LTE signal, the above test was performed with the Band 24 blocker signal applied to the DUT at levels including zero and the maximum value where the success criterion as defined in the specification is met. Additionally, full range testing was performed as above.

GPS Performance Test with non- uniform GPS Satellite power levels

The test was performed as exactly as previously defined with the exception the following GPS Satellite power levels were used: -125, -128, -131, -134, -137, -140, -143, -146 dBm. To determine the relative impact of the interfering LTE signal, the above test was performed with the Band 24 blocker signal applied to the DUT at levels including zero and the maximum value where the success criterion as defined the specification is met.

Additionally, full range testing was performed as defined in test suits 2.4.x.x throughout this document, ignoring the pass/fail criteria.

3.2.6.2.3 Radiated Anechoic Chamber Tests

The objective was to run the tests described in above which are connectorized in a radiated environment by leveraging CTIA OTA test procedures. For these OTA tests, the blocker signal was added linearly to the GPS Satellite signals and injected into the chamber from the direction of maximum gain as reported by the GPS receiver. Knowledge of the GPS Satellite and blocker power levels is necessary in the following tests.

Sensitivity Test (minimum, uniform GPS power levels)

The minimum GPS Satellite level sensitivity tests described in above A-GPS tests are essentially identical to the Sensitivity test defined in the specification without the blocker. This test was run both with and without the blocker to determine the relative impact of the blocker. As described above, to determine the relative impact of the interfering LTE signal, the above test was performed with the Band 24 blocker signal applied to the DUT at levels including zero and the maximum value where the success criterion as previously defined and are met. Again, the provision that was applied however was that when a blocker signal of non-zero-power is applied, the minimum GPS Satellite power levels determined above will be increased uniformly (for all GPS Satellites) by 1 dB.

3.2.6.2.4 Live Sky Testing

The test plan purpose is to characterize the performance of GPS receivers in the presence of L-band base station downlink signals in an outdoor environment using actual, live GPS signals. Production base station transmitter subsystems (including production PAs, filters and other RF components) and antennas were used.

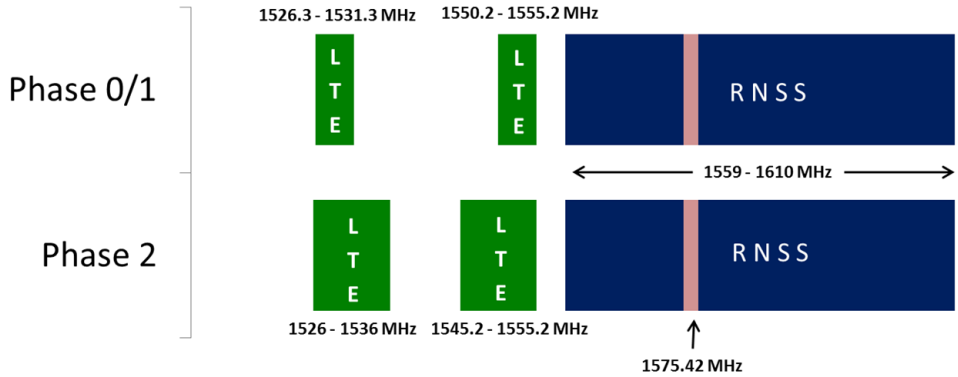
The base station installation was representative of an actual LTE deployment, including a 2^0 electrical down tilt antenna. There were a series of live sky testing conditions. For the testing done between May 16 and 17, in the single carrier case, EIRP per carrier was approximately 29 dBW. In the two carrier case, the EIRP per carrier was approximately 26 dBW. For testing completed after May 18, in the single carrier case the EIRP per carrier was increased to 32 dBW and for the two carrier case increased to 29 dBW. This difference is due to a limitation

caused by the unavailability of full power configuration software from LightSquared's network equipment supplier which was not available and is currently being completed and will be available later for actual network deployment.

100% channel loading was emulated using random "dummy" data to modulate the LTE carriers, which is a standard station diagnostic feature. The planned base station power levels and spectrum occupancies are shown in Figure 3.2.2 below. For the live-sky tests, owing to the limited time available, only variations of the Phase 1 configuration were tested. The two individual 5 MHz channels were tested separately and together as this test can show the vulnerability of a given device to third-order intermodulation products.

Figure 3.2.2: LightSquared Downlink LTE Band 24 and GPS Band (EIRP per carrier: 32 dBW when single carrier is transmitted; EIRP per carrier: 29 dBW, when two carriers are transmitted)

Note: Both were for testing completed after May 18



Individual Sub-team Member Field Tests

Some sub-team members conducted separate field tests concurrent with the Live Sky tests. For example, Verizon Wireless conducted testing of several AGPS CDMA devices in proximity to LightSquared's transmitting base stations to determine if there is any degradation to E911 location accuracy as a result of LightSquared's deployment. The Verizon Wireless test plan is included in Appendix C.8.

3.2.7 Work Plan Item 7: Identify and Engage Appropriate Neutral Test Facility(ies) for the Testing Portion of the Work Plan

The cellular sub-team engaged three different laboratories for the cellular GPS receiver testing program:

- PC TEST (Columbia, MD)
- InterTek (Lexington, KY)
- ETS Lindgren (Cedar Park, TX)

All labs were CTIA authorized test labs with extensive experience in testing various types of consumer devices utilized in the cellular industry. Each of these labs has provided a letter attesting to their review of the data and observation of quality practices, contained in Appendix C.4.1 through C.4.3.

3.2.8 Work Plan Item 8: Performance Testing

This section reports the data taken during the testing by the TWG Cellular subgroup.

3.2.8.1 Sample 3GPP & 3GPP2 Test Results

Cumulative test results were recorded for each device for the seven tests defined in the test plan and the three 3GPP Band 24 LTE frequency channel presentations, low, high and both channels. Because the standard 3GPP and 3GPP2 standards define the tests and required KPI's differently the test results were reported in somewhat different formats.

The CDMA 3GPP2 devices were all "connectorized" when they arrived at the test facility. This allowed for direct measurement of the GPS SV and blocker powers at the device. Some of the 3GPP devices were also tested in this way. Other 3GPP devices were only tested radiated and required a calibration step to assure that the power at the GPS receiver input was indeed the power desired regardless of the GPS antenna gain. The power was calibrated by setting the GPS signal power at the device to -130dBm into a 0dBi antenna and monitoring the C/No as reported by the device. Since 44dB-Hz is the C/No when the SV level is -130dBm, the difference between 44dB-Hz and the measured C/No was attributed to the antenna gain, a factor used to maintain comparable results between conducted and radiated measurements taken on the same device.

Table 3.2.2: Sample Test Record for 3GPP Test

Test Date Time Stamp	Test#	Test Name	Description	Status	ESG Amplitude Step	ESG1 Amplitude Calibrated	ESG2 Amplitude Calibrated	Completed Calls	Number of Measurements	Completed Measurements	# of Bad Results	SVs (Min)	SVs (Avg)	SVs (Max)	C/No (Min)	C/No (Avg)	C/No (Max)	Response Time - Min (s)	Response Time - Mean (s)	Response Time - Max (s)	2-D Position Error - Min (m)	2-D Position Error - Mean (m)
BOTH 10 MHz Interferers																						
20110603_223655	1	34.171 Conformance Test	2.4.1.4 OTA - Baseline (no interferer)	Pass	0.00	0.00	0.00		77.00	77.00	0.00	8.00	8.00	8.00	43.00	43.11	44.00	3.52	6.94	9.54	1.06	1.30
	2	34.171 Conformance Test	2.4.1.4 OTA - Interferer Applied	Fail	-10.00	-1.74	-2.08		2.00	0.00	2.00	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	0.00	0.00	0.00		
	3	34.171 Conformance Test	2.4.1.4 OTA - Interferer Applied	Pass	-15.00	-6.74	-7.08		77.00	77.00	1.00	8.00	8.00	8.00	21.00	26.02	28.00	4.66	8.20	10.69	1.11	7.20
Low 10 MHz Interferer																						
20110608_212023	1	34.171 Conformance Test	2.4.1.4 OTA - Interferer Applied	Pass	-10.00	-1.74	0.00	1.00	77.00	77.00	0.00	8.00	8.00	8.00	43.00	43.99	44.00	3.52	7.09	9.56	1.06	1.38
High 5MHz Interferer																						
20110608_200218	1	34.171 Conformance Test	2.4.1.4 OTA - Interferer Applied	Fail	-10.00	0.00	-2.02		2.00	0.00	2.00	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	0.00	0.00	0.00		
	2	34.171 Conformance Test	2.4.1.4 OTA - Interferer Applied	Fail	-15.00	0.00	-7.02		4.00	2.00	2.00	7.00	7.50	8.00	22.00	22.80	24.00	15.70	17.19	18.69	11.04	17.95
	3	34.171 Conformance Test	2.4.1.4 OTA - Interferer Applied	Pass	-20.00	0.00	-12.02	1.00	77.00	77.00	0.00	8.00	8.00	8.00	27.00	27.93	29.00	4.66	8.28	10.68	1.08	4.93

Table 3.2.3: Sample Test Record for 3GPP2 Test

Interference level	Description	Status	Time Stamp	Total Calls	Samples	Code Phase Rel Err (Sigma 1)	Code Phase Rel Err (Sigma 2)	Code Phase Abs Err (Sigma 1)	Code Phase Abs Err (Sigma 2)	Doppler Err (Sigma 1)	Doppler Err (Sigma 2)	C/No Err (Sigma 1)	C/No Err (Sigma 2)
BOTH 5MHz Interferers													
baseline (none)	Test Plan - section 2.4.2.2	Passed	5/17/2011 19:56	30	120	0.03	0.06	0.08	0.14	2.17	4.23	1.00	1.00
-15	Test Plan - section 2.4.2.3	Failed	5/17/2011 19:29	26	104	0.34	0.34	0.64	0.64	81.00	81.00	6.10	6.10
-20	Test Plan - section 2.4.2.4	Failed	5/17/2011 18:22	30	120	0.34	0.34	0.64	0.64	81.00	81.00	6.10	6.10
-25	Test Plan - section 2.4.2.5	Failed	5/17/2011 18:44	30	120	0.08	0.34	0.15	0.64	4.14	81.00	3.00	6.10
-30	Test Plan - section 2.4.2.6	Passed	5/17/2011 19:04	30	120	0.04	0.08	0.08	0.17	2.36	4.00	1.00	2.00
-35													
Low 5MHz Interferer													
-15	Test Plan - section 2.4.2.2	Passed	5/17/2011 20:42	30	120	0.03	0.06	0.07	0.12	2.10	3.69	1.00	1.00
-20													
High 5MHz Interferer													
-15	Test Plan - section 2.4.2.2	Failed	5/17/2011 21:08	30	120	0.34	0.34	0.64	0.64	81.00	81.00	6.10	6.10
-20	Test Plan - section 2.4.2.2	Failed	5/17/2011 21:24	21	84	0.08	0.34	0.13	0.64	4.24	81.00	3.00	6.10
-25	Test Plan - section 2.4.2.2	Passed	5/17/2011 21:46	30	120	0.04	0.10	0.09	0.15	2.92	5.31	1.00	2.00
-30													

Full details of the data obtained from the measurements conducted are available for download and viewing at the following URL: http://www.gpsworkinggroup.org/

3.2.9 Work Plan item 9: Analyze Test Results Based on Established Methodology

Based on the test results provided above, analysis of these results was derived. Below are five figures detailing the specific results of devices subjected to the following tests: (1) 3GPP/3GPP2 GPS sensitivity test; (2) 3GPP/3GPP2 GPS accuracy test; (3) lowest sensitivity search test; (4) Performance Impact testing with 4 satellites visible (SV) testing at a -135, -149 and -152 dBm sensitivity levels and 1dB above sensitivity levels. Note that some of these tests are not exactly the same for 3GPP versus 3GPP2 but we are plotting the results together.

3.2.9.1 GPS summary of results

The histogram in Figure 3.2.1 below shows the distribution of the lowest passing level the devices achieved, as specified by the 3GPP or 3GPP2 standards, in the presence of an LTE signal. The histogram values were determined by finding the most susceptible value which represents the lowest blocker level that still enabled the device to pass tests for each device across the 7 defined test suites. Figure 3.2.1 depicts data based on device results as of June 14, 2011 and is shown only as a representative illustration of the difference in device susceptibility between operating the downlink transmitter at the standalone "low and high plus low" channel configurations. Figure 3.2.2 is a histogram which depicts the performance for all devices at the lower 10 MHz configuration (1526-1536 MHz) and should be used for analysis for this channel configuration. Figure 3.2.3 gives the cumulative distribution of the same data in Figure 3.2.2.

Table 3.2.4 below is for all test suites and all devices for the lower 10 MHz.

LTE Channel	LOW CHANNEL - 10 MHz																				
Test \ Device	CD-02	CD-03	CD-04	CD-05	CD-06	CD-07	CD-08	CD-09	CD-10	CD-11	CD-12	CD-15	CD-16A	CD-16B	CD-18	CD-20	CD-21	CD-22	CD-23	CD-24	CD-25
2.4.2.1	0	0	0	0	0	0	0	-15	-10	0	0	0	N/A	0	0	0	0	0	0	0	0
2.4.2.2	0	0	0	0	-5	0	0	-15	-15	0	-5	0	N/A	0	0	0	0	0	FB	0	0
2.4.2.3 (-135)	FB	0	0	0	0	0	0	-15	-10	0	0	0	N/A	0	0	0	0	0	0	0	0
2.4.2.3 (-149)	0	0	0	0	-5	0	0	-15	-10	0	0	0	N/A	0	0	0	0	0	0	0	0
2.4.2.3 (-152)	0	0	0	0	-5	0	0	-15	-10	-5	-5	0	N/A	0	0	0	0	0	-5	0	0
2.4.2.4	0	0	0	0	0	0	0	-15	-10	0	0	0	N/A	0	0	0	0	0	0	0	0
2.4.2.5	0	0	0	0	-5	0	0	-15	-10	0	0	0	N/A	0	0	0	-5	0	0	0	0

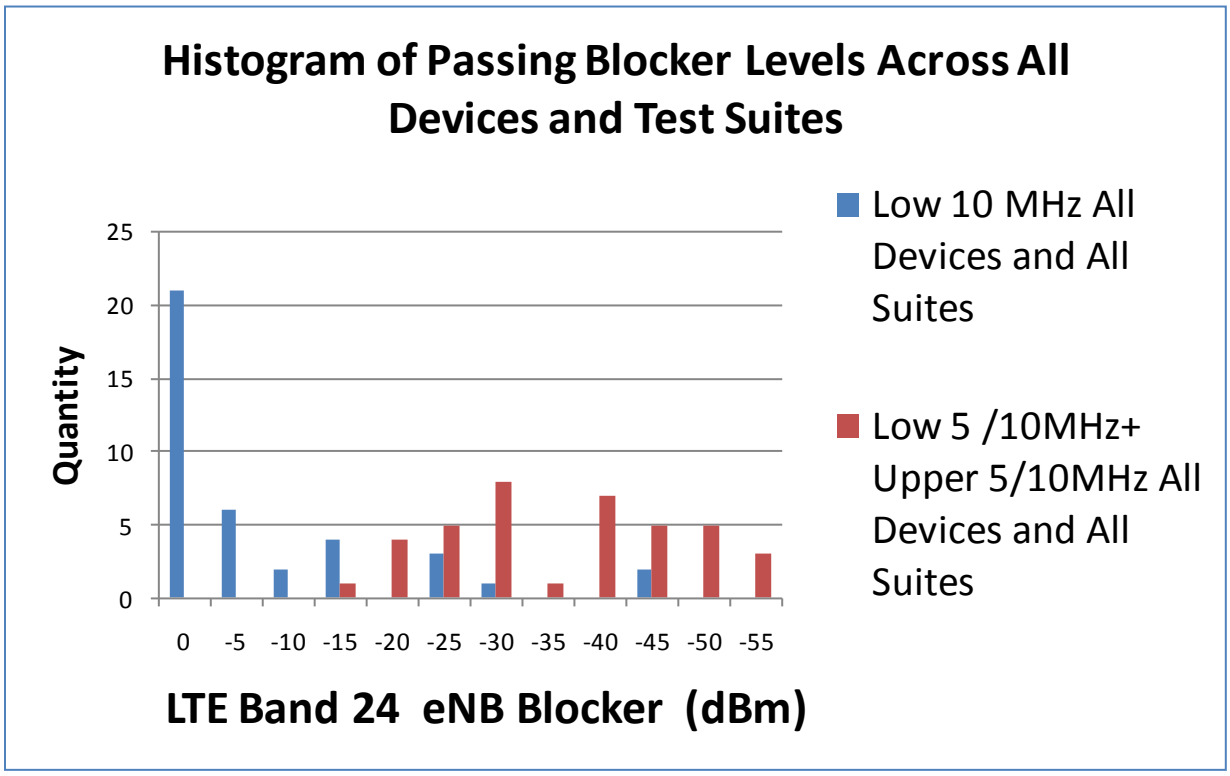
LTE Channel																					
Test \ Device	CD-26	CD-27	CD-28	CD-30	CD-31	CD-32	CD-33	CD-34	CD-35	CD-36	CD-37	CD-38	CD-39	CD-40	CD-41	CD-42A	CD-44	CD-45	CD-46	CD-47	CD-48
2.4.2.1	0	0	0	0	0	0	0	0	0	-30	-10	-20	-10	-45	-25	-10	-10	-10	-10	0	0
2.4.2.2	0	0	0	-5	0	0	0	0	0	-30	-20	-10	-10	-45	-10	-10	-15	-15	-10	0	0
2.4.2.3 (-135)	0	0	0	0	0	0	0	0	0	-30	-10	-10	-10	-35	-10	-10	-10	-10		0	0
2.4.2.3 (-149)	0	0	0	0	0	0	0	0	0	-30	-10	-45	-10	-45	-25	-10	-10	-15	-10	0	0
2.4.2.3 (-152)	0	0	0	0	0	0	0	0	0	-30	-25	FB	FB	FB	FB	-25	-15	FB	FB	0	0
2.4.2.4	0	0	0	0	0	0	0	0	0	-30	-10	-10	-10	-30	-10	-10	-10	-10	-10	0	0
2.4.2.5	0	0	0	0	0	0	0	0	0	-30	-10	FB	-10	-45	-20	-10	-10	-15		0	0

At the end of the test process it was discovered that one device, CD-40, submitted for testing was not a retail production device. This device was in fact a pre-production conformance test device sent by the device manufacturer to the operator prior to its retail launch in March or April 2008 (those dates are according to FCC records). Due to inconsistent results and the status of device CD-40, the question was raised if the device is representative of the same model devices currently in the field. Assurances were made by the wireless operator, AT&T, that sent the CD-40 device based on their discussion with the device vendor was expected to be the same as those eventually shipped to the field. No confirmation was made in the limited time available for this report that the device is in fact electrically identical to production units.

An AT&T Regulatory AVP executive provided a statement on June 28th as follows: "it has no problem representing in the (TWG) report that this device (CD-40) is an older generation of phone that is no longer sold but still being used in our production network and that it should be taken in this context. Eventually, this phone will be replaced by a newer generation of phone and will no longer be in our network although quantifying this would be difficult."

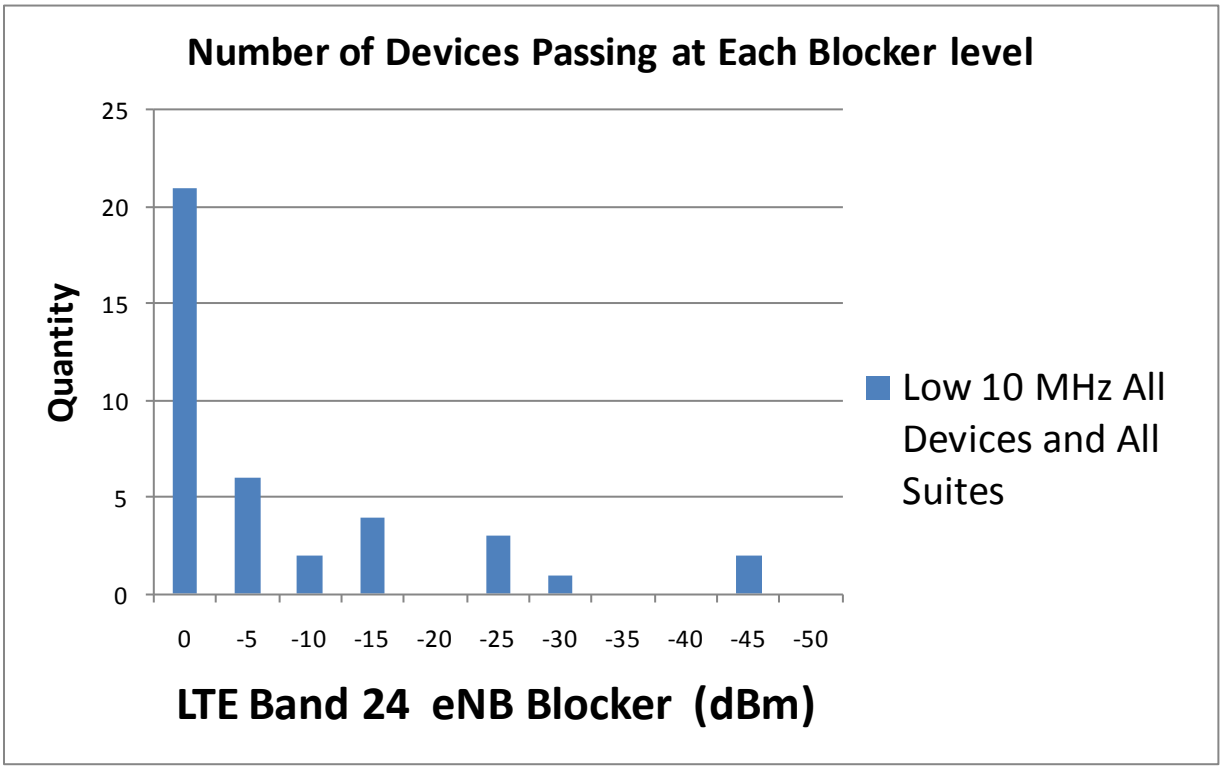
An AT&T retail outlet reported that the CD-40 model has not been sold since 2009, and this report was not disputed by AT&T. It is also known that other devices, some current and sold today by the same device supplier and sold through AT&T channels performed substantially better than CD-40. AT&T also indicated it would try, though unsuccessful to date to find one or more true production devices to replace the pre-production CD-40 device.

Figure 3.2.1 Histogram of Passing Blocker Levels across All Devices and Test Suites



Note: 0 dBm was the maximum blocker test level in these tests and over 20 devices exceeded 0 dBm test capacity.

Figure 3.2.2 Histogram of number of devices passing at each blocker across All Devices and Test Suites for the Lower 10MHz



The Lower 10 Channel Configuration blocker passing results shown above represent the entire 41 device test universe plus breakdowns by the type of device, CDMA or WCDMA. Data for all devices is shown as "Lower 10MHz, all devices and all suites". The same data was shown but with elimination of the WCDMA test suite at -152dBm because 6 of the 9 devices did not pass the no-blocker-present baseline, which means they could not provide a location fix with SV power set at -152dBm regardless of blocker presence. These data are labeled as "Lower 10MHz all devices and all suites without WCDMA @-152dBm". Then the CDMA devices and the WCDMA devices are shown seperately since we observe based on the 41 devices tested that in general the CDMA devices perform better (that is, offer greater immunity) than the WCDMA devices.

Figure 3.2.3 CDF of Final of Passing Blocker Levels across All Devices and Test Suites for the lower 10MHz

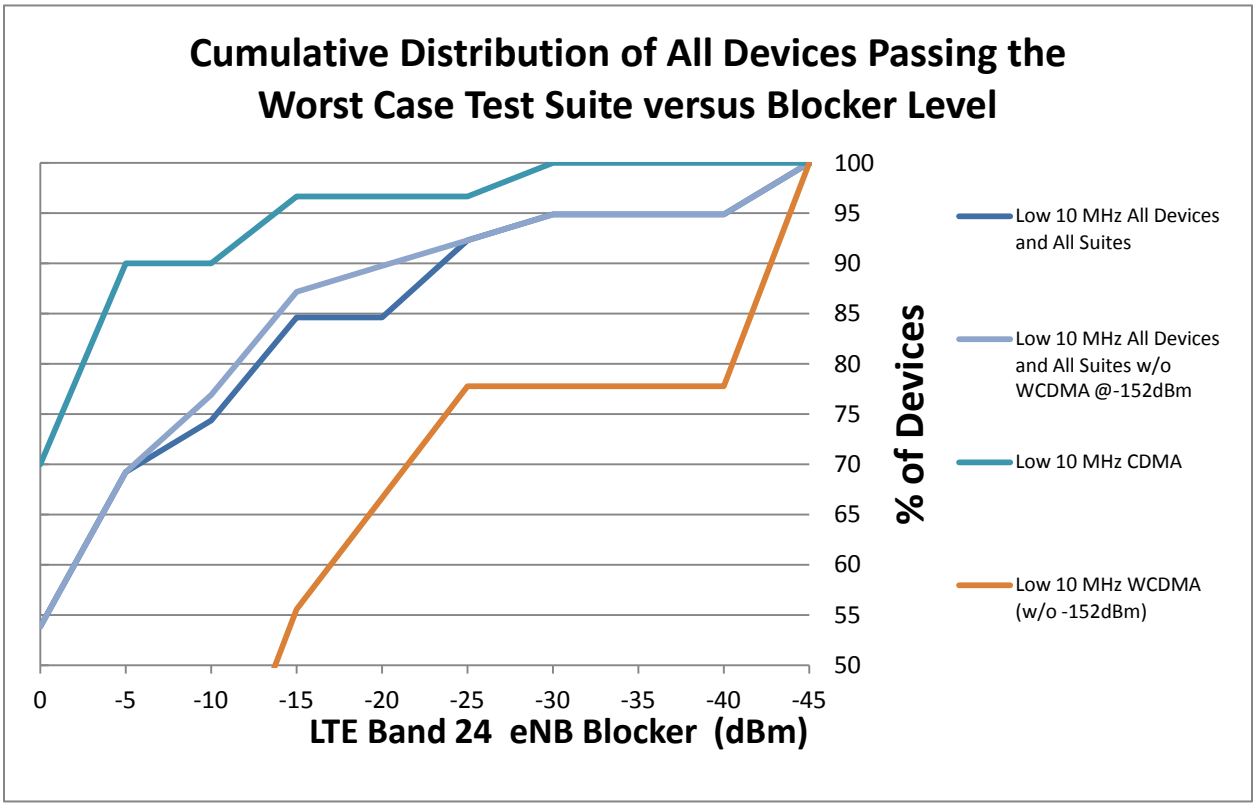


Table 3.2.4 below contains the detailed histogram data of each device as a function of LTE signal level present on the lower 10 MHz channel. Table 3.2.5 reports the cumulative percentage of devices passing for the same data. The Lower 10MHz WCDMA without -152dBm refers to elimination of the -152dBm blocker data. This was done to remove WCDMA devices that did not pass the baseline without blocker and to eliminate WCDMA devices whose sensitivity were right at -152 dBm.

Table 3.2.4: Histogram details of Devices Passing 3GPP/3GPP2 Tests as a Function of LTE Signal Level (Blocker Power versus number of units).

Power (dBm)	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
Low 10 MHz All Devices and All Suites	21	6	2	4	0	3	1	0	0	2
Low 10 MHz CDMA	21	6	0	2	0	0	1	0	0	0
Low 10 MHz WCDMA (w/o -152dBm)	0	0	3	2	1	1	0	0	0	2
Low 10 MHz All Devices and All Suites w/o WCDMA @-152dBm	21	6	3	4	1	1	1	0	0	2
Low 10 MHz All Devices at +1dBr sensitivity	25	3	5	4	1	0	1	0	0	1
Low 10 MHz All Devices at -130dBm accuracy suite	29	0	9	1	0	0	2	0	0	0

Table 3.2.5: CDF details of Devices Passing 3GPP/3GPP2 Tests as a Function of LTE Signal Level (Blocker Power versus CDF Percentage).

Power (dBm)	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
Low 10 MHz All Devices and All Suites	54	69	74	85	85	92	95	95	95	100
Low 10 MHz CDMA	70	90	90	97	97	97	100	100	100	100
Low 10 MHz WCDMA (w/o -152dBm)	0	0	33	56	67	78	78	78	78	100
Low 10 MHz All Devices and All Suites w/o WCDMA @-152dBm	54	69	77	87	90	92	95	95	95	100
Low 10 MHz All Devices at +1dBr sensitivity	63	70	83	93	95	95	98	98	98	100
Low 10 MHz All Devices at -130dBm accuracy suite	71	71	93	95	95	95	100	100	100	100

3.2.9.2 Individual GPS Sensitivity Test Suites

This initial test was used to determine how a LightSquared base station would affect the performance of a GPS receiver when the GPS receiver is operated at the standards-based required sensitivity level (4 SVs at -147 dBm, per 3GPP2 standard, and in the case of 3GPP one SV at -142 dBm and the remaining SVs at -147 dBm). The following graphics portray testing results for the 32 CDMA devices and 9 UMTS devices that were tested.

The charts below plot the highest passing blocker power level for the device under test. In some cases the maximum power level of Band 24 Downlink was set to -15dBm, while in other cases, the maximum power level of Band 24 Downlink was set as high as the system allowed, which was 0dBm.

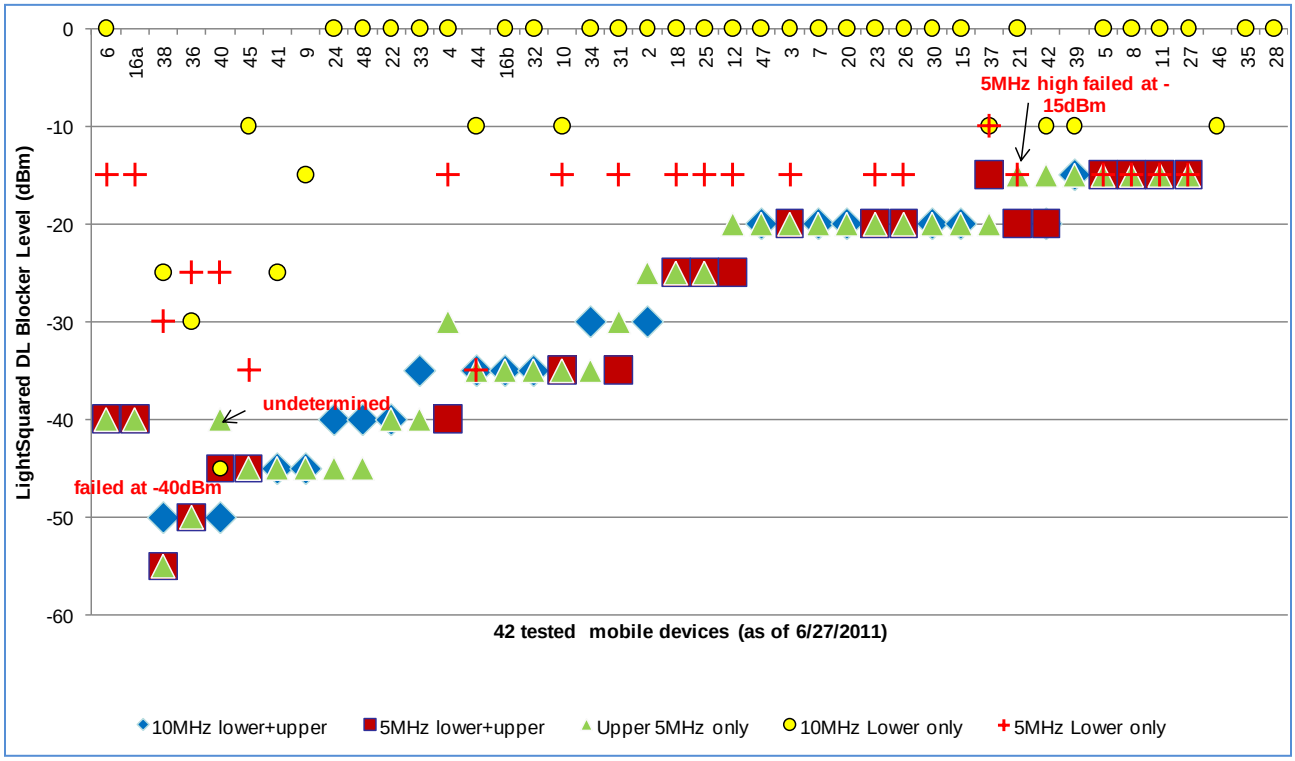
In some cases the tested device still failed at the lowest power level that B24 was configured in the tests. In these cases the device is labeled as failed in the charts.

3.2.9.2.1 Maximum Tolerable LS Blocker Level: 3GPP/3GPP2 GPS Sensitivity Test (2.4.1.1/2.4.2.1)

This test provides measurements regarding the LightSquared eNB transmission impact on cellular GPS receivers at a critical threshold of performance, in this case where the SV's signals are at the 3GPP/3GPP2 level (4 SVs at -147 dBm, per 3GPP2

standard, and in the case of 3GPP one SV at -142 dBm and the remaining SVs at -147 dBm).

Figure 3.2.3 Maximum Tolerable LS Blocker Level: 3GPP/3GPP2 GPS Sensitivity



Note: 40 device tests were taken from 39 different models.

This data generally shows that testing with LightSquared operations at the higher 5 MHz and 10 MHz band (1550.2 MHz to 1555.2 MHz) caused GPS failure for a significant number of the tested devices. In contrast, when testing in the lower bands (1526-1536 MHz) fewer devices had a level of susceptibility below -15dBm. Please refer to the Tables in Section 3.2.8 above which show the percentages of device susceptibility at various threshold levels. Note that devices that passed above 0dBm were at the maximum level of the test system capability to apply a blocker signal amplitude in CDMA devices, and -10dBm in WCDMA tested devices.

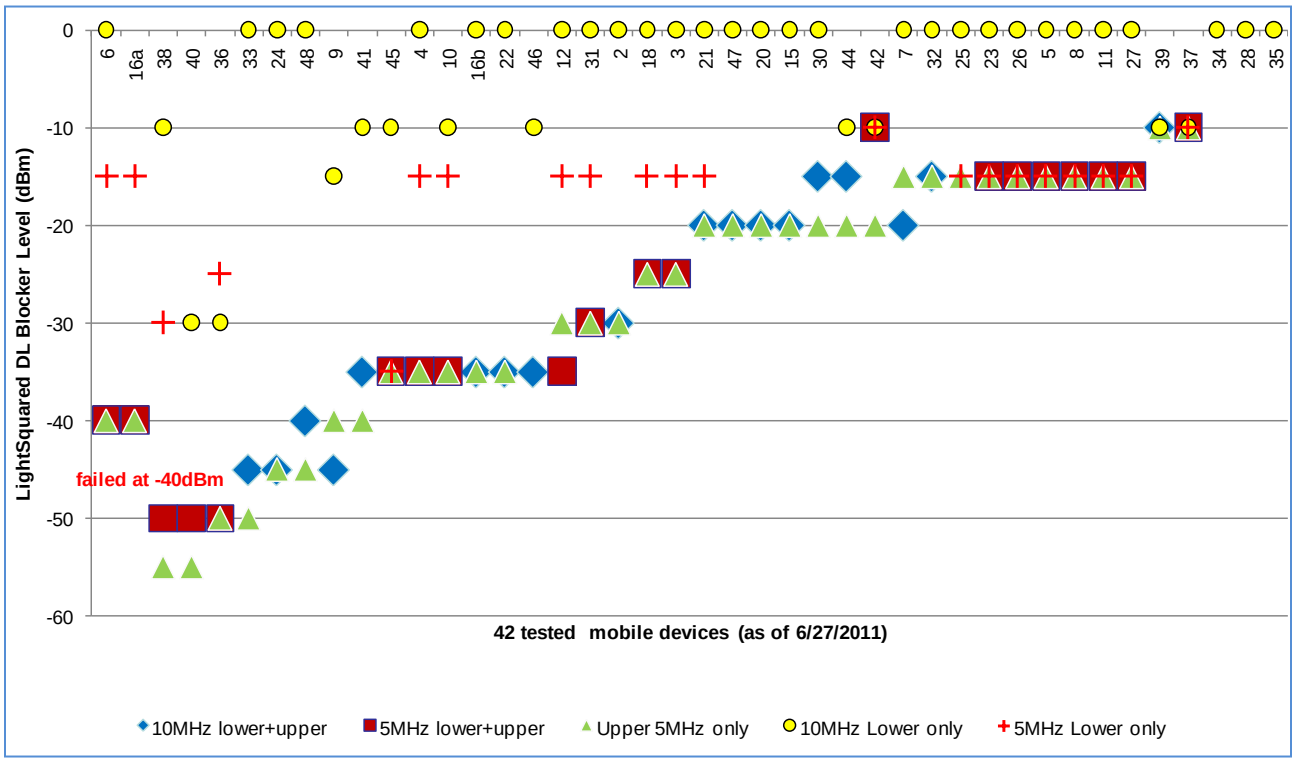
3.2.9.2.2 GPS Receiver Reported Accuracy Testing

The next test summarized was used to check how the LightSquared base station operation would affect GPS receiver performance when the GPS receiver was operated at the standards-based accuracy test case level (eight SVs with -130 dBm, per 3GPP/3GPP2 standard). The following graph portrays test results for CDMA and UMTS devices as of June 14, 2011:

3.2.9.2.3 Maximum Tolerable L Band Blocker Level: 3GPP/3GPP2 GPS Accuracy Tests (2.4.1.4 and 2.4.2.4)

Provides a view of how the LightSquared eNB transmission will affect the GPS Receiver when the 8 SV's signals are at the 3GPP/3GPP2 required accuracy level of -130dBm.

Figure 3.2.4 Maximum Tolerable L Band Blocker Level: 3GPP/3GPP2 GPS Accuracy Tests



As was true with the prior test case, upper band LightSquared base station operations caused GPS failure for some CDMA and UMTS devices, while the lower 5 or 10 MHz band interference passed at the maximum level of the test system, -15 dBm, except for one CDMA device (CD-36) at -30dBm.

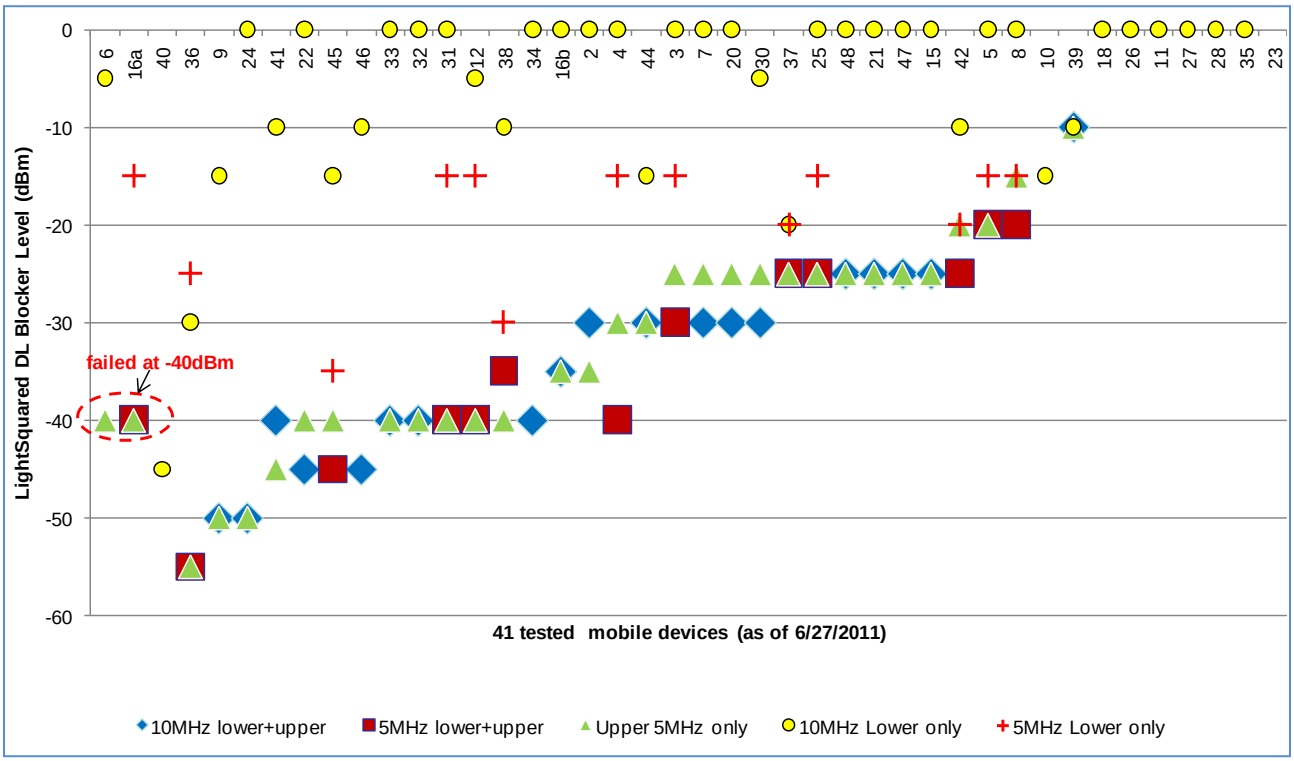
3.2.9.2.4 Lowest Sensitivity Search

This test case attempted to determine how a LightSquared base station would impact GPS receiver performance when the GPS receiver is operated at the manufacturer-specified minimum GPS sensitivity level. The graphic below portrays testing results for the 32 CDMA devices and 9 UMTS that were tested:

3.2.9.2.5 Maximum Tolerable L Band Blocker Level: Lowest /Actual Sensitivity Search +1dB (2.4.1.2 and 2.4.2.2)

This test provides a view of how the LightSquared eNB transmission will affect the GPS Receiver when the SV's signals are at the 3GPP/3GPP2 actual highest measured sensitivity level for each device tested. Maximum sensitivity is searched manually for each device before injecting the LightSquared signal.

Figure 3.2.5 Maximum Tolerable L Band Blocker Level: Lowest /Actual Sensitivity Search



+1dB

Results for this test show CD30, CD-36 CDMA devices were the only results below an otherwise consistent result of -15dBm or higher. CD-40 a UMTS devices was susceptible at -45dBm, the rest were susceptible at -15dBm or higher to the extent test capacities in the conducted or radiated chamber allowed.

3.2.9.2.6 Performance Impact Testing -Maximum Blocker level Across a Range of Sensitivity Levels using uniform satellite signal levels from -135 to -152 dBm

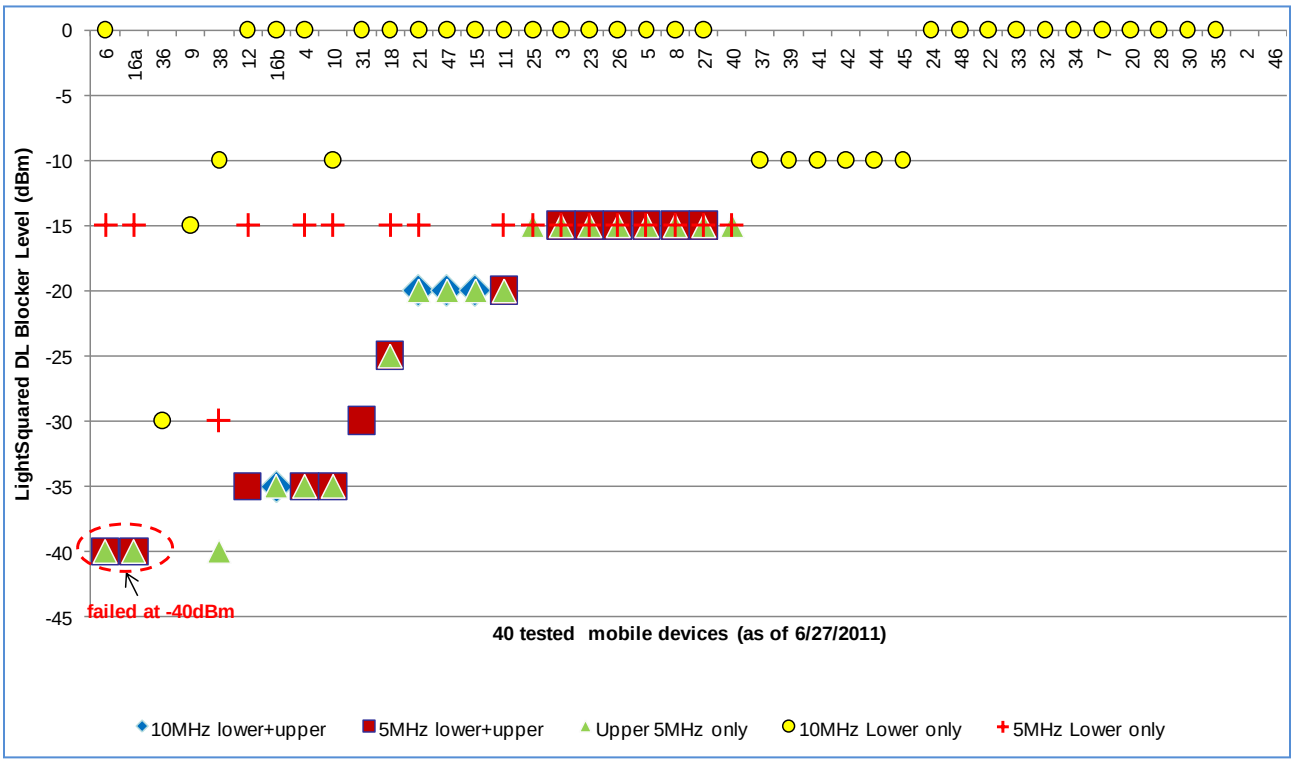
The final three tests performed measured the performance impact on GPS receivers under three different receive signal scenarios corresponding to: (1) outdoor usage (-135 dBm, 16 tested devices), (2) dense urban/significant blockage situation (-149 dBm, 15 tested devices), and (3) indoor usage (-

152 dBm, 25 tested devices). The three figures below portray testing results for the 30 CDMA devices and 9 UMTS devices that were tested.

3.2.9.2.7 Maximum Tolerable L Band Blocker Level: Uniform SV Level at -135dBm (2.4.1.3@-135 and 2.4.2.3@-135)

These tests provide a view of how LightSquared eNB transmissions affect the GPS receiver when the GPS SV signals are uniformly applied to the DUT at -135dBm.

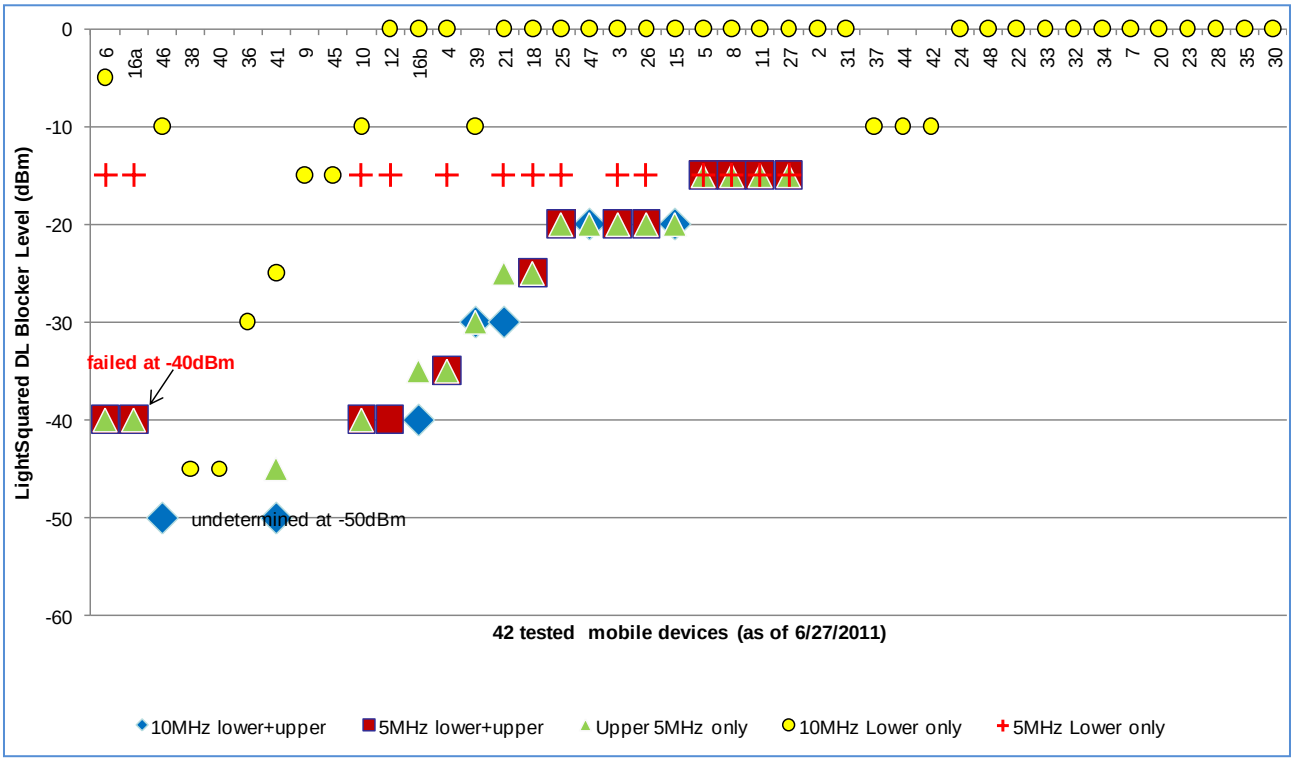
Figure 3.2.6 Maximum Tolerable L Band Blocker Level: Uniform SV Level at -135dBm



3.2.9.2.8 Maximum Tolerable L Band Blocker Level: Uniform SV Level @ -149dBm (2.4.1.3 @ -149 and 2.4.2.3 @-149)

These tests provide a view of how the LightSquared eNB transmission will affect the GPS receiver when the SV's signals are at -149dBm.

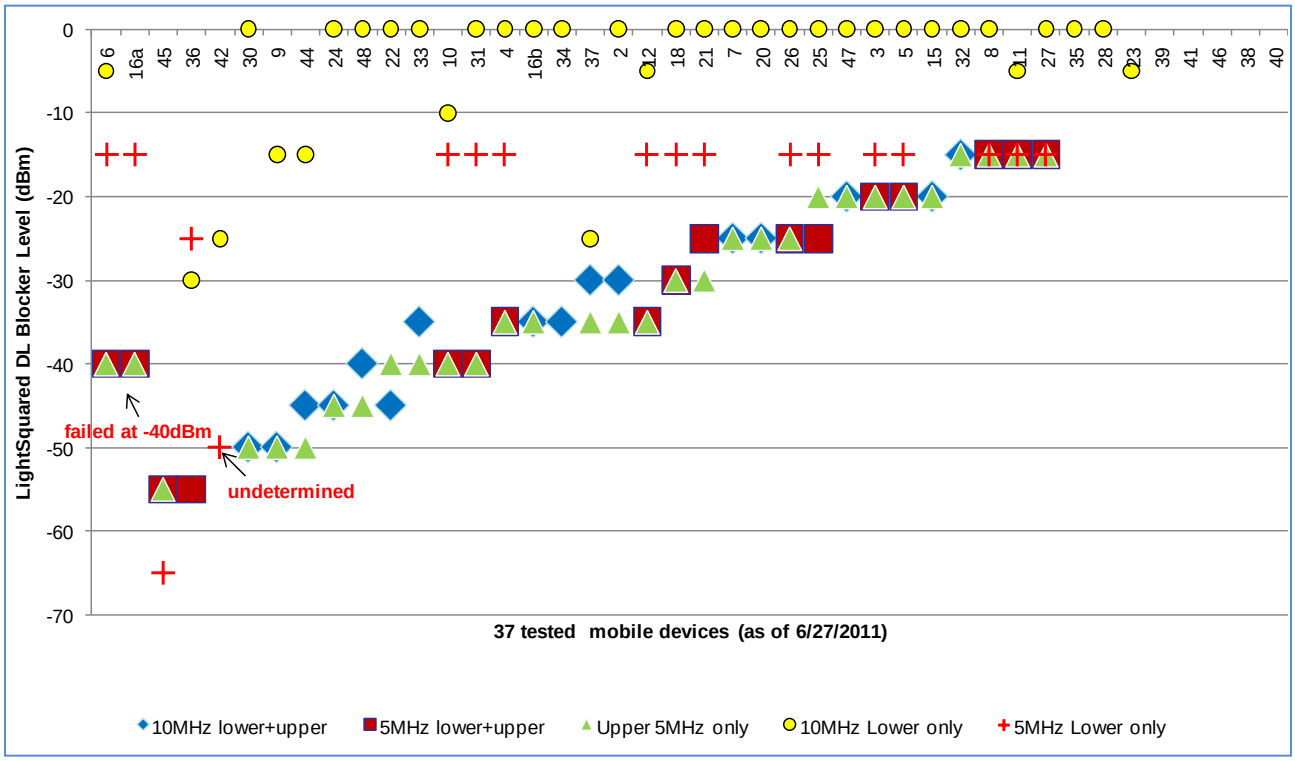
Figure 3.2.7 Maximum Tolerable L Band Blocker Level: Uniform SV Level @ -149dBm


LightSquared DL Blocker Level (dBm)
0
-10
-20
-30
-40
-50
-60
6
16a
46
38
40
36
41
9
45
10
12
16b
4
39
21
18
25
47
3
26
15
5
8
11
27
2
31
37
44
42
24
48
22
33
32
34
7
20
23
28
35
30
failed at -40dBm
undetermined at -50dBm
42 tested mobile devices (as of 6/27/2011)
10MHz lower+upper
5MHz lower+upper
Upper 5MHz only
10MHz Lower only
5MHz Lower only

Maximum Tolerable L Band Blocker Level: Uniform SV Level at -152dBm (2.4.1.3 @-152 and 2.4.2.3 @-152)

These tests provide a view of the LightSquared eNB transmission that affects the cellular GPS receivers when the SV's signals are uniformly set to -152dBm.

Figure 3.2.8 Maximum Tolerable L Band Blocker Level: Uniform SV Level at -152dBm



As expected, the performance impact was most pronounced under the most sensitive use case (indoor usage). As was true of the other testing, GPS threshold failures did occur when LightSquared base stations were operated in the upper band, but testing shows that lower band operations appears to be less problematic (although some UMTS devices were found to be susceptible to LightSquared signals in the lower band at levels of -25 dBm and in one instance to -45 dBm). Moreover, interference/impact during this testing was less severe than during the other three test cases.

It is expected that small cell urban microcells will have much less power operation than 1500W EIRP. This is relevant to many environments where GPS signal reception occurs indoors and L Band transmissions will be emitted by urban picocells, DAS systems and similar short range devices

Based on the above, it does appear that the current test data that is available would demonstrate that LightSquared operations in the lower band (1526-1536 MHz) may be possible without harmful interference to cellular operations.

3.2.9.3 Measurement and Analysis of Key Performance Indicators (KPI) – (Lower 10 MHz analysis)

As outlined in the testing plan, the GPS blocker passing threshold was not the only metric tested and analyzed.. There was a consensus agreement that four KPIs should be analyzed. KPIs determine or at least relate the effect of the L Band blocker signal on GPS position performance ("2D position error"), and are deemed important to consumers using cellular devices for a variety of location applications. Test 2.4.2.2 and 2.4.1.2 were selected for the initial KPI analysis. They later expanded the KPI analysis for all available devices. Another set of charts are shown below which rank the variation from least to most 2D position error variation, and those charts are also included below.

Not all devices could be measured to a point of failure, since most devices exhibit blocker immunity at the Lower 10 MHz channel configuration that went beyond the range of the test system (i.e., 0 dBm for conducted tests, and -10dBm for radiated tests). In these cases the KPI at the maximum blocker value were recorded for side-by-side analysis. In all cases the level reported is the level at which the device passes the 3GPP or 3GPP2 performance criteria.

3.2.9.3.1 KPI Test Results for CDMA 3GPP2 Devices

2D location error performance is specified by CDMA 3GPP2 tests using two criteria:

- The "Sigma 1" error is the standard deviation representing 67% location accuracy at a 90% confidence level.

- The "Sigma 2" error represents two standard deviations for 95% location accuracy at a 90% confidence level.

Note: Not all devices could be tested to a point of failure, which limits the extent of available KPI data for each device. Where there was a fail-to-pass threshold crossed to harvest KPI data, the results are identified with red vertical bars. Where KPI could be harvested at the top of the test capability (but again did not cross the threshold of failure), these are shown as blue vertical bars.

The figures below give the location accuracy for these two metrics for test suites 2.4.2.2 (actual sensitivity plus 1dB) and 2.4.2.1 the GPS SV's set at -147dBm.

Figure 3.2.9 CDMA Suite 2.3.2.2 (Sensitivity +1dB) sigma 1, Lower 10MHz

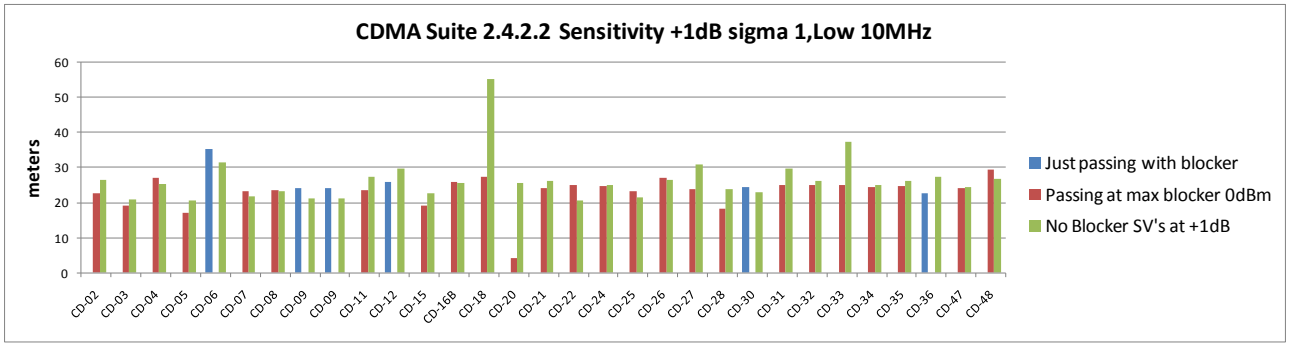


Figure 3.2.11 CDMA Suite 2.4.2.2 Sensitivity +1dB sigma 2, Lower 10MHz

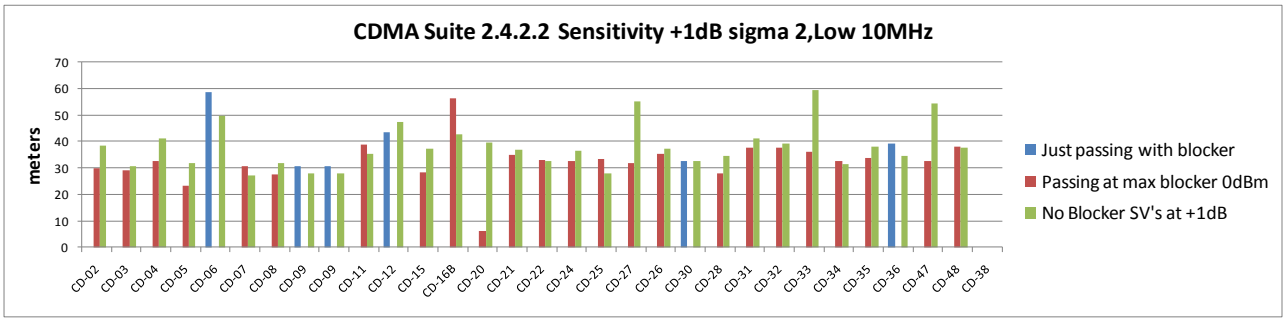


Figure 3.2.11 CDMA Suite 2.4.2.1 sigma 1, -147 dBm, Lower 10MHz

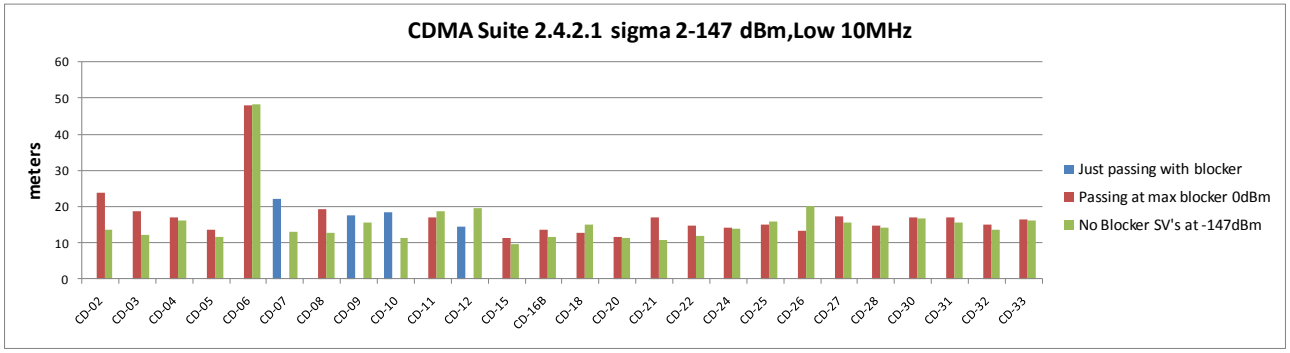
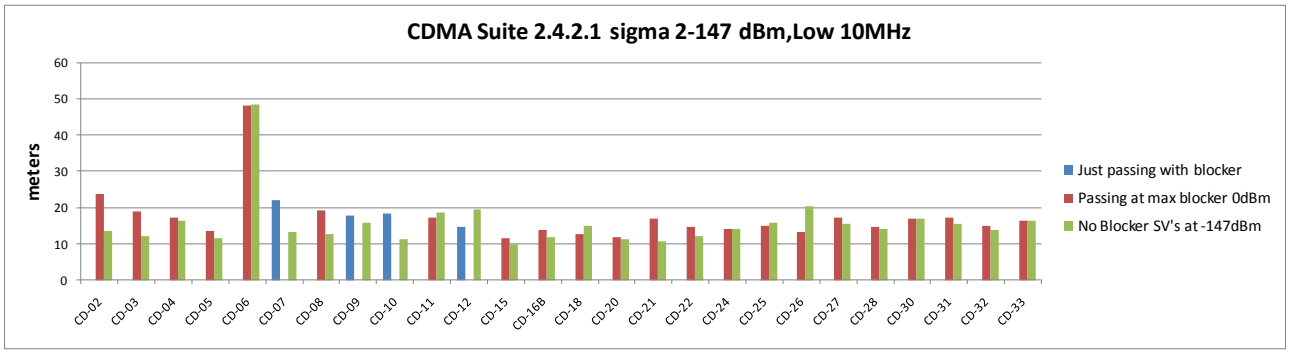


Figure 3.2.12 CDMA Suite 2.4.2.1 sigma 2 -147 dBm,Low 10MHz



For each of the two suites and sigma levels of 67 percentile and 95 percentile, the average error difference was computed to provide an overall impact of the blocker.

Of course the blocker power cannot improve the 2D position error, so the proper explanation for the negative averages are measurement "noise" related to the imperfections and limits of repeatable reported location errors in the measurement system. This is mostly a function of the extremely low levels at which the measurements are taken. There may be a few cases where the presence of the blocker measured just before failure had an impact, such as seen for CD-02 and CD-22 under the 2.4.2.1 test suite. Even granting that interpretation, these were well within the 3GPP2 passing criteria otherwise the test system would have rejected these as passing values.

The CDMA 2-D location errors were also evaluated for other test suites for sigma 1 and are included below. Here the error difference is also plotted as red bars, with graduated negative to positive margins shown left to right.

Figure 3.2.13 CDMA Test Suite 2.4.2.4: KPI 2D Position Errors for 31 Devices

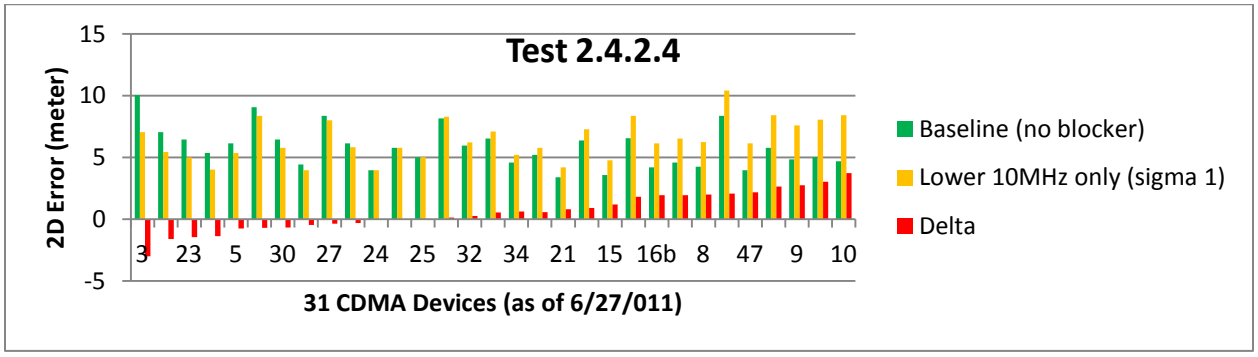
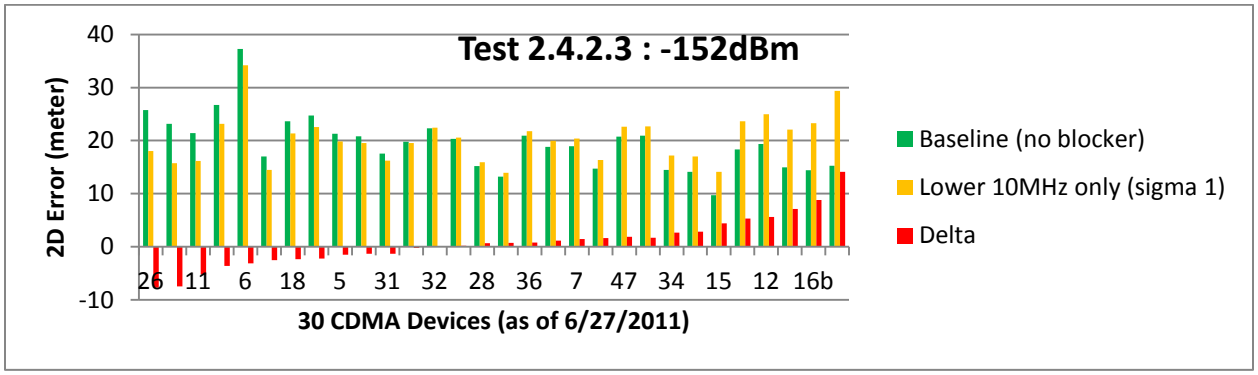


Figure 3.2.14 CDMA Test Suite 2.4.2.3 @-152: 30 tested devices



Similarly test suites 2.4.2.1 and 2.4.2.2 sigma 1 results are re-plotted with error deltas.

Figure 3.2.15 CDMA Test Suite 2.4.2.1: 31 tested devices

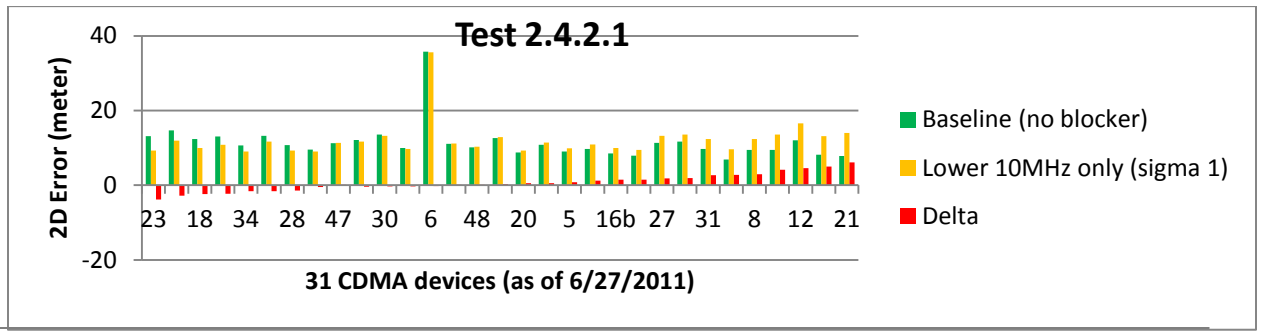
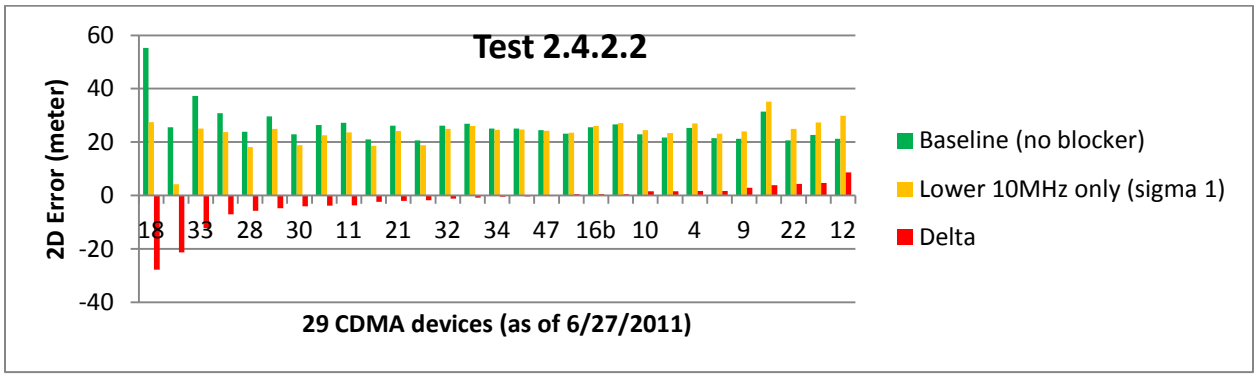


Figure 3.2.16 CDMA Test Suite 2.4.2.1: 29 tested devices



Based on tests performed across 32 devices, little to no impact to user experience or operational performance was observed based on the small average 2D errors; the fact that based on the variations of KPI was overall less than the measurement variations so as to associate a finding of no systematic effects of the blocker on various 2D and other KPI indicators of KPI performance; the fact based on observation that most values in for which KPI performance was available were from tests of at a the blocker

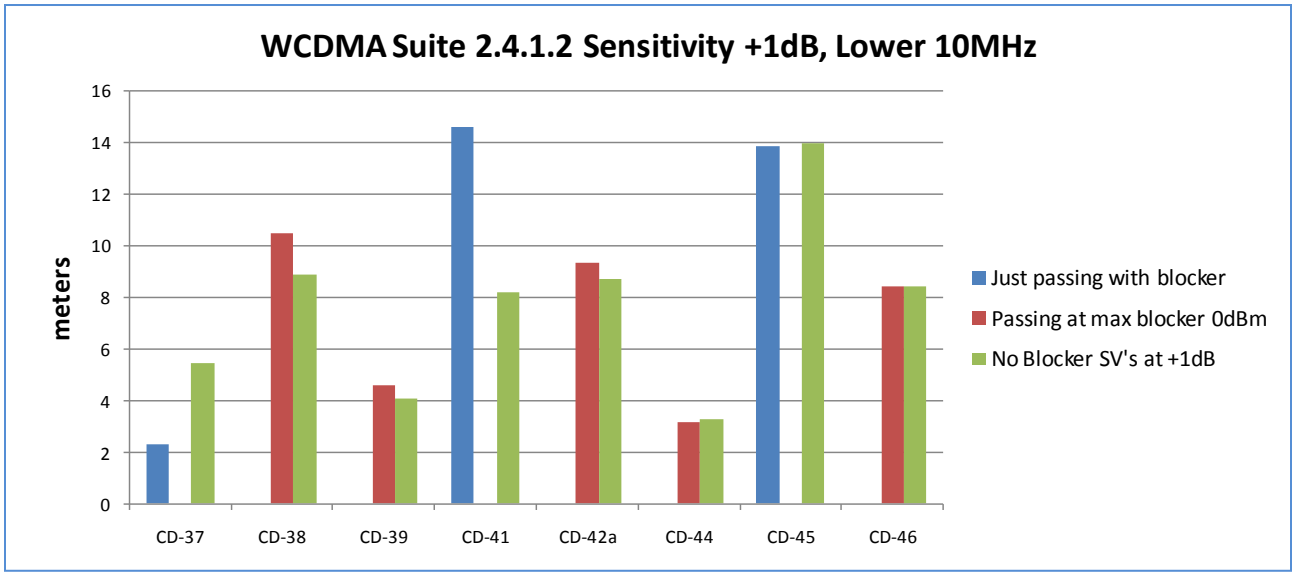
set at the highest levels that was at the highest extent of the of system capability at which a blocker signals could be applied, the subgroup consensus is:

- KPI impact is sufficiently accounted for in the test results of the seven suite pass/fail blocker values test results
- No additional margin of blocker power is required to assess susceptibility, compatibility or harmful interference limits
- KPI 2D errors averages were small when they were present and were statistically offset in some cases by the negative 2D position errors that arises from the measurement system variations
- Relative and absolute code phase values were also used to assess KPI and were found to be of similar magnitude and statistically insignificant from direct KPI measures.

Regarding the paragraph above, Verizon states separately that based on the 2D positioning error data obtained from 32 tested CDMA devices under lower 10MHz only B24 DL blocker, it's clear that at the passing level, some tested devices' 2D positioning accuracy were impacted to some extent in the presence of blocker. Based on this data, it is not clear whether such impact would cause any noticeable difference to location accuracy and E911 compliance.

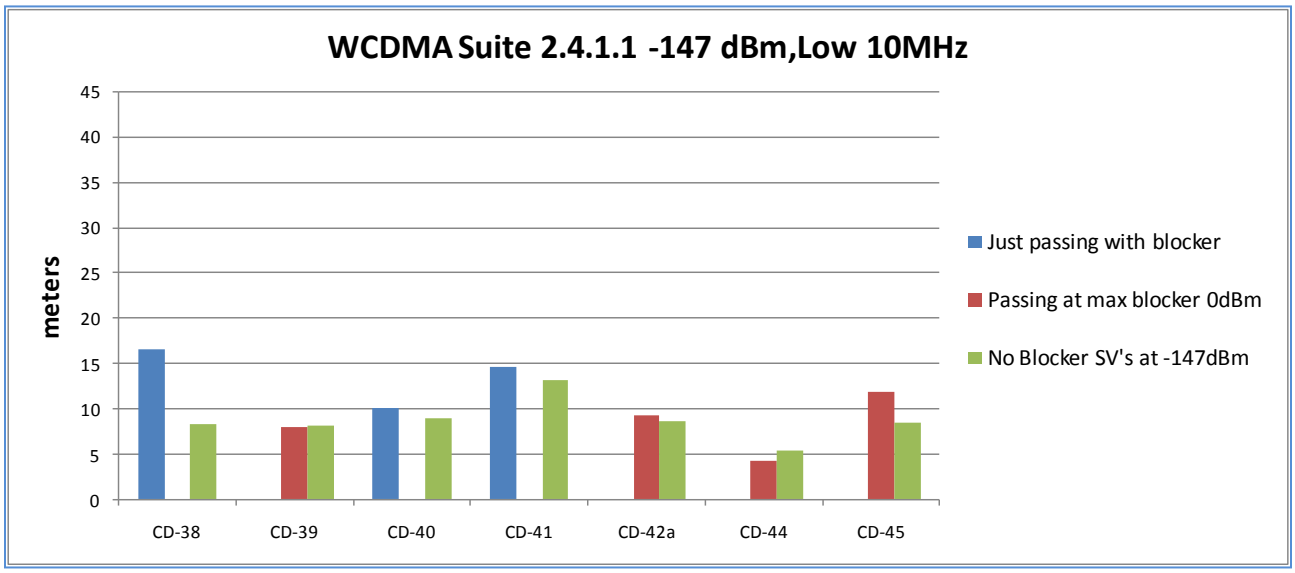
3.2.9.4 KPI Test results for WCDMA Devices Tested Under 3GPP AGPS Conditions

Figure 3.2.17 WCDMA Suite 2.4.1.2 Sensitivity +1dB, Lower 10MHz



Note: Not all devices could be tested to a point of failure, which limits the extent of available KPI data for each device. Where there was a fail-to-pass threshold crossed to harvest KPI data, the results are identified with red vertical bars. Where KPI could be harvested at the top of the test capability (but again did not cross the threshold of failure), these are shown as blue vertical bars.

Figure 3.2.18 WCDMA Suite 2.4.1.1 -147 dBm, Lower 10MHz



The impact was less than 8 meters of all 2D position error measurements. These impact measurements compare baseline (i.e. no blocker present) values to 2D position values when the blocker signal is present.

For the 2D position error, it is important to note that cellular carriers are required to provide E911 location fixes within 50 meters, 67% of time and within 150 meters,

95% of the time. An impact that causes a material rise in 2D position errors, noted by an impact that consistently causes an error that exceeds 50 meters could adversely affect a cellular carrier's ability to comply with E911 requirements assuming the impact in question was solely induced by and in all those cases attributed to L Band interference. The Cellular subgroup respects the issues that must be balanced by regulators and leaves the issue of how to quantify all factors that determine the extent of GPS performance on E911 compliance to the FCC. None of the devices tested registered an average positioning error exceeding FCC mandated 50 meters. Also note that in the lab tests devices were not exposed to real-world effects such as multipath effects.

3.2.9.5 Determination of Cellular Device Antenna Gain

The blocker data measured is referred to the input of the GPS receiver. To transfer these results and compare directly to the field propagation data requires that we first determine an appropriate GPS antenna gain based on the antenna's ability to transfer power in the 3GPP band 24 LightSquared frequency band to the receiver front end. Based on results from a collection of sample devices and their measured data from the same anechoic chamber tests used to collect susceptibility and KPI results, the sub team concluded that the antenna gain for the purpose of our study should be -5dBi. Device orientation will change the individual value but -5dBi was deemed a conservative figure for interference analysis purposes. (An analytical presentation is available upon request).

This results in an overall gain factor of -5dBi that is applied to propagation data collected with a measurement system normalized to 0 dBi. This is handled later in this section in order to compare the field blocker power levels measured at the GPS receiver with a 0dBi external reference antenna.

3.2.9.6 Determining the Range of Blocker Power from L Band eNodeB Transmitter

Once the GPS antenna gain to the band 24 signal was determined, we can use this with the laboratory blocker performance data in the tables from section 3.2.9 together with the propagation data of section 3.2.9.7 to predict the extent of geographic impact or compatibility.

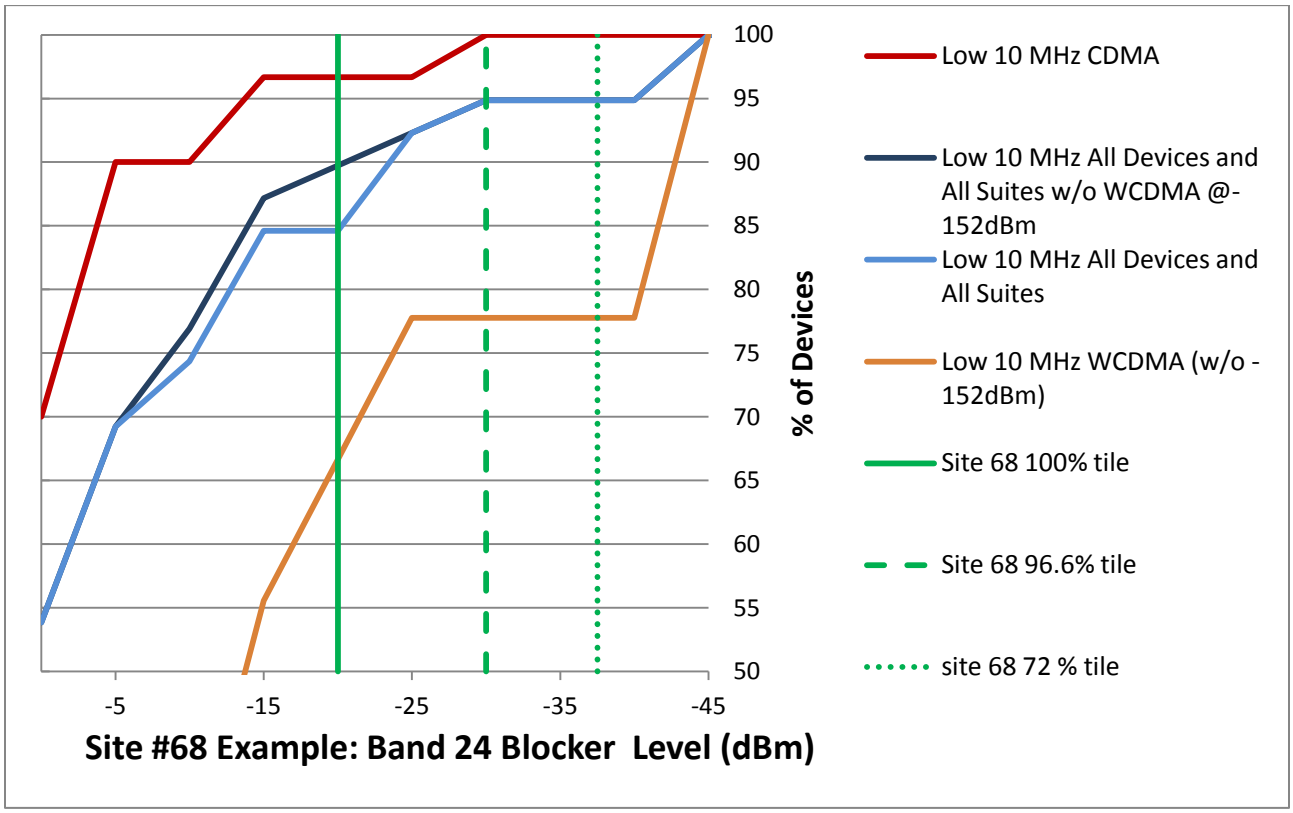
The propagation plots such as Figure 3.2.21 are derived from raw data and normalized to become the incident power transferred into the cellular GPS receiver using a 0dBi gain reference antenna. When the mobile's GPS antenna gain is considered, we find the blocker power level on the vertical axis of the propagation loss tables and adjust the power down by to be 5 dB. Next by looking at the range on the horizontal axis we can observe visually how many points are above or below this line.

To quantify the incidence of signals exceeding this threshold we use the histograms and cumulative probabilities associated with the propagation loss data. To address the -5dBi GPS antenna gain, we subtract 5dB from the field propagation 0dBi normalized power levels.

Figure 3.2.19 below adds three CDF percentiles to the blocker chart. Looking at the green long dashes vertical line for 96.6% we see that 95% of all devices have sufficient blocker performance at this level. This is not intended to say that site 68 is the typical site; rather it is an illustration of a site exhibiting high instances of LTE power on the ground near this low antenna height site, yet still shows a relatively high GPS receiver compatibility level.

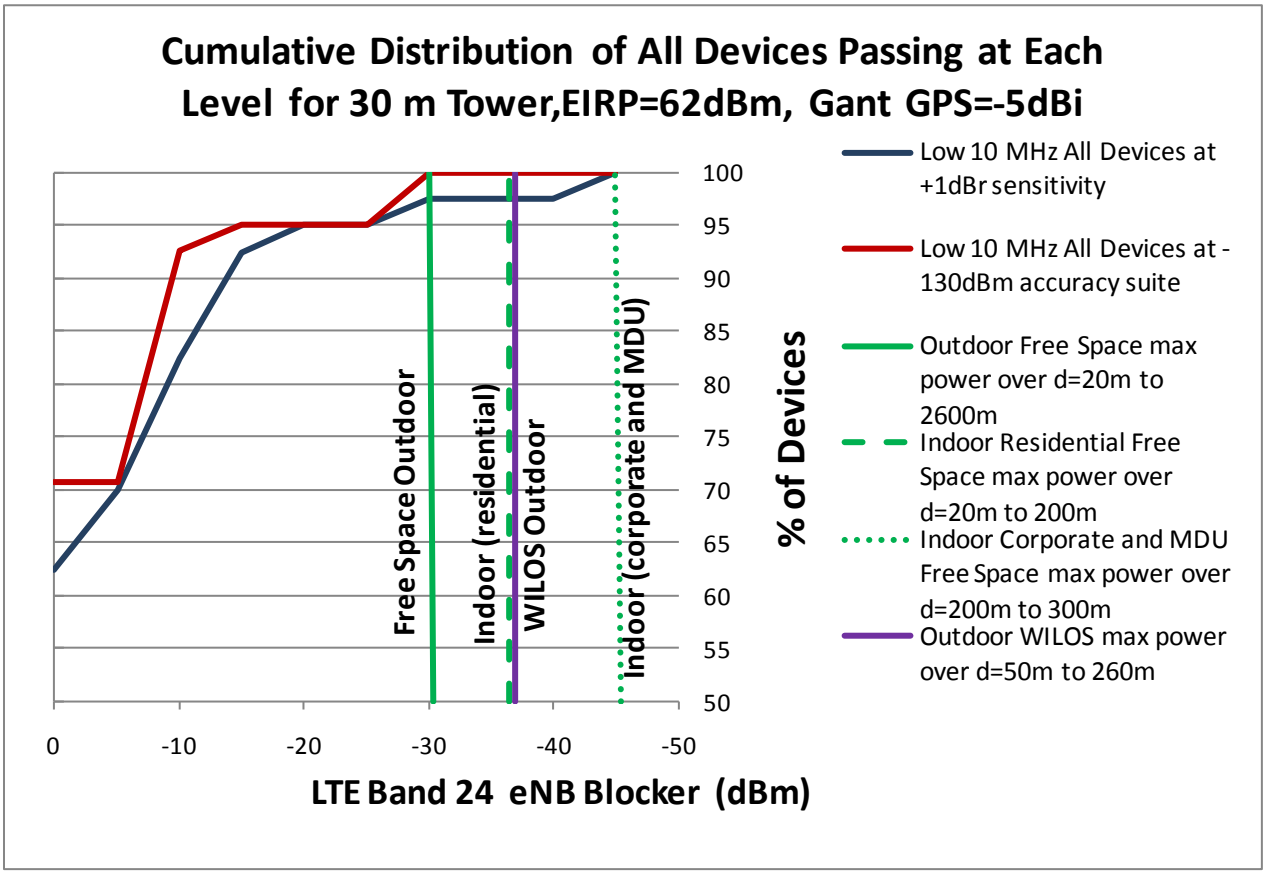
Figure 3.2.19 below is a single site example for a representative (but not the worst case) site in the Las Vegas field trial, and it was the view expressed by the group that any site specific case must recognize real world environments that would give rise to multi-path of the GPS signal among other factors.

Figure 3.2.19 Example: Test Site 68 Trimble Reported Power Levels versus Device Susceptibility



In an attempt to apply field propagation expected (based on conventional Free Space and WILOS models), the following graph is intended to address the extent of compatibility (or lack thereof) based on device test data and the LightSquared network nominal site-build plan (EIRP, tower height, downtilt, antenna gain characteristics).

Figure 3.2.20 Cumulative Distribution of Device Susceptibility Values versus "Power on the Ground" for the LightSquared Nominal Build Plan



The outdoor values represent the Free Space at 20-260m, and WILOS at 260m.

The figure above shows the nominal LightSquared base station (eNodeB) site plan with Free Space and WILOS propagation model figures at 20-260m[21] over-laying the susceptibility of the 41 tested devices in order to assess Lower 10 MHz Channel cellular/GPS compatibility.

The declared nominal LightSquared site build parameters are:

- EIRP = +62dBm
- Height of the eNodeB antenna = 30m
- Downtilt = 2 degrees electrical

[21] Note that the gain of the antenna will place peak power over the ground over a range of distances.

- Gain of the GPS UE antenna to LTE signals: -5dBi

The overlay graph 3.2.20 above shows a high degree of compatibility for operations using the Lower 10 MHz channel across a range of likely field power levels. This encloses expected power levels as seen in the live sky tests, which is represented by two propagation models: Free Space and WILOS. These models are believed based in part on field tests to amply "bracket" the range of expected on-the-ground values. Again, these data were confirmed by results of drive test data collected in the Las Vegas field trial.

To put this into a real world perspective, we looked at blocker sensitivity performance relative to both outdoor ambient and indoor blocker power levels, since both are important to use of cellular GPS device applications. To evaluate the combination of indoor performance in the presence of L Band terrestrial signals, one has to apply a minimum reasonable amount of attenuation representing common extremes of radio-opaque structures. In general these are wood frame houses (least) and corporate and MDU buildings (most attenuation). These buildings attenuate L Band signals minimally from 6 to 15 dB[22].

This does not set aside cases where GPS signals may not be optimal outdoors, especially for certain otherwise visible satellites, are blocked by nearby structures. In some cases, there could be reduced GPS signal levels relative to un-obscured outdoor signals. These signals in cellular applications are often still usable, if somewhat more inaccurate in locating one's true position due to reception of bounced, reflected signals.

From the live sky field data, it is also likely that the same complex propagation environments will significantly attenuate the L Band blocker signal in a roughly similar fashion, those signals also arriving by bounce paths formed by reflections or over rooftop refractive paths to name just two common cases. The live sky test site data showed the close to site environment has both open and highly cluttered cases. Thus it is reasonable to associate the same to both signal reception characteristics, acknowledging this is not a perfect correlation.

Examining the range of outside to in-building use cases directly (since both E911 and other location services often originate in indoor environments). In this case, these two buildings types are compared to the device susceptibility CDF graphs are placed on

[22] COST 231 indicates 4 to 10dB outer wall loss depending on building material. Total losses experienced are usually higher than these values, we chose 6dB loss (wood frame for residential) and 15 dB loss for commercial and MDU building types at the interior.

[3] See page 42

lines representing the highest ambient power based on nominal LightSquared site build out values.[23] Further to the right are values that represent minimum indoor attenuation values discussed above.

Using the most sensitive GPS receiver values, threshold sensitivity plus one dB values, from 2.4.2.2 and 2.4.1.2, which show reliable blocker test values, and are applicable from open sky to indoor, since these values are based on actual sensitivity taken to within one dB of each cellular GPS receiver's threshold sensitivity. A second CDF, representing the relatively open-sky value using results obtained from the 2.4.2.4. accuracy test suite which represents use cases closer to outdoor values. Again, it is conceivable that a cellular GPS subscriber is very close and fully exposed to a base station antenna and at the same location the GPS signals are heavily obscured, but based on both field site data in the urban relative to the suburban or rural cases, plus general experience, high levels of blocker power and high levels of GPS signals are positively if imperfectly associated.

The 3.2.20 values show a good degree of compatibility across these in- to-outdoor environmental cases.

3.2.9.7 Propagation Modeling & Field Measurements

Two methods of estimating the base station power received on the ground, Free Space (FSPL) and Walfisch-Ikegami Line-Of-Sight (WILOS) [http://www.lx.it.pt/cost231/final_report.htm]

These are presented along with actual power measurements on the ground from the Las Vegas "live sky" field trial in May 2011.

The predicted received power on the ground, received from a nominal 30m/2° down-tilt base station antenna, is shown in 20 as a function of distance along a radial line along the direction of azimuthal maximum. The key parameters in this model are as follows:

- Base Station EIRP: 32 dBW[24]
- LTE UE antenna gain: 0 dBi[25]

[24] For cases where two carriers are transmitted, an adjustment of 3 dB is made in using this graph to correct the power "on the ground" appropriately. In the time intervals where only one carrier (at 32 dBW) was transmitting, this graph reports the base station EIRP at +32 dBW.

[25] In Section 4.1.1, Work Plan Item 9: Analyze Test Results using Established Methodology, a UE coupling loss is reported, and the rationale thereof is presented in that section.

- LightSquared base station antenna gain: 16.8 dBi at boresight with an elevation and azimuth pattern as shown below in Figure 3.2.22 22a/b.

3.2.9.8 Power Measured "On the Ground" in the Las Vegas "Live Sky" Field Trial

In the Las Vegas field trials, propagation data was collected independently by Trimble and LightSquared and other organizations such as John Deere. After appropriate corrections were applied to each data set so as to reference, or normalize the measured power to a *dual-linear-orthogonal 0 dBi antenna* (the received power was the sum of that which would be received by two linear, 45 degree tilted and orthogonally polarized antennas), good correlation was found between the LightSquared and Trimble data sets to deem in the view of the Cellular Subgroup the data to be accurate for these purposes. Both are presented here, with the computations of their probability distribution function (PDF) and CDF. These data sets and their statistics are used in the previous section (Work Plan Item 9) to draw conclusions about the potential operational impact of the devices tested in the laboratories.

Figure 3.2.21 Predicted "Power on the Ground" Versus Horizontal Ground Distance from the Band 24 eNode B Antenna Using Free Space (FSLOS) and Walfisch Ikagami Line of Sight (WILOS) models

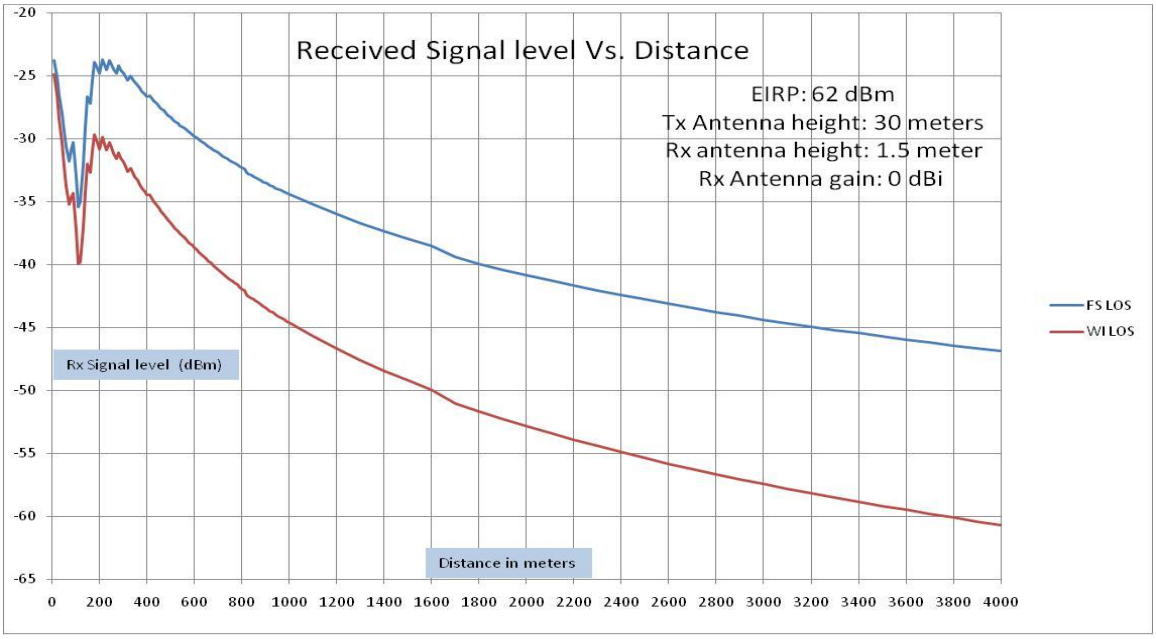


Figure 3.2.22 (a): LightSquared Base Station Antenna Pattern (Elevation)

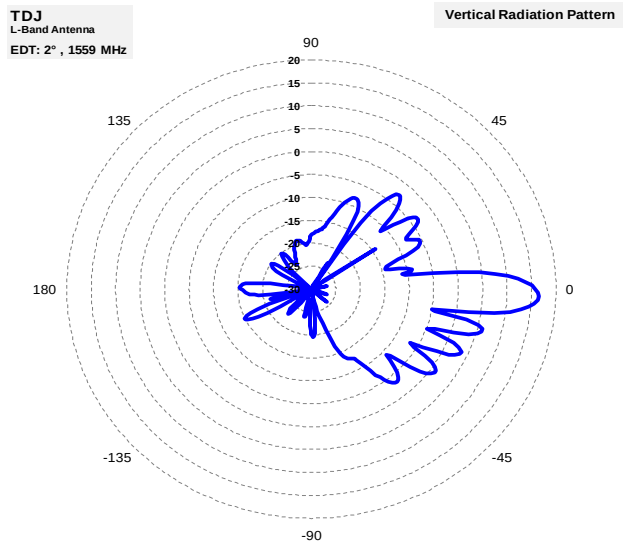


Figure 3.2.22(b): LightSquared Base Station Antenna Pattern (Azimuth)

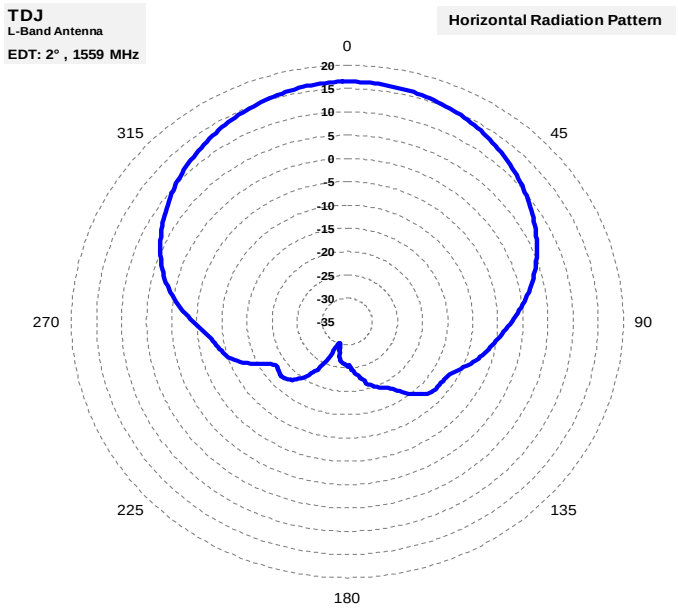
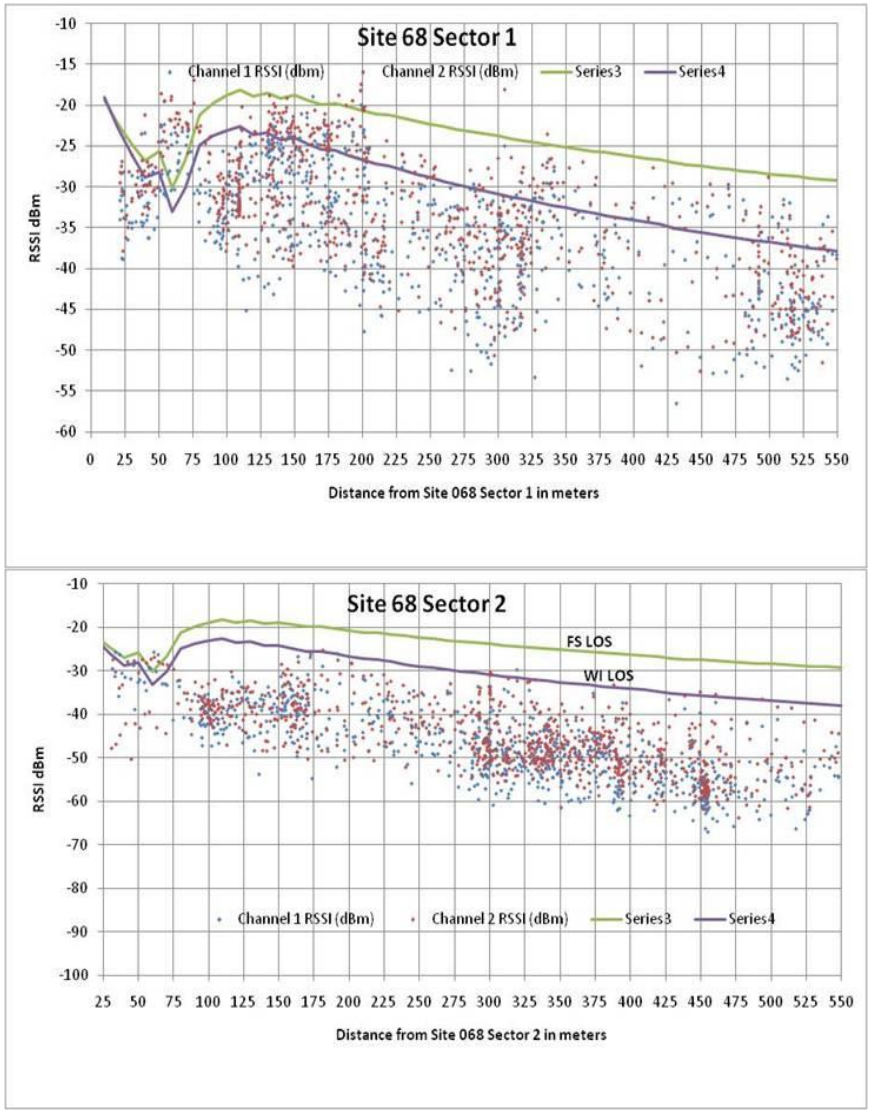


Figure 3.2.23: LightSquared Normalized "Power on the Ground" at Test Site 68 (Suburban, Tower Height 17 m)



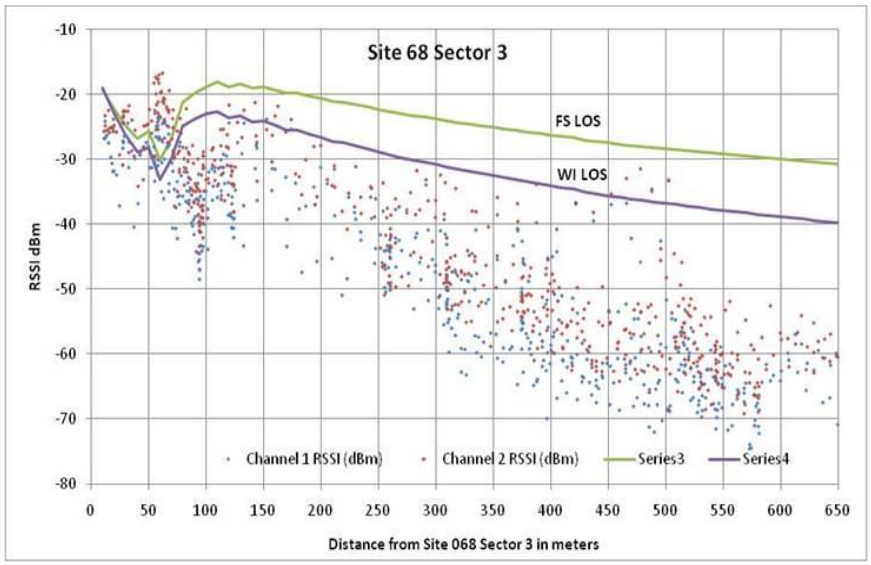


Figure 3.2.24: Trimble Reported LTE Power at User (Test Van) Antenna for LightSquared Las Vegas Test Site 68

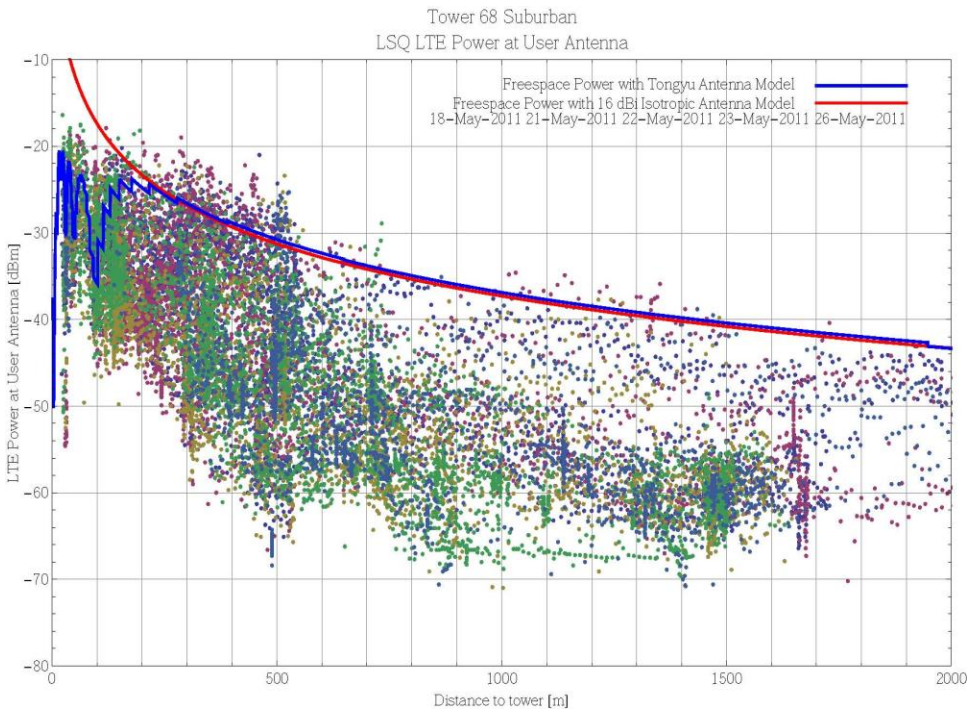
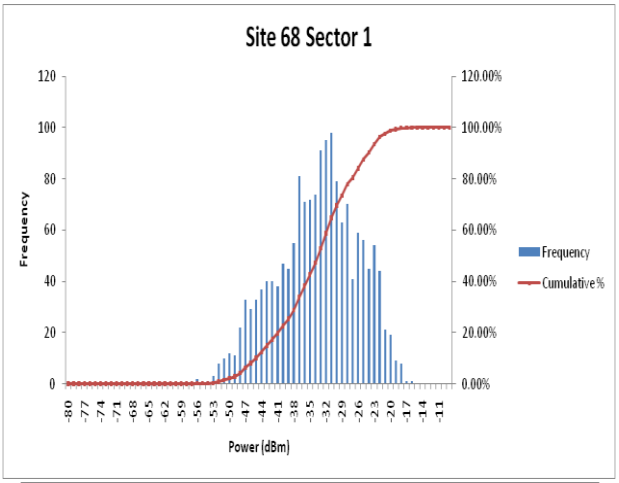
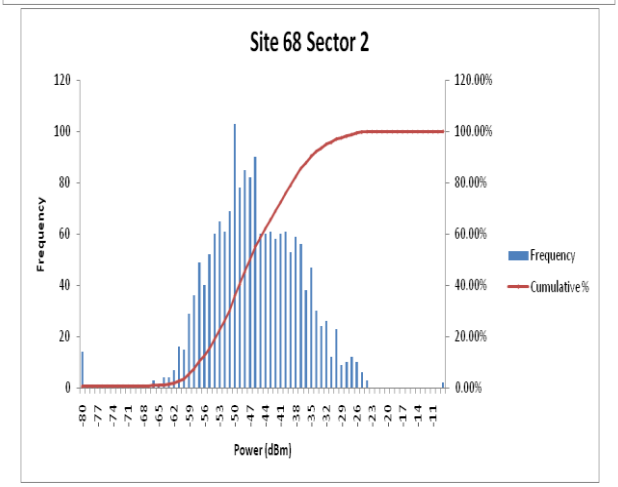


Figure 3.2.25 (a): PDF/CDF of LightSquared Reported Data "Power on the Ground" By Each Sector





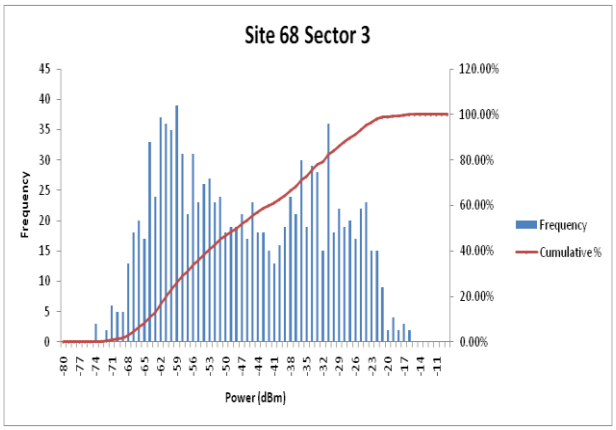


Figure 3.2.25 (b) Probability and Cumulative Distributions of Trimble Field Data at Test Site 68, All Three Sectors, Five Day Composite Measurements

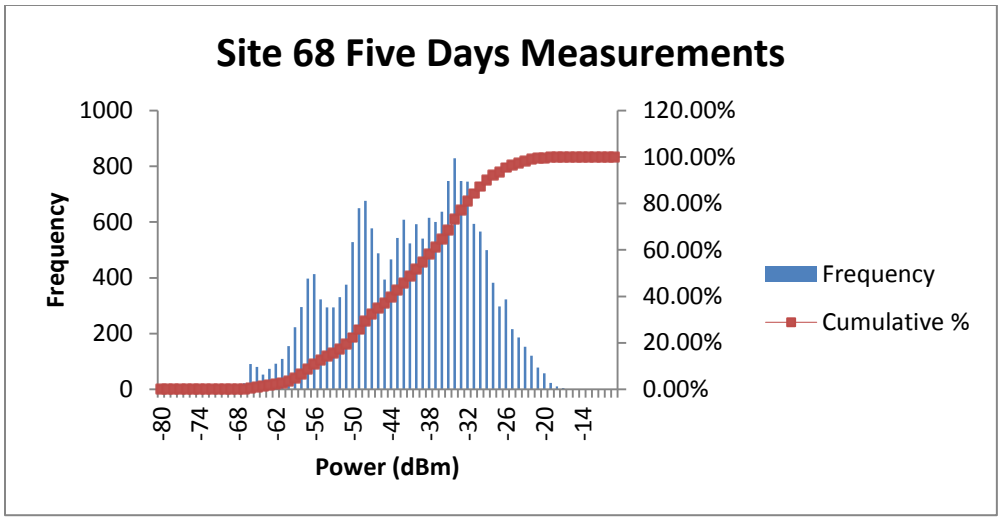


Figure 3.2.26: Cumulative Distribution (CDF) of LightSquared and Trimble Data Sets at Test Site 68

LightSquared Reported Data

Sector 1

Power	*Frequency*	*CDF %*
-50	36	2.22%
-45	128	10.14%
-40	202	22.62%
-35	324	42.65%
-30	437	69.65%
-25	289	87.52%
-20	183	98.83%
-15	19	100.00%
-10	0	100.00%

Sector 2

Power	*Frequency*	*CDF %*
-50	629	36.07%
-45	395	58.72%
-40	300	75.92%
-35	253	90.42%
-30	115	97.02%
-25	47	99.71%
-20	3	99.89%
-15	0	99.89%
-10	0	99.89%

Sector 3

Power	*Frequency*	*CDF %*
-50	517	46.58%
-45	99	55.50%
-40	80	62.70%
-35	113	72.88%
-30	126	84.23%
-25	100	93.24%
-20	64	99.01%
-15	11	100.00%
-10	0	100.00%

Trimble Reported Data Set at Test Site 68

Power (dBm)	*Frequency*	*CDF %*
-50	4163	22.31%
-45	2786	37.25%
-40	2735	51.91%
-35	3142	68.75%
-30	3482	87.41%
-25	1717	96.61%
-20	594	99.80%
-15	38	100.00%
-10	0	100.00%

Figure 3.2.27: LightSquared Reported Field Data for Test Site 217 (Dense Urban, Tower Height 72 m)

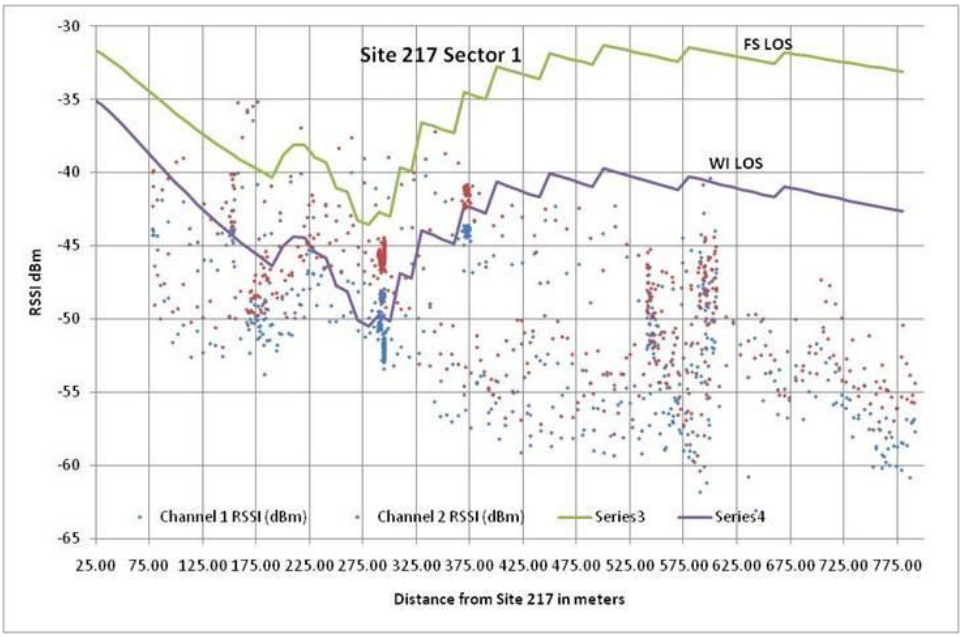


Figure 3.2.28: Trimble Reported Field Data for Test Site 217

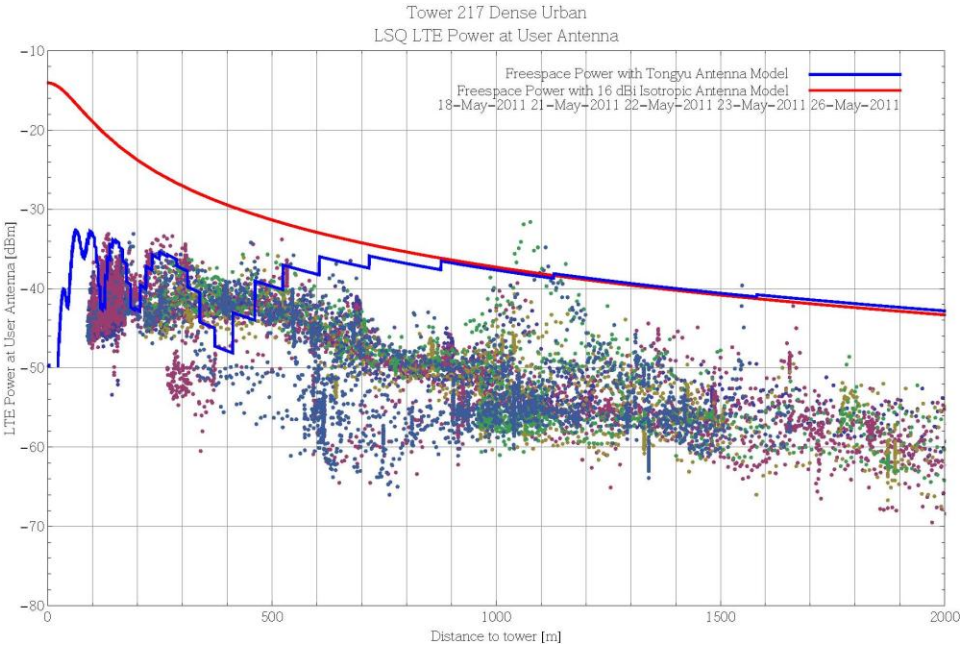


Figure 3.2.29 (a) PDF/CDF of LightSquared Reported Data

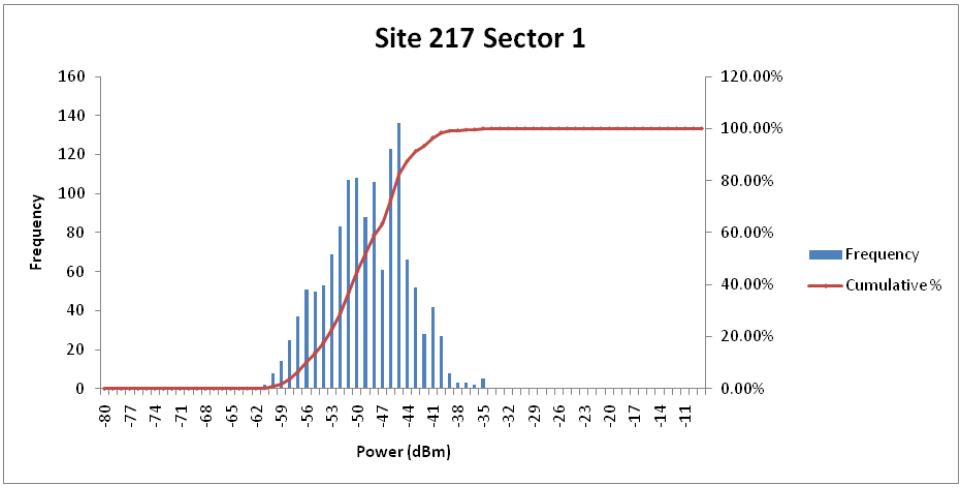


Figure 3.2.29 (b) PDF/CDF of Trimble Reported Data

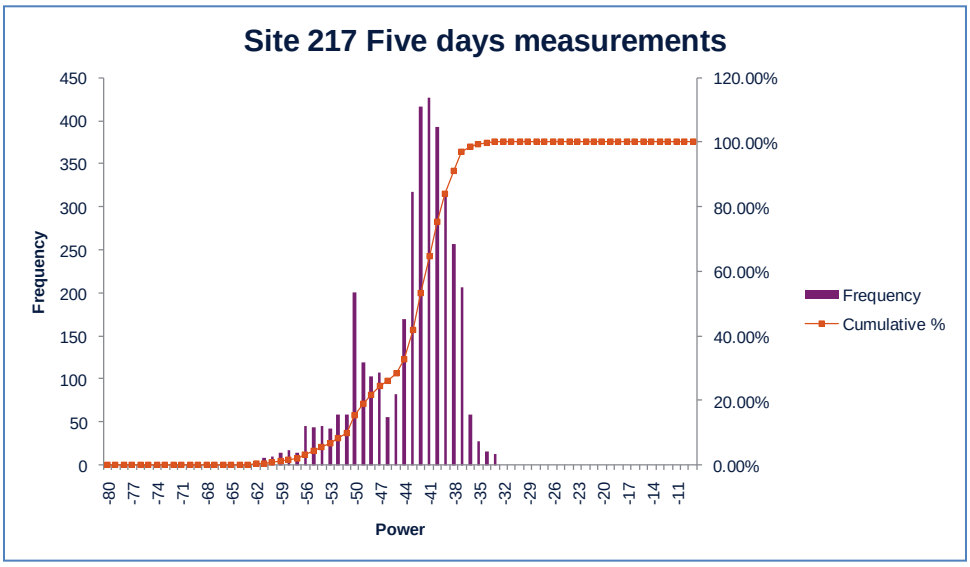


Figure 3.2.30: Numerical CDF's of LightSquared and Trimble Separately Reported Data Sets (Test Site 217)

LightSquared Reported Data for Test Site # 217

Power	*Frequency*	*CDF %*
-50	608	44.77%
-45	514	82.62%
-40	215	98.45%
-35	21	100.00%
-30	0	100.00%
-25	0	100.00%
-20	0	100.00%
-15	0	100.00%
-10	0	100.00%

Trimble Reported Field Data Test Site #217

Power(dBm)	*Frequency*	*CDF %*
-50	565	15.50%
-45	467	28.30%
-40	1722	75.53%
-35	865	99.26%
-30	27	100.00%
-25	0	100.00%
-20	0	100.00%
-15	0	100.00%
-10	0	100.00%

Figure 3.2.31: LightSquared Reported Field Data for Test Site 53 (Rural, Tower Height 18 m)

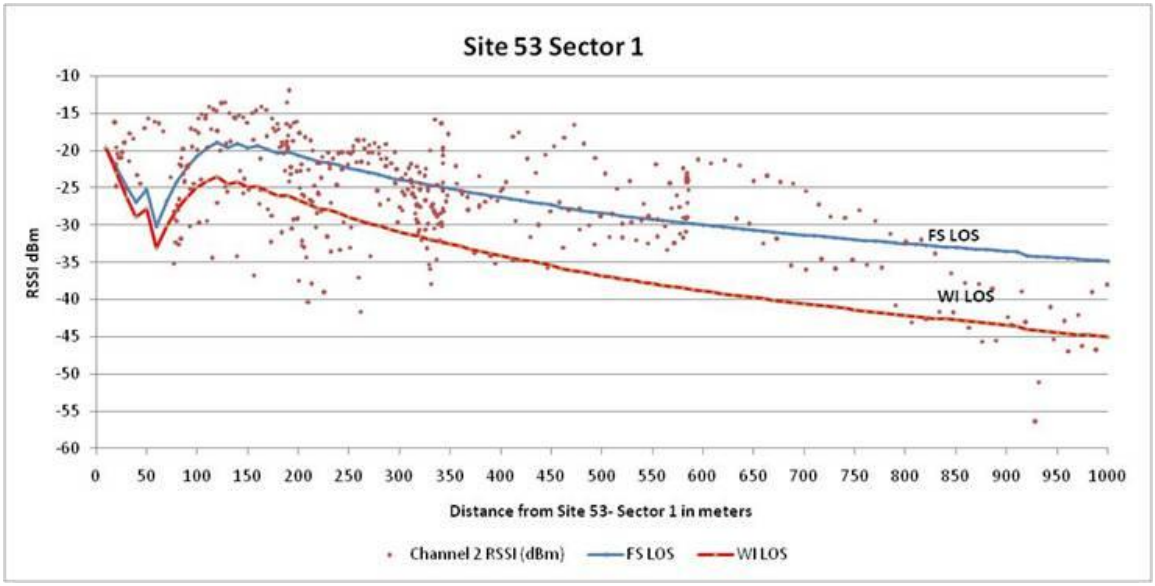


Figure 3.2.32: Trimble Reported Field Data for Test Site 53

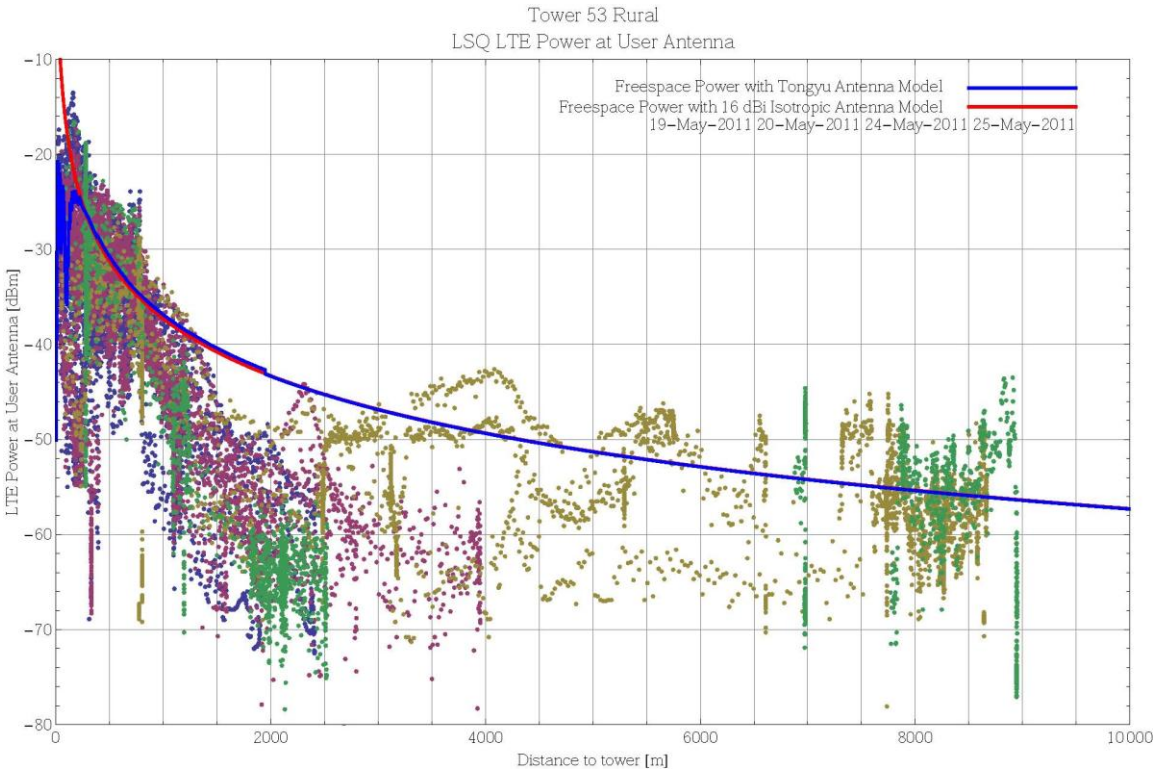


Figure 3.2.33 (a): PDF/CDF of LightSquared Reported Data Set for Test Site 53

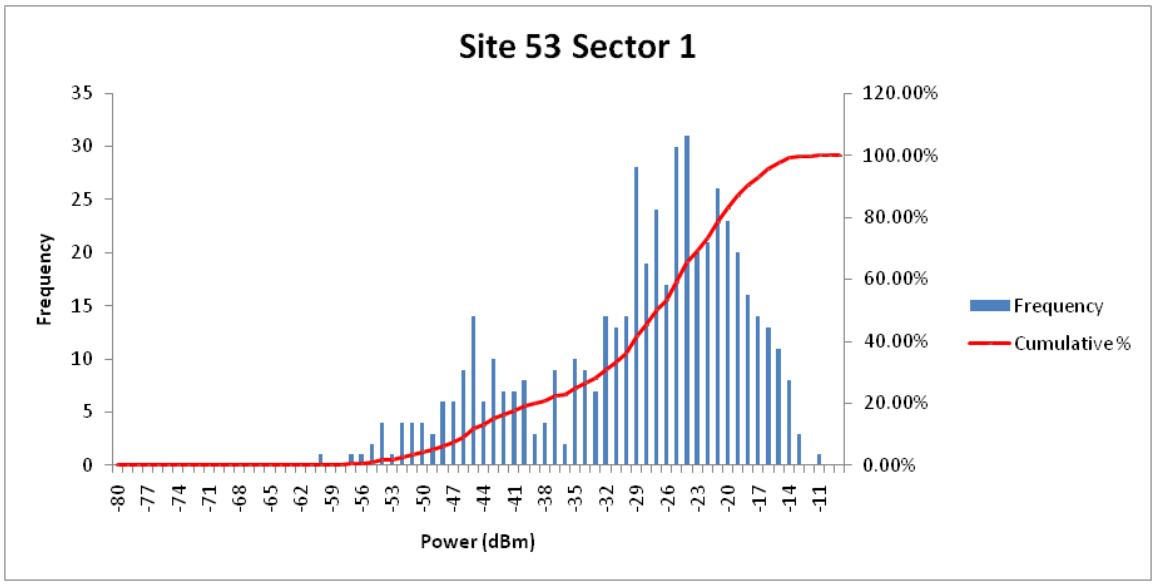


Figure 3.2.33 (b): PDF/CDF of Trimble Reported Data Set for Test Site 53

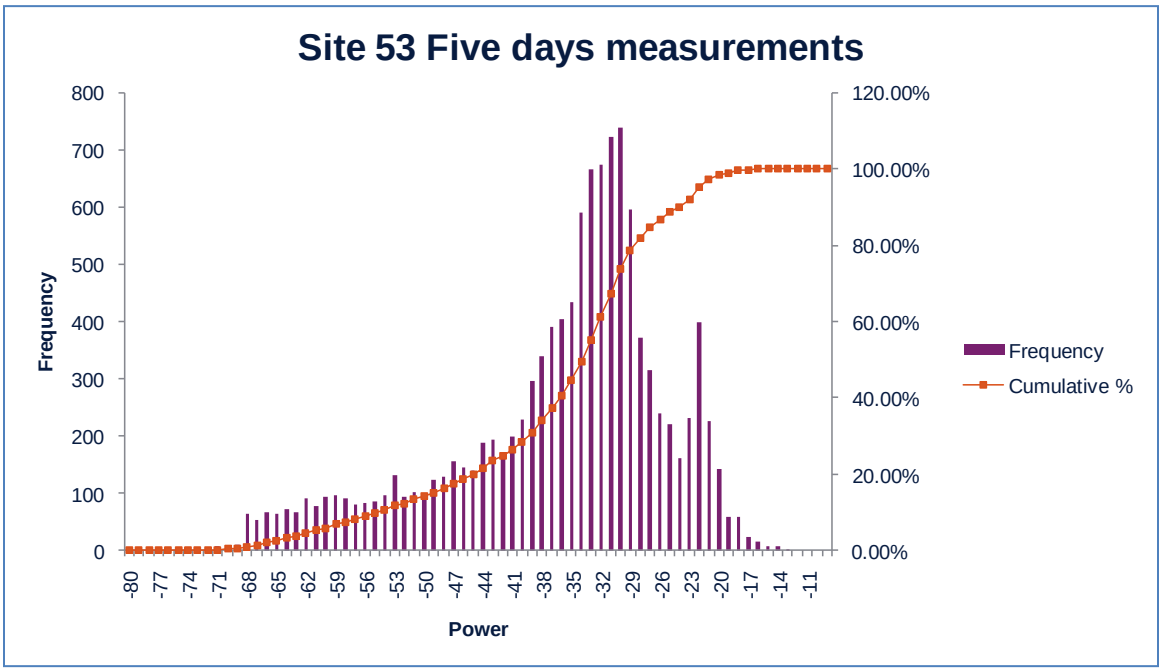


Figure 3.2.34: Numerical CDF's of LightSquared and Trimble Data (Test Site 53)

CDF for LightSquared Reported Data Set

Power	*Frequency*	*CDF %*
-50	22	4.33%
-45	38	11.81%
-40	38	19.29%
-35	28	24.80%
-30	57	36.02%
-25	118	59.25%
-20	121	83.07%
-15	74	97.64%
-10	12	100.00%

CDF for Trimble Reported Data Set

Power(dBm)	*Frequency*	*CDF %*
-50	1638	14.10%
-45	689	20.03%
-40	970	28.38%
-35	1863	44.41%
-30	3391	73.60%
-25	1740	88.58%
-20	1157	98.54%
-15	160	99.91%
-10	10	100.00%

3.2.10 Conclusions regarding L Band Interference Impact to Cellular GPS Receivers

LightSquared has obtained rights to operate subject to addressing and solving potential GPS interference issues on Phase 0 (one upper 5MHz carrier), Phase I (upper and lower 5 MHz carriers), Phase II (upper and lower 10 MHz carriers). LightSquared has recognized the issues with upper channel operation and has decided to focus exclusively on licensed operations in the Lower 10 MHz channel.

Regardless if the low carrier is used, if the high carrier is used, as can be seen from the data above, commercial devices failed between levels of -20 to -50 dBm. When considering the commercial devices' implementation margin to account for under-sampling, the upper downlink band LightSquared signals strengths where many devices exhibit susceptibility as low as -55 dBm could theoretically create interference. Upper band signal strengths in this range could be observed in field conditions at a variety of distances from LightSquared base stations depending on the urban to rural coverage characteristics, and could extend several hundreds of meters or even several kilometers from the nearest transmitter antenna. There was consensus that low level of susceptibility could become harmful interference for devices while receiving GPS at significant distances from LightSquared base stations and thus impact E911 or LBS location fixes that are either delayed or inaccurate (as permitted by FCC requirements).

Susceptibility test when using LightSquared's lower 5 and 10 MHz carriers yielded different susceptibility results (field power propagation results attributable to slight differences in the transmitter frequency were deemed insignificant). Two of the nine UMTS devices tested exceeded the limit of the test system (-10 dBm).

Consensus was reached that the Lower 10 MHz operation appears to provide significantly improved compatibility with GPS across all urban, suburban and rural coverage areas.

3.2.10.1 LightSquared UE-to-GPS UE GPS Interference Assessment

3.2.10.1.1 Objective

The objective is to determine whether a LightSquared UE operating in close proximity to another operator's cellular GPS receiver is likely to cause overload interference to the latter. For the purpose of this analysis, the standoff distance between the UE's was assumed to be 1m.

3.2.10.1.2 Methodology

Two approaches are used. First, a theoretical estimate was made of the likely level of received blocker power at the GPS receiver. In a second step measurements were made on 3 sample-CDMA phones to determine highest blocker power levels where a pass would be achieved for the standards-based sensitivity test (2.4.2.1) in the Cellular Subgroup Test Plan.

3.2.10.2 Theoretical Calculation

Before testing and to design a proper maximum power level to present the UE under test, an estimation of the blocker power referenced to the UE's antenna connector was made based on free space propagation, with the following values:

- Transmitter UE power: 23 dBm, per maximum value per 3GPP standard at Band 24
- Free space path loss at 1m: 36.6 dB
- UE gain towards blocker: -5 dBi
- Received power after GPS antenna: -18.6 dBm

3.2.10.2.1 Measurements

Measurements were performed on 3 CDMA devices (CD-30c, CD-04e and CD-20c). A single 10 MHz wide, LTE signal with a center frequency of 1632.5 MHz was emulated and used as described in the Test Plan developed by the Cellular Subgroup. Of all the ATC channel options considered in the present Report, this is the one with the highest power spectral density nearest to the RNSS band. A transmit filter with sufficient rejection in the RNSS band was used to ensure that the measurements would not be affected by OOBE from the lab signal generators, co-channel to the GPS receiver. Evaluating the potential of OOBE interference from LightSquared UE's to GPS receivers on other UE's was not an object of the present work, hence not investigated here. The LightSquared UE power was set at 23 dBm (maximum UE power for Band 24 devices).

The full results are shown below. In all cases, there was no susceptibility observed up to the limit of the system that represents values with less than one meter distance between the cellular device and LTE UE device, when the signal is set to the lowest frequency that the LightSquared user equipment (UE) can transmit. This

susceptibility test was performed using one of the CDMA GPS receiver devices from the test pool.

Interference level	Description	Status	Time Stamp	Total Calls	Samples	Code Phase Rel Err (Sigma 1)	Code Phase Rel Err (Sigma 2)	Code Phase Abs Err (Sigma 1)	Code Phase Abs Err (Sigma 2)
baseline (none)	Cellular GPS LightSquared Test Plan - section 2.4.2.1 (based on TI/	Passed	6/3/2011 16:16	30	120	0.0118	0.0216	0.0325	0.064
-10	Cellular GPS LightSquared Test Plan - section 2.4.2.1 (based on TI/	Passed	6/6/2011 17:35	30	120	0.0103	0.0219	0.0451	0.0666
-15	Cellular GPS LightSquared Test Plan - section 2.4.2.1 (based on TI/	Passed	6/3/2011 16:36	30	120	0.0103	0.0195	0.0318	0.0545
-20									

Interference level	Description	Status	Time Stamp	Total Calls	Samples	Code Phase Rel Err (Sigma 1)	Code Phase Rel Err (Sigma 2)	Code Phase Abs Err (Sigma 1)	Code Phase Abs Err (Sigma 2)	Doppler Err (Sigma 1)	Doppler Err (Sigma 2)
baseline (none)	Cellular GPS LightSquared Test Plan - section 2.4.2.1 (ba	Passed	6/3/2011 14:29	30	120	0.011	0.0197	0.0417	0.0622	0.407	0.9689
-10	Cellular GPS LightSquared Test Plan - section 2.4.2.1 (ba	Passed	6/6/2011 15:57	30	120	0.0104	0.0225	0.0435	0.0739	0.4062	0.8939
-15	Cellular GPS LightSquared Test Plan - section 2.4.2.1 (ba	Passed	6/3/2011 14:48	30	120	0.0105	0.021	0.0389	0.0877	0.4877	1.01

Interference level	Description	Status	Time Stamp	Total Calls	Samples	Code Phase Rel Err (Sigma 1)	Code Phase Rel Err (Sigma 2)	Code Phase Abs Err (Sigma 1)	Code Phase Abs Err (Sigma 2)
baseline (none)	Cellular GPS LightSquared Test Plan - section 2.4.2.1 (based on TI/	Passed	6/3/2011 15:18	30	120	0.0086	0.0196	0.0551	0.0754
-10	Cellular GPS LightSquared Test Plan - section 2.4.2.1 (based on TI/	Passed	6/6/2011 16:46	30	120	0.0091	0.016	0.05	0.0794
-15	Cellular GPS LightSquared Test Plan - section 2.4.2.1 (based on TI/	Passed	6/3/2011 15:36	26	104	0.0101	0.0204	0.0629	0.094

3.2.10.3 LightSquared UE to Cellular Device UE Interference - Conclusions

Measurements show all devices passed Test 2.4.2.1 (standards based sensitivity test) at -10 dBm with little systematic impact on the code phase errors, with and without the blocker.

It should be noted that the GLONASS center frequency is above GPS L1 frequency (GLONASS is centered at approximately 1605 MHz), thus is closer to the LightSquared UE “uplink” band than it is to the corresponding GPS center frequency. Therefore, to establish if there is potential impact to GLONASS receivers, further assessment of susceptibility of GLONASS receivers will be necessary. For the record, there were no GLONASS capable devices available for TWG cellular group testing (and was deemed at the outset to also be outside the scope of the TWG report), therefore the impact to mobile GLONASS devices could not be tested.

3.2.11 Work Plan Item 10: Assess Operational Scenarios Using Analytics and Test Results

LightSquared has obtained rights to operate subject to addressing and solving potential GPS interference issues on Phase 0 (one upper 5MHz carrier), Phase I (upper and lower 5 MHz carriers), Phase II (upper and lower 10 MHz carriers).

Regardless if the low carrier is used, if the high L Band downlink carrier were to be used, as can be seen from the data above, commercial devices could fail between -20 dBm to -50 dBm. When considering the commercial devices' implementation margin to account for under-sampling, the upper downlink band LightSquared signals strengths of as low as -55 dBm could theoretically create interference in the worst case device. Upper band signal strengths in this range could be observed in field conditions at varying distances from LightSquared base stations depending on the urban to rural coverage characteristics, and could extend several hundreds of meters or even several kilometers from the nearest transmitter antenna. There was consensus that low level of susceptibility evidenced by devices to upper channel base station transmitters could become harmful interference for devices while receiving GPS, even at significant distances from LightSquared base stations, and thus impact E911 or LBS location fixes by either being delayed or inaccurate (as permitted by FCC requirements).

Susceptibility test results when using LightSquared's lower 5 and 10 MHz carriers yielded different results, with two of nine UMTS units exceeding the limit of the test system (-10 dBm) and the rest between -10 to worst case suites were found to exist for two devices tested down to -45dBm. (It should also be noted that WCDMA devices exhibited more susceptibility result variations than CDMA across the same seven test suites. Some of this could be generally attributed to the fact that the WCDMA devices were mostly tested in anechoic chambers where power variations will exist when testing over 3 day cycles).

WCDMA devices are known to have less sensitivity than CDMA devices and that was exhibited in these tests. 6 of 9 WCDMA devices failed to reach a defined baseline test sensitivity of -152dBm, making meaningful test comparisons virtually impossible at this level. Though data taking has been completed, the group continues to analyze the WCDMA devices, but it was expected from the start that it would be more difficult to maintain calibration in the anechoic chamber test environments.

Consensus was reached that the Lower 10 MHz operation appears to provide significantly improved compatibility with GPS across all urban, suburban and rural coverage areas.

3.2.12 Work Plan item 11: Prevention and Mitigation Measures

A complete mitigation analysis must address the receivers, which means considering current, legacy and future mobile devices. On the transmit side, careful selection of the L Band operating frequency, site plan and maximum transmit power level holds

the potential to render the greatest compatibility with neighboring frequency GPS receivers, now and in the future.

In terms of legacy devices, the group consensus is that upper frequency shows conclusively that high powered terrestrial power L Band is incompatible with today's legacy cellular devices. These devices consistently exhibited GPS receiver susceptibility down to -50 dBm, as previous graphs show. These results were seen in CDMA devices many of which had very high immunity to Lower 10 LTE channel emissions, as much as 50dB or more additional immunity.

Regarding additional KPI impact above and beyond what is accounted for above; there is ample initial evidence that current legacy cellular GPS devices are compatible with either the 5 or 10 MHz lower channel eNode B nominal build out plans set forth by LightSquared. The group was interested in seeking diverse GPS chipset designs, which is most evident in the WCDMA devices which source GPS technology from several vendors, while CDMA is exclusively sourced by one vendor.

Two independent analyses by Verizon Wireless and Greenwood Telecommunications show convincing evidence that the pass/fail thresholds capture all systematic and thus significant degradation. These analyses span across four different test suites and across CDMA and WCDMA devices which have different GPS chipset designs and GPS assistance environments.

3.2.12.1 Present (Legacy) A-GPS Device Mitigation

ATC operations over LightSquared's upper 5 and 10 MHz downlink channel consistently caused test suite failure due to blocker interference for many devices. A-GPS receivers have been integrated into a large number of mobile devices, so reliable operation of GPS in these devices is an obvious objective. Therefore, operations over LightSquared's upper 5 and 10 MHz ATC downlink band will be incompatible with many current cellular devices as stated previously.

Legacy cellular A-GPS receivers appear to provide substantially more (at least 20-30 dB greater) resistance to disruptive effects of the Band 24 downlink signals in the lower 5 or 10 MHz of the downlink band (1526-1536 MHz). This may be attributable to the front end filtering in cellular GPS devices that provides high rejection at frequencies further away from the GPS L1 band, in this case approximately 45 MHz from the centers of both signal bands.

As a substantial amount of data has now been gathered, a number of mitigation techniques or remedies can begin to be fully explored. As stated above, a consensus was reached that given the current state of susceptibility of legacy cellular devices, it does not appear that compatible operations will be feasible with LightSquared's upper ATC channels until the installed base is replaced by much higher immunity devices, which is discussed in more detail below.

3.2.12.2 Future Device Mitigation

Future cellular devices may have filter technology options available (according to one supplier which made a presentation to the TWG) to further reduce susceptibility to adjacent band signals. While the group wants to ensure it is making no commercial endorsement regarding this or any other company, the largest supplier of cellular GPS chip technology, Qualcomm, in its recent FCC report (Appendix C.5) reports existing or new filter technology as a relatively straightforward and low cost remedy for future consumer devices. Quoting from their April 2011 submission, in relevant part:

> "FBAR/BAW based filters may be a potential candidate due to their low insertion loss and high stopband rejection... Filter vendors should be able to assess the feasibility of such solutions and provide a better estimate on the associated cost."

As in every similar case, this technology while it shows promise needs to be studied for full production viability in large volume, widespread deployments.

Legacy A-GPS devices use pre-selector filters that were not specifically designed to reject adjacent band signals. While these filters offer limited rejection characteristics if the spectrum separation is sufficient, their characteristics are not optimized for the higher channel occupancy of the adjacent band. The fact that some of the tested devices showed considerable resilience to the upper channel combinations suggests that it may be feasible to design cellular GPS receivers with existing components so as to achieve resilience comparable to the best performing devices, and but this requires more study and vendor interaction.

Farther out, future generation devices may be able to take advantage of current generation SAW for the lower 10MHz L Band channel or current and later generation BAW/FBAR resonator technologies. Based on a presentation to the subgroup by one leading supplier, both technologies offer solid state and miniature filters consistent with current device and chipset mobile device designs. This should be studied more closely prior to commercial deployment. FBAR designs offer even higher rejection and are expected to enable compatibility between LightSquared's upper L-band ATC channels and GPS (based on a presentation by the previously referenced supplier). However, to achieve the most aggressive L Band rollout and most aggressive wideband GNSS design (with wide and narrow band signals, operating in all regions of the world) this introduces the possibility of an additional 0.5 dB insertion loss (Avago Technologies is one published source, and its presentation to the Cellular Subgroup is found in Appendix C.2). This product should and will no doubt be studied more closely by subteam member companies for future device designs. It should be noted, that this degree of insertion loss may be compensated or offset by the availability of additional satellite constellation signals contemplated to become available in future GNSS receivers.

Following normal high volume device production standards, device vendors must study and apply pre-production testing to confirm current or new technology front end GPS receiver filtering will meet all requisite performance, cost and time to market objectives. In such a future context, it should be first determined what level of signal rejection will be required to permit operations in LightSquared's upper portion of the ATC downlink band. Once the necessary rejection levels have been determined, final filter specifications can be proposed or offered by leading vendors and evaluated for commercial viability. Effects on device design (battery life, size and operating performance within a cellular network) must be determined and tested prior to being deemed commercially acceptable.

As a final point, even assuming the capability to incorporate adequate filtering in future devices, the large embedded volume of existing devices will remain active in the field for at least several years. Experience demonstrates that it takes years for the embedded device base to turn over. Aside from the lower 10 MHz scenario, it is reasonable to expect that a significant number of mobile devices would be vulnerable to interference from LightSquared's upper band operations until new filters are available and other mitigation techniques are developed and implemented.

3.2.13 Summary of Live Sky Testing by LightSquared and TechnoCom Wireless

The detailed results are provided in Appendix C.3. The summary conclusions are provided here. This testing was based on a test plan reviewed by the Cellular Subgroup, and followed TWG procedures for review and participation in the field tests.

The static tests generally reflect the results of the laboratory tests. It is noteworthy that the static tests were conducted at sites that were selected because they were deemed "hot" sites in terms of measured blocker power on the ground. For the lower channel (5L), there was little systematic variation in the probability of successful position fix (as defined by a position error less than 25 meters and 50 meters) measured between the alternating ON/OFF 15 minute transmit time epochs.

In the cases when an upper channel was involved, whether alone or with the lower channel, there was a systematic increase in the frequency with which the position error exceeded the thresholds of 25 meters and 50 meters. However, it is noteworthy that, even in these cases (5H+5L or 5H channels) the frequency of "good fixes" (where the error was below the chosen threshold of 25 m or 50 m) was still at about 80% or higher of the frequency of the same with the blocker off.

In the case of the Dynamic (mobile, continuous position tracking) tests, for the rural site #53, with the presence of the 5H and 5L channel configuration, there is a noticeable increase in the frequency of obviously erroneous fixes within 300 m of the base station tower. A number of cases of "catastrophic error", e.g., swings as high as 600 meters, were observed for distances of or under 300 meters from the base station transmitter tower. However, the results were more stable and accurate at more distant segments of the test route -beyond 300 meters distance from the tower, the 2D errors

were generally less than 100 meters[26]. It is noteworthy that this site showed good propagation out to several kilometers and was of the four live sky test sites deemed the "hottest" in terms of L Band power on the ground.

For the other sites, even when an upper channel was on, the impact on position fixes shown on the route map is less but still somewhat obvious (e.g. see results for test Site-68, Dual May 18), although a close scrutiny of the error scatter plots does show a slightly higher average value (by a casual, visual estimation) of the 2D Position Error (when the transmitter was on relative to when it was off).

In the case of the single lower channel (5L), there was no observable differential impact between the presence and absence of blocker power at any of the four live sky test sites.

In the dense urban test Site #217, which was the "coldest" test site in terms of power on the ground, there were many inaccurate fixes both with and without the blocker present, not atypical for urban environments where physical blocking due to buildings occurs. Due to these effects, these results were most likely owe to an insufficient number of satellites visible with an adequate signal level, and in other cases effects of multipath in the vicinity of test Site #217.

Live sky in-building results showed, across all channel configurations, little or no systematic degradation for position error frequencies of both 25m and 50m in the presence of the blocker signal. It therefore may be concluded that for indoor cases the blocker was additionally attenuated such that its effect was not noticeable.

[26] A few incidences of errors greater than 100 m were observed both with and without the blocker.

3.3 General Location / Navigation Sub-Team

3.3.0 Executive Summary

Note: There were significant areas within Section 3.3.4 of this Final Report (General Location and Navigation) where LightSquared and the sub-team could not reach agreement. Where different perspectives exist, they are clearly labeled as the "GPS Industry Perspective" or "LightSquared's Perspective."

GPS Industry Perspective

The General Location/Navigation sub-team has concluded that all phases of the LightSquared deployment plan will result in widespread harmful interference to GPS signals and service and that mitigation is not possible. The team devoted considerable time and effort to studying all three deployment phases proposed by LightSquared. The Phase 1 deployment scenario, which includes both the upper and lower 5 MHz channels at a power level of +62 dBm (which is 10 dB below the FCC authorized level), was studied comprehensively. Phase 1 Interference Susceptibility tests show that the majority of devices tested will be subject to harmful interference within 1.1 km of a LightSquared transmit tower. Using the FCC authorized transmit power levels, which are ten times higher than those used in Phase 1, the majority of devices tested would be jammed within 4.3 km of the transmit tower. The projected impact to the Washington D.C. area (including the National Mall and Ronald Reagan Washington National Airport) is illustrated in Figure 3.3.1. Red areas show where GPS receivers will experience harmful interference from the LightSquared proposed deployment plan, and yellow areas show the broader areas affected by the FCC authorized deployment plan.

Figure 3.3.1

Numerous conference calls and countless hours were spent studying potential mitigation strategies that might allow the proposed LightSquared service to coexist with the well established GPS user base. No stone was left unturned as the team evaluated proposals for mitigation options involving both LightSquared's transmitters and GPS receivers. One proposed mitigation was to permanently eliminate the upper channel and deploy only on the lower 10 MHz channel. Although LightSquared insisted that this was not part of its deployment plan, this mitigation strategy was discussed at length in the General Location /Navigation sub-team. In fact, the sub-team even altered its test plan after testing had commenced in order to accommodate LightSquared's interest in this mitigation strategy. Lab testing revealed that many devices suffered from harmful interference from the lower 10 MHz channel; specifically, 20 out of 29 devices experienced harmful interference. Most of LightSquared's conclusions throughout this document apparently were drawn principally from this proposed mitigation scenario, and do not address the rest of the actual proposed deployment scenarios.

Several simulated filters were proposed as options for GPS receivers; however, no testing could be performed since these filters do not exist, not even in prototype form. While the PowerPoint presentations depicting these filters purportedly described marginal improvements in rejection of the LightSquared signals, these simulated filters would only do so at the expense of increased degradation of GPS signals. Furthermore, the filter simulations under discussion only attempted to address a small subset of the universe of GPS receivers currently deployed. Many different

filters would be needed to accommodate the multiple and diverse receiver types in use today. As a result, the General Location/Navigation sub-team has concluded that no mitigations exist for the existing user base or for future products as long LightSquared remains in the MSS L-band. The only option for coexistence with GPS is for LightSquared to move to another frequency band.

LightSquared has asserted that the General Location/Navigation sub-team's conclusions paint an "alarming" and "highly inaccurate" picture of the interference caused by LightSquared transmitters. While we agree that the results are alarming, they are anything but inaccurate. While LightSquared has attempted to hide behind the apron strings of probabilistic propagation models such as the Walfisch-Ikegami and Korowajczuk-Picquenard models, which obscure the effects of unobstructed or complementary propagation paths, the General Location/Navigation sub-team has consistently used a free-space propagation model to explore the effects of harmful interference. Several "Live Sky" tests were run over the past few months, and while the transmitter power level was only a fraction of that specified in LightSquared's proposed deployment plan, these tests were very useful in confirming the validity of a free-space propagation model to show extremes in interference effects, which is critical when designing products that have safety of life applications. It is for this very reason that the free-space model is the de facto standard for any interference analysis conducted within the industry.

With this in mind, LightSquared's discussions of margin and percentage of areas affected are doubly frightening. Not only are they false and misleading, but the mere suggestion that it could be acceptable to cripple some percentage of General Location/Navigation GPS devices—not to mention those used in business sectors such as aviation and agriculture—is unthinkable. In safety of life applications, there is no margin for error and no room for inaccuracy. The GPS service must be preserved – our lives depend on it.

LightSquared Perspective

Individual manufacturers participating in the General Location/Navigation sub-team did extensive laboratory tests on the potential impact of the LightSquared terrestrial network on 29 of their own devices.

The sub-team reached consensus on the selection of devices and the methodology for testing. There was no consensus regarding the interpretation of the results or the potential for mitigation through either limiting LightSquared base stations to operation on the lower 10 MHz channel or adding filters to future devices.

The representatives of some GPS manufacturers interpret the results based on a definition of harmful interference as a 1 dB change in C/N_0 and a worst-case propagation model using free space only. They concluded that no devices passed when tested against upper channel configurations and only eight devices passed when tested against the lower 10 MHz channel configuration. They contend that the feasibility of adding filters to future devices is unproven. LightSquared strongly believes that the feasibility of adding filters to future devices has been demonstrated by experienced filter manufacturers using proven technology.

In assessing the performance of legacy devices, LightSquared interprets the results based on definition of harmful interference as a 6 dB change in C/N_0 and a probabilistic propagation model. This analysis shows that 13 devices passed when tested against upper channel configurations and all 29 devices passed when tested against the lower 10 MHz channel configuration. The analysis established that all devices tested against the Lower 10 MHz channel experienced a 6 dB change in C/N_0 only at signal strengths greater than -25 dBM; a signal strength which will occur only in up to 1.2% of LightSquared's service area as shown in the maps below.

WI-LOS Analysis of -25 dBm[27] Signal Strength and Greater in Washington DC using morphology data collected through drive testing

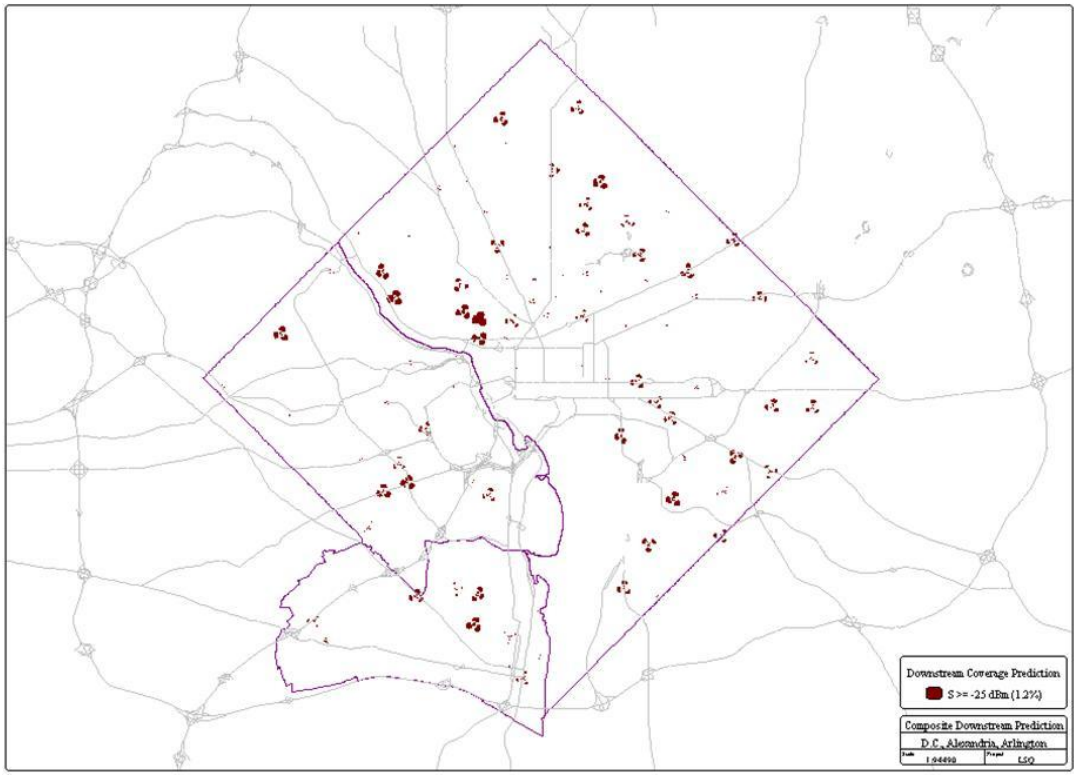


Figure 3.3.2

[27] This model is part of the cellular RF planning tool, CelPlan

Korowajczuk Propagation Model Analysis of -25 dBM Signal Strength and Greater in Washington DC

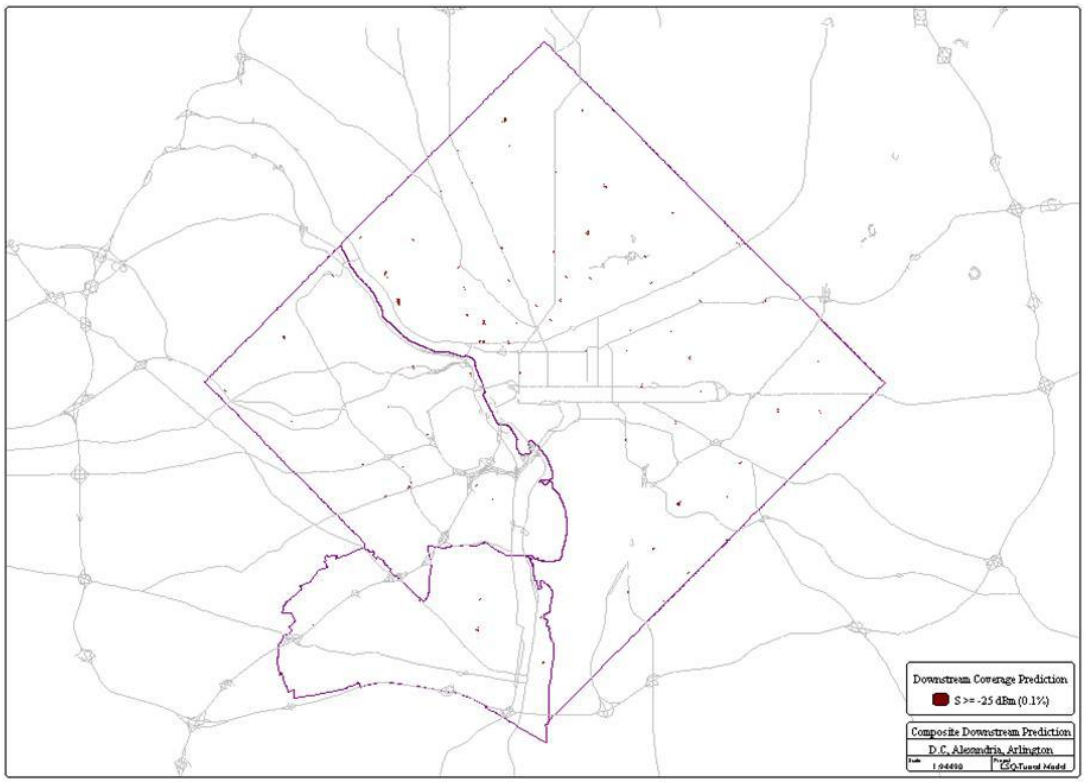


Figure 3.3.3

Introduction

The GPS Interference Technical Working Group (TWG), in its report to the FCC on 25 February 2011, established a work plan consisting of 11 items. During the course of its work, the TWG established that several broad GPS receiver equipment categories existed and split the investigation into several sub-teams. Each sub-team was tasked with investigating and reporting on the effects of interference by the LightSquared signals upon the receivers in its category. This report is the final report from the General Location/Navigation sub-team.

The TWG defined 11 work plan elements:

1. Establish pertinent analytical and test methodologies and assumptions underlying the test regime
2. Select the categories of receivers and receivers to be tested
3. Develop operational scenarios
4. Establish the methodology for analyzing test results
5. Derive the test conditions based on the established operational scenarios
6. Write the test plan and procedures
7. Identify and engage appropriate neutral test facility(ies) for the testing portion of the work plan
8. Perform testing
9. Analyze test results based on established methodology
10. Assess operational scenarios using analytics and test results
11. Assess whether any mitigation measures are feasible and appropriate

The General Location/Navigation sub-team will report on each of these items separately.

3.3.1 Establish Pertinent Analytical and Test Methodologies and Assumptions Underlying the Test Regime

3.3.1.1 GPS Industry Perspective

The General Location/Navigation sub-team defined the following:

3.3.1.1.1 Degradation of Carrier to Noise Ratio (C/N_0)

Any signal or service that causes perceptible degradation in C/N_0 or causes any change to existing capabilities or user expectations. For General Location/Navigation, the maximum permissible degradation in C/N_0 is 1 dB.

The use of a 1 dB reduction in effective C/N_0 (also referred to as a rise in the total noise floor of 1 dB over the environmental noise floor) as a quantification of harmful interference to GPS has a well-recognized basis in the products of seven years of technical work on protection of radionavigation-satellite service receivers, which are now up for final approval within the ITU's Radiocommunication Sector. The protection levels for various types of receivers that operate with RNSS systems, including GPS, in the 1559–1610 MHz band that are provided in Draft New Recommendation ITU-R .[1477_New] are based (in combinations of technical parameters such as “system noise temperature” and “acquisition mode threshold power density level of aggregate wideband interference at the passive antenna output”) on a maximum permissible increase in the noise floor from interferers of 1 dB.

There will be cases where reductions in effective C/N_0 of less than 1 dB will result in harmful interference to a particular GPS application based on the effect of the interference on key performance indicators for that application or use, but the 1 dB reduction metric is nevertheless viewed by the global RNSS community as a reasonable criterion. The 1 dB criterion represents the maximum tolerable interference contributions from all non-RNSS interference sources. To the extent that there are multiple sources of interference to be taken into account, an apportionment analysis would need to be considered.

3.3.1.1.2 Degradation of Acquisition Sensitivity

The Sub-team agrees that acquisition Sensitivity Degradation is the increase in GPS signal required to acquire and track in the presence of a LightSquared signal. The metric is the amount of increase in GPS signal required above the amount of C/N_0 degradation.

3.3.1.1.3 Increase in Time to First Fix (TTFF)

Increase in TTFF is determined by the operational scenario for the GPS receiver equipment. For some operational scenarios, any increase in TTFF is unacceptable.

3.3.1.2 LightSquared Perspective

3.3.1.2.1 Degradation of Carrier to Noise Ratio (C/N_0)

A definition of harmful interference which is based on the FCC's rules is most appropriate. The FCC defines it as "interference which endangers the functioning of a radionavigation service or other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the ITU] Radio Regulations.[28]" LightSquared believes this must be evaluated from the end-user's perspective and, as such, should be based on any material changes to user observable key performance indicators. LightSquared's assessment of the dynamic test results indicate that overall positioning accuracy shows little difference for a change in C/N_0 of up to 6dB and believes this is an appropriate benchmark for overload interference determination. Additional information is provided in Section 3.3.9.

3.3.2 Work Plan Item 2: Select the Categories of Receivers and Receivers to be Tested

Combined Sub-Team Perspective

To preserve the anonymity of each manufacturer, all devices have been assigned random identification numbers. The prefix (P or a G) indicates whether the device is a public safety device (P) or a General Navigation Device (G).

A. Fitness

- Garmin® Forerunner® 110
- Garmin Forerunner 305
- Garmin Edge® 500 (*not tested due to time constraints*)
- Garmin Edge 800 (*not tested due to time constraints*)

B. Outdoor

- Garmin eTrex® H
- Garmin Dakota® 20
- Garmin Oregon® 550
- Garmin GPSMAP® 62 (*not tested due to time constraints*)
- Garmin Astro® 220 (*not tested due to time constraints*)
- Garmin Rino® 530HCx (*not tested due to time constraints*)

[28] Section 2.1 of the FCC's Rules, 47 C.F.R. § 2.1: No. 1.169 of the ITU Radio Regulations.

C. Tracking

- Garmin GTU™ 10
- Garmin DC™ 40 (*not tested due to time constraints*)
- BI® ExacuTrack® One

D. Marine

- Garmin GPS 17x (NMEA)
- Garmin GPSMAP 441
- Furuno® GP 150
- Garmin GPSMAP 740 (*not tested due to time constraints*)
- Garmin GPSMAP 541 (*not tested due to time constraints*)
- Garmin GPSMAP 546 (*not tested due to time constraints*)

E. Automotive (in-dash)

- General Motors OnStar® System
- Garmin GVN 54

F. PND

- TomTom® XL335
- TomTom ONE® 3RD Edition
- TomTom GO® 2505
- TomTom 1400/1405 or 1500/1505 (*not tested due to time constraints*)
- TomTom XXL 530/530S or XXL 540/540S (*not tested due to time constraints*)
- TomTom GO 720 or GO 920 (*not tested due to time constraints*)
- TomTom GO 730 or GO 930 (*not tested due to time constraints*)
- Garmin nüvi® 2X5W
- Garmin nüvi 13XX
- Garmin nüvi 3XX
- Garmin nüvi 37XX
- Garmin zumo® 550 (*not tested due to time constraints*)
- Garmin StreetPilot® c330 (*not tested due to time constraints*)
- Garmin zumo® 220 (*not tested due to time constraints*)
- Garmin nüvi 760 (*not tested due to time constraints*)
- Hemisphere GPS® Outback S3 (Low Precision Ground Agricultural Navigation) (*not tested by the General Location/Navigation sub-team – tested by the Timing sub-team instead*)

G. Fleet Management

- Trimble® iLM® 2730 (with Mobile Mark Option J antenna)
- Trimble TVG 850 (with Mobile Mark Option E glass-mount antenna)

- Trimble MTS521 (with CAT Shark Fin antenna) (*not tested due to time constraints*)
- DCM300G (with Taoglas Combo antenna) (*not tested due to time constraints*)
- e-Ride Opus 5SD
- Hemisphere GPS® Vector MV101 (*not tested by the General Location/Navigation sub-team – tested by the Timing sub-team instead*)

H. First Responder Location

- Motorola® APX7000
- Motorola APX6000

I. Emergency Vehicles (post-OEM mounted in vehicle)

- Trimble Placer™ Gold
- Motorola MW810
- Motorola DMR/MotoTRBO (*not tested due to time constraints*)
- Motorola External Antenna/LNA (*not tested due to time constraints*)

J. Portable Aviation (non-FAA certified)

- Garmin GPSMAP 496
- Garmin aera® 5xx
- Garmin GPSMAP 696
- Honeywell Bendix/King® AV8OR™ (*not tested due to time constraints*)

3.3.3 Work Plan Item 3: Develop Operational Scenarios

3.3.3.1 Combined Sub-Team Perspective

As developed in earlier reports, the initial operational scenarios were:

A. PND Use Case 1: Suburban

Suburban, tree lined environment mounted on dash of vehicle. Frequent changes of direction, obscuration of signals by the roof of the car, signal attenuation through windscreen, mild dynamics. Unit needs the ability to lock on to the correct road and navigate turns successfully. Need to distinguish between adjacent roads and ramps.

B. PND Use Case 2: Urban Canyon

Urban canyon environment mounted on dash of vehicle. Frequent changes of direction, obscuration of signals by the roof of the car, blockage of satellites in view by tall buildings, signal attenuation through windscreen, mild dynamics. Unit needs the ability to lock on to the correct road and navigate turns successfully. Need to distinguish between adjacent roads and ramps.

C. Outdoor Use Case: Golfing

Open area environment. Unit is held in the hand of a user who is walking and standing. Some dynamics associated with walking with the device, partial obscuration of signals by

user's body. Unit needs the ability to measure distance, track user's position, and navigate to waypoints successfully.

D. Outdoor Use Case: Deep Forest

Deep forest environment. Unit is held in the hand of a moving user. Some dynamics associated with walking with the device, obscuration of signals by forest canopy and body of user. Unit needs the ability to measure distance, track user's position, and navigate to waypoints successfully.

E. Fitness Use Case: Arm Swing Environment

Unit under test mounted on the arm of a user who is swinging his or her arms in a manner consistent with distance running. The unit will experience frequent heading changes and the signal will be obscured by the body at times. Stressful dynamics are associated with the arm swing. Unit needs the ability to measure distance, track user's position/velocity, and navigate to waypoints successfully.

3.3.4 Work Plan Item 4: Establish the Methodology for Analyzing Test Results

3.3.4.1 Combined Sub-Team Perspective

Test results must be analyzed in light of the aforementioned Operational Scenarios, which were used to develop test conditions per Section 3.3.5 and which are contained in the Test Plan (see Appendix G.1).

3.3.5 Work Plan Item 5: Derive the Test Conditions Based on the Established Operational Scenarios

3.3.5.1 Combined Sub-Team Perspective

The test conditions derived from the operational scenarios are included in the test plan (see Appendix G.1).

3.3.6 Work Plan Item 6: Write the Test Plan and Procedures

Combined Sub-Team Perspective

The final revision of the General Location/Navigation test plan (version 2.1) is included Appendix G.1.

3.3.7 Work Plan Item 7: Identify and Engage Appropriate Neutral Test Facility(ies) for the Testing Portion of the Work Plan

Combined Sub-Team Perspective

The General Location/Navigation sub-team chose Alcatel-Lucent's Bell Laboratories (Bell Labs) for its test facility. Bell Labs had two sites running in two shifts to accomplish the testing in the time allotted.

3.3.8 Work Plan Item 8: Perform Testing

3.3.8.1 Combined Sub-Team Perspective

All testing was performed by Alcatel-Lucent/Bell Labs per the test plan, provided in Appendix G.1 for reference. Bell Labs provided two labs, one in Naperville, IL and the other in Murray Hill, NJ. Both labs ran two eight-hour shifts per day, from 8 am – 12 am for the duration of the tests, which took place between May 9, 2011 and June 3, 2011. As noted in the February 25th progress report to the FCC in section 8, TWG members and advisors whose devices were tested were required to be on-site at the lab for technical observation and to participate in testing. All device manufacturers complied with this stipulation. In addition, LightSquared representatives were present for portions of the testing.

Bell Labs provided a detailed test report that contains the test results for the limited subset of devices that were tested. This report is included for reference in Appendix G.2.

3.3.8.2 GPS Industry Perspective

As noted in Section 3.3.2, above, the short time frame provided for testing did not permit the sub-team to test a representative sample of devices from the General Location/Navigation sub-category. Furthermore, Bell Labs was unable to execute the full test plan on every device. Though these exceptions were noted in the test plan, they were not described as optional.

3.3.8.3 LightSquared Perspective

LightSquared notes that the test cases which were not run had been identified as "optional" by the sub-team. All non-optional test cases were completed by Bell Labs.

3.3.9 Work Plan Item 9: Analyze Test Results Based on Established Methodology

3.3.9.1 GPS Industry Perspective (pages 136 to 152)

3.3.9.1.1 Methodology—Path Loss Model

In addition to the lab testing performed by Bell Labs, several manufacturers from the General Location/Navigation sub-team participated in the Live Sky Testing in Las Vegas, NV. Despite the fact that the LightSquared transmitter power was only a fraction of that specified in the proposed LightSquared deployment plan, these tests were very useful in confirming two hypotheses. First of all, it allowed the sub-team to verify that a free-space propagation model accurately represents the path loss that is realizable in the real world. Correspondingly, it allowed the team to observe the inadequacy of both the Walfisch-Ikegami and Korowajczuk-Picquenard models as neither of them came close to adequately capturing the path losses that were observed in Las Vegas. Secondly, this testing allowed the sub-team to observe how severe jamming is to devices in a vehicle.

Figure 3.3.4 shows data points measured by the Garmin team in Las Vegas. In an interference analysis such as this, it is imperative to use a propagation model that represents the extremes in interference. The data clearly shows that the measured power of the interfering signals was consistent with a free space model. Consequently, the sub-team believes that the free space model is the only appropriate model to use in an interference analysis.

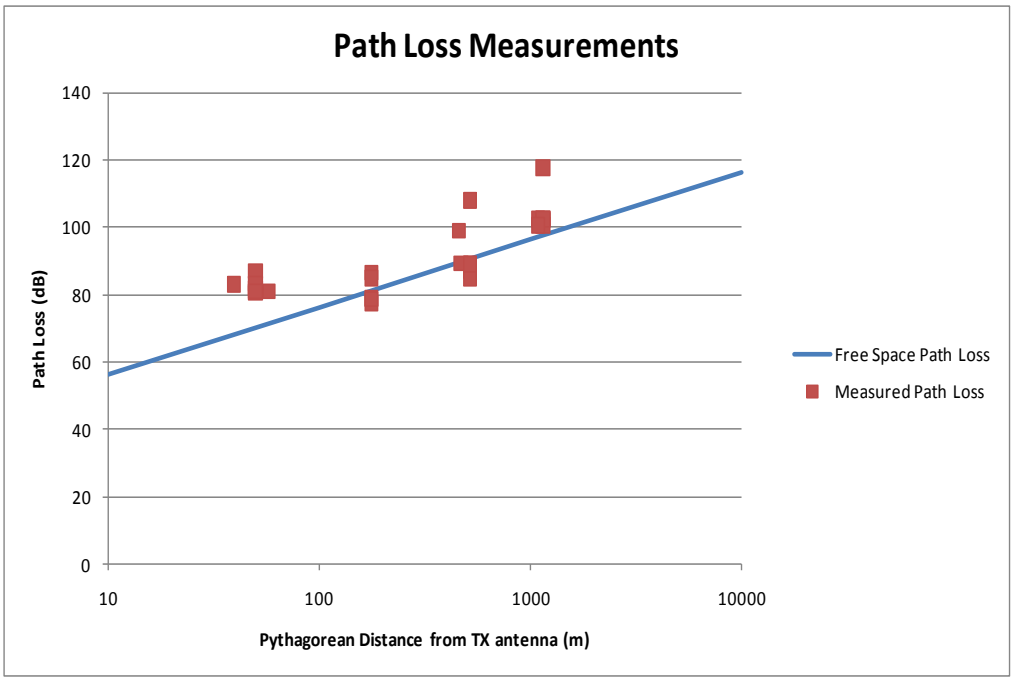


Figure 3.3.4

Another very interesting point that was observed during this testing relates to the polarization of the interfering signals from the LightSquared transmit tower. As Figure 3.3.5 aptly demonstrates, at any given point of measurement, the peak polarization of the signal may vary widely. One interesting thing to note is that, in the samples taken, the peak polarization is never vertical. This data calls into question any propagation studies that rely solely on a vertically polarized antenna.

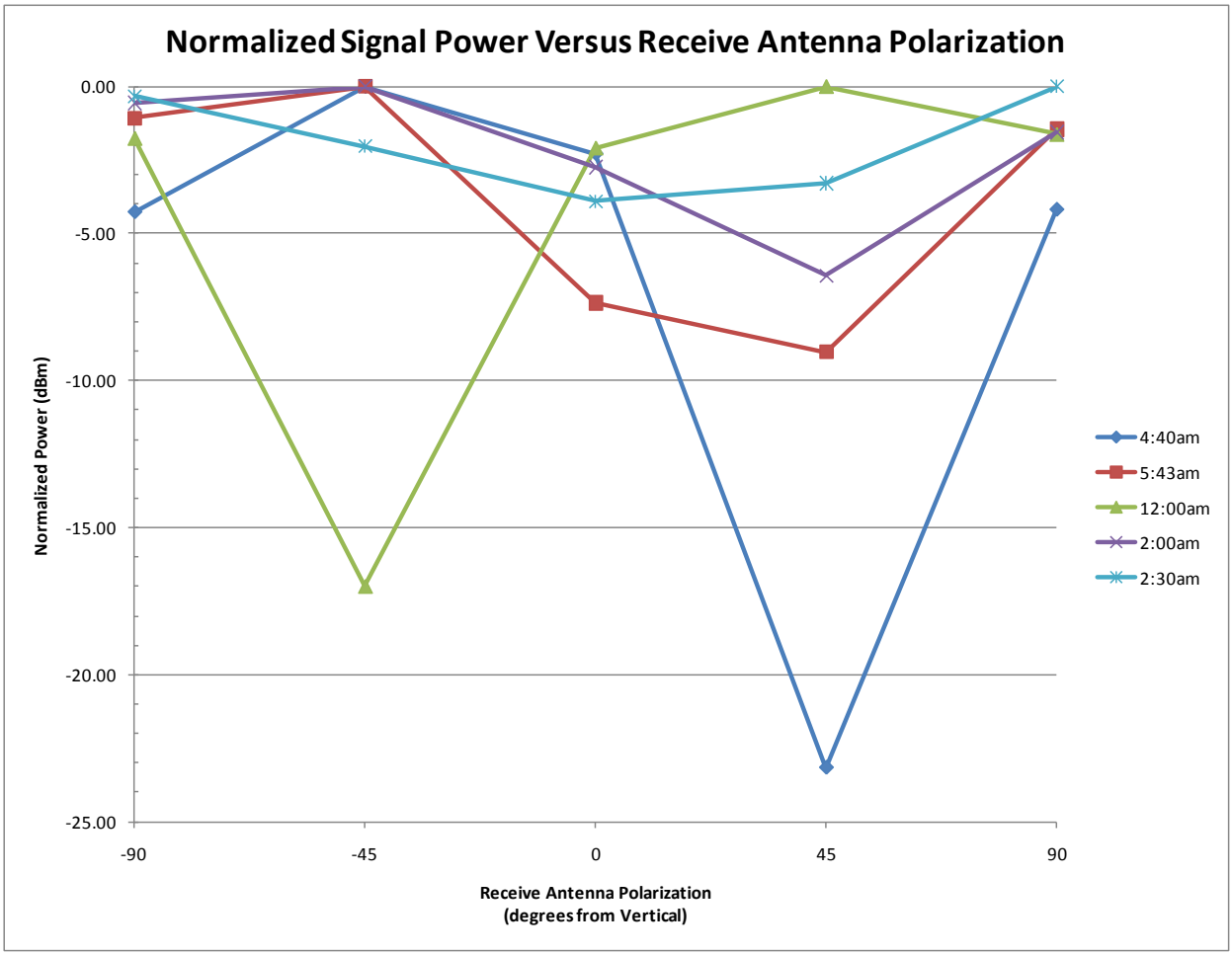


Figure 3.3.5

Path Loss Model Discussion

There are differing views on which path loss model to use. LightSquared is using probabilistic models such as Walfisch-Ikegami and Korowajczuk-Picquenard which statistically predict the likelihood of the signal power at a given range from the transmitter. These models are generally used in communications link budget analyses, but not in interference analyses. The GPS Industry recognizes that a free space line of sight model is more appropriate

for use in an interference analysis because it accurately predicts the extremes of interference rather than a probability of interference.

LightSquared asserts that a free space propagation model radically overstates the probability of interference and paints an alarming picture. However, a free space path-loss model makes no statement about probabilities. It simply gives a better idea of the extremes in interference that one can expect from the LightSquared signals. The variability in LightSquared's own propagation study (reference Figure 3.3.16 to Figure 3.3.19), despite its limitations, validates the necessity of a free space path loss model because the latter more accurately predicts the extremes in interference.

Fundamentally, the LightSquared propagation model from Las Vegas has serious problems which call its validity into question. First of all, the measurement antenna used for this study was a magnet mount, vertically polarized antenna which was only rated to 1500 MHz (whereas these measurements were made at 1526 – 1555 MHz). In addition, their test failed to take into account any gain variations caused by the vehicle ground plane on which it was mounted. Furthermore, as the data in Figure 3.3.5 clearly shows, a vertically polarized antenna is a very poor choice when measuring signals polarized at ±45°.

3.3.9.1.2 Degradation of Carrier to Noise Ratio

Harmful interference is defined by a 1 dB degradation in Carrier to Noise ratio (C/N_0). This ratio expresses the amount of usable signal that a GPS device can receive over the noise that is present. While there is always a small amount of environmental noise present in any receiver, these test results show the amount of additional noise contributed by a LightSquared transmitter.

LightSquared states that a 6 dB degradation in C/N_0 is the appropriate threshold for defining harmful interference. The GPS Industry experience in the dense urban environment demonstrates that unacceptable loss of system capability will result if more than 1 dB of C/N_0 degradation is allowed. In the dense urban environment, satellite signals are attenuated and obstructed to the point where 1 dB of interference impacts satellite availability, and thus fix availability (which was not analyzed in this report). Also, the GPS Industry notes that Harmful Interference is clearly observed at interference levels of greater than 1 dB for the Warm Start TTFF, Cold Start TTFF, and WAAS TTFF Key Performance Indicators Table 3.3.1, and Table 3.3.2 respectively).

For the dynamic tests, LightSquared implies that GPS position reports in the Urban Canyon are often already so degraded that effect of the LightSquared signal will not be evident to the user. The GPS Industry notes that there is observed degradation in positional

accuracy due to LightSquared interference when compared to the baseline tracks. This degradation is noted in the dynamic plots, below. When analyzing such results, it is important to keep the definition of Harmful Interference in mind, which is defined in Section 3.3.1 as "any signal or service that causes perceptible degradation in C/N_0 or causes any change to existing capabilities or user expectations."

Furthermore, LightSquared states that the suburban test results show there is sufficient margin (however, no references have been offered to substantiate this claim) so that 6 dB C/N_0 degradation caused no user perceptible degradation in GPS positional performance. The GPS industry notes that the assertion that 6 dB of C/N_0 degradation did not cause positional problems in a suburban environment is insufficient to prove that 6 dB of C/N_0 degradation will not cause problems in all GPS use cases and all Key Performance Indicators. This assertion also ignores the complete denial of service of the WAAS signal by all devices tested as demonstrated by the WAAS TTFF test (Table). 6 dB of interference also prevented 6 of 25 devices from achieving a fix in the Cold Start TTFF test; 11 of 25 devices experienced delays of 30 seconds or more in achieving a fix in the Cold Start TTFF test. Also, two devices failed to acquire GPS signals at all with 6 dB of C/N_0 degradation, as demonstrated by the Acquisition Sensitivity Test (Table 3.3.1).

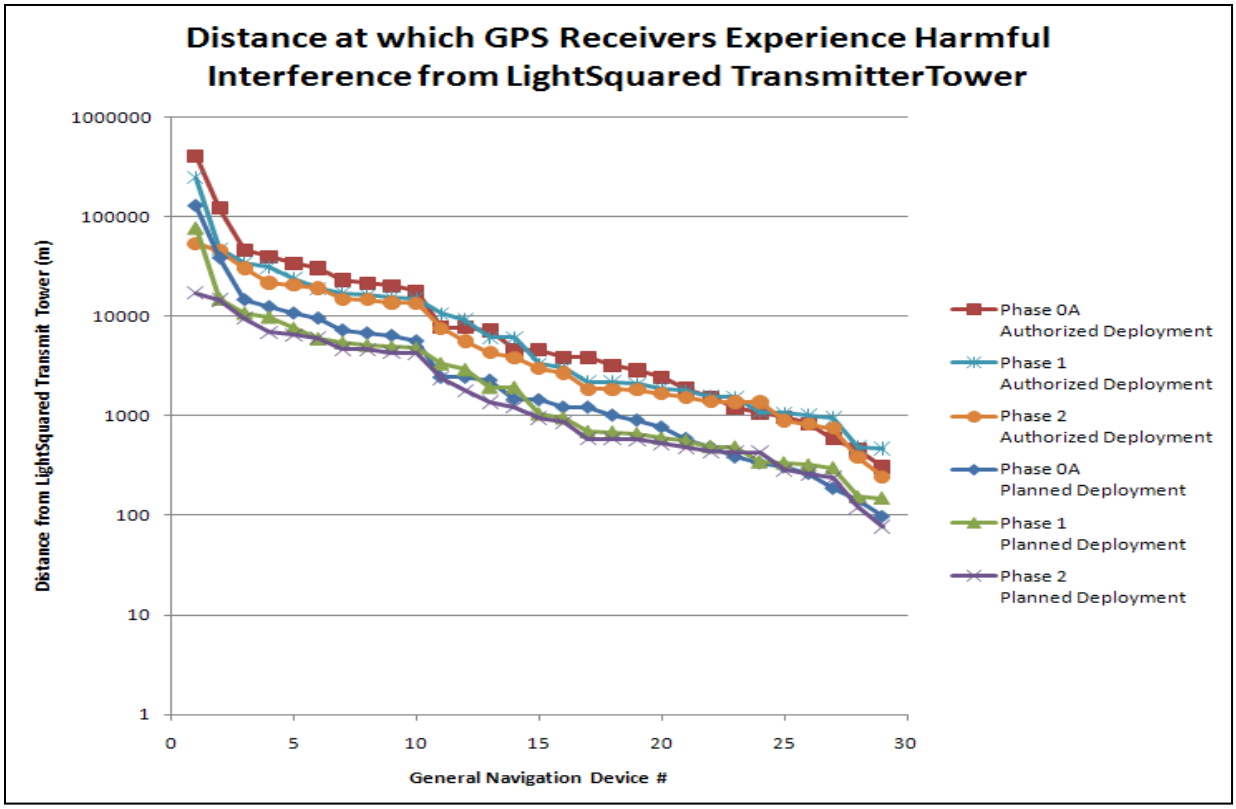


Figure 3.3.6

Figure 3.3.6 above clearly indicates that any of the proposed LightSquared deployment scenarios cause harmful interference to General Location/Navigation devices many kilometers away from a LightSquared transmitter tower. This level of jamming is unacceptable to the millions of individuals, families, and corporations which rely on GPS for their personal safety and livelihood.

Figure 3.3.7

Figure 3.3.7 is a Google Earth view of the Washington D.C. area including the National Mall and Ronald Reagan Washington National Airport. It illustrates the levels of GPS jamming that can be anticipated as a result of the proposed LightSquared service.[29] Washington D.C. was simply used as an example, and similar results should be anticipated in any major metropolitan area.

The red color signifies areas that will experience harmful interference from the proposed LightSquared deployment transmit power of +62 dBm. The yellow color represents areas that will experience harmful interference from the FCC authorized LightSquared deployment transmit power of +72 dBm.[30]

[29] The circle locations are based upon antenna and transmitter locations from a representative 4G network deployment.

[30] The radius of each circle is based on the free space path loss denial of service distance as represented by the median of the Interference Susceptibility data for Phase 1 deployment.

The implications of this analysis are alarming. No part of the Washington D.C. metro area is unaffected by this harmful interference if LightSquared were to deploy at the FCC authorized power levels. Any similar metropolitan area will be blanketed by harmful interference from the LightSquared signal as well.

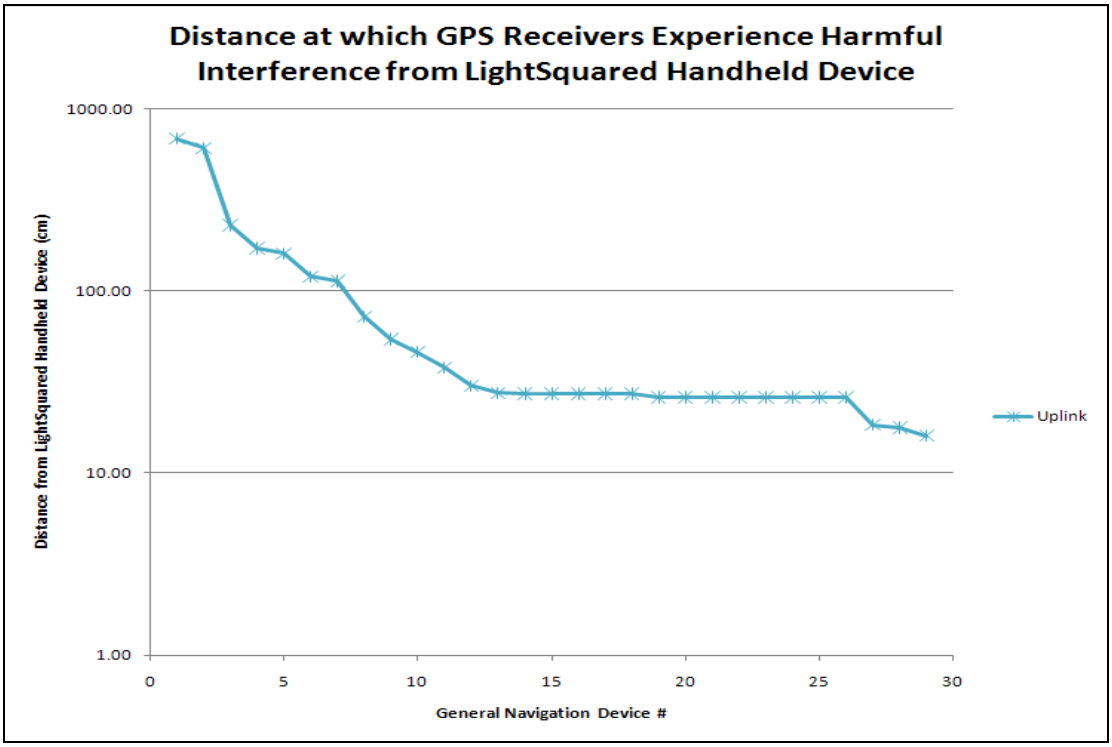


Figure 3.3.8

Figure 3.3.8 above shows the interference from a single LightSquared handset. It should be noted that no LightSquared handsets exist, so no one has been able to verify the actual effects of multiple handsets in close proximity. Despite the lack of real prototypes to test, the simulated handset interference signal still shows severe degradation at distances over 1 meter (several feet) from the handset. This means that GPS receivers used in close proximity to a LightSquared handset (such as in the same vehicle, aircraft, or carried in a person's hand or pocket) will experience harmful interference. This is particularly concerning for someone like a police officer who may depend on his first responder location device, but also happens to carry a LightSquared handset in his pocket. These scenarios are explored in greater detail in Section 3.3.10.

3.3.9.1.3 Degradation of Acquisition Sensitivity

24 units were tested for acquisition sensitivity degradation in the presence of jamming signals according to the LightSquared

Deployment Phase 1 frequency scheme. The raw data is shown in Table 3.3.1.

Acquisition Sensitivity with Static Susceptibility C/N_0 Degradation Level						
Receiver #	**Baseline**	**1 dB**	**3 dB**	**6 dB**	**10 dB**	**20 dB**
G18062	-146.5	-145.5	-141.5	-137.5	-132.5	
G10607	-132.5	-130.5	-129.5			
G18161	-144.5	-142.5	-141.5	-134.5	-131.5	
G14298	-139.6	-137.6	-135.6	-129.6		
G16382	-143.5	-143.5	-138.5	-135.5	-131.5	NO FIX
P18892	-143.5	-139.5	-137.5	-130.5		
G14666	-143.5	-139.5	-136.5	-132.5	NO FIX	NO FIX
P14949	-139.5	-137.5	-135.5	-132.5	-128.5	
G16382	-138.5	-137.5	-132.5	-131.5		
G16534	-147.5	-145.5	-143.5	-140.5	-135.5	NO FIX
G11207	-132.6	-132.6	-128.6			
P17655	-138.5	-137.5	-134.5	-132.5	-128.5	
G17783	-153.5	-151.5	-148.5	-144.5	-141.5	NO FIX
G15343	-145.5	-143.5	-140.5	-137.5	-133.5	
P13275	-149.5	-148.5	-137.5	-130.5		
G18696	-139.5	-139.5	-137.5	-133.5	-129.5	
G15028	-137.6	-136.6	-134.6	-131.6	-128.6	
G16449	-139.5	-138.5	-135.5	-132.5	-129.5	NO FIX
G12867	-146.5	-144.5	-139.5	-136.5	-133.5	NO FIX
G13445	-139.6	-139.6	-138.6	-132.6	-130.6	
G12586	-144.6	-143.6	-140.6	-137.6	-133.6	
G17641	-138.6	-136.6	-134.6	-131.6		
G10968	-140.6	-140.6	-136.6	-132.6		
G15448	-143.6	-142.6	-138.6	-133.6	-127.6	NO FIX

Table 3.3.1

There is significant degradation of the acquisition sensitivity at all jamming levels:

- For signal levels causing a 1 dB degradation in C/N_0, there was a corresponding mean degradation in acquisition sensitivity of 1.42 dB;
- For signal levels causing a 3 dB degradation in C/N_0, there was a corresponding mean degradation in acquisition sensitivity of 4.63 dB;
- For signal levels causing a 6 dB degradation in C/N_0, there was a corresponding mean degradation in acquisition sensitivity of 8.73 dB;

- For signal levels causing a 10 dB degradation in C/N_0, there was a corresponding mean degradation in acquisition sensitivity of 11.60 dB; and
- For signal levels causing a 20 dB degradation in C/N_0, there was generally a loss of the ability to acquire the GPS signal and obtain a location fix.

TTFF Increase

TTFF is a very important Key Performance Indicator. The amount of time it takes for a device to get a fix is of critical importance to GPS users. The nominal amount of time to get a fix varies, but it is typically 18–36 seconds. Any external signal that causes a delay in TTFF represents a very noticeable degradation of performance to the GPS user base. Such a signal must be classified as harmful interference per the sub- team's definition.

The General Location/Navigation sub-team tested several variations of TTFF.

3.3.9.1.4 Cold Start TTFF Testing

The test procedure for Cold Start TTFF testing is described in section IV.C.1 of Appendix G.1. It is important to note that the receivers were commanded to Cold Start at the 10th second of a GPS minute. This is critical as it means the same initial conditions were present for each device for each trial. Further, a Cold Start TTFF was measured three times at the baseline and at each interference level (1, 3, 6, 10, and 20 dB) to account for some statistical variation in the results.

It is also important to note that the satellite signal power simulated for these tests was -128.5 dBm.[31] This is considered a very strong signal, and common factors that greatly attenuate the signal, such as heavy foliage and buildings, were not simulated. In other words, this scenario represents optimum signal conditions.

The full test results appear on page 31 of Appendix G.2. An analysis of these results follows:

A total of 25 devices were tested (not all devices supported this test as their communications interface was not capable of issuing a Cold Start command).

[31] See *GPS Standard Positioning Service Performance Standard*, 4th Ed., 2008, pg. 7, paragraph 2.2.1.

A degradation of performance for the sample devices was noted whenever the baseline TTFF increased by 30 seconds (on a trial by trial basis).

Cold Start TTFF Analysis		
Interference Level	**Harmful Interference Observed**	**No Fix Within Three Minutes One or More Trials**
1 dB	0/25	0/25
3 dB	5/25	2/25
6 dB	11/25	6/25
10 dB	23/25	15/25
20 dB	25/25	25/25

Table 3.3.2

It is important to note that substantial increases in TTFF were observed for interference levels greater than 1 dB. This is an unacceptable degradation in performance.

3.3.9.1.5 Warm Start TTFF Testing

The test procedure for Warm Start TTFF testing is described in section IV.D.1 of Appendix G.1. It is important to note that the receivers were commanded to Warm Start at the 10th second of a GPS minute. This is critical as it means the same initial conditions were present for each device for each trial. Further, a Warm Start TTFF was measured three times at the baseline and at each interference level (1, 3, 6, 10, and 20 dB) to account for some statistical variation in the results.

It is also important to note that the satellite signal power being simulated for these tests was -128.5 dBm.[32] This is considered a very strong signal, and common factors that greatly attenuate the signal, such as heavy foliage and buildings, were not simulated. In other words, this scenario represents optimum signal conditions.

The full results are tabulated on page 32 of the Appendix G.2. An analysis of these results follows:

A total of 21 devices were tested (not all devices supported this test as their communications interface was not capable of issuing a Warm Start command).

A degradation of performance was noted whenever the baseline TTFF increased by 30 seconds (on a trial by trial basis).

[32] See *GPS Standard Positioning Service Performance Standard*, 4th Ed., 2008, pg. 7, paragraph 2.2.1.

Warm Start TTFF Analysis		
Interference Level	**Harmful Interference Observed**	**No Fix Within Three Minutes One or More Trials**
1 dB	1/21	0/21
3 dB	4/21	0/21
6 dB	6/21	2/21
10 dB	15/21	10/21
20 dB	21/21	21/21

Table 3.3.3

GPS manufacturers believe that it is important to note that substantial increases in TTFF were observed for interference levels greater than 1 dB when tested against potential spectrum deployments including upper band channels. One device even exhibited problems with 1 dB of interference. This is an unacceptable degradation in performance.

3.3.9.1.6 WAAS TTFF Testing

The test procedure for WAAS TTFF testing is described in section IV.E.1 of Appendix G.1. A WAAS TTFF is defined as the amount of time that a GPS receiver took to achieve a differential fix after receiving a commanded Cold Start. It is important to note that the receivers were commanded to Cold Start at the 10th second of a GPS minute. Further, a WAAS TTFF was measured three times at the baseline and each interference level (1, 3, 6, and 10 dB) to account for some statistical variation in the results. Please note that the 20 dB tests were not run as no device tested survived more than 6 dB of interference.

It is also important to note that the satellite signal power being simulated for these tests was -128.5 dBm[33]. This is considered a very strong signal, and common factors that greatly attenuate the signal, such as heavy foliage and buildings, were not simulated. In other words, this scenario represents optimum signal conditions. The WAAS signal power being simulated was also -128.5 dBm.

The full results are tabulated on page 32 of Appendix G.2. An analysis of these results follows:

A total of 5 devices were tested (not all devices supported this test as their communications interface was not capable of issuing a Cold Start command).

[33] See *GPS Standard Positioning Service Performance Standard*, 4th Ed., 2008, pg. 7, paragraph 2.2.1.

A degradation of performance was noted whenever the baseline TTFF increased by 60 seconds (on a trial by trial basis).

WAAS TTFF Analysis		
Interference Level	**Harmful Interference Observed**	**No Fix Within Five Minutes One or More Trials**
1 dB	1/5	1/5
3 dB	3/5	2/5
6 dB	5/5	5/5
10 dB	5/5	5/5

Table 3.3.4

It is important to note that substantial increases in TTFF were observed for interference levels greater than 1 dB. One device even exhibited problems with 1 dB of interference. This is an unacceptable degradation in performance.

3.3.9.1.7 Pre-Recorded Dynamic Testing

Live GPS satellite data from the representative operational scenarios was recorded using a high bandwidth data recorder (Spirent GSS 6400). This data was played back in the laboratory and various levels of LightSquared jamming were introduced. The positional plots are tabulated in the test results of Appendix G.2. Several notable examples of positional errors and harmful interference are discussed below.

In each of the examples discussed below, the Key Performance Indicators from the dynamic testing clearly show harmful interference. Despite LightSquared's claims that the Key Performance Indicators contradict Figure 3.3.7, these Key Performance Indicators actually substantiate the assertion that 1 dB of degradation in C/N_0 constitutes harmful interference. Each of the figures below demonstrate that LightSquared interference that causes more than 1 dB of degradation in C/N_0 results in an unacceptable compromise to positional accuracy and safety of life features.

3.3.9.1.8 Urban Canyon Dynamic

The urban canyon use case represents a very challenging environment for GPS. Signals are blocked by tall buildings. Some signals reach the GPS receiver via reflection paths and are severely attenuated in power when they reach the receiver. The urban canyon use case is a difficult environment for GPS to operate, and one that

requires the full capability of the system. Any degradation of the GPS system due to LightSquared interference will represent an unacceptable reduction in performance to the system.

The test procedure for urban canyon dynamic testing is described in section V.B.1 of Appendix G.1. The test results are plotted in Appendix G.2. Reviewing those results, it is evident that the positional accuracy significantly degrades when jammed by the LightSquared signal. Two devices are studied in more detail below.

Device G17641: The track with 3 dB of LightSquared jamming is discussed here. G17641, a general navigation device, demonstrated some significant offsets on parts of the plot. Figure 3.3.9 illustrates one instance where the track exhibited an offset of 46 meters at time 1:57:32. The baseline track properly follows the path around the corner, yet the track with 3 dB of interference does not make the corner. In another instance, at time 2:12:04, the track of 3dB interference is offset from the baseline track by 69 meters. The baseline track is properly tracking a straight segment of the path at this time, but the 3dB interference track is offset by 69 meters.

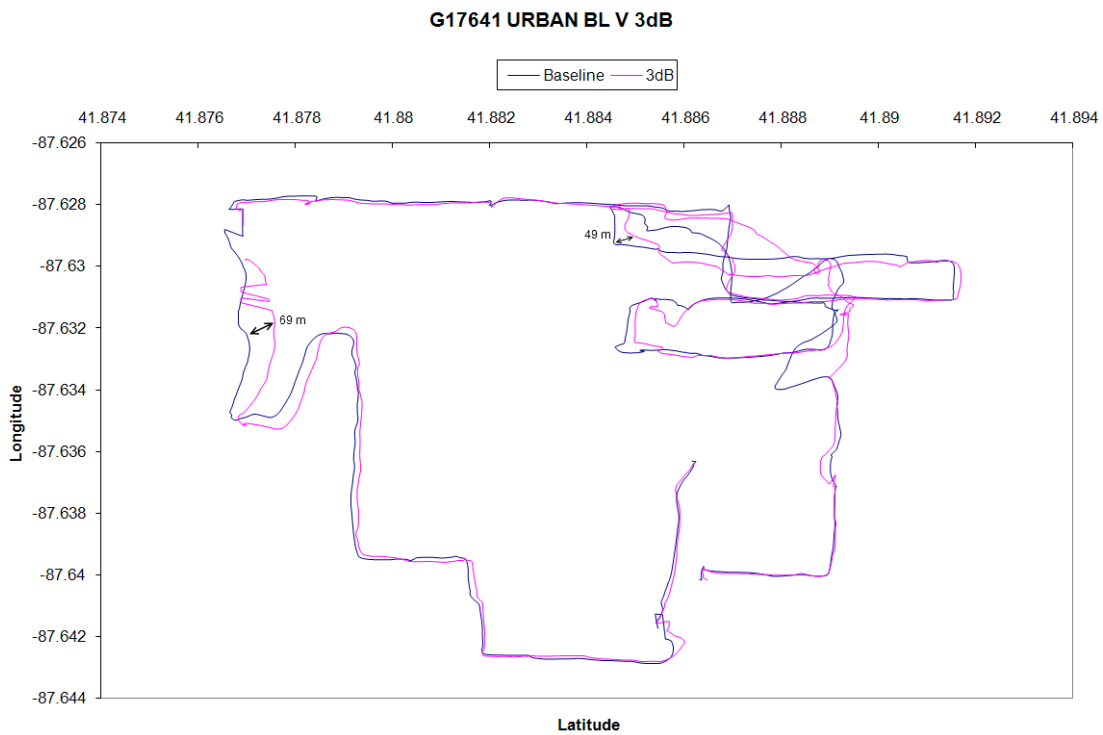


Figure 3.3.9

Device P14730: As noted in Figure 3.3.10 below, the positioning of P14730, a public safety device, completely falls apart in portions of the track log with 6 dB of jamming. The offsets are very large. At time 8:55:41, the offset between the baseline and the 6dB track is 315 meters. At time 8:58:59, the offset between the baseline and the 6dB track is 329 meters. This is a huge increase in error and completely unacceptable for public safety applications.

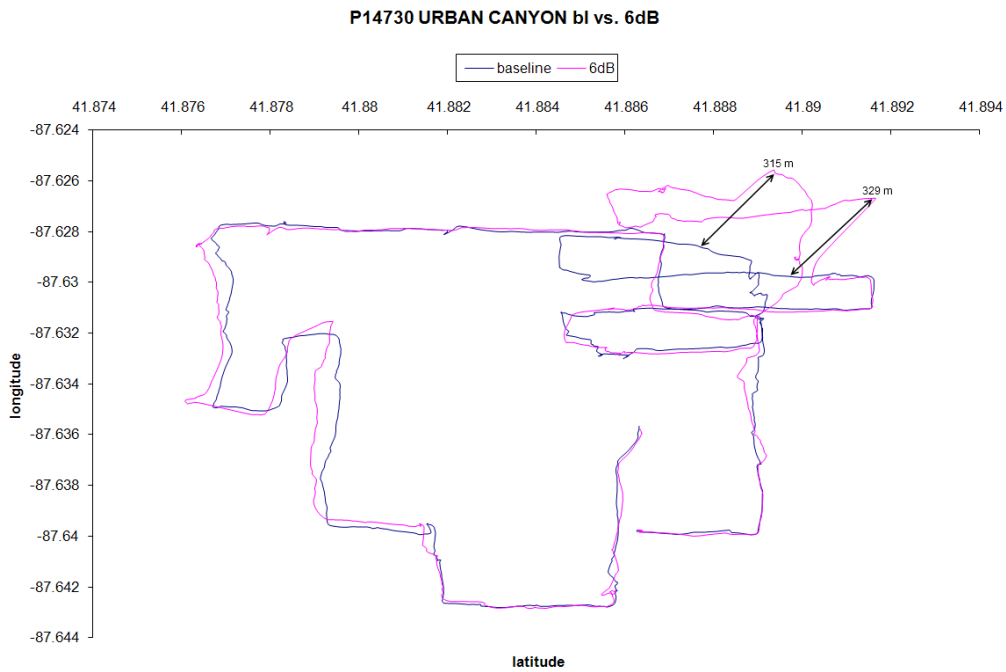


Figure 3.3.10 300+ meters of offset between baseline and 6dB tracks.

3.3.9.1.9 Suburban Dynamic

The suburban dynamic use case is very benign and represents a use case where the GPS system is operating with the most operating margin possible. Even so, examples of degraded performance are evident. The positional plots are tabulated in the test results of Appendix G.2. For example, P18892 shows degraded performance in the 6 dB interference plot.

Figure 3.3.11 is a close-up of the plot of P18892, 6dB of interference, page 64 of Appendix G.2. It shows an offset between the baseline and the 6dB track to be 14 meters at time 10:15:44.

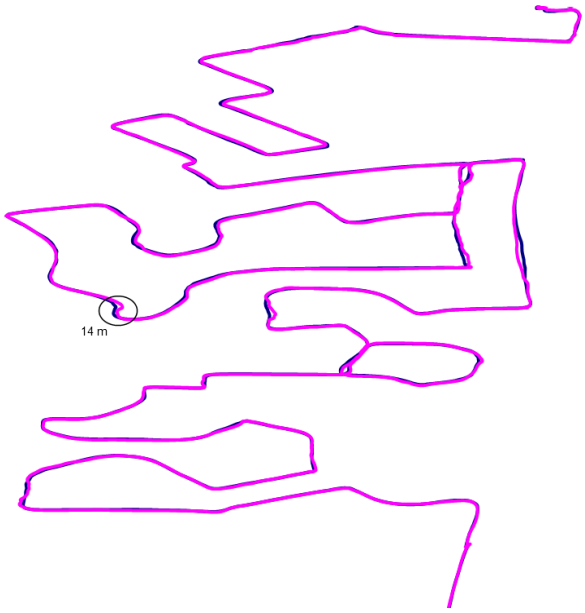


Figure 3.3.11 P18892. 14 meter offset at time 10:15:44, 6 dB of Interference.

Figure 3.3.12 shows even worse degradation of P18892 at 10 dB of jamming. This is a close-up of the 10 dB plot on page 64, Appendix G.2. At time 10:15:42, the difference between the baseline and the 10 dB track is 19 meters. At time 10:11:02, the difference between the baseline and the 10 dB track is 24 meters.

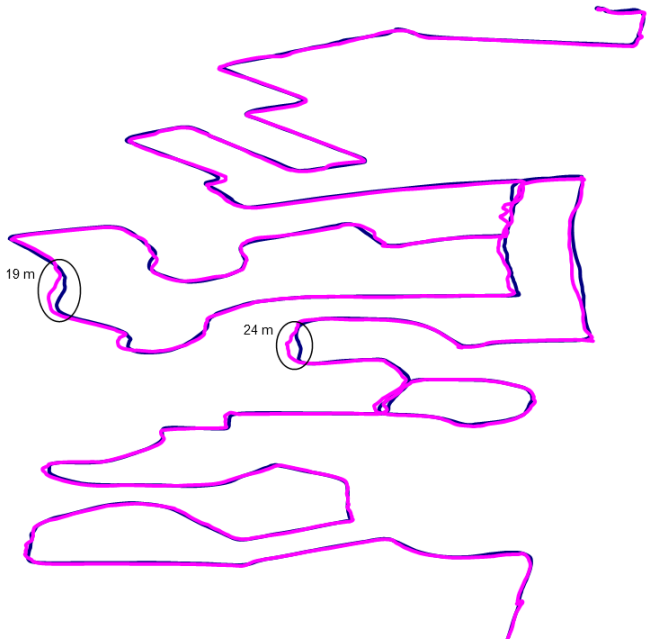


Figure 3.3.12 P18892. 19 and 24 meter offsets, 10 dB of Interference.

3.3.9.1.10 Deep Woods Dynamic

The deep woods use case also represents a challenging environment for GPS. Signals are blocked by terrain and tree foliage. The user's body also may block some signals. Some signals reach the GPS receiver via reflection paths and are severely attenuated in power when they reach the receiver. The deep woods use case is a difficult environment for GPS to operate, and one that requires the full capability of the system. Any degradation of the GPS system due to LightSquared interference will represent an unacceptable reduction in performance to the system

An example of degraded performance at 3dB of signal degradation was exhibited by device G15343. As shown in Figure 3.3.13, offsets of 15 meters and 23 meters were observed at times 11:02:50 and 10:54:50, respectively.

Figure 3.3.13

3.3.9.2 LightSquared Perspective (pages 153 to 166)

Propagation Model. LightSquared disagrees fundamentally with an analysis based solely on free space propagation, because it radically overstates the probability of interference. For example, the GPS Industry's "propagation map" in Figure 3.3.7 is based on the assumption that free space propagation exists throughout the entire Washington, DC metro area, which is clearly incorrect. LightSquared also disagrees with the general approach of presenting the results of overload measurements in units of standoff distance, using the free space equation to translate power (dBm) to distance. Conclusions based on these types of criteria result in the type of graphics depicted in Figure 3.3.7 – which paint an alarming, and highly inaccurate perspective of so-called exclusion zones. Figure 3.3.7 is directly contradicted by the KPI results obtained in the dynamic testing analysis.

The Walfisch Ikegami line of site model more accurately depicts signal propagation variations due to terrain and building clutter. In the Washington, DC market, a WI-LOS model shows that signal strength in excess of -25 dBM would occur in about 1.2% of the coverage area. -25 dBM is an important measurement as it represents the lowest signal strength at which overload interference to General Location/Navigation devices can occur (see *Interference Threshold* section below)

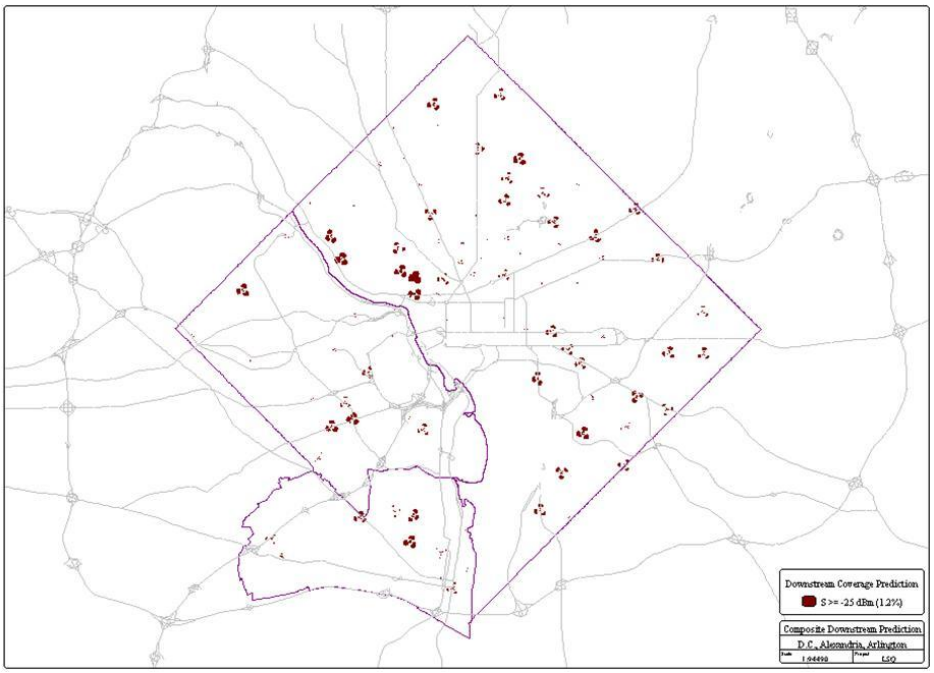


Figure 3.3.14

In order to most accurately predict signal propagation in a real world environment, more sophisticated models, such as the Korowajczuk model, are appropriate. This model, which has been tuned for L-Band propagation in the

Washington, DC area, that signal strength in excess of -25 dBM will occur in about 0.1% of the coverage area of the Washington, DC market.

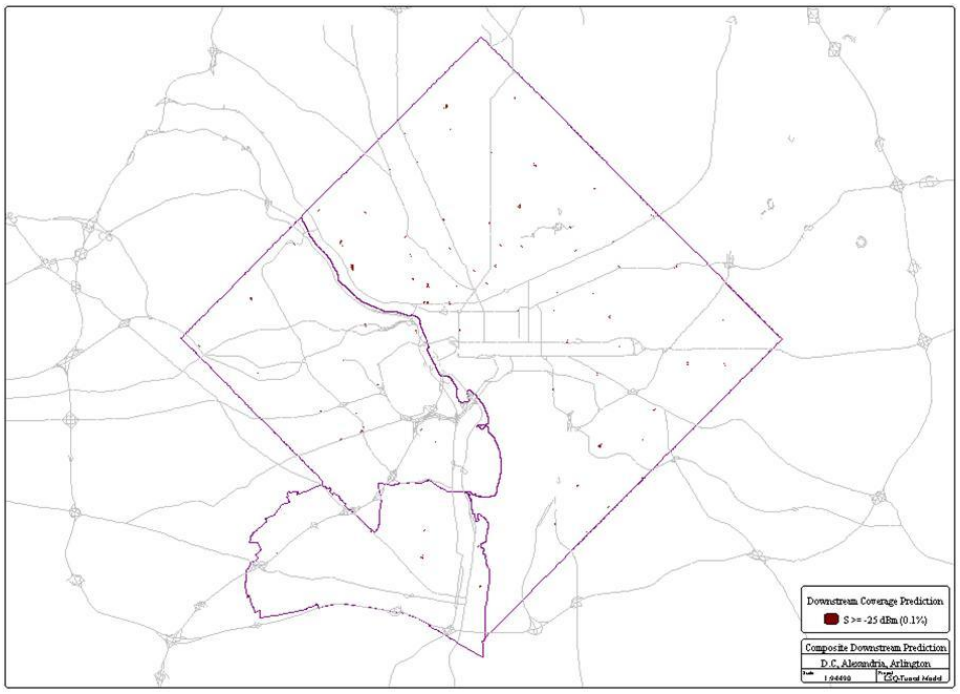


Figure 3.3.15

The examples below demonstrate how recorded signal strengths in the Las Vegas market test varied between levels predicted by the free space line-of-sight model and the WI-LOS model.

Dense Urban

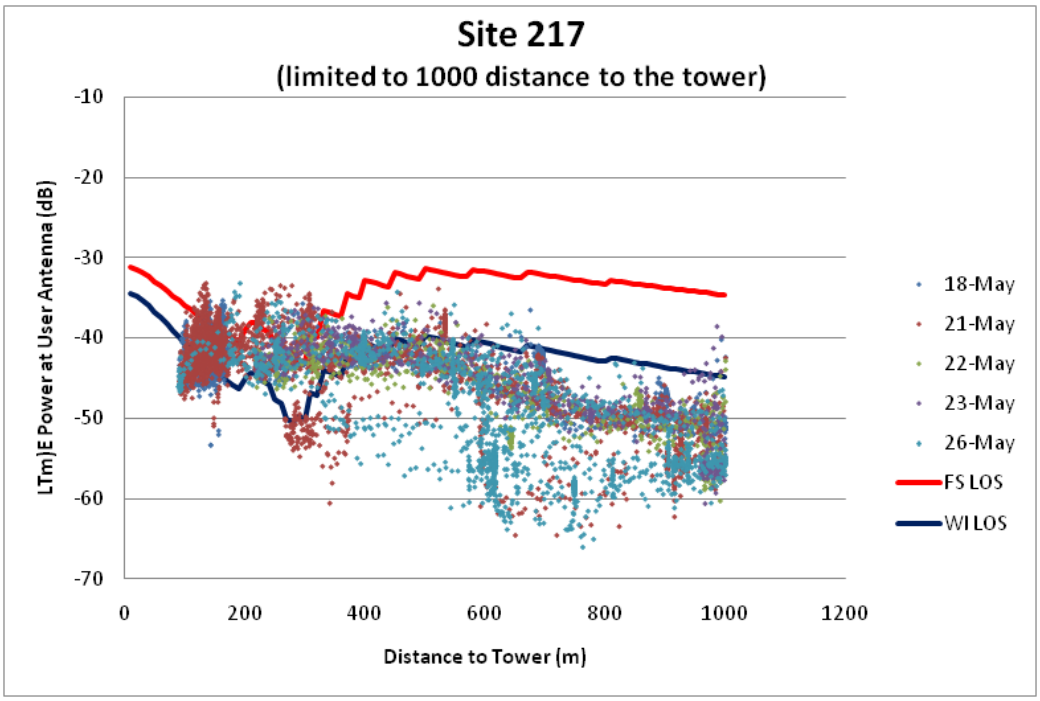


Figure 3.3.16

Suburban

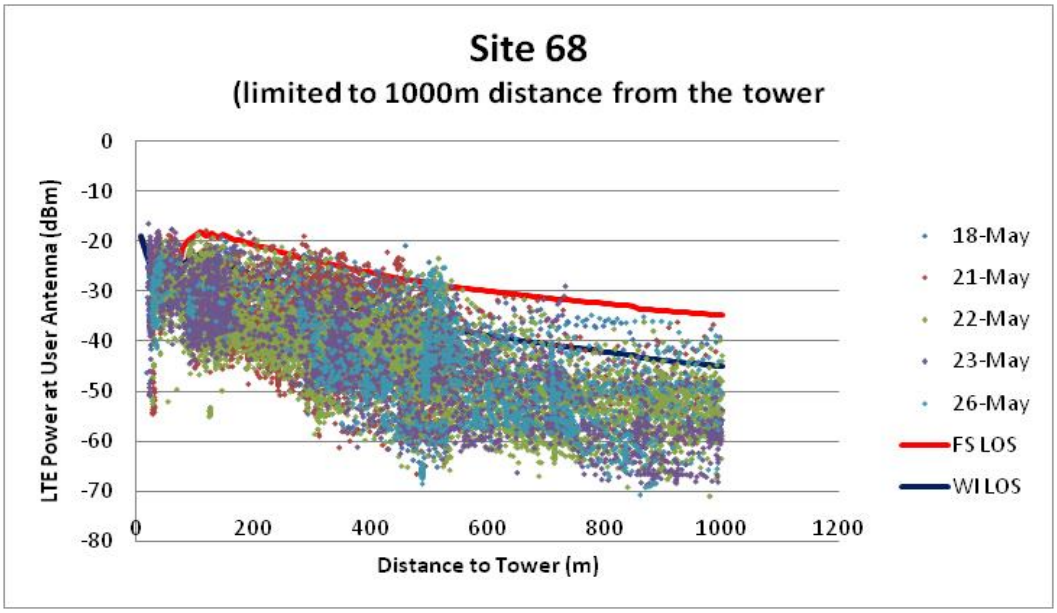


Figure 3.3.17

Rural

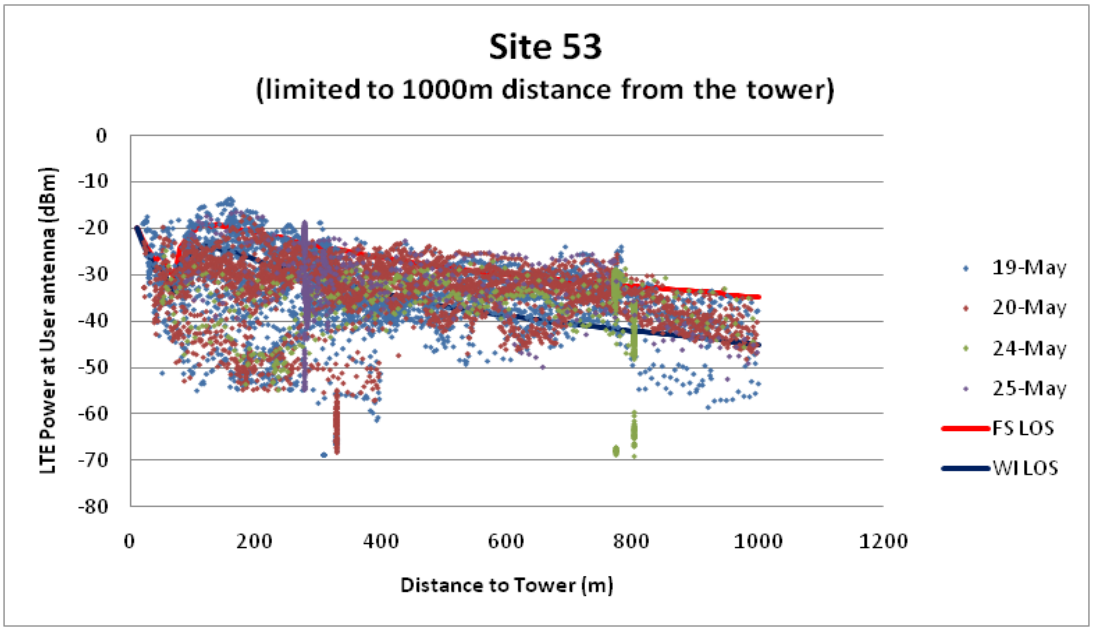


Figure 3.3.18

Urban

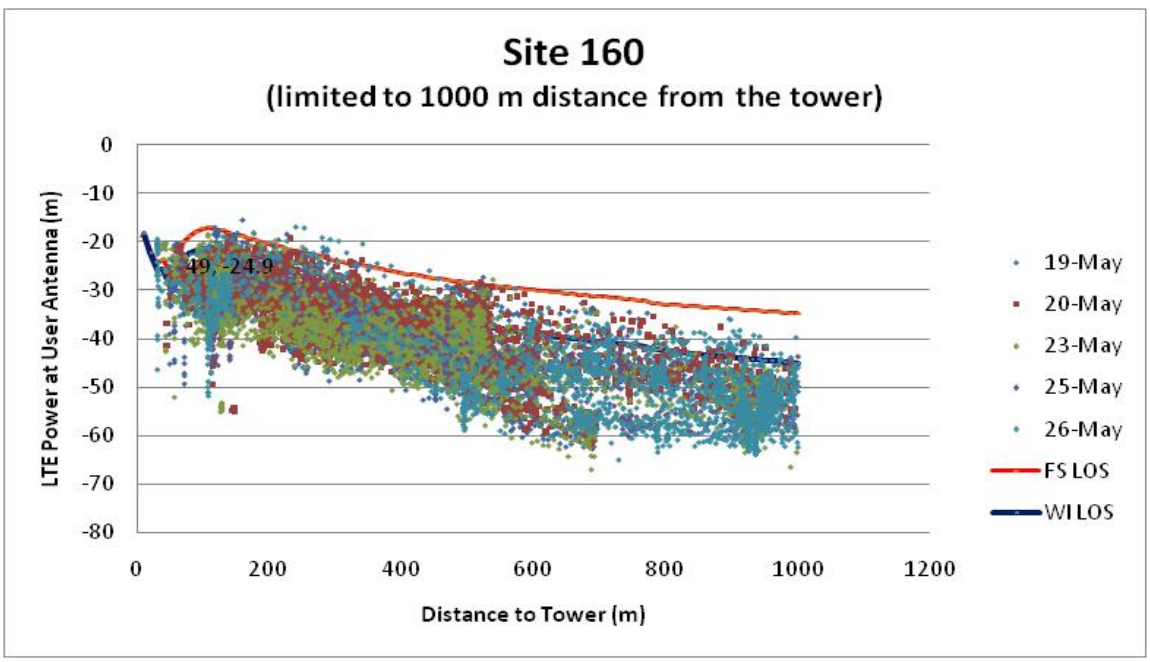


Figure 3.3.19

Interference threshold. Based on the above, LightSquared supports a definition of harmful interference that acknowledges the possibility of interference in at signal strengths in excess -25 dBm, which reliable propagation models indicate is likely in 0.1% to 1.2% of the coverage area. LightSquared objects strongly to the use of 1 dB C/No as the interference threshold. The manufacturers present no hard evidence to support their theory that the user experiences any reduced

accuracy at that level of interference. The dynamic test data they present demonstrates very little if any difference in accuracy between 1 dB and 6 dB. This is a critical element as the static tests did not attempt to examine the user impact.

For example, the dynamic test results for the Urban Canyons shows that the position reports are often already so degraded that effect of the LightSquared signal will not be evident to the user. The following figures are for Dense Urban environments in downtown Chicago, showing the results for three cases: no interference, 3 dB, and 6 dB. (Figure 3.3.20 – Figure 3.3.23. Predicted position fixes with SV signals recorded in downtown Chicago (with and without LightSquared signals)

Aquamarine = Base Line (with no LightSquared signal), blue = 3 dB C/No and red = 6 dB C/No)

Moreover, the suburban results show that there is sufficient margin in the GPS signal link that the presence of the LightSquared base stations signal, at a level that corresponds to 6 dB C/N_0 degradation in the static tests, caused no user perceptible degradation.

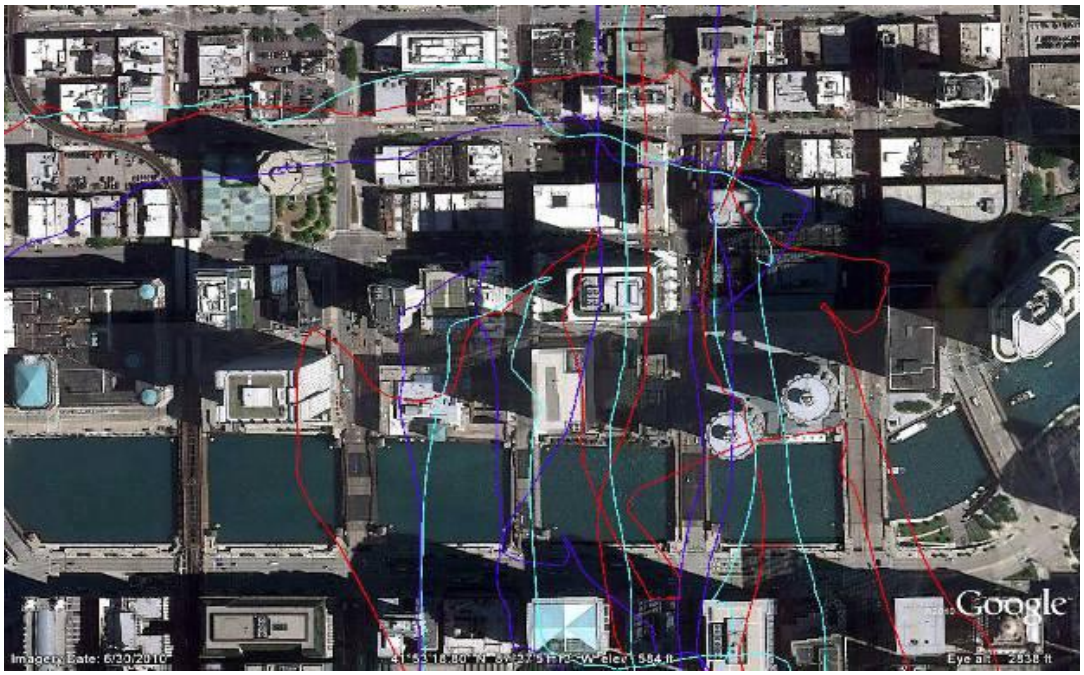


Figure 3.3.20

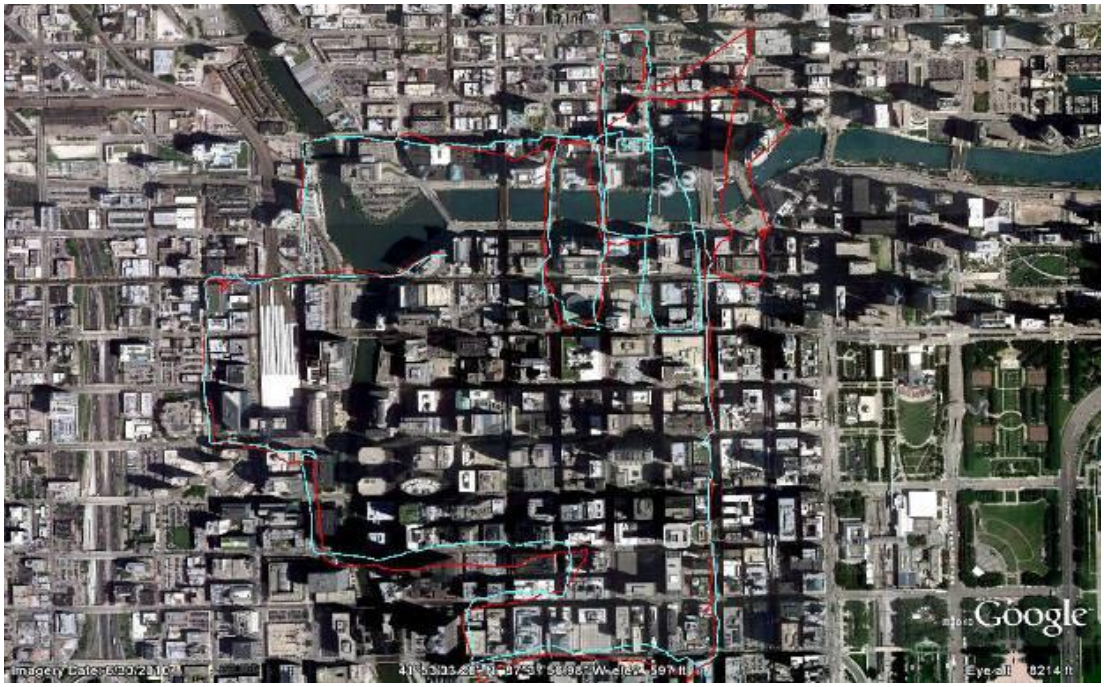


Figure 3.3.21

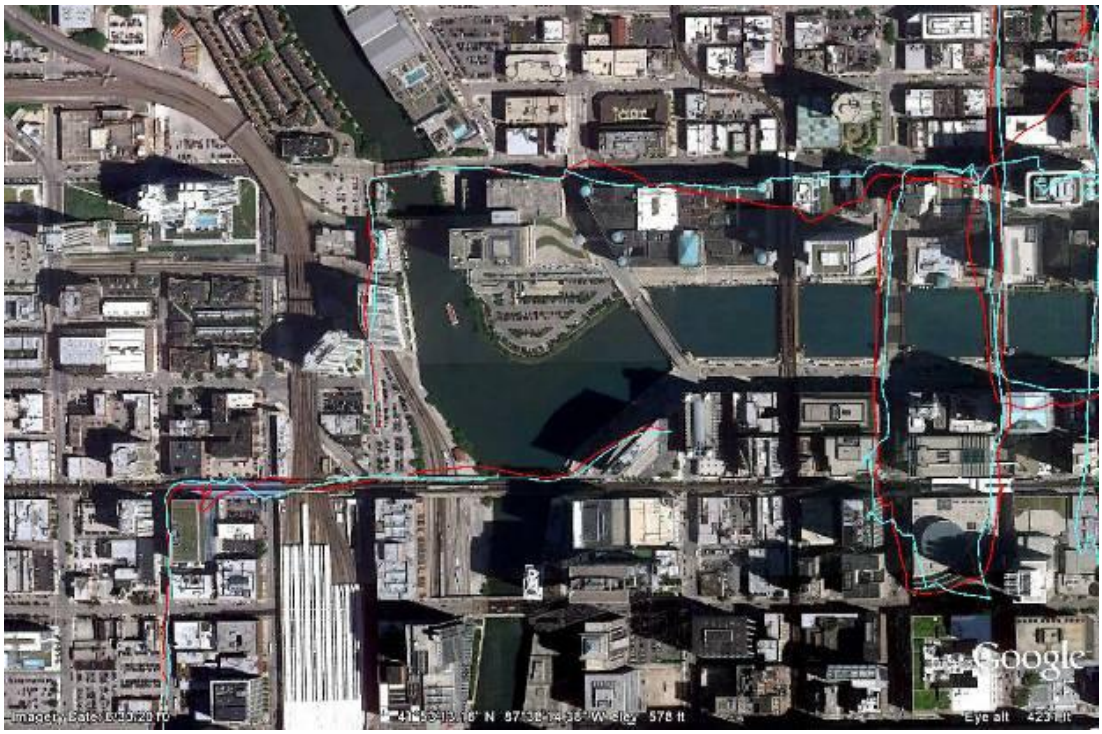


Figure 3.3.22

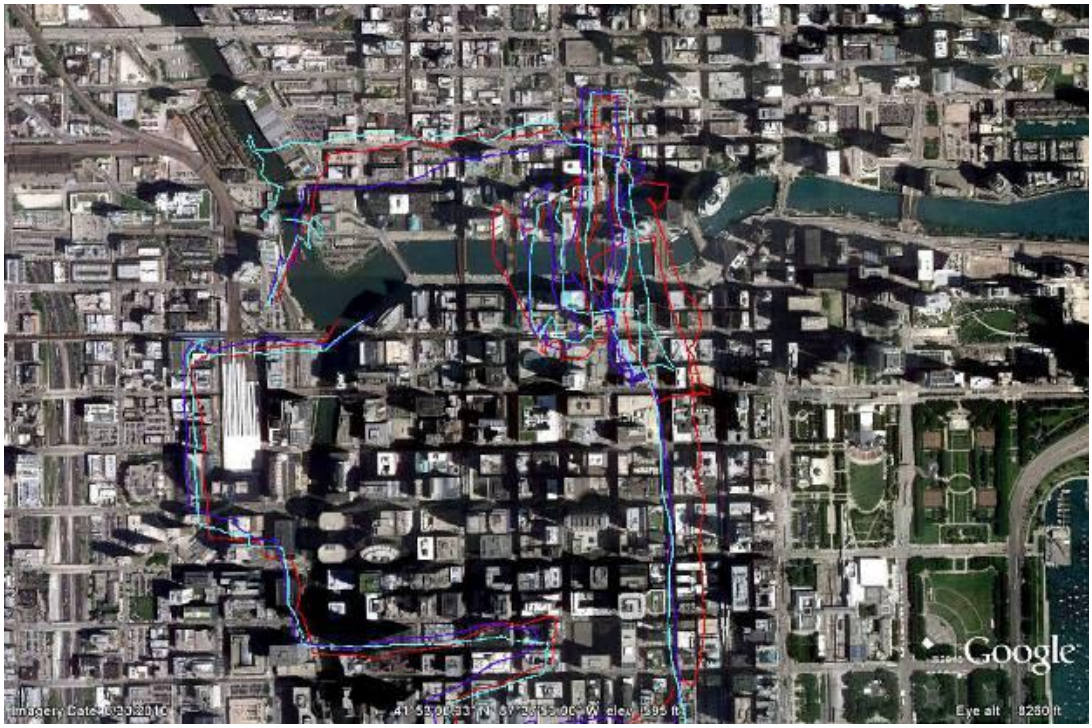


Figure 3.3.23

The same results obtain in Suburban environments.

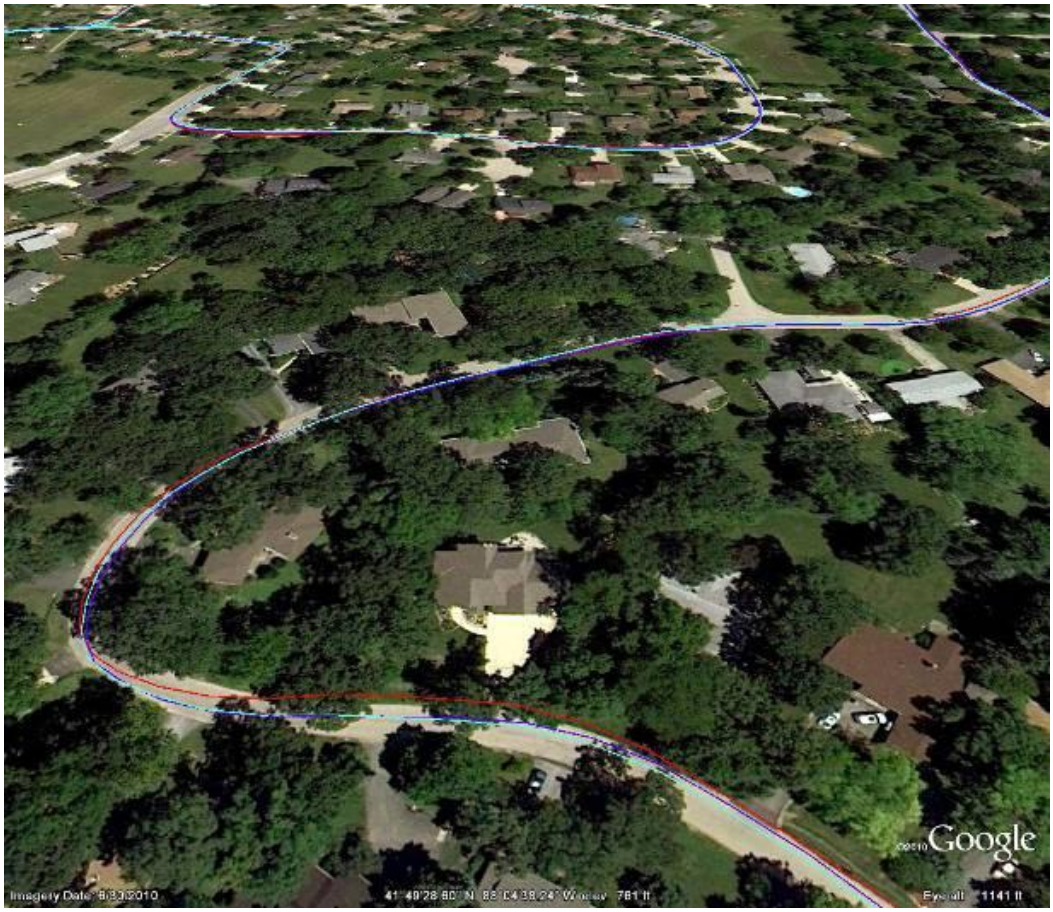


Figure 3.3.24

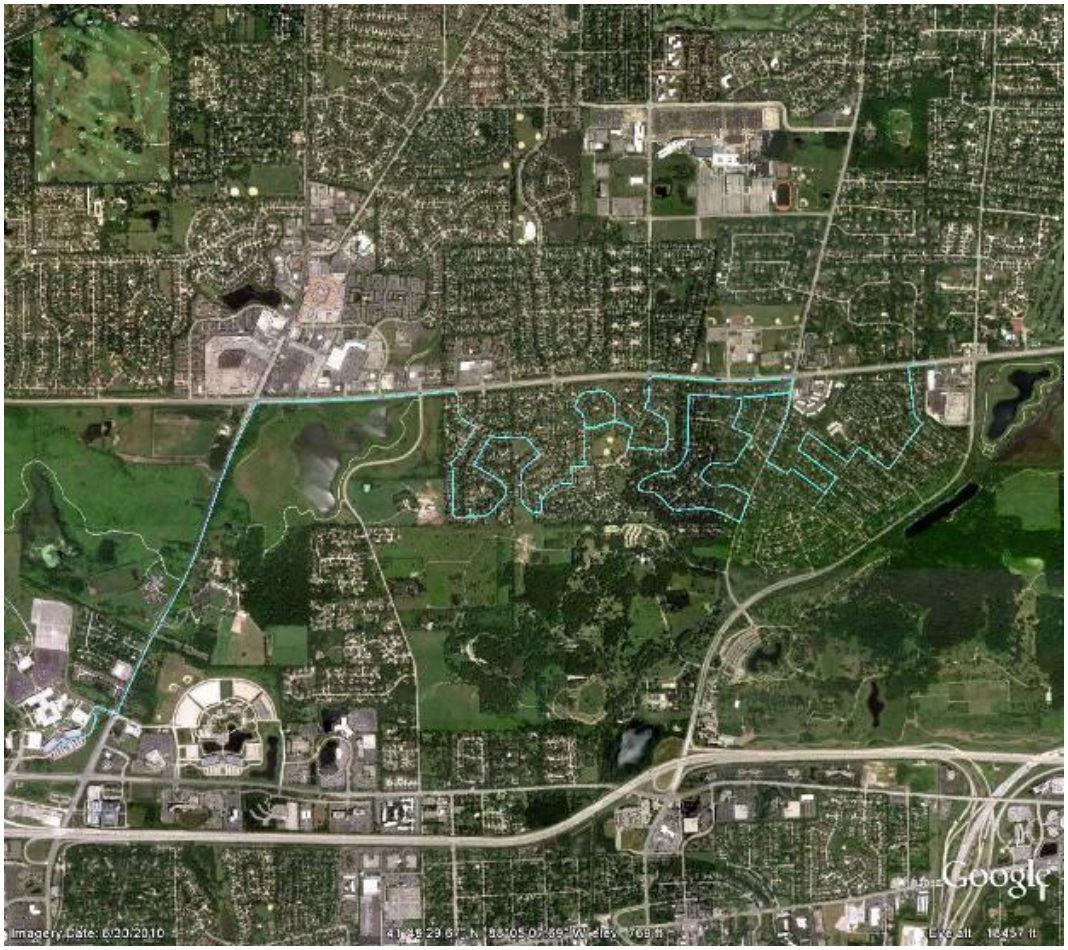


Figure 3.3.25

Google
Imagery Date: 6/30/2010
41°49'41.15" N 88°04'51.88" W elev 769 ft
Eye alt 1243 ft

Figure 3.3.26

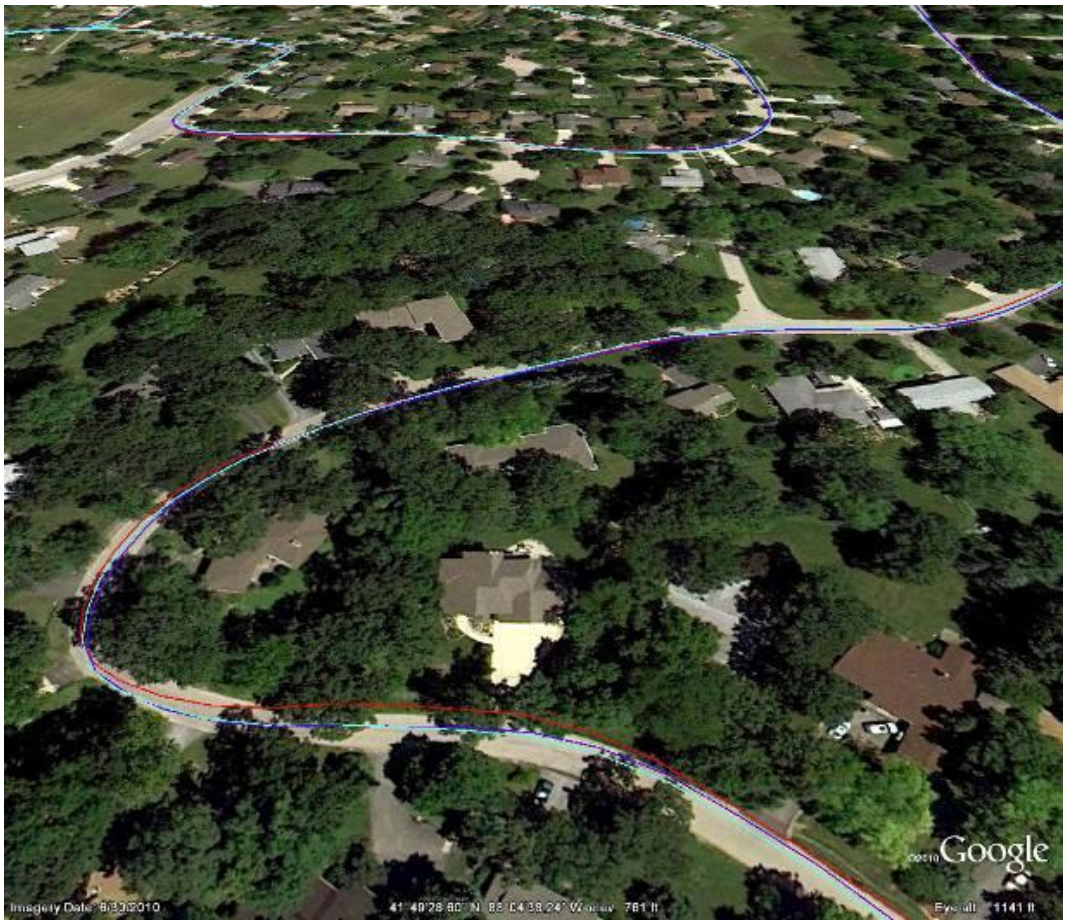


Figure 3.3.27

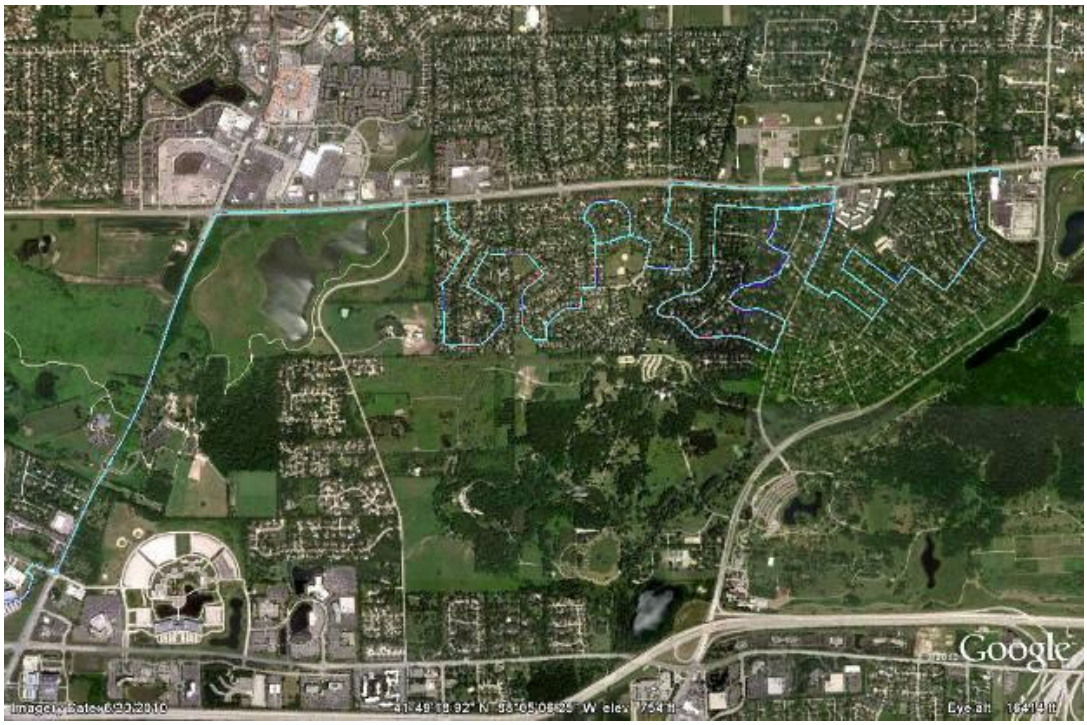


Figure 3.3.28

Figure 3.3.29

Data Analysis. The following table summarizes the results of the static interference susceptibility tests in the presence of both the upper and lower 10 MHz channels.

	Phase 2						
	TEST:	Static InterferenceSuceptibility, downlink 1531.0 & 1550.2 (10 MHz BW)					
	Power at Device (dBm) vs C/N degradation						
	Device	1 dB	3 dB	6 dB	10 dB	20 dB	LOF
1	G11207	*-58.9*	*-55.6*	*-52.0*	lof	lof	*-49.7*
2	G14298	*-57.5*	*-49.5*	*-43.5*	-40.5	lof	-33.9
3	G12586	*-53.9*	*-50.9*	*-47.9*	*-43.9*	-34.8	-29.9
4	G17641	*-51.0*	*-47.6*	*-43.9*	-34.7	lof	-32.3
5	G15343	*-50.5*	*-47.7*	*-45.1*	-41.6	-30.7	-16.7
6	G17783	*-49.9*	*-45.9*	*-41.9*	-39.1	-30.9	-20.9
7	G13445	*-47.7*	*-42.7*	-36.5	-32.6	lof	-26.7
8	P14949	*-47.6*	*-44.0*	-42.0	-39.0	-32.0	-28.0
9	G12867	*-47.0*	-39.6	-34.1	-28.5	-20.1	-16.8
10	G18161	-46.9	-43.9	-42.0	-38.0	-30.0	-27.0
11	G17169	-41.8	-35.8	-32.4	-29.0	-21.7	-14.7
12	P14730	-39.3	-34.2	-30.9	-27.9	-20.6	-12.0
13	G16382	-37.0	-34.0	-31.0	-29.0	lof	-25.0
14	P15427	-36.0	-32.0	-26.0	-22.0	lof	-16.0
15	G14188	-33.8	-31.2	-28.1	-24.0	-17.9	-15.8
16	G15028	-32.9	-30.0	-28.0	-25.1	lof	-16.1
17	G10195	-29.6	-26.3	-24.0	-20.6	lof	-13.6
18	G18062	-29.6	-23.3	-18.4	-14.4	-7.1	-2.0
19	G18696	-29.5	-23.0	-17.4	-13.9	-7.7	-5.4
20	G10968	-28.7	-26.8	-24.9	-23.0	lof	-20.0
21	P18892	-28.0	-23.0	-21.0	-18.0	***MPNE***	
22	G16449	-27.1	-20.6	-16.1	-13.4	-5.7	-2.7
23	G14666	-27.0	-25.7	-21.6	-18.3	-9.3	-2.7
24	G16534	-27.0	-24.0	-22.0	-20.0	-16.0	-14.0
25	P17655	-23.3	-20.3	-17.9	-14.9	lof	-9.6
26	G10607	-22.6	-19.6	-17.5	-14.5	-8.5	-3.0
27	G12559	-21.8	-18.8	-15.8	-13.3	-8.4	***MPNE***
28	G15448	-15.9	-12.9	-10.9	-8.9	-5.0	-4.0
29	P13275	-12.0	-8.0	-5.0	***MPNE***		
		italics	below power meter range; estimated from amplifier gain				
		lof	loss of fix				
		MPNE	Maximum Power reached with No Effect				

Table 3.3.5

The data shows that 16 devices experienced less than -25 dBm at 6 dB C/N_0.

The following table summarizes the results of the static interference susceptibility tests in the presence of the Lower 10 MHz channel alone.

	Phase 0b						
	TEST:	Static InterferenceSuceptibility, downlink 1531.0 (10 MHz BW)					
	Power at Device (dBm) vs C/N degradation						
	Device	1 dB	3 dB	6 dB	10 dB	20 dB	LOF
1	P14949	-33.0	-26.0	-21.0	-15.0	-8.0	-3.0
2	G15343	-32.0	-27.7	-24.3	-20.1	-9.4	-2.0
3	G14298	-29.5	-22.5	-17.5	-14.6	-8.6	-6.6
4	G18161	-23.6	-20.6	-18.2	-15.9	-9.3	-5.5
5	G15028	-23.5	-19.7	-14.5	-10.5	lof	-5.2
6	G16382	-22.0	-13.0	-9.0	-8.0	lof	-5.0
7	G12586	-19.7	-15.6	-12.7	-8.8	-3.5	*MPNE*
8	G17641	-13.7	-9.7	-8.7	-4.6	*MPNE*	
9	G12867	-13.3	-9.4	-6.5	-3.0	*MPNE*	
10	G10195	-9.6	-6.4	4.0	*MPNE*		
11	G12559	-9.5	-3.8	*MPNE*			
12	P15427	-8.0	-5.0	-3.0	*MPNE*		
13	G10968	-7.5	*MPNE*				
14	G18062	-7.3	*MPNE*				
15	G15448	-5.2	*MPNE*				
16	G13445	-5.1	*MPNE*				
17	G16534	-4.0	*MPNE*				
18	G17169	-3.5	*MPNE*				
19	G11207	-3.4	*MPNE*				
20	P17655	-2.0	*MPNE*				
21	G10607	*MPNE*					
22	G14188	*MPNE*					
23	G14666	*MPNE*					
24	G16449	*MPNE*					
25	G17783	*MPNE*					
26	G18696	*MPNE*					
27	P13275	*MPNE*					
28	P14730	*MPNE*					
29	P18892	*MPNE*					
		MPNE	Maximum Power reached with No Effect (> 0 dBm)				

Table 3.3.6

The data shows that all 29 devices experienced less than -25 dBm at 6 dB C/N_0.

LightSquared also disagrees with the characterization of potential interference from LightSquared user devices. This is in part because the analysis incorrectly uses 1 dB C/N_0 as the measure of harmful interference. In addition, the analysis ignores the fact that, because of return link power control, wireless handsets typically will transmit at low very power to minimize intra-network interference and conserve battery life.

On the subject of the impact to TTFF (warm or cold), LightSquared notes that the GPS receivers already operate in an environment of dynamically changing C/N_0 much greater than 6 dB (in urban canyons, the C/N_0 could be 15 dB below clear sky conditions). Therefore, a 6 dB C/N_0 variation, a small percent of time, should not be an operationally significant effect.

3.3.10 Work Plan Item 10: Assess Operational Scenarios Using Analytics and Test Results

3.3.10.1 GPS Industry Perspective (pages 167 to 174)

An advisor to the sub-team wrote the following.

We are a consumer electronics company and customers have come to expect a certain (good) quality from us. We invest a lot in optimizing our systems to ensure that we incrementally improve our products even though this may only be by a fraction of a dB in sensitivity or a second in TTFF. The point is that our users would not accept degraded product performance due to a new (unrelated) technology being deployed. Please also bear in mind that there is no mitigation, device-side, for devices already deployed in the field.

This section describes various operational scenarios in light of lab test results and explains why they matter. (For reference the distance from a LightSquared transmit tower at which a General Location/Navigation device experiences harmful interference is 1.1 km.[34])

3.3.10.1.1 Suburban

The suburban operational scenario is perhaps the most benign of all the use cases that were considered. This scenario was recorded near Chicago as the trees were just growing leaves, so there was very little signal attenuation due to foliage. The signals recorded experienced frequent changes of direction, obscuration of signals by the roof of the car, signal attenuation through windshield, and mild dynamics. Many of the devices tested will experience suburban operational scenarios.

3.3.10.1.2 Urban Canyon

The urban operational scenario is one of the most difficult of all the use cases that were considered. This scenario was recorded in downtown Chicago, which is an industry-standard test environment for the urban canyon. Devices in this environment experience frequent changes of direction, obscuration of signals by the roof of the car, blockage of satellites in view by tall buildings, signal attenuation through windshield, mild dynamics. Receivers in this scenario need the ability to lock on to the correct road and navigate turns successfully. Likewise, they need to distinguish between adjacent roads and ramps.

The operational scenarios that follow are organized by device category. These scenarios apply both to suburban and urban environments, as described above.

[34] Based on a Phase 1 deployment scenario, using the median of all General Location/Navigation devices tested.

3.3.10.1.3 PNDs and Automotive In-Dash

GPS users make use of automotive navigation for a variety of reasons, both in suburban and urban environments. Many users rely on these devices for their daily commute, while others use them to navigate in unfamiliar areas. One unique feature that many automotive GPS receivers offer is the ability to locate a hospital or police station very quickly.

Recently, a Garmin PND user submitted an account of an incident in which he experienced a heart attack while on vacation and had to rely on his GPS device to find the nearest hospital as quickly as possible. The doctors were surprised that he lived through the ordeal and later informed him that were he to have arrived at the hospital just a few minutes later, he would have died.

Another Garmin PND user submitted an account of an incident where his 9-month old great-grandchild had an extreme allergic reaction to eggs on a road trip near Glendale, California. The child's mother used the GPS to quickly find and navigate to the nearest hospital. Within five minutes of exiting the freeway, the family arrived at the hospital. With the guidance of the GPS, the child arrived at the hospital in time and received treatment that saved her life.

Yet another Garmin user submitted this story of how her GPS helped find a hospital in Minneapolis, MN. As the user and her husband ordered lunch, her husband started feeling ill. He handed her the keys and told her to take him to the hospital. Being in an unfamiliar city, the wife grabbed the PND and used the Nearest Hospital feature to find and navigate to the nearest hospital. As her husband was suffering a heart attack, she followed the route to the hospital. The husband was rushed into emergency heart surgery, and his life was saved.

Users like these rely on flawless navigation and rapid TTFF. For some, it is literally a matter of life and death. The scenarios above depict situations where the user is responsible for operating the GPS receiver; however, in some cases a user may become incapacitated from an automobile accident and require remote assistance. It should be noted that telematic safety systems use GPS data for position information when reporting these life-threatening situations (such as crash detection or air bag deployment). Should an incident occur within the denial of service zone of a LightSquared transmitter, the emergency operator would not be able to direct emergency personnel to the precise location in order to render aid quickly.

In addition to safety of life scenarios, many users rely on flawless and uninterrupted GPS performance as part of their daily life. These users' daily commutes and routes take them through challenging

environments where even small reductions in GPS C/N_0 ratio can cause significant performance degradations. One advisor to the sub-team noted the following:

It is very difficult to navigate in regions surrounded by large areas of standing water, such as roads adjacent to and between rivers or canals. Multipath reflections in these areas are much more challenging than other suburban areas, and can even approximate the urban canyon. Even small reductions in C/N_0 can exacerbate this already difficult situation and degrade GPS performance.

Another observed the following:

Interference and degradation of TTFF is a scenario that is unacceptable in many consumer situations. This is particularly true when users turn on their navigation device from a cold start and drive immediately. The acquisition time is challenged by the directional changes, and the degradation of C/N_0 in this situation can lead to much extended time to first fix. The data in Section 3.3.9 shows, even in non-challenging situations, that a 1 dB degradation can increase acquisition times. Furthermore, when navigation devices are used by emergency services, as they sometimes are, in situations that require immediate use, the TTFF can be of particular importance and concern.

As the data in Section 3.3.9 shows, some General Location/Navigation devices show a dramatic increase in TTFF at distances up to several kilometers from a LightSquared transmit tower. Other devices are simply unable to acquire any type of fix at all. The implications of such interference are severe. Consider the following:

In urban canyons where we have a somewhat restricted line of sight to satellites, we already have a compromised situation compared to open sky. A degradation of even 1 dB will both affect C/N_0 directly and increase our reliance on map matching technology. The effect is very dependent on the precise situation but could be that users see more jumping between closely adjacent roads. So the road topology at any certain point will lead to different behaviors. Although the device's ability to snap to the best fit road is based on a number of factors including, primarily, the GPS signal itself but also heading and route, any GPS degradation in challenging areas around road bifurcations (where the road may split in 2 or more directions) render a user momentarily confused at a decision making junction. This is unacceptable.

Some have questioned the validity of a harmful interference criterion which cites 1 dB as the maximum permissible degradation to C/N_0, yet it is operational scenarios like these that demonstrate the

necessity of such a criterion. The plot in Figure 3.3.7 demonstrates this very clearly.

3.3.10.1.4 Fleet Management Devices

Vehicle fleets across the United States use GPS to plan and navigate the most fuel-efficient routes that reduce operator costs and environmental impact, to guide drivers safely in unfamiliar areas, and to improve safety through driver monitoring. Operators report saving as much as 30 percent in fuel consumption, and a typical US operator reported fuel savings of more than one million gallons in its fleet of 5,000 vehicles. GPS fleet management can also reduce wastage in the transport of perishable items, such as in ready-mix concrete delivery. The useful life of a load of ready-mix concrete is a few hours; it is a product more perishable than fresh food. The consequences of delivery delay are both economic, lost value of the concrete and labor, and environmental, because the load must be discarded rather than used.

Onboard GPS systems can be integrated with vehicle diagnostic systems and communications networks, providing information on the location and status of a vehicle to supervisors and dispatch teams. These GPS systems reduce fuel consumption due to idling. These systems also enable early warnings regarding maintenance issues to be identified, reported, and resolved prior to the development of serious problems. Integrated L-Band MSS-GPS equipment enables long-haul trucks to determine and report positions via satellite communications in routine situations and in distress, emergency, or hi-jack situations.

3.3.10.1.5 Emergency Vehicles

General Location/Navigation devices are used in emergency response vehicles and vessels to navigate the way to incidents. They also serve as a critical data input for Automatic Vehicle Location and Computer Aided Dispatch systems, which are used extensively for public-safety fleets across the United States. Such systems enable first responders to access and view Geographic Information Systems (GIS) mapping databases in real time and to determine the location of fire hydrants, hazardous objects such as chemical tanks, or the GPS/e-911 reported location of cell phone caller(s). In large open areas, such as public parks where it is difficult to provide the responder with a precise address, response times can be significantly reduced. Many public safety organizations report 15% or better improvements in response times because of GPS use and report that these reduced response times can save lives. GPS in vehicles also sends position information back to dispatchers in both routine reporting and distress or ‘panic button’ situations. GPS is used in emergency response vessels to navigate to other vessels in distress

and is also used in general aviation aircraft used by police, fire fighters, and air ambulances. These often operate close to the ground away from airports or other protected areas in order to fight or monitor wildfires; they also frequently need to land in the area of a major accident or other incident.

3.3.10.1.6 First Responders

One advisor to the sub-team writes the following.

It has been shown that strong RF emissions located in frequencies near the GPS allocation of 1575.42 MHz can impact the availability, acquisition, and accuracy of GPS services. While such interruptions may affect multiple services, Public Safety and associated supporting services have unique needs that are critical to the public welfare.

GPS is utilized within the Public Safety services for first responders in a number of ways. Primarily, GPS is used to determine the location of police officers via embedded GPS systems in portable "Handie-Talkie" radios, and then that location is automatically reported to a dispatch center allowing the following:

- Rapid response to an officer in need, "man down" signaling, which can be critical to the health and safety of an officer, including ultimately saving an officer's life;
- Efficient and rapid dispatch of the closest officer to a situation; and
- Tracking of officers' movements and timing for introduction as evidentiary information.

Disruption of GPS service affects each of the above-listed use-cases in unique ways. A considerable investment of public funds has been made at the Federal, State, and Local levels to build out communications networks for the safety of our law enforcement, fire response, and numerous public works agencies leading to the ultimate protection of human life of the civilian population as well as the responding officers and officials.

In addition to utilizing professional GPS receivers, many first responders carry consumer devices as a backup, or sometimes primary, means of navigation. One user recounted visiting Haiti after the devastating earthquake. This user traveled to the island to offer medical assistance by surveying the devastated city and recording the exact locations of wounded people using a Rino device. When sorting through the rubble, positional accuracy matters. Inaccuracies of more than a few meters would likely mean death for those desperately waiting to be rescued.

Another first responder submitted a story explaining how Marion County, Oregon Search and Rescue uses GPS to deploy teams to the search grids. "GPS enables us to get higher confidence of covering an area and finding our subject while keeping the searchers safe. GPS also provides a standard to communicate position when our search subject is found and emergency air evacuation is critical to our subject's survival. Without an accurate location source, errors from map and compass on the ground, and navigation in the air would severely diminish our ability to command a life-flight air ambulance directly to our location."

Everyone depends on first responders in times of crisis—and they depend on GPS. Any denial of GPS service to these public servants is a disservice to everyone.

3.3.10.1.7 Tracking Devices

Tracking devices are used to track individuals for various reasons:

3.3.10.1.8 Criminals and Terrorist Suspects

GPS is an important tool in monitoring and tracking the location of criminals and terrorist suspects. Courts frequently order that individuals subject to restraining orders, such as restrictions on proximity to schools, be monitored and tracked to ensure that they do not violate the terms of the judicial decrees. Were GPS to degrade or service be denied, law enforcement officials would have no way to prevent these individuals from violating the restraining orders.

Nationwide, there are over 30,000 offenders monitored with GPS equipment. One company that is an advisor to the General Location/Navigation sub-team monitors over 10,000 individuals via GPS tracking products. These individuals include sexually violent predators, domestic violence offenders, murder suspects, and a large number of various persons of interest to law enforcement. In addition, this company has a contract with the Department of Homeland Security that requires GPS monitoring and tracking of over 4,000 illegal immigrants who are in the process of being deported; these illegal immigrants include some individuals who are on the federal government's terrorist watch list.

3.3.10.1.9 Children

Parents use GPS tracking units to help learn the whereabouts of their children at all times. Parents can locate and monitor their children in many situations. Examples include a new teen driver or where getting separated from a child is possible, both of which can be very scary and dangerous. GPS tracking devices provide an invaluable aid and peace of mind to parents in these situations. This would not be possible if GPS service was degraded or denied.

3.3.10.1.10 Animals

Many dog owners use GPS-enabled collars to track their dogs while they are hunting. Others use tracking devices during routine exercise so their pets do not have to be leashed. More importantly, many search and rescue teams use tracking devices on their service animals to assist in rescue operations. Again, none of these scenarios would be possible with degraded GPS service.

3.3.10.1.11 Deep Forest

The deep forest operational scenario is an outdoor use case that presents a unique challenge for General Location/Navigation receivers. Devices in this environment are held in the hand of a moving user and experience some dynamics associated with walking, running, or climbing. These receivers may experience obscuration of signals by the forest canopy and the body of the user. Receivers in this scenario need the ability to measure distance, track users' positions, and navigate to waypoints (saved locations) successfully.

Not only is the deep forest operational scenario challenging for GPS receivers, it also presents many dangers for the people using the GPS receivers. The forest can be very unforgiving, and users count on their GPS receivers to provide reliable, accurate, and repeatable results day after day. Any degradation to these units' performance is unacceptable.

A hiker contributed the following story to *Rocky Mountain Tracking.*[35] After being chased by a bear, the hiker was lost, and night was quickly approaching. He used his GPS to locate and navigate to a ranger station. He stated, "My GPS tracking device was a lifesaver!" Had his GPS accuracy been degraded, his trek to the ranger station would have been much longer, and with night approaching, much more dangerous.

Similarly, a Garmin Rino user submitted this story about hunting with his father, brother, and friend. His 73-year-old father followed some elk down into a canyon. In the course of his pursuit, he fell and hit his head, triggering a full asthma attack. With the Rinos, the sons located their dad and quickly moved to his location. The brother and friend then used their Rinos to navigate to camp and get the father's medicine. "I have no doubt that your products saved the life of our father," he said.

[35] Jonathan Tipton. GPS Tracking Saves a Hiker – My Story. http://www.rmtracking.com/blog/2009/04/04/gps-tracking-saves-a-hiker-my-story/. April 4, 2009.

3.3.10.1.12 Fitness Use Case: Arm Swing Environment

The fitness operational scenario is an outdoor use case that presents its own set of challenges for General Location/Navigation receivers. Devices in this environment are fastened on the arm of a user who is swinging his or her arms in a manner consistent with running, jogging, or hiking. The device will experience frequent heading changes, and the signal will be obscured by the body at times. In addition, stressful dynamics are associated with the arm swing. Units in this category need the ability to measure distance, track users' positions and velocities, and navigate to waypoints successfully.

Many users rely on fitness GPS devices to monitor their progress in a weight loss regime. By using such features as the Virtual Partner, the GPS device can encourage and push a user to achieve fitness levels he or she could not reach before, shedding pounds and improving health and life expectancy. These users expect a quick TTFF and reliable, stable navigation in the fitness scenario.

More importantly, many runners have come to rely on the heart monitor features that come as standard items, or are available on an optional basis, on GPS-enabled watches that provide training-related functions. An example is Garmin's Forerunner series. One Garmin Forerunner user in Dallas, Texas recently informed the company that the data he received from his Forerunner caused him to suspect that he had some type of heart problem. When he informed his physicians of this concern, they were able, at an early stage, to diagnose a hereditary heart disease. This user told Garmin that, if he had not found the problem when he did, it would have killed him. He now says that he will not run without his Forerunner, a device that he credits with saving his life. Without GPS being a viable service this individual would never have known about his medical condition. GPS provided a life-saving function.

3.3.10.2 LightSquared Perspective

LightSquared agrees that GPS devices bring great benefit to their users. LightSquared has also concluded that operation on the upper part of its spectrum could cause disruption to many, but not all, existing GPS devices due to a lack of appropriate filtration. At the same time, the data clearly show that operating on the lower 10 MHz channel alone is a viable mitigation option that would not disrupt existing GPS devices in the General Location/Navigation device category.

3.3.11 Work Plan Item 11: Assess Whether any Mitigation Measures Are Feasible and Appropriate

3.3.11.1 GPS Industry Perspective (pages 176 to 179)

The General Location/Navigation sub-team has dedicated considerable time and effort to discussions about potential mitigation. These discussions have fallen into one of two categories: LightSquared transmitter mitigation and GPS receiver mitigation. GPS receiver mitigation can be further sub-divided into mitigation for existing devices currently on the market and mitigation for future devices yet to be designed.

There is no known mitigation for LightSquared's proposed deployment plan.

3.3.11.1.1 LightSquared Transmitter Mitigation

Frequency Shift

One proposed mitigation would be to shift the LightSquared base station transmissions to another frequency band outside of the MSS L-band. This might potentially eliminate all interference effects with GPS receivers and allow both existing and future devices to coexist peacefully with LightSquared transmissions. There are numerous possibilities that could be considered for a terrestrial broadband network, including MSS bands where MSS ATC is currently permitted such as in the 2 GHz MSS bands.[36] However, under the President's Broadband Initiative, up to 500 MHz[37] will be made available for wireless broadband applications in the next 5–10 years and some of the bands already identified via the "Fast Track" process[38] may also be suitable for use by the LightSquared network and could be examined.

Transmit Power and Transmitter Deployment Density Reduction

Another proposed mitigation is to dramatically reduce the LightSquared transmitter power and transmitter deployment density. LightSquared's stated deployment plans are to transmit at 62 dBm EIRP per channel on forty-thousand (40,000) base stations; however, the current authorization allows for base

36 See FCC Public Notice, "Spectrum Task Force Invites Technical Input on Approaches to Maximize Broadband Use of Fixed/Mobile Spectrum Allocations in the 2 GHz Range" (ET Docket No. 10-142, WT Docket Nos. 04-356, 07-195), DA 11-929, released May 20, 2011.

37 See *Presidential Memorandum: Unleashing the Wireless Broadband Revolution*, June 28, 2010.

38 The bands 1695-1710 and 3550-3650 were identified by NTIA as becoming available within the next 5 years and other bands (such as 1755–1850 MHz) are being evaluated for possible reallocation. See U.S. Department of Commerce, "An Assessment of the Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, 4200-4220 MHz, and 4380-4400 MHz Bands," Oct. 2010 at 1-4 to 1-8 (available at http://www.ntia.doc.gov/reports/2010/FastTrackEvaluation_11152010.pdf);see also FCC Public Notice, "Spectrum Task Force Requests Information on Frequency Bands Identified by NTIA as Potential Broadband Spectrum" (ET Docket No. 10-123), DA 11-444, released Mar. 8, 2011.

station transmissions of up to 72 dBm EIRP. At a minimum, the authorization number should be decreased to be commensurate with the deployment plan. To have any positive mitigation effect, the transmit power must be reduced substantially below 62 dBm EIRP. However, such a substantial reduction in transmit power is incompatible with LightSquared's proposed LTE network deployment as it would require a substantial increase in base station density. No matter how one approaches this proposal—high power/low density or low power/high density—the net result is catastrophic harmful interference for GPS users.

Lower Channel Only

Another proposed mitigation would be to permanently eliminate the upper channel and deploy only on the lower 10 MHz channel. Although LightSquared insists that this is not part of its deployment plan, this mitigation strategy was discussed at length in the General Location/Navigation sub-team. In fact, the sub-team even altered its test plan after testing had commenced in order to accommodate LightSquared's interest in this mitigation strategy.

Lab testing revealed that many devices suffered from harmful interference from the lower 10 MHz channel; specifically, 20 out of 29 devices experienced harmful interference. Refer to Appendices G.2 and G.3 for more details on this testing.

3.3.11.1.2 GPS Receiver Mitigation

Existing Devices Mitigation

There is no mitigation for the very extensive existing user base.

Some have suggested that better filtering could enhance GPS receiver resilience in the presence of LightSquared transmissions; however, no such filters exist. Furthermore, the majority of GPS devices are not user serviceable or capable of being retrofitted even if a filter did someday exist. This fact should not be taken lightly, given that the existing user base for GPS receivers exceeds 1 billion (1,000,000,000) users world-wide. Even if any mitigation were suggested, it would need to address the feasibility of retrofitting such a substantial user base.

The General Location/Navigation sub-team tested all of the scenarios documented in the LightSquared deployment plan (see the test plan in Appendix G.1). In every phase of the deployment plan, harmful interference was measured and documented. As the test results included in this report clearly demonstrate, the majority of devices failed at distances greater than 1.1 km (~0.66 miles) from a LightSquared transmit tower. Accordingly, the data indicates that a General Location/Navigation device within 1.1 km of a LightSquared tower will be subject to harmful interference. Figure 3.3.6 and Figure 3.3.7 show the impact of interference versus distance.

Future Devices Mitigation

As discussed previously, the General Location/Navigation sub-team has spent a considerable amount of time analyzing and discussing various proposals for mitigation on future devices. The sub-team is conscious of the many challenges associated with bringing new devices and technology to market, but has kept an open mind in order to focus its time and efforts on finding any kind of solution that might allow the LightSquared proposal to coexist with GPS. Regrettably, no suitable mitigation has been identified, although several proposals have been considered. All of these proposals have been related to improved filtering on the GPS receiver.

The sub-team evaluated proposals from every filter manufacturer that LightSquared put forward, including Avago, TriQuint, and Taiyo Yuden. It must be pointed out that most of the proposals were simulations of filters that do not yet exist—mere conjectures of what might be possible. .

There is no evidence to show that the proposed filter simulations yield sufficient rejection to protect against the enormously high LightSquared transmitter power. (Recall that the LightSquared transmit power is over one billion (1,000,000,000) times greater than that of a GPS device at ½ mile from the LightSquared transmitter.) In addition, while the proposed filter simulations endeavored to ameliorate LightSquared interference they also caused degraded performance in the GPS band. Specifically, the filter simulations caused increased roll-off on the low-side of the GPS pass-band and increased insertion loss in the pass-band. While LightSquared asserts that 40 dB of rejection is needed to protect GPS receivers from their transmissions, it cannot be substantiated that 40 dB is sufficient to prevent harmful interference. Further, the proposed simulated filters cannot achieve 40 dB of rejection without compromises to insertion loss, pass-band ripple, and group delay. So contrary to LightSquared's assertion that the filter manufacturers have provided convincing evidence that adequate filters could be possible, the GPS Industry maintains that no evidence has been provided, nothing has been demonstrated, and even the simulations fail to address the multiple performance compromises that would result from this approach.

The sub-team also spent a great deal of time discussing the challenges in designing and implementing a new filter for future GPS devices. Many variables must be weighed carefully in the design process to ensure that GPS performance is not compromised. As indicated previously, these include, but are not limited to, insertion loss, bandwidth, stop-band rejection, group delay, pass-band ripple, temperature stability, manufacturing variation, physical size (in relation to available space on the PCB), and cost . The filter design process almost always takes many months and even years. Once a suitable filter has been realized, it can take several more years to integrate it into an actual product.

There is no filter or proposed filter simulation available today that can suppress the LightSquared transmission adequately; however, even if there were, it

would take years to bring it to market and much longer to replace the existing user base.

Regrettably, the sub-team did not have time to consider the impact of the proposed filters on GLONASS, Galileo, Compass, and GPS L1C.

3.3.11.2 LightSquared Perspective

LightSquared's position regarding mitigation is as follows:

1. Operation on the lower 10 MHz channel only is sufficient to protect even the worst performing general location navigation devices. See Section 3.3.9.

2. The wide range of resilience within a given class of receivers, observed in the laboratory testing, clearly demonstrates that it is possible to design and build receivers that are sufficiently resilient to operate in the presence of both lower and upper channels.

3. Both Avago and Taiyo have provided convincing evidence that at least 40 dB additional rejection of LS signals could be created at frequencies less than 1555 MHz and greater than 1626.5 MHz. The minor resulting degradation in sensitivity (typical of new filters using BAW technology and offering the targeted additional rejection, c.f. Appendices G.4 and G.5) is not operationally perceptible in the field. The General Navigation equipment manufacturers have not provided any concrete evidence that it is. LightSquared is aware that other vendors, who declined to participate in the TWG process, have also performed this evaluation with similar results. The filter vendors have stated that the performance realized with physical samples is usually quite close to that predicted by simulations – there is no reason to believe that that would not be true in the present case.

3.4 High Precision, Timing, and Networks Sub-Team

(PLEASE NOTE: DUE TO THE FORMATTING OF THIS REPORT, THE NUMBERING OF THE HIGH PRECISION, TIMING, AND NETWORKS SECTION IS STANDALONE)

1. Executive Summary

This report summarizes the test results and presents the conclusions for the High Precision, Timing, and Network Sub-Teams. These Sub-Teams combined their efforts, as the types of testing required were compatible, and this helped meet the testing schedule.

Three types of interference studies were conducted:

- Anechoic Chamber – radiated tests in a controlled environment.
- Live Sky – radiated tests in an uncontrolled open environment.
- Laboratory – conducted tests in a controlled environment.

1.1 GPS Community Positions

These three interference studies collectively are sufficient to reach the following conclusions with respect to LightSquared interference with GPS for High Precision, Timing, and Network receivers:

1) The LightSquared Base Station 4G LTE signals harmfully interfere with High Precision, Timing, and Network GPS receivers over long ranges.
2) The LightSquared Base Station signals cause harmful co-channel interference with the FCC licensed StarFire and OmniSTAR augmentation systems.
3) LightSquared handsets, when operated close to a GPS receiver, harmfully interfere with it.
4) Current GPS receivers using other GNSS constellations such as Galileo and Compass and augmentation systems such as Wide Area Augmentation System (WAAS) with signals in the GPS L1 band will suffer harmful interference from the LightSquared signals for the same reasons as do the GPS signals[39].
5) In the lower 10 MHz channel configuration, 31 of 33 High Precision and Network GPS receivers tested experienced harmful interference within the range of power levels that would be seen inside the network (Fig 84). High precision receivers fielded today would experience harmful interference at up to 5km from a single LightSquared base station.

[39] These other constellations and signals were not studied, but because their signals occupy the GPS L1 band, and the interference affects the RF front end of the receivers, they will necessarily suffer interference.

With respect to possible mitigations:

1) We know of nothing feasible that can be done to make currently fielded wide band High Precision, Timing, and Network receivers and augmentation systems operate properly when in the vicinity of a LightSquared base station, with respect to either GPS or augmentation systems, under LightSquared's Phase 0, 1 or 2 rollout plans, or the recently announced 10 MHz Low Band rollout plan.
2) For some currently fielded narrow band Timing receivers, mitigation may be feasible if LightSquared operations are restricted solely to the 5/10 MHz Low Band or to the 5/10 MHz High Band.
3) We know of no currently available receiver, filter, antenna or other mitigation technology that would enable the construction of future wideband High Precision, Timing, or Network GPS receivers and augmentation systems that are compatible with the Phase 0, 1, or 2 LightSquared rollout plans.
4) We believe more study is required on the feasibility of building future wideband High Precision, Network, and Timing receivers and augmentation systems that would be compatible with LightSquared terrestrial signals and which would provide the same performance as today's receivers and systems. We do not foresee any possibility that LightSquared signals near the GPS band could ever be compatible with wideband receivers.
5) The most straightforward mitigation would be for LightSquared to use a different frequency band for their terrestrial network.
6) The viability of proposed future concepts to accommodate high precision GPS and MSS augmentations in the presence of interference from LightSquared terrestrial operations only in the lower 10MHz band has not been tested or validated as part of this study.

In addition to these conclusions, we note the following concerns:

1) Many users maintain their current receivers and systems for up to 15 years (and occasionally longer) to achieve an economic return on investment.
2) The use by LightSquared of power levels beyond those planned, up to the authorized FCC maximum of 72 dBm, would extend the range of interference and receiver degradation.

1.2 LightSquared Positions

The studies are sufficient to reach the following conclusions:

1) High Precision and Network GPS receivers are designed in such a way that they may receive harmful interference due to receiver overload from the LightSquared Base Station 4G LTE signals operating in an adjacent band. Timing receivers experience overload in some spectrum configurations; with almost all performing well in the presence of the lower 10 MHz channel.
2) High Precision and Network GPS receivers utilizing StarFire and OmniStar augmentation systems are designed with RF front ends to accommodate both GPS and augmentations signals. Due to this design, interference between

LightSquared base station signals and the StarFire and OmniSTAR augmentation systems is possible.

3) Some GPS receivers, when a LightSquared handset is operated very close by (within 1 meter distance), may also experience receiver overload.

With respect to possible mitigations:

1) Mitigation is feasible, particularly in connection with LightSquared operation on the 10 MHz Low Band. Such mitigations could include, but not be limited to the following options:

    - Operating the MSS augmentation link close to the upper end (1559 MHz) of the MSS L-band and using a narrower bandwidth, but still common preselector for the augmentation signal and GPS. Basically, this would involve operating the augmentation link in the guard band of the preselector.
    - Operating the MSS link with a dedicated (not common) preselector, separate from the GPS preselector. This would allow the MSS augmentation link to be operated in more frequencies than immediately adjacent to 1559 MHz.
    - Operate the augmentation link on a multimode (terrestrial-satellite) link that LightSquared could provide in the future. This would allow (a) operation anywhere in the L-band, including frequencies co-channel with the ATC, and (b) offer the added benefit of much higher throughputs when in terrestrial coverage.
    - Operate the augmentation link on a non-L-band cellular data link. Filter the GPS signal with an improved preselector sufficient to protect it in proximity to ATC channels. Software in the application layer causes augmentation link to be switched between the existing MSS L-band link and the cellular data link.

2) Due to time constraints, the sub-teams were not able to give adequate consideration to potential receiver-side mitigation options. Such options appear to be viable, and need to be worked jointly between the GPS community and LightSquared going forward.

2 Introduction and Background

High Precision receivers are widely used in applications such as survey, construction, agriculture, machine control, mining, Geographic Information Systems (GIS), structural deformation monitoring, and science. Such receivers often use all available and planned GNSS (Global Navigation Satellite System) constellations, and all signals generated by those constellations, not just the GPS constellation and the L1 C/A code. These receivers also use space and ground based augmentation systems to provide the most accurate navigation and positioning results possible. These receivers routinely provide accuracies of 1-2 cm (centimeters), under one inch, and in some modes can measure to 1-2 mm (millimeters). They normally have wide band front ends designed to capture all satellite signal characteristics, and they rely on measurements of the carrier phase of these signals for the highest accuracy levels. With these characteristics, which generate the navigation and positioning accuracy the user communities for these devices demand, High Precision receivers are particularly vulnerable to interference.

Timing receivers are widely used to provide precise time synchronization in applications such as wireless, wireline, and fiber optic telecommunications networks, electric power grids, paging systems, public safety radio systems, and financial networks. Such receivers typically provide timing pulses accurate to under 20 ns (nanoseconds) with respect to GPS time or UTC (Universal Time Coordinated) time. In some cases, timing receivers also provide a high precision frequency reference accurate to ± 1 part per 100 billion. This high precision frequency reference is critical to the interoperability of telecommunications networks.

Networks are combinations of high precision receivers operating together to provide increased accuracy and reliability for navigation and positioning applications. Networks such as StarFire and Omnistar are representatives of one type of global network. Other examples include Real Time Kinematic (RTK) networks, which are local networks. Because the receivers in Networks are generally high precision receivers, they are studied in this report as an operational use case of high precision receivers.

Three types of interference studies were conducted:

- Anechoic Chamber – radiated tests in a controlled environment isolated from other signals that could cloud the interpretation of the results, permitting the effects of LightSquared's signals to be clearly identified. This testing involved all participants in the High Precision and Timing Sub-Teams.
- Live Sky – radiated tests in an uncontrolled open environment, subject to other effects, but providing operating conditions that cannot be replicated in a chamber environment, and permitting an understanding of the ranges at which the LTE signal would affect GPS receivers. This testing involves a subset of the High Precision Sub-Team participants.
- Laboratory – conducted tests in a controlled environment in which signals are injected directly into GPS receivers, providing the most accurate measurement of interference effects, and illuminating the mechanisms internal to the receivers that fail to operate properly in the presence of interference. This test was conducted by JPL/NASA and submitted to the High Precision Sub-Team for its use.

The Anechoic Chamber testing was conducted at the Naval Air Warfare Center Aircraft Division (NAVAIR) chamber in Maryland from May 10, 2011 to May 14, 2011. A total of 57 GPS receivers were tested (44 high precision receivers and 13 timing receivers). The testing used a GPS simulator to generate the GPS signals and Agilent signal generators to create the LTE signals. Signals representing the StarFire and OmniSTAR GPS augmentation systems were also created from simulators so that the effects of the LTE signals on those signals could be studied, as many high precision receivers make use of these augmentation signals for significantly increased accuracy[40]. Multiple LTE modes were tested to understand the effects of the different LightSquared licensed channels and bandwidths[41]. The effects of a LightSquared handset operating near a GPS receiver were also simulated and tested. Multiple GPS operational modes were evaluated, including RTK.

The Live Sky testing was conducted as part of LightSquared's open air testing in Las Vegas, NV from May 16, 2011 to May 27, 2011. Four cell sites were operational, intended to simulate signal conditions in Dense Urban, Urban, Suburban, and Rural environments, as defined by the LightSquared Live Sky Test Plan. The signals radiated from these towers were active for 15 minutes at a time, followed by 15 minutes off, to permit comparisons between periods with and without interference. The power levels radiated were below those that would be employed in an operational environment, but adequate for these studies. Dynamic and static tests were conducted.

Thoroughly documented Laboratory tests were conducted by JPL/NASA (Jet Propulsion Laboratory/National Aeronautics and Space Administration) on March 22, 2011 on four receivers, two of which were high precision receivers. These tests examined in detail the performance of these receivers when subjected to injected LightSquared signals. Extraordinary care was taken to calibrate the equipment involved to ensure that interference effects were properly characterized.

In developing and conducting the study, it was important to keep in mind that a GPS device must accomplish two goals with respect to the signals it receives. It must function as a communication device, collecting the information that each satellite broadcasts; and it must function as a measurement device, making precise measurements of the received waveform as a prelude to positioning. The communication portion must be carried out simultaneously with multiple satellites – for high-accuracy applications, a minimum of five – to perform successfully. Coverage is a key metric of communication. With respect to the measurement function, accurate measurements rely not only on good communications, but on adequate signal bandwidth as well. Measurements for high-precision applications utilize a greater bandwidth than the minimum needed for

[40] The StarFire and OmniSTAR system purchase bandwidth from FCC licensed operators in the MSS-L-band spectrum where LightSquared proposes to operate to deliver GPS corrections to users globally via geostationary satellites, and have FCC licenses to receive those corrections.

[41] The LightSquared rollout plan supposes the eventual use of two 10 MHz bands. Although other configurations were tested, interference analysis considered all phases of the rollout plan, including the assumption of two 10 MHz bands. LightSquared notes that the Sub-Teams also evaluated the Lower 10 MHz channel on a stand-alone basis..

communications because the shape of the received signal matters when attempting to achieve the required accuracy.

The GPS Community takes the following position:

> An interference study is different from a communication coverage study. The key difference is that a coverage study aims to ensure coverage in every part of the service area. Thus it properly makes the most pessimistic assumptions of link margin between the signal source and receiver, whether it is the propagation model, the antenna losses, or the equipment location. An interference study must take the opposite view. It aims to avoid interference in every part of the service area. Thus it must make less pessimistic assumptions of link margins from the interferor to the receiver.

LightSquared takes the following position:

> Any study, regarding coverage or interference, should take a probabilistic approach and examine the likelihood and extent of coverage or interference in a particular environment. LightSquared believes that the GPS Community's approach of using a worst-case analysis to establish a baseline for impact to all receivers will greatly exaggerate the areas in which interference may occur. There are other approaches available that properly take into account the probability that users will experience particular signal strengths at specific locations; but such approaches were not evaluated by the sub-team.

In the sections of this report below, the TWG Work Plan items for the High Precision, Timing, and Networks subgroup are addressed in detail. The report includes the operational scenarios covered by the Sub-Teams, the Sub-Team's test plans and procedures, a detailed compilation of the interference effects of LightSquared's 4G LTE broadband transmissions on tested receivers and devices in several transmission modes, and a discussion of the appropriateness and feasibility of potential techniques for mitigating those interference effects.

3 Test Methodologies and Assumptions

The overall goal of the testing is to discover what, if any, harmful interference might be induced in GPS receivers from the proposed LightSquared terrestrial transmissions. This section identifies the reasoning that led to the selection of a test regime. Assumptions were used to guide the test regime, but where possible and appropriate within the time and scope of the study, they were not used to unduly limit investigation.

3.1 Background Assumptions

The following assumptions were used to help define the test methodologies:

- The principal interference mechanism is likely to be overload in the RF path components of GPS receivers arising from the LightSquared terrestrial broadcast signals in the adjacent band.
- Different architectures of precision and timing receivers exist due to different applications requirements, so receivers are consequently likely to show different levels of sensitivity to interference.
- The test regime should tie the GPS receiver performance to the power on the ground arising from the LightSquared transmissions.
- It was expected that the terrestrial transmissions follow LightSquared's rollout plan as filed with NTIA in February 2011 (see Section 3.2 below). LightSquared notes that alternate spectrum configurations were tested during the testing process.
- The testing schedule must allow sufficient time for the final report to be filed by June 15, 2011.
- Good scientific procedures will be followed, including impartiality, transparency, and repeatability.
- To ensure cooperation among participants, the study should not compromise commercial confidentially.

3.2 LightSquared Rollout Plan

The test plan was designed to ensure evaluation of the effects on GPS from the LightSquared rollout plan, as filed with NTIA. The rollout plan has three phases, as follows:

- **Phase 0** - one 5 MHz channel: 1550.2 MHz- 1555.2 MHz, 62 dBm EIRP total.
- **Phase 1** - two 5 MHz channels: 1526.3 MHz -1531.3 MHz; 1550.2 MHz - 1555.2 MHz, 62 dBm EIRP per 5 MHz channel., 65dBm total.
- **Phase 2** - two 10 MHz channels: 1526.3 MHz – 1536.3 MHz; 1545.2 MHz - 1555.2 MHz, 62 dBm EIRP per 10 MHz channel, 65dBm total.

The signal is a 3GPP LTE (see Glossary for definitions) compliant modulation, consisting of multiple OFDM (see Glossary for definition) carriers. The test plan addressed all three rollout phases.

3.3Harmful Interference

3.3.1 Introduction

In the FCC rules[42], harmful interference is defined as "interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the ITU] Radio Regulations."

The GPS Community takes the following position:

> The High Precision, Timing, and Network Sub-Teams agreed to use a maximum receiver degradation level of 1 dB in effective C/N_0 and loss of RTK as the reference KPI points for determining the presence of harmful interference to a receiver under test. The use of a 1 dB reduction in effective C/N_0 (also referred to as a rise in the total noise floor of 1 dB over the environmental noise floor) as a quantification of harmful interference to GPS has a well-recognized basis in the seven years of technical work on protection of radionavigation-satellite service receivers (now awaiting final approval within the ITU's Radiocommunication Sector[43]). The FCC has also used the criterion of a 1 dB rise in the noise floor as a basis for protecting the sensitivity, and consequently the coverage, for GPS receivers (e.g., in FCC decisions on Ultra Wide Band (UWB)).

LightSquared takes the following position:

> The development of an interference metric in this case should rely heavily on the impact on performance from the user perspective. The use of a 1 dB reduction in C/N_0 is unduly conservative and there has been no relationship established between this measure and any noticeable change in the user experience.

The GPS Community takes the following position:

> The GPS Community notes that High Precision GPS applications include those where the accuracy of the determined position is governed by regulation or law, therefore the definition of harmful interference includes the functioning of the device in this regard See section 5.

3.3.2 Coverage Measure

The GPS Community takes the following position:

> For High Precision, Timing, and Network receivers, it is necessary to limit the rise in the receiver noise floor caused by LightSquared's 4G LTE signal and all other non-RNSS sources of interference to 1 dB or less to protect the sensitivity, and consequently the coverage, for these classes of receivers. The desensitization effect

[42] Section 2.1 of the FCC's rules, 47 CFR §2.1: No. 1.169 of the ITU Radio Regulations.

[43] The protection levels for various types of receivers that operate with RNSS systems – including GPS – in the 1559-1610 MHz band that are provided in Draft New Recommendation ITU-R M.[1477_New] are based (in combinations of technical parameters such as "system noise temperature" and "acquisition mode threshold power density level of aggregate wideband interference at the passive antenna output") on a maximum permissible increase in the noise floor from interferers of 1 dB.

on the receiver's RF path reduces the signal-to-noise ratio (SNR) of received satellites in a one-to-one ratio between the receiver RF path compression and the received satellite SNR reduction. The Sub-Teams view greater than 1dB of desensitization to be harmful to High Precision, Timing, and Network receivers.

The 1 dB criterion represents the maximum tolerable interference contributions from all non-RNSS interference sources. Loss of sensitivity from compression is continuous, and therefore intrinsically correlated to other interference sources, which means it is directly additive to other sources of sensitivity loss (rather than a sum of variances that arise when combining uncorrelated noise sources). For these reasons, applying the 1 dB standard of harmful interference to assess the impact of LightSquared's 4G LTE signal on high precision, timing, and network receivers is arguably an overallotment.

The LightSquared position is:

The development of an interference metric in this case requires more analysis of the impact on performance from the user perspective. Test results indicate that a 1 dB reduction in C/N_0 may be unduly conservative and the test results have shown no correlation of the 1 dB reduction to an impact on the end-user's experience.

3.3.3 Accuracy Measure

For precision receivers, the requirements of the application drive individual and separate accuracy specifications that depend not just on the receiver, but on the nature of, and the ability to receive, augmentation and correction signals. The GPS Community believes that, consequently, there is no single accuracy criteria for all varieties of precision receivers. A set of accuracy measures can and, if needed, will be determined based on operational scenarios. It is anticipated, however, that the coverage measure of harmful interference will be reached prior to harmful accuracy degradation. Accuracy data will be collected during test to determine if this is correct.

3.4Resulting Test Methodologies and Rationale

Table 5 below provides the test methodologies and their rationale.

Methodology	Rationale
Anechoic chamber and live sky testing are required.	Anechoic chamber testing is needed to ensure test repeatability and to enable separation between receiver effects and propagation variability. Live sky testing is needed to validate the propagation models through direct power measurement and correspondence of GPS results.
All testing must be completed by 5/31/2011.	Required to meeting the June 15 deadline.
Test multiple receivers simultaneously.	Required to perform adequate testing and

Methodology	Rationale
	meet the May 31 deadline.
An anechoic chamber of sufficient size to permit the testing of multiple receivers simultaneously must be available. To avoid geometric effects that could result from having transmitting and receiving antennas too close, at least 1 meter is needed between them.	Required for good scientific procedure.
Testing must be controlled and executed by a laboratory independent of LightSquared and of USGIC and its members.	Required to meet both the image and substance of good scientific procedure.
All testing must be transparent, i.e., the testing can be observed by the concerned parties.	Required to meet both the image and substance of good scientific procedure.
The test data must be recorded and available to all appropriate parties, in accordance with overall TWG agreements. The test results must be made publicly available in a consolidated form with coding that does not disclose the identity of individual receivers.	Required for both scientific procedure and commercial confidentiality.
We expect the processing of the raw data into performance data to be done by the manufacturers, with LightSquared as observers if LightSquared desires.	Needed to meet the deadlines.
The selection of receivers to be tested must represent the installed base as well as current production receivers, and must represent critical applications.	Needed to meet the variability criteria.
Testing of receivers must range broadly over the population, and not be restricted to “obvious” receivers.	Needed for variability and good scientific procedure.
Testing of LightSquared handsets (or functionally similar replicas) is to be done, but the emphasis will be on testing interference from LightSquared base stations.	Done in the interest of collecting additional information.
Calibration of the transmitters and anechoic chamber must be done to ensure the transmitted signals are well	For good scientific procedure.

Methodology	Rationale
characterized and understood. There must be sufficient high quality instrumentation to ensure that the measurements taken are valid.	
It must be possible to generate the StarFire and OmniSTAR augmentation signals for those receivers which use them.	Needed to do controlled chamber testing while observing the effect on augmentation signals.
Each high precision manufacturer may have one receiver outside the chamber which will receive the GPS simulator signal to characterize the differences in performance between units subject to LightSquared signals and those not subject to it. This will also enable the RTK test cases to be performed.	Needed to do controlled chamber testing while observing the effect on RTK.
The signals generated by the LightSquared generators must replicate the signals that will be used in field operations.	For good scientific procedure.
It must be possible to vary the LightSquared signal power, to generate both the 5 MHz and 10 MHz LightSquared signals, and to operate the two generators simultaneously.	Needed to enable simulation of LightSquared signals to emulate varying distances from towers under rollout plan.
It must be possible to generate GPS L1 and L2 satellite signals with varying number of satellites and signal powers. The only GPS signals to be generated are L1 C/A, L1P, and L2P.	Needed to measure the effect on precision and timing receiver operation.
There must be sufficient isolation and attenuation to ensure that signals from inside the chamber do not feed back or affect the measuring instruments or receivers outside the chamber.	For good scientific procedure.
The frequency stability of the GNSS Signal Generator must be of higher quality than the oscillators in the Timing UUTs.	For good scientific procedure

Table 5 Methodology and Rationale – Basic Issues

Some methodology decisions were made for reasons of test and schedule efficiency. See Table 6 below.

Methodology	Rationale
GLONASS will not be radiated in the chamber tests.	Those receivers that are GLONASS capable will share the RF channel, so the GPS performance is a rough indicator of GLONASS reception.
Process variations for a given receiver type will not be considered.	There are enough receivers of various types that having an abnormal receiver should not affect the conclusions.
Testing over temperature is not required, and can be at ambient temperature.	Results could be de-rated to account for temperature variability of the RF paths (particularly of filters).
WAAS will not be used.	Sensitivity reduction of WAAS should follow GPS.
Testing of a handset in the chamber will be done as one of the LTE modes, not in combination with the base station testing.	Based on the availability of equipment and time.

Table 6 Methodology and Rationale – Test and Schedule Efficiency

3.5High Precision Receivers

The GPS Community points out that there are several characteristics of high precision receivers that should be noted, as they affect the test requirements:

- They have much wider bandwidths than lower precision receivers.
- For centimeter level accuracy, they require the use of both GPS frequencies L1 and L2.
- The most useful measurement for centimeter level accuracy is of carrier phase, not pseudorange.

3.5.1 Wide Bandwidths and Filters

The following is the view of the GPS Community.

There are at least three reasons wide bandwidths are used in high precision receivers. The most fundamental is that the bandwidth of some of the signals is wide. The second is because these receivers are attempting to make the most precise pseudorange measurements possible, and need all the signal energy that can be captured for this purpose. The third is that high precision receivers are attempting to reduce multipath, and need the full bandwidth of the signal for this purpose.

3.5.1.1 Background

It is true that the majority of the signal energy of the GPS L1 C/A code is contained with ±1 MHz of the center frequency, 1575.42 MHz, as the code clock rate is 1.023 MHz. However, the satellite broadcasts an L1 C/A signal that is only band limited by the satellite's much wider band pass filters required by the military signals. There is information content in the C/A code in this much wider bandwidth even though it does not contain significant signal power. The sharpness of the code transitions are contained in this additional bandwidth. Figure 10 shows code transitions that are band limited to ±1 MHz, ±12 MHz, and ±16 MHz. Early GPS satellites transmitted a ±12 MHz bandwidth, which was widened to ±16 MHz on more recent modern satellites. It is easily seen from this figure that the actual code transitions are much faster than the signal occupying only the center 2 MHz (±1 MHz).

LightSquared notes that even with the widest bandwidth, ±16 MHz, the separation between the bottom edge of the GPS signal and the top edge of the lower 10 MHz LightSquared signal is over 23 MHz.

The GPS Community notes that a 23 MHz band separation is not sufficient for a reasonable filter implementation. The combined primary filter requirements of low insertion loss to preserve the GPS noise figure, high band stop attenuation to adequately suppress the high ATC channel power, and the band separation of 23 MHz that make the filter difficult to design. Factor in the secondary requirements of performance over process and temperature, cost and size, the ability to obtain a filter becomes extremely challenging. The proposed requirement (see Lightsquared position in Section 3.5.1.4 below) that the filter provide 40 dBc of stop band rejection at the upper edge of an ATC channel (either in the upper or lower L-Band) forces manufacturers to adopt filters that are very large (2.16"x1.30"x1.18" connectorized filter versus 0.50"x0.55"x0.25" PCB filter) and prohibitively high in cost

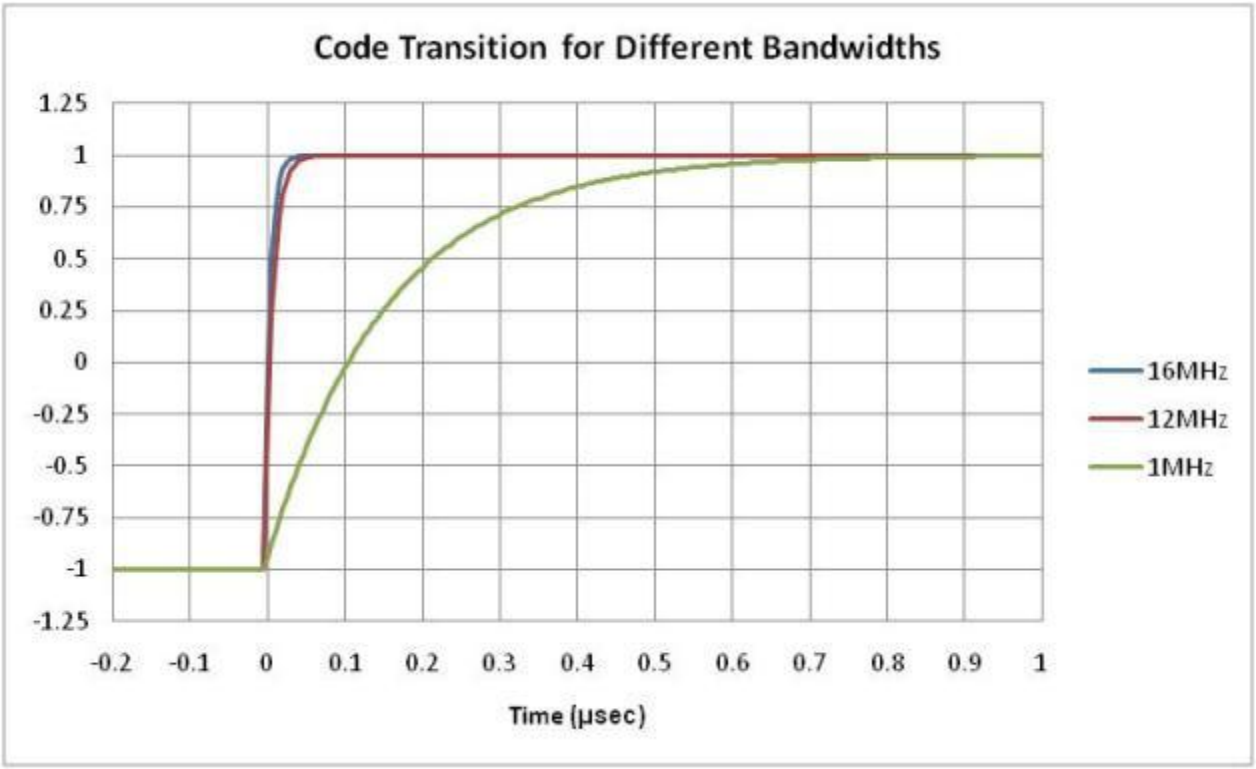


Figure 10 Code Transitions

3.5.1.2 Why Transitions are so Important

The phase of the received code, from which range measurements to the satellite are constructed, is estimated in high precision GPS receivers by employing a tracking loop. An excellent metric in comparing the performance of a tracking loop is the SNR of the error detector. Also, understand that all of the information of tracking error is restricted to the time during which the transition occurs. Outside of that time no information about the error can be obtained. Compare the duration of the transition of the wideband filters and the narrow band filters of Figure 10. For the wide band filters, the tracking information is contained over a very brief duration so the error function only has to observe the received signal for a very short time compared to the duration required for the narrow band filter. This indicates that the noise content of the narrow band error detector will be much greater than the noise content of the wide band error detector, resulting is a much higher error detector SNR for the wide band case than the narrow band case.

The slope of the code transition is also an excellent indicator of the observability of multipath. The faster the transition occurs, the shorter time delay (path length difference) between direct path and multipath before a multipath signal transition can be observed. The main key to mitigating multipath induced errors is the ability to observe the multipath signal. Consider Figure 11 in light of the desire to observe the multipath and also provide as much information as possible (i.e., integrate over the entire transition) to the loop error detector. It becomes obvious that the wideband case can achieve these two objectives significantly better. The direct path code transition is complete before the

multipath code transition begins so it doesn't corrupt the direct path transition, unlike the narrow band case.

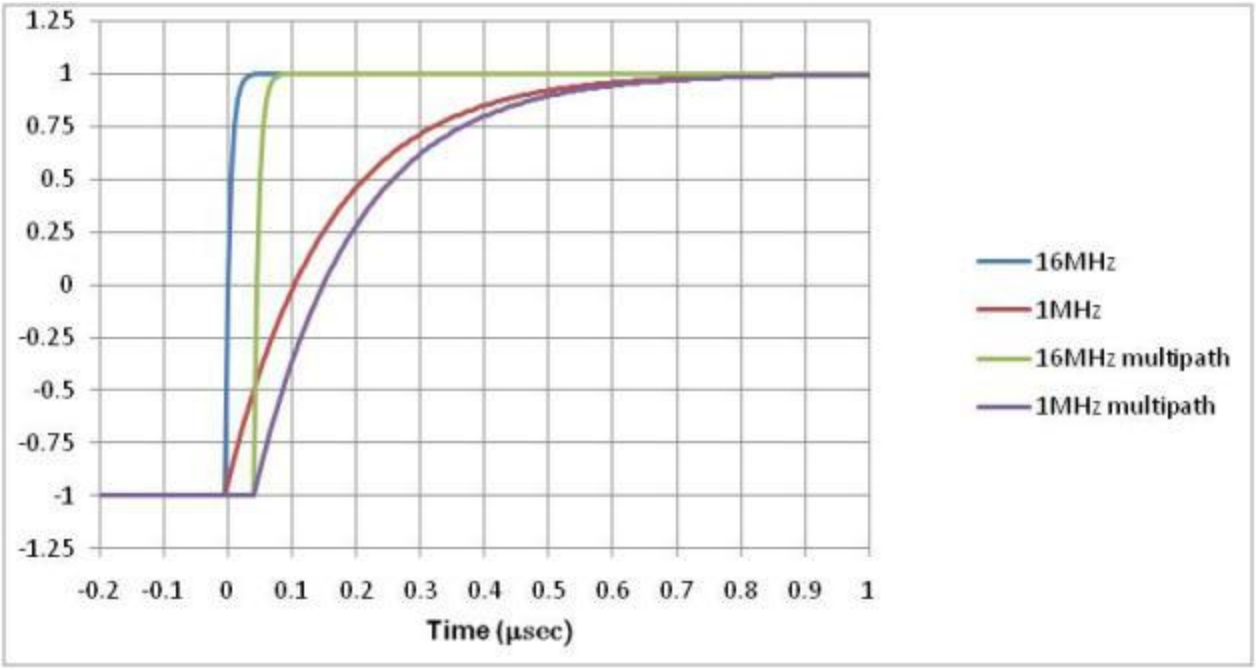


Figure 11 Code Transition with Multipath

The relationship between tracking performance and multipath impact has been analyzed and discussed by many for many years. The current thoughts are that an accurate performance metric for this is the RMS bandwidth of the received signal after filtering. If the RMS bandwidth increases as the receiver bandwidth increases, then the performance will also increase with an increase in bandwidth. The RMS bandwidth is equivalent to the Gabor bandwidth. This relationship between Gabor bandwidth and ranging performance has been observed in other direct sequence spread spectrum applications as well: "Thus, for any transmitted signal s(t), the range error of an optimal receiver will be completely determined by the energy received, the noise floor, and the effective (Gabor) bandwidth…".[44]

3.5.1.3 Why Linear Phase Response (Group Delay) is Required

The range measured by a GPS receiver is derived from a measurement of propagation time from the satellite to the receiver. This measurement is constructed by comparing the time tags inherent in the GPS signal structure (such as the code epoch) in the received signal with a reconstructed version generated within the receiver. The version generated within the receiver can have several bias, or error, terms. One bias that is obvious is the difference between local receiver time and GPS time. However, this bias is the same for all observed satellites and thus becomes a single nuisance parameter that can be easily estimated. Another bias term in this "time of arrival" measurement is the delay through

[44] Porcino et al, "Empowering 'Ambient Intelligence' with a Direct Sequence Spread Spectrum CDMA Positioning System", Philips Research Lab White Paper, Redhill, England

the receiver, the main contributor being the group delay of the filtering. This group delay must be reasonably constant over the GPS signal bandwidth for three reasons:

- The satellite motion with respect to the receiver results in each received signal having a unique Doppler shift in its received frequency. Unless the group delay is the same for all received frequencies, there will be different delays for different satellites. High precision GPS receivers are in essence measuring time to the sub-nanosecond level so the consistency across the range of possible Doppler measurements must be sub-nanosecond.
- One of the current state of the art limitations on the accuracy of high precision GPS receivers is the consistency of the receiver group delay, not only as a function of temperature and time, but also consistency between receivers.
- Since the main time tag used by the GPS receivers to measure the time of arrival is the code epoch, and the precision with which this time tag can be observed is a function of receiver bandwidth (see discussion on code transition), any deviation from constant group delay across the entire (±16 MHz) GPS signal band will cause distortions to this transition, thus limiting the performance that can be attained.

3.5.1.4 Conclusions

Through the years significant progress has been made and continues to be made in the areas of multipath mitigation and time measurement precision. However, this progress has necessitated the use of very wideband filtering. The absolute limit to attainable performance, however, is the consistency of receiver group delay. Any restrictions placed on the filter topologies will limit this field of innovation.

LightSquared takes the following position:

The information about the necessity of the wider filter passbands as pertaining to the GPS processing in the GPS band is not relevant to this document. No concrete, supporting information has been provided about why it would be difficult to realize a filter offering a given stopband rejection (say 40 dB) at the upper edge of an ATC channel (either in the upper or lower L-band) while meeting the stated passband objectives of amplitude ripple and group delay variation.

3.5.2 L1 and L2 GPS Frequencies

With two frequencies, high precision receivers can remove ionospheric effects by measuring the effects of the ionosphere on the different frequencies, and largely remove an error source that is very difficult to model.

Although the L2C signal is being deployed on the Block IIR-M, IIF, and III satellites, the number of satellites with L2C is still in the minority and the complete constellation will not have migrated to L2C until after 2020. For the foreseeable future on at least some GPS satellites, L2 must be tracked with techniques quite different from those used for L1. These techniques make the C/N_0 for L2 inherently significantly lower than for L1, and require that L1 be used to aid the tracking of L2. This reduced C/N_0 for L2 means that

interference to L1 makes it more difficult to track L2, and L2 is fundamental to the precision that this class of receivers produces.

3.5.3 Carrier Phase Navigation

GPS satellites broadcast signals on two separate bands - L1 and L2. Most low cost navigation type receivers only track the L1 band and just use the code signals for the purposes of making distance (range) measurements to satellites. High precision receivers make use of code and carrier phase measurements.

GPS carrier phase measurements have a precision of 1-2 mm (0.04-0.08 inches), compared to the precision of GPS code measurements of 0.1-0.3m (0.3-1 feet). Although carrier phase measurements are very precise, they contain an initial integer cycle ambiguity term which needs to be resolved in order to be able to use the measurements for precise positioning (see Figure 12).

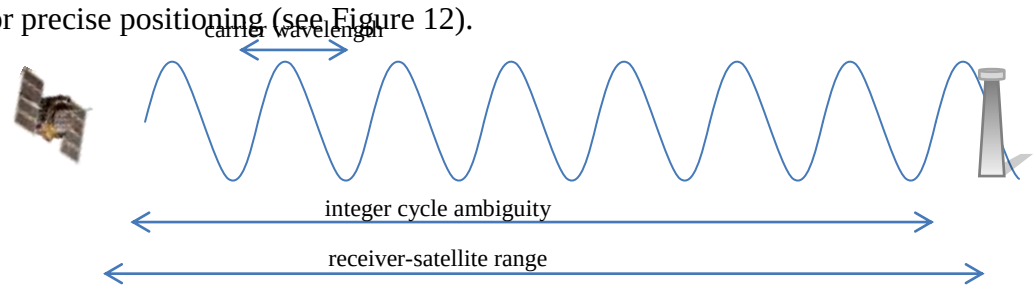


Figure 12 GPS Carrier Phase Measurements

Once the integer carrier cycle ambiguities are resolved on each tracked satellite, a high precision receiver is able to determine its position with centimeter (sub-inch) level accuracy. Prior to integer carrier cycle ambiguity resolution, the user's position can only be determined to sub-meter (several feet) accuracy.

It is important to rapidly and reliably resolve the integer carrier cycle ambiguities in high-precision GPS products. The techniques used to determine the cycle ambiguities involve searching over all possible integers to find the correct values. Given only single-frequency (L1 only) observations, the number of integer values that need to be searched can be many millions and the likelihood of choosing the incorrect integer cycle values is relatively high. The time taken to resolve the integer cycle ambiguities using single-frequency GPS observations is typically 5-30 minutes, which is unacceptably long for most precise applications.

High precision GPS receivers make simultaneous code and carrier phase measurements on the L1 and L2 bands (dual-frequency). With dual frequency carrier phase measurements, it is possible to form linear combinations of L1 and L2 with particularly desirable properties. For example, the ionospheric-free combination is useful because the effects of ionospheric errors can be essentially removed. The wide lane combination has an effective wavelength of 86 cm (34 inches) which is roughly 4.5 times longer than the wavelength of the L1 band. Because of its relatively long wavelength, the wide lane phase combination is often used for ambiguity resolution. With the wide lane phase combination, the number of integer ambiguities that need to be search is vastly reduced. Dual frequency high precision GPS receivers are able to very reliably resolve integers within seconds. See Figure 13.

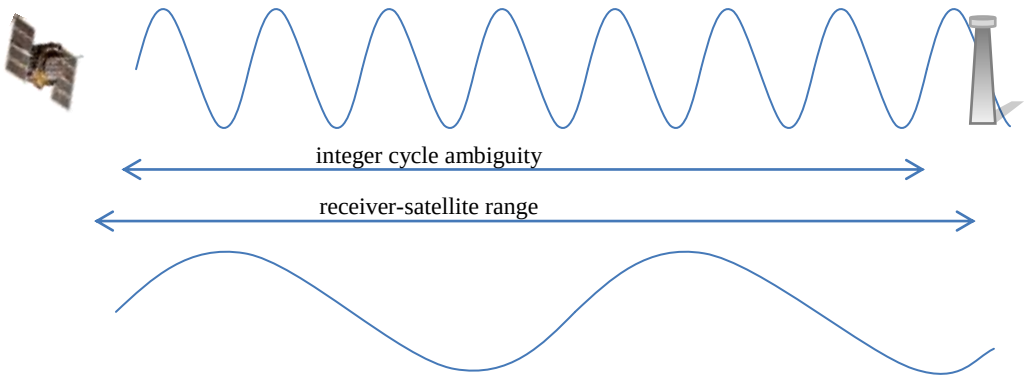


Figure 13 Wide Lane Carrier Phase Measurements

4 Receivers Tested

The TWG required that the choice of receivers to be tested include current generation receivers now in production, legacy receivers that are no longer in production but which have a substantial installed base, and receivers that may neither be of the current generation nor have a substantial installed base, but which represent critical applications.

4.1 Anechoic Chamber

The receivers tested in the NAVAIR anechoic chamber are as shown below in Figure 14. In some cases, there were multiple receivers of the same type using different antennas.

High Precision Receivers

Company	Models	Company	Models
Hemisphere	R320	**Leica**	SR530
	S3		GX1230
			GX1230GG
Deere	iTC		GR10
	SF-3000		Uno
	SF-3050		GS15
Trimble	MS990	**Topcon**	HiPer Ga
	MS992		HiPer II
	AgGPS 252		GR-3
	AgGPS 262		GR-5
	AgGPS EZguide 500		MC-R3 (1)
	CFX 750		NET-G3A
	FMX		SGR-1
	GeoExplorer 3000 series GeoXH		MC-R3 (2)
	GeoExplorer 3000 series GeoXT		
	GeoExplorer 6000 series GeoXH	**NovAtel**	OEMV1
	GeoExplorer 6000 series GeoXT		OEMV2G
	Juno SB		OEMV3G
	NetR9		OEM628
	NetR9		OEMV3G
	R8 GNSS		
	5800	**Septentrio**	AsteRx2e
	NetR5		AsteRx3
	NetR5		

Timing Receivers

TruePosition	GPS Timing Receiver	**FEI-Zyfer**	UNISync GPS/PRS
			AccuSync II
Symmetricom	SSU 2000		
	Time Source 1000/1100	**Trimble**	Resolution T
	Time Source 3500		Accutime Gold
			Resolution SMT
			MiniThunderbolt
NovAtel	OEM4		
	OEMSTAR		
	OEMSTAR		

Figure 14 Receivers for NAVAIR Testing

There are 44 High Precision receivers and 13 Timing receivers. We believe this selection of receivers meets the selection criteria noted earlier.

4.2 Live Sky

The Live Sky testing followed too closely behind the NAVAIR testing for the High Precision, Timing, and Networks Sub-Teams to have organized a common test plan. Consequently, each company or organization participating in the Live Sky testing did so primarily on its own. The following companies and organizations from these Sub-Teams provided reports on their testing.

- Trimble – power and receiver testing
- Deere – power and receiver testing
- Verizon Wireless –cell site Timing receiver testing
- NOAA/NGS - receiver testing
- Sprint Nextel –cell site Timing receiver testing
- Topcon - power and receiver testing

4.3 Laboratory

JPL/NASA tested four receivers in their laboratory. Two of these were High Precision receivers:

- Ashtech Z-12
- Javad Delta G3T

5 Operational Scenarios

5.1Key Performance Requirements

The installed user base for high precision GPS requires predictable, continuous access to multiple high fidelity GPS signals to obtain and sustain the level of accuracy required in commercial applications.

Most high precision GPS users depend on resolution of carrier phase ambiguity to provide less than 2 centimeters in 3 dimensions (latitude, longitude, altitude) in real-time for most applications while operating in either dynamic or static mode and often in stressed environments.

The key performance requirements for high precision users are noted in the following sections.

5.1.1 Availability

- The installed user base for high precision GPS works in all geographic locations where commercial work occurs. Commercial high precision GPS applications require predictable, reliable availability of GPS signals in these coverage areas. Commercial users deploy high precision GPS receivers and systems across a range of challenging operational environments.
- Stressed operational environments include urban canyons (dynamic environment where tall buildings cause obscuration of satellite signals), suburban (dynamic environment where tree canopy and buildings cause obscuration of satellite signals), and rural (dynamic environment where terrain or foliage causes obscuration of satellite signals).
- Ability to very rapidly resolve carrier phase ambiguities On-The-Fly (OTF) and to continuously sustain integer ambiguities is required in the commercial application of high precision GPS in each of these stressed or non-stressed environments.

5.1.2 Accuracy

- High precision receivers and systems are wide band to exploit multiple existing and planned GPS satellite signals and can also include various augmentation systems to obtain precise positional accuracy. The accuracy requirements vary by application, and range, including: meter, decimeter, centimeter, or millimeter.

5.1.3 Commercial Integrity

- As commercial users increase their operational dependence on high precision results, they require high integrity and repeatability of positional accuracies including predictability of coverage in their commercial applications.

- Reliable and accurate a posteriori statistical data regarding positional precision, accuracy, and reliability are needed, along with an absence of biases or systematic errors in data.
- Reliable propagation of GPS data through algorithms used in RTK engines, post-processing engines, monitoring analysis and warning systems, GIS databases, and other systems using GPS as an input are required.

5.2 Operational Scenarios

5.2.1 Agriculture

Precision agriculture uses high accuracy real-time GPS on-board agricultural machinery to manage distribution of fertilizer and pesticides, and planting and harvesting of crops. Using GPS precision guidance, farmers can plant rows closer together and with greater precision, to increase crop yields and reduce waste due to overlaps or gaps. When used on harvesting machines, the collection of GPS precise positioning data, combined with information about crop yields, is applied to seeding and fertilization plans for the following season's crops. The GPS positioning adds precision to weed and insect control, allowing farms to decrease the use of potentially toxic pesticides and herbicides by as much as 80 percent.

Precision agriculture requires 24/7 delivery of continuous real time position accuracies with Key Performance Indicators (KPI) from 1 cm to 10 cm during agricultural operations. This positional capability enables the grower to operate a range of farm machinery, including at night, that carefully follows precision farming plans requiring repeatable KPI throughout the growing cycle, from tilling through harvesting. Many precision agriculture receivers require a real-time differential data stream, often delivered by integrated L-Band MSS receiver equipment.

The GPS Community has presented the following Operational Use Scenarios.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Increased Yield
A grower in the southern U.S. operates a harvesting machine under foliage so dense that visibility of the rows on the ground is impeded. Using precision GPS guidance on the harvester, this grower can plant crops in rows 30 inches apart compared to 37 inches without precision GPS. The resulting crops crop yield has increased by 200 to 400 pounds per acre.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy, and Repeatability
Benefit - Increased Yield
A grower in the Southern U.S. uses a high-precision GPS system that produces 2"- 4" positioning accuracy to obtain average increase in yield of 200 pounds per acre across 400 acres of peanuts. A grower in the central U.S. deploys high precision GPS machine control to knife anhydrous in the fall with pass-to-pass KPI accuracy of one inch or better—often ¼ inch to ½ inch which are then required to be repeatable throughout the growing cycle. Following with the next farm implement, the Nitrogen applicator, using the same KPI, the knives drop precisely right back into the same grooves. In the spring,

this grower uses high precision GPS machine control on a farm implement to plant. Then this high precision GPS autopilot is transferred to the sprayer for precision application of appropriate amounts of fertilizer.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Reduced Input Costs and Environmental Impact
In the central U.S., a grower working 17,000 acres uses precision GPS guidance with electronic maps of soil and yield to dynamically vary the rates of fertilizer application in the field which has resulted in a 35 percent decrease in the amount of products needed to maintain the pH balance of the soil. The GPS positioning adds precision to weed and insect control, allowing farms to decrease the use of potentially toxic pesticides and herbicides by as much as 80 percent. Routes followed by the farm machines can be carefully planned and controlled, reducing fuel consumption.

5.2.2 Construction – Heavy and Civil Engineering

GPS construction machine control systems consist of rugged, high-precision GPS receivers mounted on construction machines of various types. With reference to a computer model of a job grading plan, the GPS system is required to determine the precise position of the machine's blade continuously (24/7) to within one inch or less using the on-board computer to continuously compare the blade's precise position to the design plan. By watching a display in the machine's cab, the operator controls the machine to produce the desired results. In some applications, the machine control system handles the steering and blade positioning automatically through hydraulic interfaces, with the operator functioning as a monitor and safety check. Off-machine high precision GPS is also used extensively on construction sites for site measurement, layout and dimensional control functions.

The GPS Community has presented the following Operational Use Scenarios.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Increased Productivity, Reduced Re-work
A North American earthmoving contractor reports a 500% increase in productivity in their earthmoving operations due to reduced waiting time for wooden stakes to be placed in the ground, reduced re-work (re-doing a portion of the job) due to errors, and reduced disputes over accuracy and quantity of work completed. Another contractor reports reduction of rework by 70 % using a precision GPS system as well as a 400% increase in productivity measured over a four acre section of parking lot construction graded in 1 and ½ days, which they estimated would have taken six days by conventional methods driving hubs every 25 feet.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Reduced Cost and Rework
A construction project building a 2 million-square-foot footprint of a logistics warehouse for a large national discount retailer reported that finished pad constructed using high precision GPS was consistently within a half inch of the plan throughout the whole expanse, fully one-third of the mandated tolerances. Accuracy has been increased as operators no longer have to interpolate between grade stakes. The right tolerances of the graded pad made for much smoother placement of concrete - a quarter-inch off on two

million square feet, is approximately $1 million dollars of concrete. A contractor in the non-contiguous U.S. reported that finished grades on a golf course constructed with high precision GPS match exactly what is on the plan with no deviations or exceptions— the developer client verified that they were constructing to grade consistently within three tenths of an inch of the finished contour.

5.2.3 Professional Services: Land Surveying, Architecture, Engineering

High precision GPS is used in many surveying functions necessary for civil engineering and architectural design, production and maintenance of maps and Geographic Information Systems (GIS), land management and title transactions, and management of critical assets such as utility infrastructure, pipelines, dams, roads, rail and waterways. High precision GPS is also used to provide services to cities and counties for tax appraisal purposes and flood zone mapping. Survey work may be commissioned at any geographic location and predictable GPS coverage and operation is critical given the unpredictable work locations. Accuracies of 1-2 cm are required and accuracy standards are often dictated by regulation and law.

The GPS Community has presented the following Operational Use Scenarios.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Productivity and Compliance
State Boards of Licensure and Professional Land Surveying Boards across the United States set regulations and standards for measurement precision and accuracy, which must be adhered to by practicing land surveyors, making accuracy a critical KPI for this profession. More than 50,000 U.S. land surveyors are using high precision GPS routinely in their work in a $7B U.S. industry. A surveyor from the central US states that they use GPS for 90% of their fieldwork, another from the East Coast states 75%. A surveyor in the Southern U.S. states that accuracy standards must be met at a 95% or greater confidence level and that anything less would be non-compliant with the law.

High precision GPS is used extensively in surveying tasks due to significant productivity gains, as reported by surveyors from across the United States:

> "We have eliminated the need to conduct long traverses though the woods that may take as long as two or three days. GPS has enabled us to collect the same data in the time it takes to drive and setup the equipment, literally in just minutes."
>
> "The need to conduct long, time consuming traverses from geodetic control to a site have been eliminated."
>
> "GPS saves thousands of person-hours per year for survey-type work."
>
> "After Hurricane Katrina, GPS was essential for surveying the damaged bridges, elevations of homes for insurance, reconstruction of roads and highways and aerial mapping that would assess the damage. Some results were needed immediately. GPS has made it possible to transfer an elevation for a homeowner who may need flood insurance in a matter of a couple of hours and from distances of 20 miles."

5.2.4 Public Administration: Federal, State, and Local Government

Commercial high precision GPS is used widely within Federal Government, including within the Department of Defense, Department of Transportation, Department of Agriculture, Department of Interior, Department of Homeland Security as well as other Departments and Bureaus.

State and Local Government uses of high precision GPS include State DOT mapping, surveying and other transportation uses, Geographic Information Systems (GIS) for asset management, emergency preparedness, disaster response and e911 mapping, public sector water, wastewater and electric utilities, public works, environmental management, dam and structure monitoring, environmental health, insurance rating districts, flood zones, tax appraisals, the provision of geodetic control networks, and other functions.

High-precision GPS is used in response and disaster planning to capture the location of critical infrastructure for utilities, transportation and emergency services. By combining GPS measurements with elevation models, planners can identify areas susceptible to flooding or other damage. The information is stored in Geographic Information Systems (GIS) where it can be accessed by emergency managers and response organizations.

The GPS Community has presented the following Operational Use Scenarios.

Operational Use Scenario/KPI - Availability (Coverage), Precise Location
Benefit - Public Safety
A County GIS Office in the Southern U.S. uses high precision GPS units for Emergency Management and 911 mapping projects that must have extremely accurate and precise location. High precision GPS is used to determine precise positions and map features used for environmental health, insurance rating districts and other GIS purposes. For emergency response systems, high precision GPS uses include:

- Mapping addresses – e911 systems depend on an accurate mapping database which can relate a GPS position to an address.
- Mapping utilities – mapping the precise location of fire hydrants and other water points reduces the time taken in the field in an emergency to locate a water point. In an emergency, responders need to quickly find hydrants, water points, valves and switch boxes to control the flow of water, electricity and natural gas. Components may be hidden by darkness, buried in debris or under floodwaters. To prepare for this, utilities and municipalities use high precision GPS to create detailed maps of their utility infrastructure. When the need arises, they navigate to the exact location of a component, even distinguishing a gas valve from a similar-looking water shutoff just a foot away.
- Mapping hazardous objects – Knowing the location of objects which may be hazardous in a fire, such as underground gasoline or chemical storage tanks (even disused ones which may be hidden but still hazardous) enables firefighters to be aware of hazards in an emergency, particularly when this information is accessed in real-time.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Increased Productivity and Efficiency

A State Department of Transportation (DOT) in the South has six survey crews operating and has invested heavily since 1996 in high precision GPS technology, with the goal of improving productivity, efficiency and reducing costs. Equipment purchased 15 years ago is still in use today, along with equipment purchased in an $800,000 investment last year. GPS is heavily embedded in the DOT's work processes, procedures and work manuals and enables some aspects of the work to be done in a fraction of the time it would have taken using older methods. Job sites are often 20-30 km from the geodetic control points to which the work has to be referenced and GPS has provided particular productivity advantages in the process of transferring that control information.

The DOT recently commissioned a 30 mile survey using both mobile ground based and airborne three dimensional LIDAR (Light Detection And Ranging) systems which create accurate 3D models of the surveyed area. Both the ground and airborne systems used for these kinds of surveys depend on high precision dynamic GPS.

A County GIS office in the Southern U.S. states that when mapping insurance rating districts, about 245 points can be mapped per day using high precision GPS, with a crew of 2 – one to drive and one to operate the equipment. By combining a hand held laser with the high precision GPS, most points can be mapped from the vehicle. By conventional methods, the County estimates that 245 points would have taken a crew of 4 about 3 weeks to complete; 60 person-days versus 2 person-days to complete the same task. Additionally, the digital data flow reduces the likelihood of error and eliminates the cost of manually recording data back in the office.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Cost Savings

A Northwestern State Department of Transportation estimates that it saves about $4M in the annual State budget by its use of high precision GPS (less than 2 centimeters in 3 dimensions), relative to costlier legacy positioning methods. These costs reflect the ability to predictably bid and reliably complete projects using high precision GPS throughout the State. In addition, it estimates that its State's Public Utilities saves approximately half a million more annually in decreased costs on capital projects (i.e., the construction, replacement and maintenance of drainage pipes, sewer lines, water lines) by using GPS over legacy technologies.

A Northeastern Department of Transportation (DOT) uses high-precision GPS for preliminary and final design of highway and bridge projects throughout the state. GPS is used for establishing permanent control networks, state plane coordinates, topographic features and digital terrain models (DTM) for design projects and machine control for construction equipment. The DOT uses GPS internally and through its consultants and contractors and believes that this saves taxpayers millions of dollars annually by improving field survey efficiencies for highway and bridge projects.

A small city in the Southeastern U.S. covering a population of 200,000 estimates that it saves $14.6M per year through the use of GPS across all functions. First responders use GPS and GIS data to reduce response times. Engineers, Planners, Tax Assessors use GPS coordinates from surveys and plats recorded in order to interpret and display accurate land and tax information. Engineers use GPS locations during bridge design, development, construction, inventory, repair and mitigation assessments.

The Federal Emergency Management Agency (FEMA) uses GPS locations of spatially enabled data for mitigating damage assessments from natural disasters. Assessments can be generated in a few hours instead of several days for a cost of $80 per task rather than $800 per task.

5.2.5 Utilities (Electric, Gas and Water), Energy, Mining, Oil & Natural Gas

High precision GPS is used by electric, gas and water utilities to map and manage their widely dispersed assets, in the avoidance and management of major power, water, or gas outages, in vegetation management, rapid location of damaged equipment, in pipeline integrity inspections and in tasks related to environmental and safety compliance. In Energy and Natural Resources, GPS is used extensively in the construction of sustainable energy projects such as wind farms and solar power sites, seismic exploration and production of domestic oil and gas reserves, mine surveying, measurement and safety monitoring, pipeline construction, pipeline integrity and safety monitoring, drill location and environmental monitoring, measurement and compliance.

The GPS Community has presented the following Operational Use Scenarios.

Operational Use Scenario/KPI—Availability (Coverage), Accuracy
Benefit - Safety and Compliance
A large Midwestern electric utility designs its distribution facilities to meet applicable codes and standards including the National Electric Safety Code, its own Distribution Standards, and local codes as required. The engineering and design of distribution facilities in the past was based on tables and charts that were conservative due to the lack of accurate data that could be easily gathered in the field. The use of high-accuracy GPS data allows their designers and engineers to design safe and more cost-effective distribution facilities. This highly accurate GPS data also allows the subsequent re-locating of these underground facilities with high certainty; knowing where the facilities are located can reduce the likelihood of damage, thus providing a greater margin of safety for those that need to work near these facilities.

In U.S. shale development projects, survey crews use GPS to locate areas of environmental concerns as part of the pre-construction planning and to meet environmental compliance requirements; well sites, ponds and drainage plans are carefully mapped and laid out to meet requirements for environmental protection as well as health and safety regulations.

Extensive integrity and safety inspections of gas networks are currently underway across the United States following a recent gas explosion in the Western U.S. One gas utility states that they would not be able to complete the necessary inspections on schedule without the use of high precision GPS.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Efficiency and Productivity
Utilities use high-precision GPS to measure routes for access roads, construction easements, line and pipeline locations, completing the work in a fraction of the time that conventional methods would require. A large Midwestern electric utility estimates an improvement in field efficiency from 25 to 50% by using high precision GPS over historical methods such as pacing, measuring wheels, tape measures and optical

instruments. Additionally, the utility estimates a further office workflow efficiency gain of 25-50% due to the direct flow of digital data replacing notebooks and paper processing or data entry in the office, with the additional benefit of reduced data entry errors.

Another electric utility states that the creation of the required state plane control for a survey of power lines using GPS is completed in minutes with the real time network versus days running traverse lines from geodetic control located miles away from the proposed power line easement.

High precision GPS is used extensively in renewable energy projects; the locations for more than 240 wind turbines were established for a central U.S. wind project using high precision GPS measurements, as well as to create easements and rights of way for the new transmission lines that deliver more than 300 MW of power from that site to the electric grid.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy, Repeatability
Benefit - Reduced Recovery Costs, Reduced Errors, Operator Safety
Many utility, energy and natural resource applications of high precision GPS require high levels of repeatability of position over long periods of time. During construction of buried pipelines, underground cables and other assets, precise GPS positions are recorded to facilitate accurate relocation months or years afterwards. Geophysicists create detailed models of the earth's crust by using seismic data combined with high precision GPS positions. Once the location of oil and gas deposits has been determined, drilling teams rely on GPS to accurately mark the locations for the wells.

5.2.6 Transportation: Road and Rail

High Precision GPS is used in the construction, maintenance and operation of road and rail transportation infrastructure across the United States. In addition to Surveying and GPS Machine Control, high precision GPS is used in intelligent transportation systems.

The GPS Community has presented the following Operational Use Scenarios.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Reduced Infrastructure Costs, Public Safety
High precision GPS combined with GPS networks are used operationally in the United States to provide all-weather high precision lane guidance to heavy vehicles including buses and snowplows. These systems compare the precise position of the vehicle with a very high accuracy GPS survey database of the lane edges, monitoring the vehicle positioning within the lane to within 2 to 4 inches up to ten times every second, immediately warning the driver of any potential departure. The use of these systems enables buses to use shoulder lanes barely wider than the bus itself and enables snow plows to operate in zero visibility blizzard conditions to keep critical roads and mountain passes open, neither of which a human driver can safely conduct unaided.

Lane guidance is key for improved road safety; approximately 60% of annual US road deaths are the result of a lane departure. However, the distribution of accident locations is uniform along any given road, meaning that it is not possible to predict or define geographical 'protection zones' from radio interference based on location. These systems require continuous, reliable 24/7 high accuracy positioning. High precision GPS lane guidance does not require the installation of fixed markers along the road, such as

magnetic markers, nor does it require the good visibility necessary for optical systems to work.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Public Safety
The Congressionally mandated positive train control (PTC) effort is designed to improve safety by reducing the risk of train to train collisions. GPS is used for positioning, timing, and speed, principally in locating the lead locomotive on a train, although other applications use GPS for car location and track inspection vehicles. Multiple inputs are fed into location filters to improve accuracy and smooth inputs into reliable safe output of train location, speed, and confidence factor. These systems are designed to detect when a locomotive is in danger of a collision and have the ability to apply the brakes without human intervention. GPS data is central to PTC operation.

5.2.7 Networks, Monitoring and Scientific

High precision GPS networks operate across the United States and provide continuous, high precision GPS data for a broad range of uses including land surveying, construction, agriculture, transportation, emergency preparedness, monitoring of critical structures and seismic hazards, GIS and mapping, environmental protection, public safety, public works, utilities, intelligent transportation, environmental management, dredging, atmospheric science and meteorology, and other uses.

The National Geodetic Service (NGS) reports approximately 1,800 Continuously Operating Reference Stations (CORS) in the United States as of May 2011. In addition to these stations, many states and private sector organizations have established their own local and regional networks. It is estimated that 8,000 high precision GPS stations are operating in the US across every state in the US. See Figure 15 below.

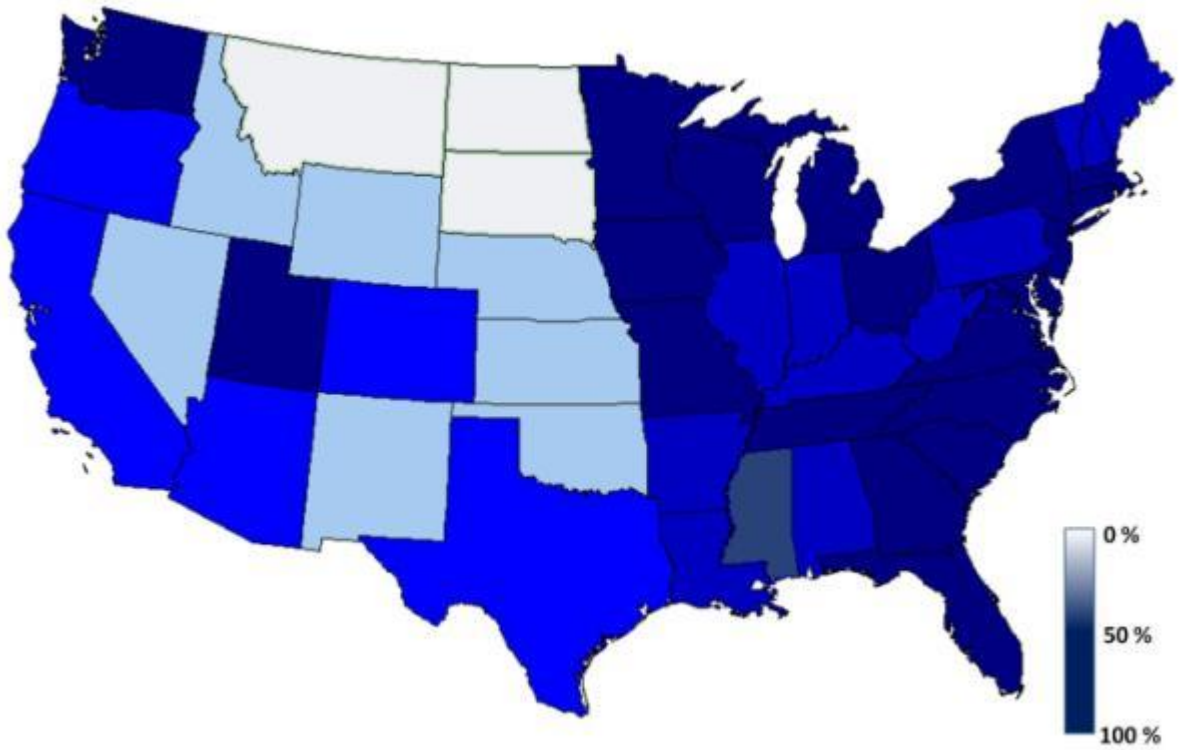


Figure 15 High Precision GPS Network Coverage[45]

The GPS Community has presented the following Operational Use Scenarios.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Public Safety, Science

The western U.S. is blanketed with arrays of high-precision GPS receivers. Information from these receivers is used to study the motion of the Earth's tectonic plates. One of the largest arrays includes more than 1,100 GPS receivers along the West Coast and makes continuous observations that can detect and measure crustal plate motion of just a few millimeters per year. These are the most precise and sensitive uses of high precision GPS globally. Similar GPS arrays along the Pacific Coast help seismologists and geophysicists understand the motion and potential strength for earthquakes as stresses accumulate along the region's fault lines.

A dozen universities are utilizing real-time and post-processed L1 and L2 products from 104 high precision GPS ground stations for geophysical studies of active volcanoes, plate tectonics, earthquake, and potential tsunamis in the Pacific Northwest.[46]. In a large Midwestern city with many very tall structures and high winds, high precision GPS is

[45] From Schrock, 2010.
[46] http://seattletimes.nwsource.com/html/localnews/2015183992_gps30m.html

used to measure millimeter-level motion of tall buildings in order to improve design models used to test survivability limits for 50 or 100 year wind storms[47]

Operational Use Scenario/KPI - Availability (Coverage), Accuracy, Continuous Data
Benefit - Efficiency and Productivity
High precision GPS in Real Time Kinematic or Post Processing mode requires both a fixed reference station and a moving high precision GPS receiver. The centimeter-level positioning is determined by a three dimensional vector relative to the known reference station.

As an alternative to operating their own reference stations, many high precision GPS users across the United States in Agriculture, Government, Construction, Surveying, Utilities, Energy, Transportation, Academia and Science rely on available networks to provide their high precision reference. Continuous availability of data from the network is critical to the operation of those high precision end user systems, for economic activity across a range of sectors and in some cases such as structure monitoring and GPS lane guidance, continuous availability of data is safety critical.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy, Time to Alarm
Benefit - Public Safety:
GPS networks and permanent high precision GPS installations are used to monitor and detect movement of dams, bridges, other structures, tectonic plates along earthquake fault zones and volcanoes, providing input data to alert and alarm systems that provide early warning of potential disasters. Earthquake alert systems can detect motion in the earth and alert emergency managers of incoming shockwaves and potential tsunamis, potentially providing enough warning (30-120 seconds) to shut down sources of secondary disaster such as high voltage electricity facilities, nuclear power plants, and natural gas transmission and distribution networks.

Dams and levees across the United States are measured and monitored with high precision GPS, increasingly so after the Katrina disaster. A water district in the coastal southwestern U.S. uses high precision GPS to monitor 35 dams and critical structures built in active earthquake fault zones. A state in the Pacific northwest uses high-precision GPS to monitor dams under varying loads as reservoirs rise and fall with seasonal rains, as well as bridges, electricity transmission towers, retaining walls and levees.

During large construction projects, engineers use GPS to ensure that nearby buildings and structures are not moving or tilting as a result of tunneling or excavation. In all cases, time to alarm is a critical KPI, driven by continuous availability of very high precision GPS data.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit - Public Safety
High precision GPS network data is used to measure ionospheric and tropospheric activity, providing data used in meteorological weather prediction as well as for space weather prediction necessary for radio communications and prediction of atmospheric

[47] GPS World, The Height of Precision, Sep 2003

events which can cause power grid disturbances. These applications require the use of low elevation satellite data which has passed obliquely through various layers of the earth's atmosphere. GPS is also used in meteorological dropsondes which are deposited into major storms and hurricanes to precisely track and predict their motion. In addition to the safety-of-life implications, accurate prediction of the probable location, timing and intensity of hurricane landfalls reduces unnecessary evacuations; a single mile of coastal evacuation costs more than $1 million[48]

5.2.8 GPS Precision Timing

The GPS constellation, signal structure, and associated mathematical models were designed to enable precision user time synchronization to be accomplished along with three dimensional positions. GPS timing is used across a range of civilian and government activities due to its ability to reliably transfer precise time synchronization to global standards over very large distances with low cost, very low maintenance user equipment.

The GPS Community has presented the following Operational Use Scenarios.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit – Efficiency and Productivity, Public Safety
GPS timing is used to provide time synchronization to within 100 billionths of a second or less and/or stable frequency outputs in applications including:

- **Syncrophasors** used in electricity transmission and distribution networks enable the relative phase angle divergence and oscillations often seen prior to large scale regional 'blackouts' to be detected and corrected, a key component in prevention of large scale power outages such as the August 2003 event that affected 55 million people in eight US states and parts of Canada. Additionally, North American Electric Reliability Corporation (NERC) regulations require sequence of event logs to have accurate time stamping, for which GPS is routinely used.
- **Digital Radio and Television Broadcast** systems use GPS timing to synchronize their bit streams. The timing keeps the signals locked on frequency and in-phase throughout the coverage area and with the studio. It is critical for preventing interference in the recently FCC approved Distributed Transmission System.
- **Financial and Business Transactions** are time-stamped using GPS receivers, providing a consistent and accurate way to maintain and trace records. Major investment banks use GPS to synchronize network computers located around the world.
- **Public Safety** uses of GPS timing include determination of emergency calls locations made from cell phones and synchronization of simulcast communications equipment.
- **Instrumentation** uses of GPS timing include seismic monitoring networks to improve the precise location of the epicenters of earthquakes and other seismic events. GPS timing is also used to synchronize the reporting of hazardous

[48] GPS World, Hurricane Hunters, July 2005

weather from terminal Doppler weather radar systems, as well as in a range of scientific and government related activities.

Operational Use Scenario/KPI - Availability (Coverage), Accuracy
Benefit – Efficiency and Productivity, Public Safety
Some GPS timing receivers are specialized units known as a Primary Reference Source (PRS), which are used in telecommunications applications. GPS PRS systems deliver a Stratum 1 traceable frequency reference accurate to +/- 1part per 100 billion, in addition to a UTC traceable precision time reference. SONET based transport systems and switching systems require Stratum 1 traceability for interoperability. As an example, a wireless network Radio Node Controller with SONET interfaces requires ST1 frequency traceability; as do all the SONET network elements in the transport system that deliver the traffic to and from the cell sites. If these elements are not precisely frequency aligned, timing 'slips' occur which dramatically reduce the throughput of the network. In some cases, such as UMTS, a GPS derived frequency reference is used to center the RF carrier frequency to insure alignment that facilitates call handoff between adjacent cells. There are thousands of these specialized GPS PRS systems deployed in North American telecommunications networks.

6 Methodology for Analyzing Test Results

The method of analysis is a three step process.

1) The first step is to establish the susceptibility of the receivers to the proposed LightSquared emissions to their Key Performance Indicators (KPI). This is accomplished by controlled tests at the NAVAIR anechoic chamber. As discussed elsewhere in this report, detailed tests were conducted to ascertain how the various LightSquared proposed base station and handset configurations would impact a large variety of High Precision and Timing receivers over a large range of LightSquared power levels. The results of these tests will be used to establish detailed performance impact of the LightSquared transmissions on these receivers as a function of power level.

2) The second step is to establish the appropriate propagation model to use for the analysis. From the NAVAIR test data a strong correlation between power level and performance impairment can be established; however it does not provide an indication of the range over which the LightSquared signal will impair the operation of the GPS receivers being tested and to what extent a receiver will be

3) impaired at a given distance. This is accomplished by analyzing the Live Sky testing in Las Vegas.

4) The last step is to illustrate the geographical area of area impact to the KPI using the established propagation models and the power levels of susceptibility.

6.1 Susceptibility

The following Key Performance Indicators (KPI) were examined and summarized from the recorded receiver data in the form of 10%, 50% and 90% percentiles:

- 1 dB drop L1 C/N_0
- Loss of satellite lock
- 1 dB drop L2 C/N_0
- Maintain acceptable Position
- Maintain acceptable RTK solution
- Maintain GPS Lock (Timing)
- Sensitivity Degradation
- Acquisition Degradation
- Reacquisition Degradation

In each of the KPI summaries, the Divergence Point from normal operation was noted. The Divergence Point is the power level of the LightSquared emission (dBm) at the point a noticeable change in the KPI was detected.

It was expected that there will be a large range of Divergence Points considering the diverse set of receivers being tested.

6.2 Propagation Model

From the raw data collected in the Live Sky Las Vegas field trial, plots of received power levels vs. radial distance from the LTE towers were produced. Various proposed propagation models were superimposed on the field data. Two propagation models were chosen that bracket the field data (Best Case/Worst Case). The first that was chosen is the free space propagation model which seems to bracket the worse case interference (most damaging) in most but not all situations with some interference actually exceeding the level predicted by free space, presumably caused by constructive multipath. However, the GPS Community believes this is a case that must be considered when interference is the parameter of interest. The second propagation model that was chosen is the WILOS propagation model which seems to bracket the best case (least damaging) interference in most but not all situations with some interference observed being below that predicted by WILOS, presumably caused by severe Rayleigh fades.

LightSquared believes that theoretical propagation models have limited utility for this type of analysis as they make no account for terrain, morphologies or other variables which can serve to attenuate signal strength. For these reasons, LightSquared believes

that a probabilistic models, properly tuned for the environment that is to be evaluated would be a much more accurate predictor of signal strength in a given area.

6.3 Area of Impact

Using the Propagation Models chosen, graphic illustrations and tables were produced to show the area affected in each of the environments surrounding the Las Vegas tower installations.

6.4 Manufacturing and Temperature Variability

We note that the filters used in the RF paths of GPS receivers have significant manufacturing and temperature variability. In the course of testing, the results we see may thus be different than what can be guaranteed over manufacturing and temperature variability. While the time and scope of this study precludes establishing a de-rating model that can be applied to the test data, it should be kept in mind that the results will be optimistic.

7 Test Conditions

Operational scenarios identify the importance of signal coverage, positional accuracy, and augmentation signals.

To ensure repeatability of the measurements, indoor testing under controlled environment was called for. Radiated testing was chosen rather than conducted testing as the antenna subsystems in precision and timing receivers contain active elements and are an essential part of interference resistance. The goal of the radiated tests is to establish a relationship between interference power and measured parameters.

Live Sky testing then establishes the relationship between received power and location within the specific test areas.

7.1 Anechoic Chamber

To address accuracy, high precision receivers recorded the following information, from which accuracy can be computed:

- Pseudorange
- Carrier Phase
- Doppler

In addition, to the extent possible, the following GPS and augmentation accuracy-related performance parameters were recorded at a minimum rate of 1 second for each receiver undergoing test, inside or outside the chamber:

- Position and velocity accuracy: GPS stand alone and RTK
- Pseudorange accuracy
- Carrier phase accuracy
- Range Rate (Doppler) accuracy
- RTK ambiguity resolution statistics
- 1PPS error as measured by the TIC (for timing receivers)

For RTK testing, there are four sub-cases to consider:

1) The Rover and Base both experience interference.
2) The Rover experiences interference and the Base does not.
3) The Base experiences interference and the Rover does not.
4) The Rover and Base both do not experience interference (this is for comparison to the interference cases).

Control receivers outside the chamber received simulator signals just as the receivers inside the chamber did. Real time connection between receivers in the chamber and the control receivers outside the chamber was not be feasible, so post-processing was required for RTK results. Only the second mode above was evaluated in this report.

To address coverage, high precision and timing receivers, to the extent possible, recorded the following information (or the necessary raw data to compute the following information):

- C/N_0 (L1 and L2)
- Satellite tracking statistics
- Reacquisition time statistics (Hot Start)
- Acquisition time statistics (Warm Start)
- Position resolution statistics
- RTK ambiguity resolution statistics
- Receiver Status including GPS Lock Holdover Mode flag (for timing receivers)

For those receivers with L-band augmentation communication capability, the following information was collected to assess coverage:

- Packet Error Rate
- E_b/N_0

The radiation source emulated the LightSquared modulation at power levels that ensured the devices under test see the entire span of signal power likely to occur in the field. The GPS signal was provided by a GPS simulator using a standard constellation. Augmentation signals were actual modulation but with dummy data, as it was not practical to have actual augmentation data (StarFire, OmniSTAR) with simulated GPS data.

7.2Live Sky

Live sky tests were aimed at studying the relationship of broadcast power to received power on the ground. In the absence of such testing, antenna gain patterns and common propagation models might be used to establish the correspondence. Since the modeling differs between a communication coverage requirement and an interference requirement, testing was preferred.

The test conditions require towers with the rollout antenna broadcasting at a known power. Power data inside the intended radiation bands were collected on the ground.

GPS receiver parameters may also be collected as a check to validate the correspondence between live-sky received power and anechoic chamber received power.

7.3Laboratory

The Space Sub-Team performed conducted interference tests on two precision receivers. See the Space Sub-Team report in Appendix H.1.1.

8 Test Plans

8.1Anechoic Chamber

A test plan was developed for the anechoic test, and is attached in Appendix H.1.6.

8.2 Live Sky

A live sky test bed was initially devised in Las Vegas for the Cellular Sub-Team. Due to the schedule involved, no formal test plan was developed prior to the test by the High Precision, Timing, or Networks Sub-Teams. However, the testing that was done by Precision and Timing Sub-Team members, including the test conditions and procedures, is partly documented in Appendix H.1.2 and Appendix H.1.3.

8.3Laboratory

The test plan for Laboratory testing is that defined by the Space Sub-Team. Their report is found in Appendix H.1.1.

9 Test Facilities

9.1 Anechoic Chamber

Special requirements regarding the study schedule, the nature of the devices to be tested, and the number of devices to be tested guided the selection of a test facility.

The Sub Team had selected over 60 high precision and timing devices to be tested, but as the testing, analysis and reporting had to be complete by June 15, this required testing of the devices to be done in parallel. To maintain the requisite device-under-test antenna spacing, a chamber large enough to accommodate at least half, but optimally all of the devices under test at the same time was required. To fit all the receivers simultaneously, the height and width of the chamber would have to be approximately 40 feet, and to maintain sufficiently uniform radiation over the array of test devices, the chamber needed to be over 60 feet long. Testing these devices in parallel also required a temporary structure to be built and to occupy a cross-section of the chamber for the duration of the test. For this purpose the chamber would need sufficient access for the structural pieces to be brought in, and the chamber operators willing for this level of facility modification to take place.

Since the test devices in this category generally record data in proprietary formats, manufacturer's representatives would need to be onsite to collect the data and later convert it into a standard set of KPIs for analysis. Thus, the facility needed to have sufficient space to accommodate these people in addition to having space for observers to ensure impartiality.

Finally, the chamber was required to be anechoic in the L-band due to the significant power level differences between the interferor and the desired signal for the devices under test.

The NAVAIR facility in Maryland was chosen for the indoor testing as it best met the needs. The anechoic chamber measures 40 ft x 40 ft x 100 ft. See Figure 16 below.

Figure 16 NAVAIR Anechoic Chamber

There are two small doors into the chamber, and one large access door. The normal entrance leads into a ground floor lab, and it has a door into the chamber. This door is at the transmit end of the chamber. There is an elevated floor for personnel access to the chamber and which can be used for cabling. The second small door is at the receive end of the chamber and exits outdoors. The large access door is at the receive end of the chamber.

The transmit window is half way up the 40 foot wall (centered 20 ft from the floor and the sides). The opening is about 3 ft x 3 ft. The GPS/StarFire/OmniSTAR antenna will be mounted through the transmit window (there is an upstairs lab behind the transmit window). The LTE transmit antennas will be mounted on a wood structure at the rear of the chamber.

The antennas (and receivers with integral antennas) were mounted in a grid framework to give them a boresight arrangement with the transmitters. This required a wood structure that was partially built outside and assembled inside the chamber. There is a hoist inside the chamber that was used to erect it inside the chamber. There was a Hi-Reach that was used to help mount the antennas or receivers after the grid was erected. See Figure 17 and Figure 18.

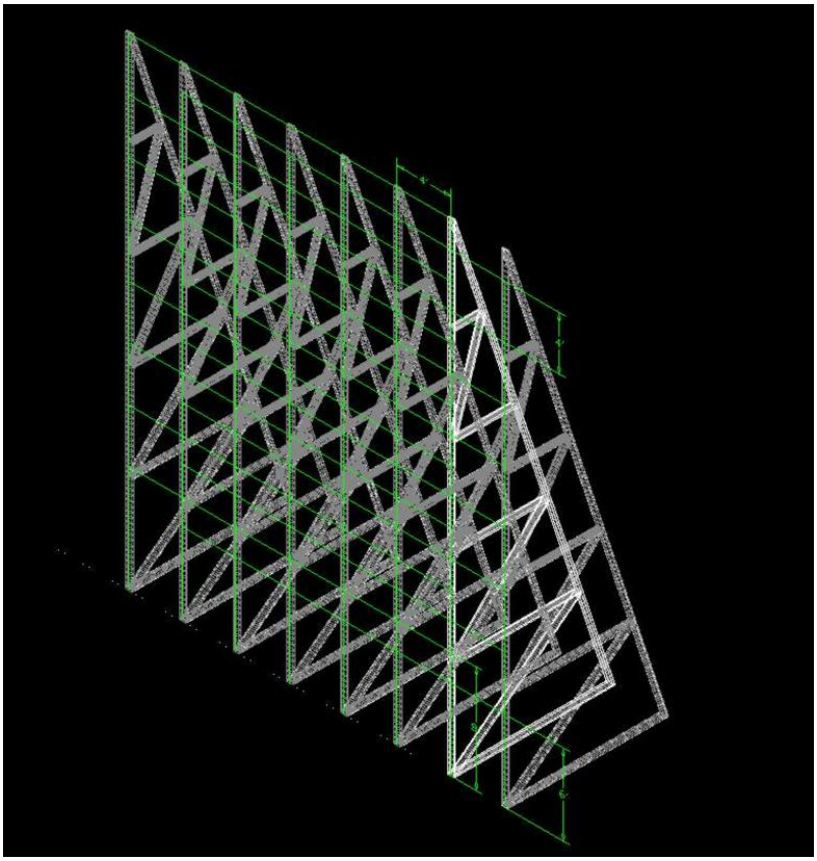


Figure 17 Antenna/Receiver Grid-1

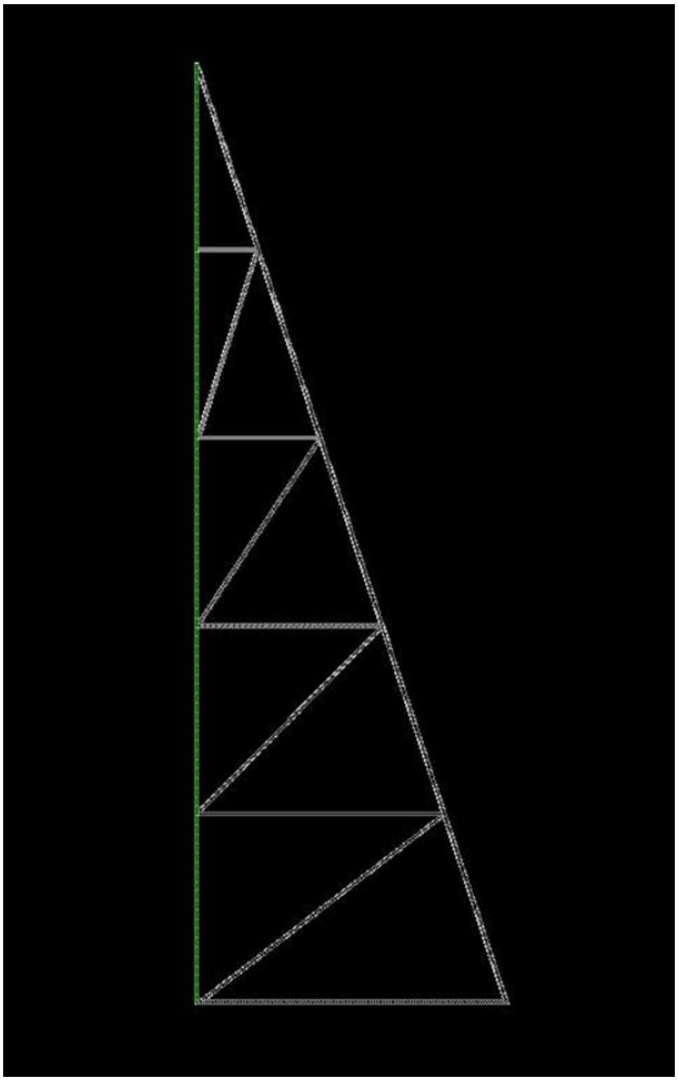


Figure 18 Antenna/Receiver Grid-2

The grid was constructed so that the receivers could be placed at the bottom of it and sheltered with absorber. The logging laptops were placed in the labs at the transmit end of the chamber.

9.2Live Sky

Facilities for the live sky testing comprised four towers in the Las Vegas, Nevada area with test transmitters and antennas installed by LightSquared. See Appendix H.1.2 for details for each broadcast location and height.

Facilities for testing devices were at the discretion of each manufacturer, but generally comprised vehicle-mounted antennas and receivers for data collection. Just as with chamber testing, the data would be converted by manufacturers into KPIs for later use. See Section 10.2 for more details on the facilities used for each participating manufacturer's live sky testing.

Some Sub-Team members also conducted on-the-ground power measurements during the live sky testing. Generally speaking this also comprised vehicle-mounted antennas and test equipment. See Appendix H.1.2 and Appendix H.1.3 for details on the facilities used for Trimble and Deere for power measurements.

9.3 Laboratory

Testing was done by the Space Sub-Team of two precision receivers in a facility at the Jet Propulsion Laboratory in Pasadena, California. These were conducted radiation tests. See Appendix H.1.1.

10 Testing

This section addresses the testing that was performed in the NAVAIR anechoic chamber, during the Las Vegas Live Sky testing, and by JPL/NASA in the laboratory.

10.1 Anechoic Chamber

Figure 19 below illustrates the test setup used in the NAVAIR testing.

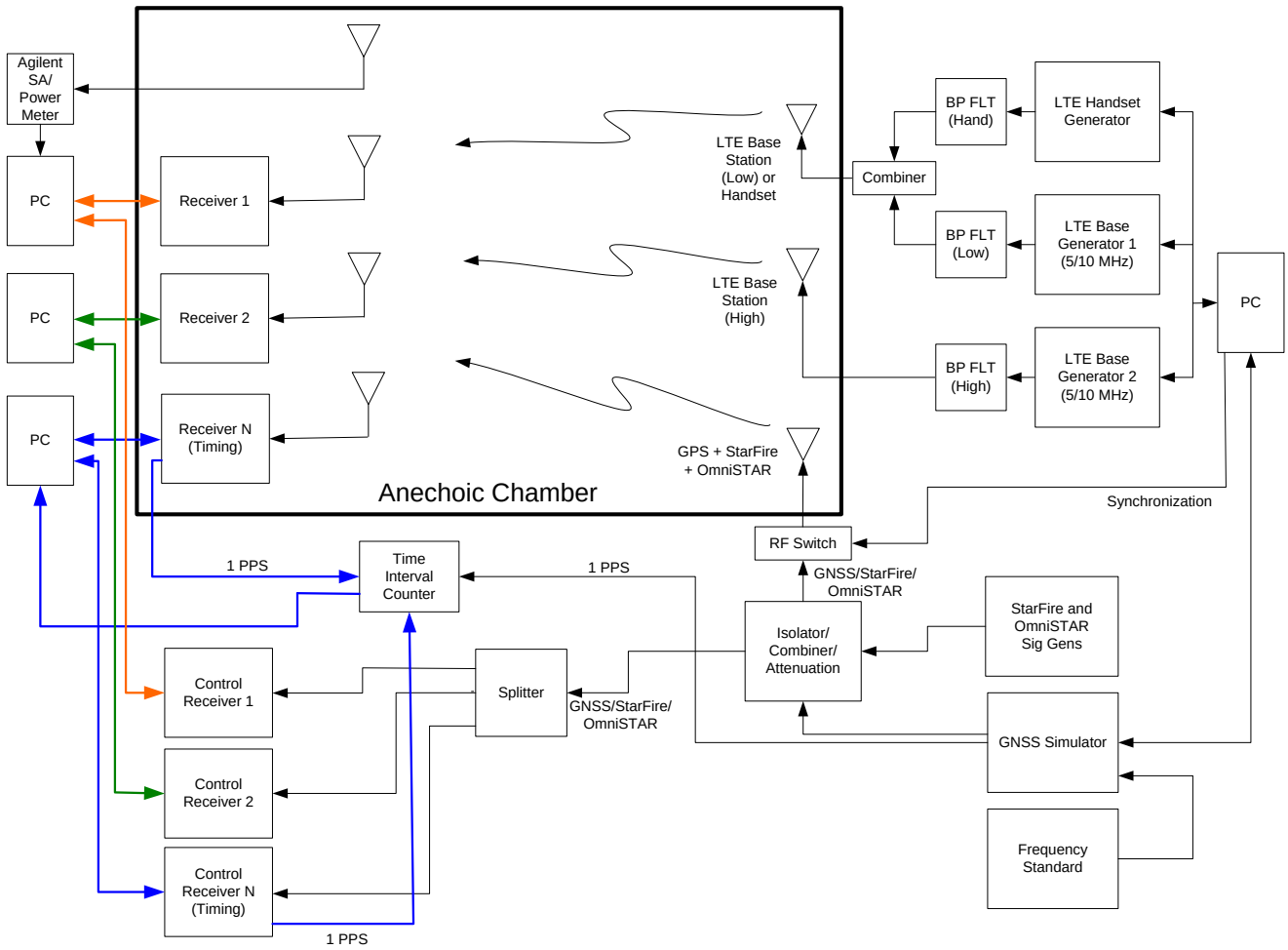


Figure 19 Test Setup

10.1.1 Physical Test Structure

The anechoic chamber tests were conducted at the NAVAIR facility in Maryland. The chamber measured 40 ft x 40 ft x 100 ft. The receivers under test were arranged on the test structure per the plan. Figure 20 below shows the physical arrangement of the block diagram above.

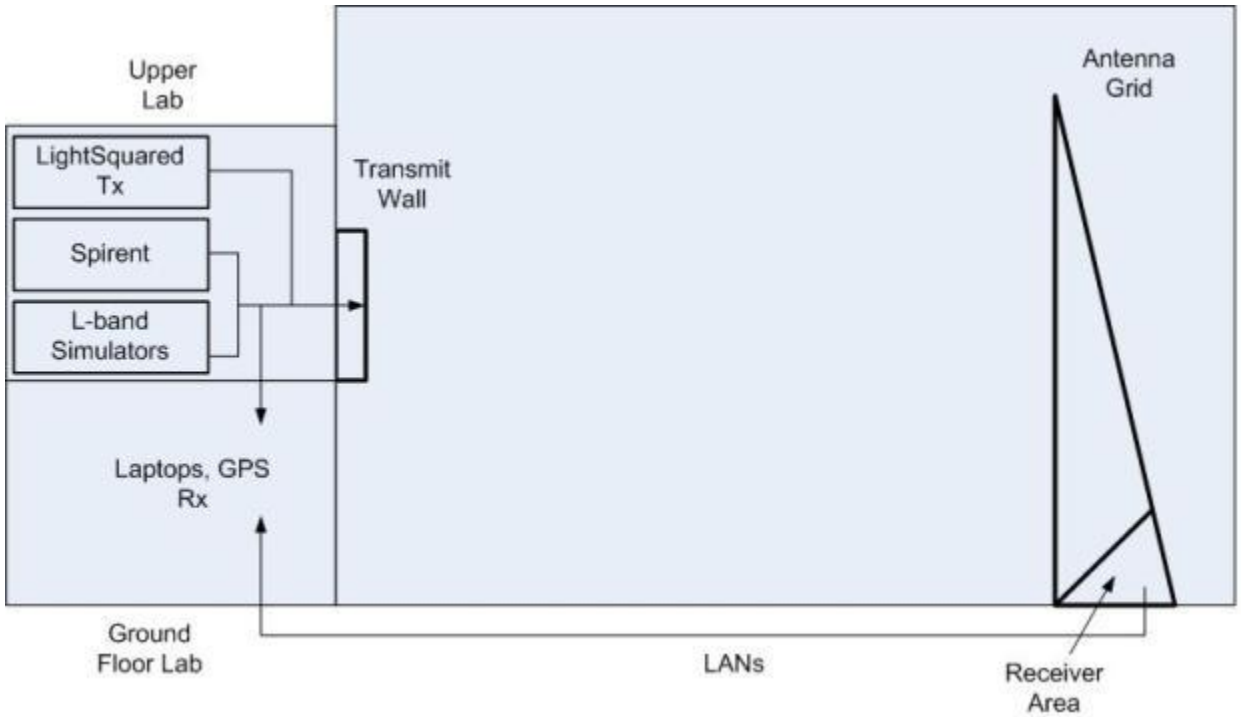


Figure 20 Physical Test Structure

10.1.2 Receivers Tested

The receivers tested are defined in Section 4.1.

Figure 21 below shows the final configuration of the receivers on the wall. Five calibration horns at the corners of the array and the center were used to calibrate LTE power, and a power monitor at the center of the array was used during all tests to monitor and record the received power.

Row\Col	A	B	C	D	E	F	G	H	I
8A									
8									
7A	Calibration Horn		Trim-ResSMT		Trim-Geo 6000 XH				
7		Nov-OEMV3G		Trim-NetR5-Z2		Trim-Geo 3000 XH			Calibration Horn
6A	Nov-OEMV1		Trim-ResT		Trim-R9-Z1		Leica SR530		FEIZ-AccuSync
6		Nov-OEM4		Trim-NetR9-Z2		Trim Juno SB		Top-NET-G3A	
5A	Nov-OEMV2G		Trim CFX750		Trim-Geo 3000 XT		Top-HiPer Ga		FEIZ-UNISync
5		Nov-OEMSTAR		Trim-NetR5-Z1		Leica GX1200		TruePosition	
4A	Nov-OEMV3G		Trim EZg500		Trim-Agilent Pwr		Top-MC-R3 (1)		Sep-AsteRx2e
4		Nov-OEMSTAR		Trim-AccuGold	Horn-LSQ Monitor	Leica GX1230		Sym-SSU2000	
3A	Nov-OEM628		Trim FMX		Trim GeoE 6000 XT		Top-GR-5		Sep-AsteRx3
3		Trim-MiniThblt		Trim-R8 GNSS		Leica GR10		Sym-TSource1000	
2A	Hem R320		Trim-5800		Trim Ag252		Top-MC-R3 (2)		
2		Deere 3050		Trim-Ag 262		Leica Uno		Sym-Tsource3500	
1A	Hem S3		Deere SF-3000		Trim MS992		Top-GR-3		Top-SGR-1
1	Calibration Horn	Deere iTC		Trim MS990		Leica GS15		Top-HiPerII	Calibration Horn

Figure 21 Physical Test Structure

10.1.3 LightSquared LTE Signals

The LightSquared LTE base station signals will be in the 1525 MHz – 1559 MHz band. The LightSquared handset signals will be in the 1626.5 MHz – 1660.5 MHz band.

- $F5_{High}$: 1550.2 MHz – 1555.2 MHz
- $F5_{Low}$: 1526.3 MHz – 1531.3 MHz

- $F10_{High}$: 1545.2 MHz – 1555.2 MHz
- $F10_{Low}$: 1526.0 MHz -1536.0 MHz
- F_{HS}: 1627.5 – 1637.5 MHz

The LTE signals were generated using an Agilent Vector Signal Generator Model E4438C loaded with the Agilent N7624B Signal Studio for 3GPP LTE FDD option package. The representative LightSquared LTE downlink signal was generated from the parameters in Table 7.

Name	Setting	Comment
Center Frequency	1552.7 MHz & 1528.8 MHz 1531.0 MHz & 1550.2 MHz	For 5 MHz BW For 10 MHz BW
Release	3GPP R8	
Duplexing	FDD	
Modulation	OFDM/OFDMA	
Frame Duration	10 ms	
Sub frame duration	1.0 ms	
Subcarrier Modulation	QPSK	For PCH, PDCCH, PDSCH
Subcarrier Size	15 kHz	
Channel Bandwidth	5 MHz or 10 MHz	According to test
PRB Bandwidth	0.180 MHz	
Sampling Rate	7.68 MHz or 15.36 MHz	For 5 MHz or 10 MHz channel
FFT Size	512 or 1024	For 5 MHz or 10 MHz channel
Dummy data	PN9	

Table 7 Downlink Parameters

The representative LightSquared LTE uplink signal was generated from the parameters in Table 8.

Name	Setting	Comment
Center Frequency	1632.5 MHz	
Release	3GPP R8	
Duplexing	FDD	
Allocation	1 Leftmost RB Freq 1628-1628.180 MHz	
RB Bandwidth	180 kHz	
UE Power	23 dBm	
Subcarrier Modulation	QPSK	
Dummy Data	PN9	

Table 8 Uplink Parameters

10.1.4 Setup and Calibration of LightSquared LTE Signals

The steps involved in calibrating the LTE signals are noted below:

- LTE signals were radiated from a pair of 16 dBi linearly polarized horn antennas separated approximately 2m horizontally and 1m under the GPS radiator. One of

the horns was oriented to transmit vertical polarization and one oriented to horizontal. The different polarizations were used to prevent cross-talk between the antennas that would create unwanted intermodulation products during the dual band tests. Figure 22 below shows the LTE transmit chain. The coupling from one antenna to the other was measured at -75 dB.

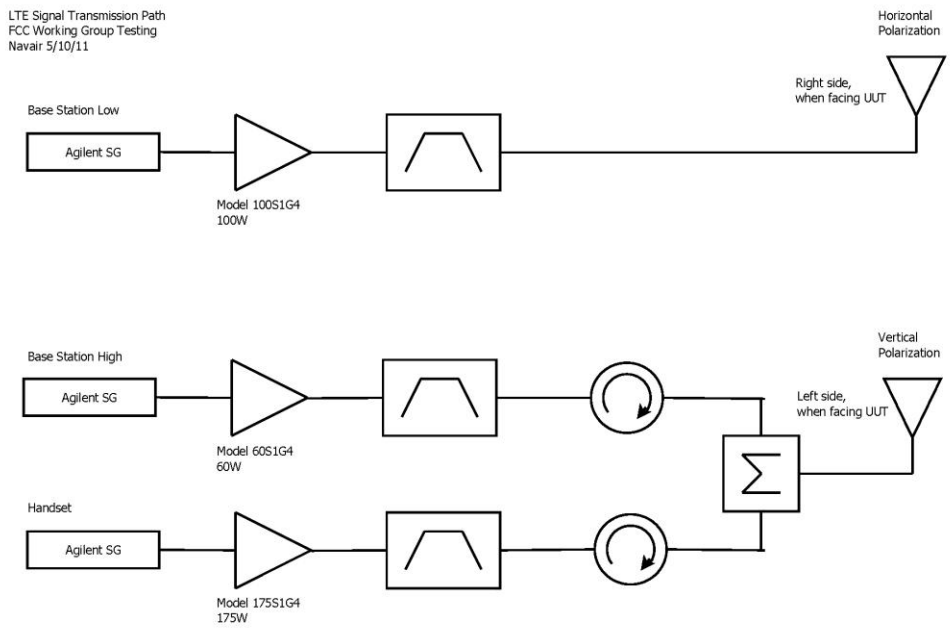


Figure 22 Transmit Chain

- The following seven LTE base station and handset carrier frequency configurations were used for the interference testing and are shown below with their respective transmit polarizations.
  - $F5_{Low}$ Horizontal
  - $F5_{High}$ Vertical
  - $F5_{High} + F5_{Low}$ Vertical and Horizontal
  - $F10_{Low}$ Horizontal
  - $F10_{High}$ Vertical
  - $F10_{High} + F10_{Low}$ Vertical and Horizontal
  - F_{HS} Horizontal
- Although a two tone intermodulation test was done as part of the LTE setup, CW tones have much higher levels of intermod products than an equivalent power of

LTE signal. The analysis in Section 11.5 is a rigorous treatment of the possibility of intermodulation in the LTE transmit system.

- The distance in meters between the face of the horn antenna and the UUTs was approximately 23 m.
- The effective LTE transmit power range as measured into a 0 dBi antenna at the wall was -17 dBm to -85 dBm.
- Five standard gain horns were mounted to the wall in the four corners and the center. These horns were used to determine the spread of LTE powers across the GPS receivers. The range showed a minimal LTE power spread across the wall of +/-3 dB. The measured spread is shown in the Figure 23 below.

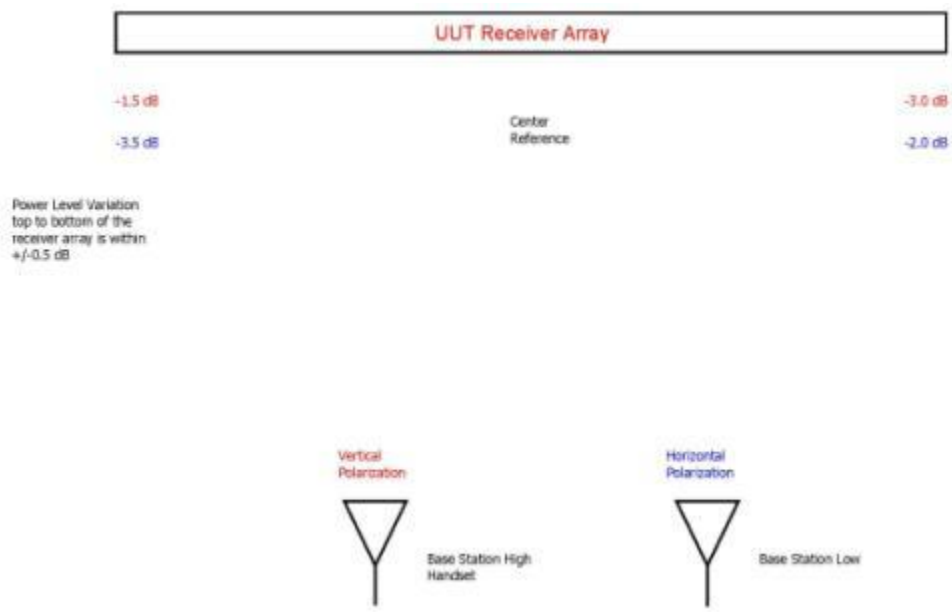


Figure 23 Transmit Polarizations

- The Handset signal was passed through a K&L cavity filter prior to being transmitted to the UUT. This signal did not represent a realizable handset filter. The frequency response of the filter is shown below in Figure 24. The results for this portion of the test should be viewed as the best case performance of the GPS receivers.

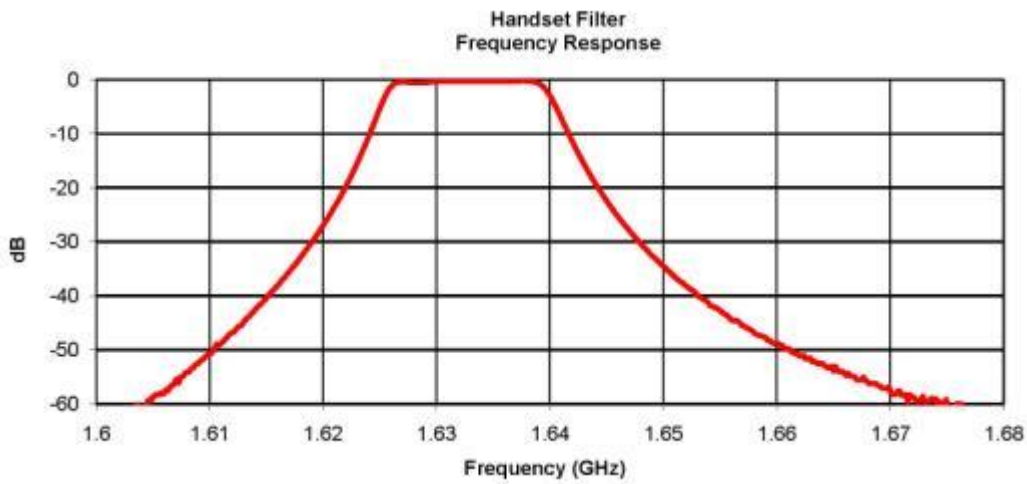


Figure 24 Handset Filter

The LTE signal was be pointed directly at the boresight of the UUT, while a typical use case will be at a lower elevation. One will need to evaluate the elevation gain pattern of the particular antenna under test and apply the necessary offset.

10.1.5 Setup and Calibration of GPS Signals

The steps involved in calibrating the GPS signals are noted below:

- The Spirent GNSS simulator was locked to an external, free running rubidium 10 MHz source.
- The simulator used to generate the GNSS signals will have internal noise that permits the C/N_0 ratios to be set independent of the actual output power. This can be maintained even when using external amplifiers, provided the additional amplifier's noise power is well below the simulator output power.
- A broadband, cavity backed spiral with right hand circular polarization was used to transmit the GPS and MSS correction signals (OmniSTAR and StarFire).
- The peak C/N_0 was set to 47 dB-Hz.
- Setting the Spirent GPS simulator to output a CW signal at the same power level as the modulated carrier, the four corners and the center were measured. It was found that all points on the wall were measured to be within 3 dB.
- The reference receiver from each company was supplied a direct cable feed to the Spirent simulator via a power splitter. The attenuation to each reference receiver was adjusted to yield a nominal C/N_0 value that matched the receiver in the chamber. This attenuation accounted for the variation in LNA gains by the various manufacturers.

10.1.6 Setup and Calibration of the Timing Equipment

The steps involved in calibrating the Timing equipment are noted below:

- Some Timing UUTs will have an associated Time Interval Counter (TIC).

- The primary 1PPS control signal shall be provided by the GNSS Signal Generator.
- If required by the TIC, a stable frequency source can be provided by the GNSS frequency reference.
- Measure and record the steady-state time interval before the LTE signals are applied.
- Use the clean steady-state measurement above as the "truth" value during the subsequent LTE emissions tests.

10.1.7 Interference Among Receivers

Interference from adjacent receivers on the wall was determined by examining the C/N_0 value with all receivers turned on and then comparing to C/N_0 values with only the receivers from a single company turned on. It was found that there was no significant difference in C/N_0 from each condition.

10.1.8 Test Automation

Spirent will be providing automation of the LTE generators and the Spirent simulator. There are constraints that apply to this automation:

1) Time from the Spirent GPS simulator was used to coordinate all testing activities. Time must increase monotonically throughout the tests, but will not be synchronized to real world time.
2) The GPS scenarios in the Spirent simulator used 24 satellites. The power from the satellites will be set to the minimums specified in ICD-GPS-200C (Navstar GPS Space Segment/Navigation User Interfaces, the signal specification for GPS L1). There will be 4 satellites in each of the 6 GPS planes, with spacing between satellites reasonably uniform.
3) The receive antenna model used in the Spirent simulator will be that from a hypothetical GPS rover antenna. The gain drop from zenith to horizontal was set to 10 dB. See Figure 25 below for actual values.

Nominal GPS Rover antenna
Gain pattern relative to boresight
RHCP
1575.42 MHz

Deg	Amplitude
0	0
5	0
10	-0.1
15	-0.2
20	-0.5
25	-0.9
30	-1.4
35	-1.9
40	-2.5
45	-3.15
50	-3.85
55	-4.5
60	-5.1
65	-5.8
70	-6.5
75	-7.3
80	-8.1
85	-9
90	-10

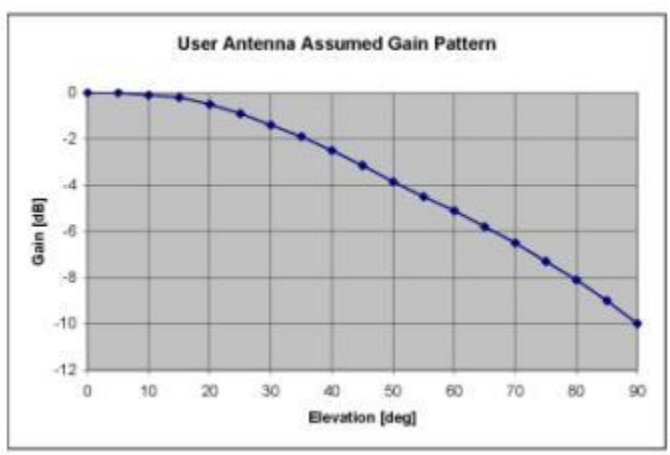


Figure 25 Spirent Antenna Gain

4) The location of the receivers for the Spirent scenarios was:
    - Latitude: N 38° 15’
    - Longitude W 76° 25’

10.2 Live Sky

The Live Sky testing followed too closely behind the NAVAIR testing for the High Precision, Timing, and Networks Sub-Teams to have organized a common test plan. Consequently, each company or organization participating in the Live Sky testing did so primarily on its own. The following companies and organizations from these Sub-Teams provided reports on their testing.

- Trimble – power and receiver testing
- Deere – power and receiver testing
- Verizon Wireless –cell site Timing receiver testing
- NOAA/NGS - receiver testing
- Sprint Nextel –cell site Timing receiver testing
- Topcon - power and receiver testing

The Trimble and Deere teams focused particularly on power testing. The following sections detail the calibration and testing procedures used for the Las Vegas testing.

10.2.1 Trimble Live Sky Testing

10.2.1.1 Set-Up

The set-up for collecting GNSS signals and LTE power levels consisted of a van with antennas mounted to the roof with GNSS receivers and computers for logging the data located inside. A picture of the Trimble configured van can be seen in Figure 26 below.

Figure 26 Trimble Van

The Trimble method for measuring the LightSquared LTE signal consisted of a modified, passive Zephyr Model 2 antenna feeding a high linearity pre-amplifier that is then filtered and sampled by a Agilent true averaging power meter. A block diagram with the various components is shown in Figure 27 below.

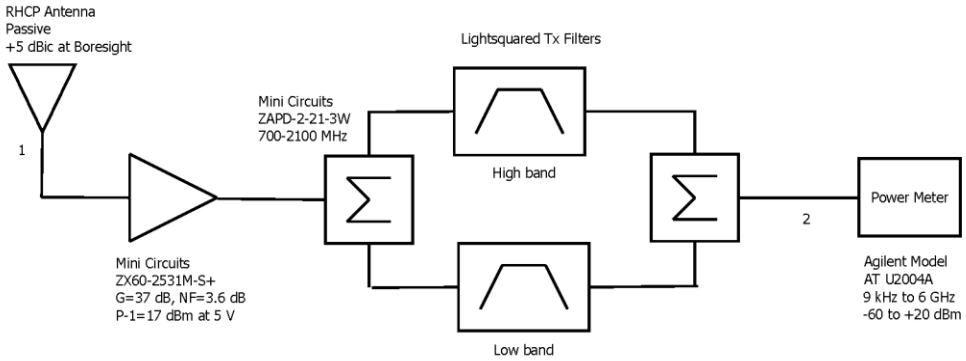


Figure 27 Power Measurement Block Diagram

10.2.1.2 Calibration

The nature of a broadband power meter, like the Agilent AT U2004A, is to measure the average power over its entire bandwidth. Since the primary mission of the present exercise was to measure only the power of the LTE signal, filters were employed to remove all the unwanted signals. The filters used for this test were constructed to the same specifications as the LightSquared transmit filters and did an excellent job of only presenting the LTE signal to the power meter. Figure 28 below shows the measured frequency response of the signal chain between the passive antenna and the power meter.

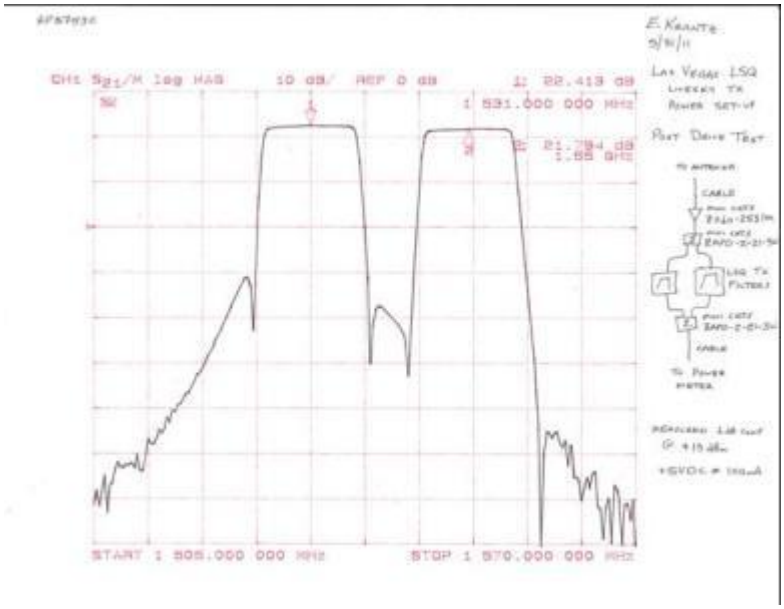


Figure 28 Frequency Response

The signal chain above can be seen to have 22 dB of gain. The measured dynamic range was from -15 dBm to -65 dBm. The high end was limited by the linearity of the pre-amplifier and the low end by the noise figure of the pre-amplifier coupled with the power meter.

The gain of the passive Zephyr Model 2 antenna when measured with a Right Hand Circularly Polarized (RHCP) source was 5 dBic of the frequency of interest (1525-1555 MHz) with less than 0.75 dB of variation. See Figure 29 below.

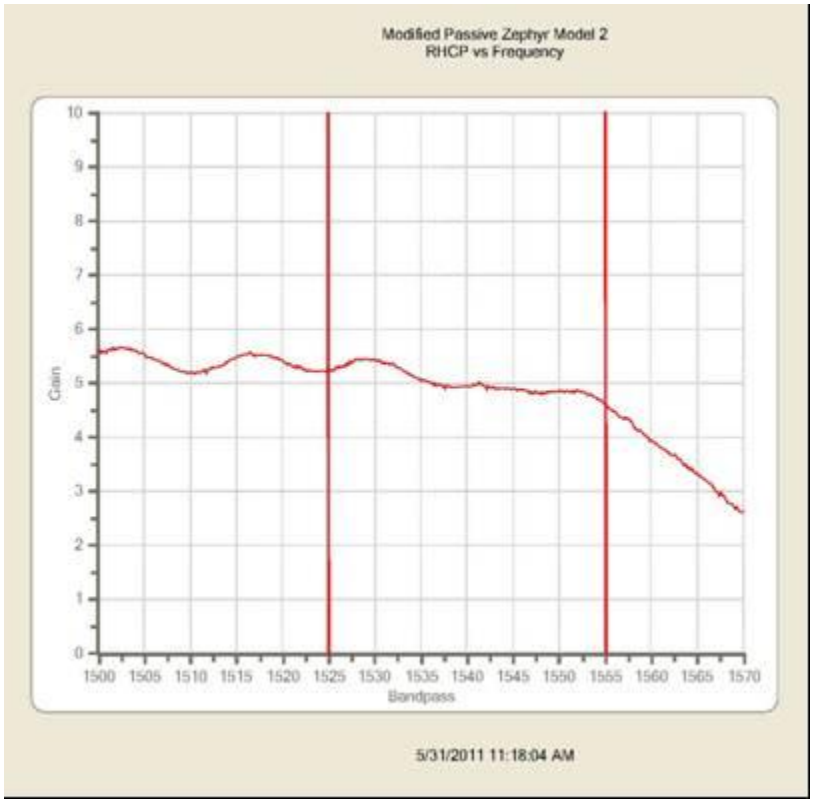


Figure 29 Antenna Gain vs. Frequency

The LightSquared transmit antennas consisted of +45 deg and -45 deg linearly polarized elements . An ideal RHCP antenna will lose 3 dB when receiving a linearly polarized signal. For the ideal RHCP antenna, the incident angle of the linear polarization has no effect on the received signal strength; horizontal, vertical, slant or arbitrary angle linear polarization will be 3 dB lower than the RHCP antenna gain.. The measured passive Zephyr Model 2 antenna gain versus elevation for a linearly polarized source is shown below in Figure 30. The peak gain for the antenna is +2 dBi for a linearly polarized source (+5 dBic - 3 dB polarization mismatch loss).

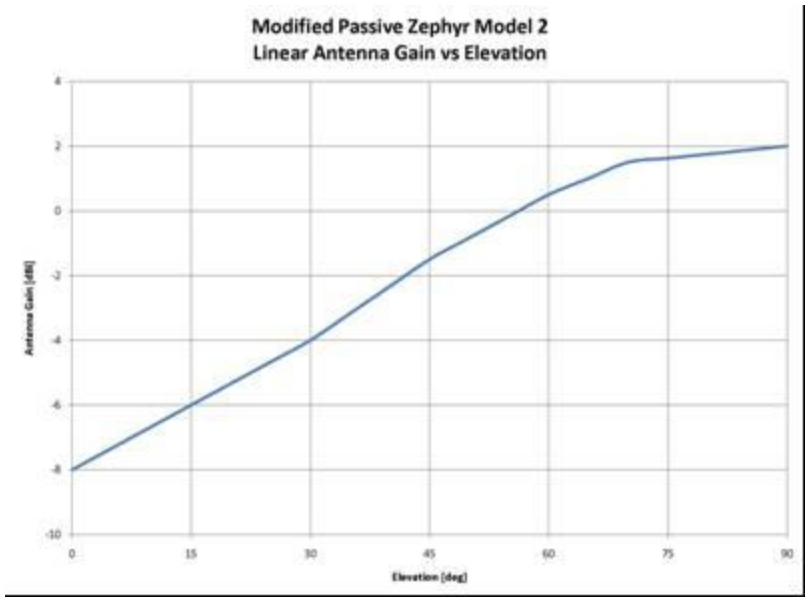


Figure 30 Antenna Gain vs. Elevation

Using the measured gain of the amplifier/filter chain (+22 dB) and the nominal antenna gain for a linearly polarized source antenna (+2 to -8 dBi depending on elevation), one can calculate the LTE power level into an equivalent 0 dBi GPS antenna. The LTE received power levels were transformed to an equivalent 0 dBi GPS antenna to provide the most general use of the data gathered during the Live Sky testing. With the wide range of antenna gains from the various GPS applications (cellular, general navigation, survey, machine control, etc), it was not possible to determine a "average" gain thus 0 dBi was chosen. The calculation provides the LTE power level for the nominal behavior of the RHCP antenna receiving a linearly polarized signal. The power levels reported below have taken into account the elevation dependence of the receive antenna but not the azimuthal dependence nor the non-ideal behavior of the antenna. The discussion that follows allows one to place a bound on the total uncertainty of the power measurement using a non-ideal RHCP antenna to receive an arbitrary linear polarized signal.There are some sources of error using a RHCP patch antenna to measure linearly polarized signals. Ideally receiving a linear signal into a RHCP antenna would cause a 3 dB reduction in signal level due to the polarization mismatch. For a non-ideal antenna, RHCP is really more elliptical instead of circular and thus will receive some angle of linear polarization better than others. A patch antenna, like the Zephyr Model 2, will become more elliptical as the elevation tends towards the horizon. This attribute can be seen in Figure 31 below. This figure shows how the gain varies when a linear source antenna is rotated through all angles as a function of the antenna under test's elevation. It can be noted that the difference between the highest gain and the lowest gain is 3 dB at elevations within 30 degrees of vertical and reaching a maximum variation of 8 dB at the horizon. This measurement shows that the uncertainty of the measurement was lower at higher incident angles (i.e., locations closer to the towers). In addition, the measurement puts an upper bound on the errors when measuring a linear source with a RHCP antenna at the horizon (+/-4 dB).

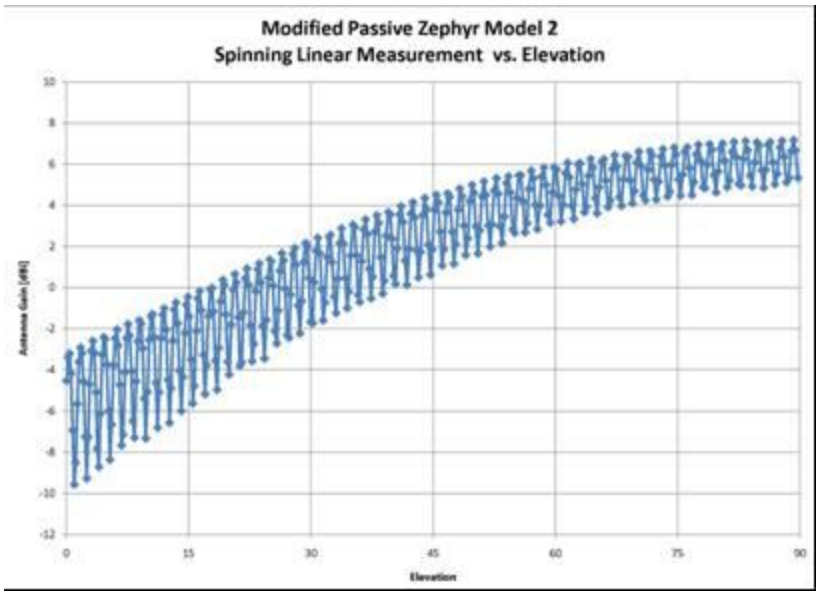


Figure 31 Gain Variation vs. Polarization and Elevation

One must also be aware that there is an azimuthal variation to the gain. Figure 32 below shows a similar measurement as above but with the antenna rotated azimuthally. Again the uncertainty can be bounded to +/-4 dB.

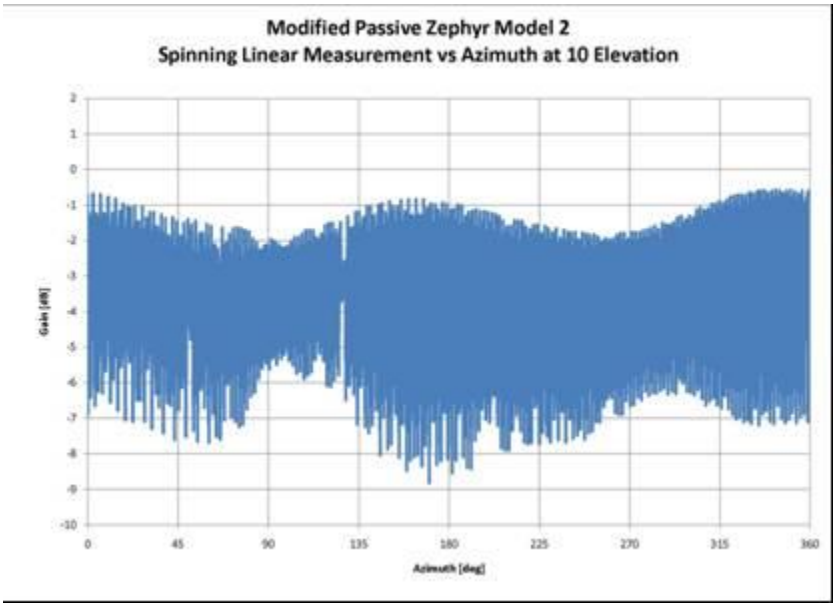


Figure 32 Gain Variation vs. Polarization and Azimuth

The upper bound on the error is +/-4 dB based on the minimum and maximum antenna gain using an arbitrarily angled linear source. The actual error should be less since the LightSquared transmit signals are orthogonal (+/-45 deg). Trimble tested this theory by parking the test van and rotating the measurement antenna in 45 deg increments over a 3 minute period. The results of this test are shown below in Figure 33 below. The measurement resulted in a field measured uncertainty of +/-2 dB at the horizon.

Las Vegas

Azimuth	5/24/2011 Dual 5 MHz Pwr Reading	5/26/2011 Dual 5 MHz Pwr Reading
0	-30.45	-32.02
45	-32.71	-33.24
90	-34.05	-32.47
135	-34.87	-34.32
180	-34.11	-31.73
225	-32.23	-30.52
270	-32.97	-31.51
315	-32.4	-33.06
360	-30.76	-32.8
	4.4	**3.8**

dB Pk-pk

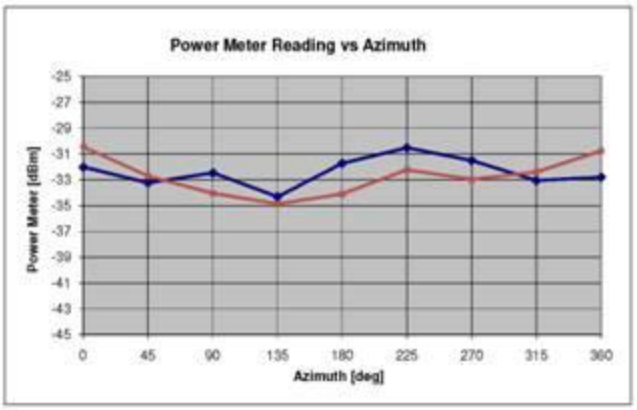


Figure 33 Measured Error in Azimuth

10.2.1.3 Correlation with John Deere Power Measurements

The Deere team chose to use a spectrum analyzer in the channel power mode to measure the RF power. Since the range of received power was 70 dB and that power was spread over a 30 MHz wide band, the possibility of deceptive power readings was a concern. To avoid distortion before the measuring device Deere ran the spectrum analyzer with the internal LNA disengaged. Deere used an SF-3000 with the LNA bypassed. Configured with no active circuitry, this antenna had no possibility of overload. The antenna was characterized for linear polarization near the horizon with a tilt of plus or minus 45 degrees, so as to best measure the transmitted LTE signal.

During the morning of 5/24/2011, the Trimble and Deere teams were able to meet up at various locations surrounding Rural tower 53 to compare the power readings at similar points in space and time. The corrected power measurements from each team is shown in Table 9 below.

Collected 5/24/2011 AM			
Dual 5 MHz			
Time	Trimble [dBm	Deere [dBm]	Trimble - Deere
00:06	-25	-24	-1

00:33	-42	-42	0
00:44	-33	-36	3
01:32	-57	-54	-3
02:01	-56	-52	-4

Table 9 Trimble and Deere Power Measurements

It can be seen that even though different power measurement methodologies and antennas were employed, similar powers were measured. The differences noted below can be attributed to the fact that the trucks, and therefore the receiver antennas, did not occupy the exact same point in space. The received power levels varied substantially over small distances.

10.2.1.4 Geotagging of Power Measurements

Multiple precision GNSS receivers were available on the truck during all of the data collection. Narrow band L1 only receivers capable of enhanced sensitivity tracking (more typical of the General Navigation class of receiver) were used to provide geotagging of the power data. As an inertial system was not available, several General Navigation class receivers and antennas were tested prior to deployment to select the one least susceptible to the impact of the LightSquared LTE signal so that it could be used to provide geolocation information for the measured power data.

Even the best General Navigation receiver that we could quickly source for the test had accuracy impaired and lost 1-2% of its position data when the receiver was close to an active LightSquared tower. The position loss percentage from the precision receivers was much greater, with impairment of the tracking for an even larger percentage of the data collected.

If a position was available from any of the receivers, it was used to geotag the power measurements. When no position was available for a particular power measurement, the measurement was ignored. This results in optimistic power measurements close to the tower, as some of the highest power data is lost when no position is available to geotag it.

Position data from each test was carefully manually analyzed against a map to eliminate any positions used for power geotagging that were in significant error. For example, Figure 34 shows data from tower 68 on May 18th collected using a consumer grade popular chipset attached to a narrow band L1 antenna. All data collected during the test is shown, including data when the LTE transmitter was on and off. During one of the transmit periods the unit is positioning, but the position had significant error. As this is not a class of receiver representative of High Precision, this was not explored further and data from this receiver was subsequently not used in the geotagging during the May 18th test; data from another narrow band L1 only receiver was used.

Figure 34 Tower 68 Positions

A laptop PC was used to control and log power meter data. The power meter time stamped the data using the PC clock. To maintain high correlation with the time stamps on the position data, the PC time was synchronized to UTC using Network Time Protocol (NTP) over an intranet in the test vehicle with time provided by a Trimble timing receiver. All data logged should be geotagged to better than 1 second time accuracy and position accuracy typically under 2 m unless the GNSS receivers were jammed.

The power measurements were logged at a rate of 2 Hz and the positions were logged at a 10 Hz rate. During the data processing stage the time stamped power data and position data were combined. The assumption was made that the power was from the closest tower and the distance to the closest tower was calculated. Using the distance to the tower, height information from the tower and calculated GPS receiver height the elevation angle to the tower was computed. An elevation dependent correction was made to the power measurement to remove the elevation dependent gain of the Zephyr 2 element. The resulting power data presented in this report is therefore referenced to a 0 dBi antenna over all azimuth and elevations subject to the measurement error budget described in the earlier sections.

10.2.1.5 Receivers Tested

Trimble receivers tested during the live sky events included:

- NetR9 with a Zephyr Model 1 antenna

- NetR9 with a Zephyr Model 2 antenna
- MS992 with an integral antenna
- FMx with a Ag25 antenna

10.2.2 Deere Live Sky Testing

10.2.2.1 Introduction

The test in Las Vegas with open air LTE signals and live sky GNSS and L-band augmentation signals was set up to evaluate cellular GPS receivers, but the High Precision Sub-Team realized that its participation could add a real life context to the laboratory measurements and assist the Sub-Teams by increasing the density of power readings. Although the late entry of the High Precision Sub-Team into this test precluded the generation of a coordinated, detailed test plan, the transmit side was well organized, so all the participants were synchronized.

10.2.2.2 Power Measurement Approach

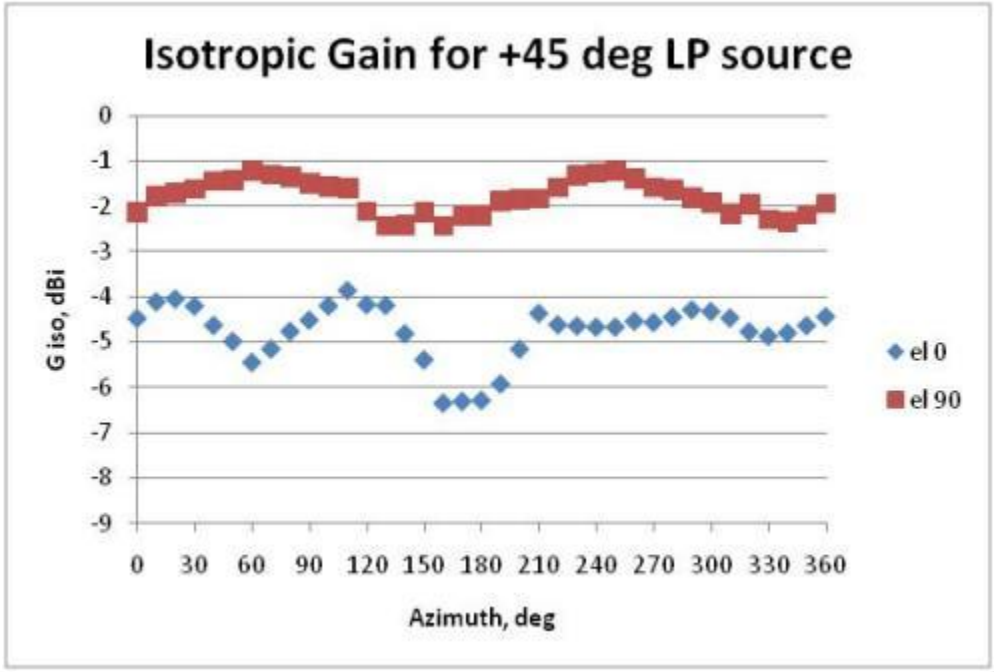
Both Deere and Trimble sent teams equipped with vans having GNSS receivers and LTE monitoring antennas on the roofs. Inside the van were computers for logging and equipment to measure the received LTE power. The Trimble power measurement apparatus consisted of a wideband RF power meter with a filter bank to reject all power outside of the two designated LTE bands. The Deere team chose to use a spectrum analyzer in the channel power mode to measure the RF power. Since the range of received power was 70 dB and that power was spread over a 30 MHz wide band, the possibility of deceptive power readings was a concern.

To avoid distortion before the measuring device Trimble used a high compression point amplifier and Deere ran the spectrum analyzer with the internal LNA disengaged. Both parties checked the linearity in the presence of high power signals by inserting attenuators and verifying that the reading dropped by the attenuation amount. At the low end, the LTE transmit cycle of 15 minutes on and 15 minutes off permitted the noise floor of the surrounding environment and the receive system to be observed, ensuring that only relevant power on readings were used. Finally, by using fundamentally different power measurement approaches, problems specific to spectrum analyzers and problems specific to RF power meters could be identified in the data.

10.2.2.3 Power Measurement Antennas

Both teams used modified GNSS antennas to gather the radiated LTE power. Trimble had a Zephyr with the LNA bypassed, and Deere used an SF3000 with the LNA bypassed. Configured with no active circuitry, these antennas had no possibility of overload. Both antennas were characterized for Linear Polarization near the horizon with a tilt of plus or minus 45 degrees, so as to best measure the transmitted LTE signal. The Deere antenna has a primarily vertical polarization response near the horizon, but there is enough of a horizontal component to cause a lower gain for the -45 degree tilt than for +45 degree. Since we do not know which tower was transmitting at which angle, this

response variation adds to the error budget. Specifically, the isotropic gain at the horizon is -6.0 dBi ±2.5 dB.



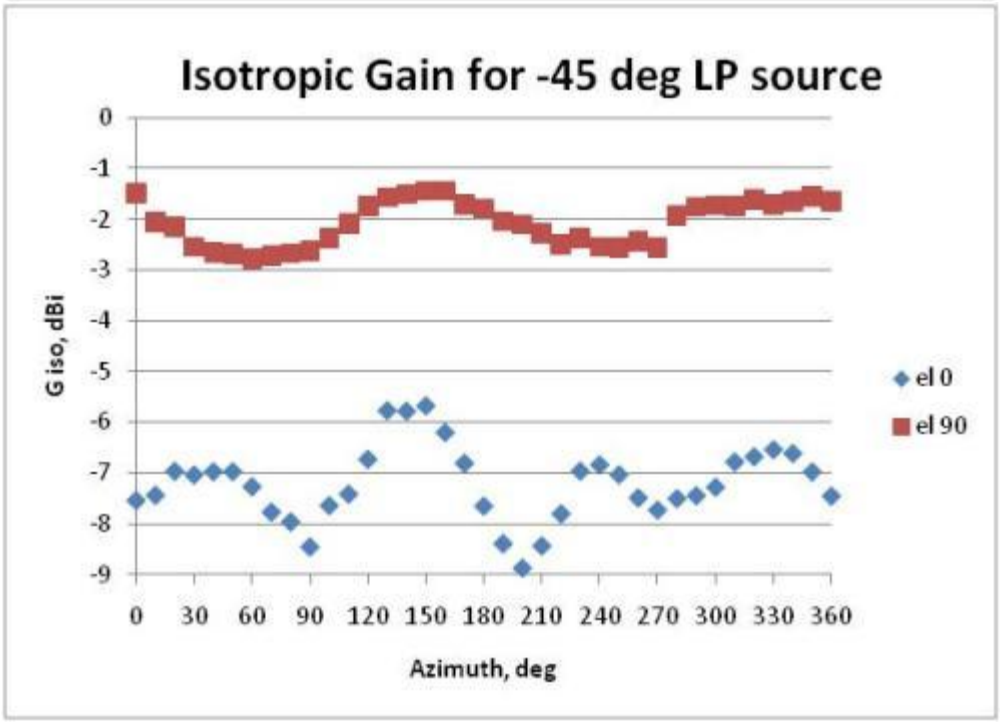


Figure 35 Gain vs. Azimuth for the Passive SF3000 Antenna

The response of the antenna for the two possible transmit polarizations is shown in Figure 35. As expected the response at 0 deg elevation is fairly insensitive to polarization angle.

10.2.2.4 Other Calibration Items

The spectrum analyzer was factory calibrated in April 2011. The cable from the antenna to the analyzer was post calibrated, and its loss is 2.5 dB at 1540 MHz.

10.2.2.5 Position Tagging of Data

The Deere team used a combination GNSS/INS positioning unit to log position simultaneously with received power. The INS (inertial navigation system) was able to maintain position even when the GNSS was unable to track satellites.

10.3 Laboratory

High Precision, Timing and Network Sub-Teams relied on Laboratory results provided by the Space Sub-Team. This group provided carefully prepared laboratory test data for two common High Precision receivers. Please refer to Appendix H.1.1 in this report and to their Sub-Team report for details on their testing plans, setup and procedures.

11 Test Results Analysis

11.1 Anechoic Chamber

A total of 57 receivers were mounted and tested in the anechoic chamber during the NAVAIR testing

Of the 57 receivers:

48 data Templates were received by the Sub-Teams and included in this report,

3 data Templates were received too late to be included but are available,

6 receivers failed to produce valid data Templates due to data recording problems, configuration errors, power problems or equipment failure.

.

We do not believe the absence of the remaining receiver data would have any effect on the conclusions of this report, as the remaining number of receivers is quite large.

11.1.1 Tests Executed

This section lists the tests that were run in the anechoic chamber for each of the LTE power scenarios. See Section 8 for more details on the tests.

1) F5H
    - Tracking
    - Sensitivity
    - Acquisition (Warm Start, receiver re-start)
    - Re-Acquisition (Hot Start, signal block)
2) F5H+F5L
    - Tracking
    - Sensitivity
    - Acquisition (Warm Start, receiver re-start)
    - Re-Acquisition (Hot Start, signal block)
3) F10H+F10KL
    - Tracking
    - Sensitivity
    - Acquisition (Warm Start, receiver re-start)
    - Re-Acquisition (Hot Start, signal block)
4) F10L

- Tracking
- Sensitivity
- Acquisition (Warm Start, receiver re-start)
- Re-Acquisition (Hot Start, signal block)

5) F10H
    - Tracking
6) F5L
    - Tracking
7) F-Handset
    - Tracking

11.1.2 Data Processing

Fifty-seven receivers were tested in the NAVAIR anechoic chamber. However, only 48 data sets were received from the individual manufacturers in time to be processed for this report.

The results of 48 of the receivers are included in the main sections of this report. Of the 48 receivers, 34 were High Precision units, 12 were Timing units with conventional GNSS antennas and 2 were Timing units with PCTEL antennas. The following are the codes of the receivers that were included in this processing:

- 34 High Precision Receivers

  H01411, H03143, H05279, H06347, H09552,
  H09956, H12497, H13565, H14892, H19165,
  H20637, H25314, H35187, H36255, H39200,
  H40932, H41336, H45609, H47341, H50950,
  H54154, H64026, H64431, H76180, H77912,
  H79385, H80048, H81521, H87121, H90730,
  H91393, H92461, H97802, H99275

- 12 Timing Receivers

  T02075, T05684, T25574, T26383, T29846
  T30251, T37728, T52681, T80453, T85389
  T90325, T93270

- 2 Timing Receivers with PCTEL antennas

  T44136, T92202

The Timing units were processed separately from the High Precision receivers in this report.

Two of the receivers tested, and for which data was received, were prototype Timing units utilizing the PCTEL narrow band L1 antenna[49]. These two units were studied separately from the other Timing receivers and included in a different section of this report.

Unfortunately, not all manufacturers provided data results for all tests. Nor did all manufacturers provide summary data for these tests. For this reason, the number of High Precision samples in all of the charts below are generally less than the total number of data sets. For the files missing data summaries, because these are very important parameters, NovAtel personnel manually examined these data sets to derive the necessary values. Most files received from the individual manufacturers had some incompatible anomalies for the automated data extraction process. Some of these anomalies included:

- Deleted Rows and Columns
- Rows and Columns moved to different locations
- Renaming Spreadsheet Tabs
- ASCII data in numeric fields such as "NA" or "Not Tested"
- Zeros or erroneous data in cells when the receiver was not tracking satellites
- Summary data not supplied

It was necessary for NovAtel personnel to modify some of the original data files received so that they could be processed.

The response of the receivers to each test was characterized by the 10th, 50th, and 90th, percentiles based on the list of participating receiver results sorted by the specific test outcome.

11.1.3 High Precision Receivers - Conclusions

The detailed results from the NAVAIR testing for High Precision receivers are found in Appendix H.1.10. The results are summarized in this section.

Table 10 below shows the High Precision receiver Key Performance Indicators for the tests run in the Anechoic chamber.

[49] The receivers are production units, and the PCTEL antenna is a production antenna, but the combination is a prototype assembly.

	F5H			F5L+F5H			F10L+F10H			Handset			F10L			F5L			F10H		
Receivers Affected	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
1dB drop in L1 C/No	-82	-56	-49	-82	-66	-57	-83	-72	-55	-77	-41	0	-67	-43	-25	-61	-43	-25	-81	-56	-47
loss of satellite lock	-61	-42	-30	-65	-54	-44	-63	-50	-43	-39	-22	0	-54	-28	0	-34	0	0	-61	-43	-38
1dB drop in L2 C/No	-78	-56	-45	-83	-63	-55	-77	-61	-53	-63	-41	-29	-73	-43	-24	-62	-42	-20	-75	-57	-47
Loss of Good Position	-68	-45	-35	-70	-58	-49	-67	-53	-47	-43	-26	0	-48	-30	0	-38	-18	0	-62	-47	-40
Loss of Good RTK	-69	-47	-38	-70	-58	-50	-69	-55	-47	-46	-27	-15	-46	-35	-16	-43	-21	0	-63	-47	-42
Sensitivity	-70	-60	-45	-75	-60	-50	-70	-65	-50				-60	-35	-15						
Reacquisition	-55	-45	-35	-75	-55	-45	-70	-55	-40				-55	-35	0						
Acquisition	-75	-55	-45	-75	-55	-45	-75	-65	-45				-75	-35	-15						

Table 10 LTE Power for Changes in High Precision KPI (dBm)

Each cell in Table 10 represents the LTE power required to affect the KPI value. Zeros indicate that the Test Condition was not observed. For example, a drop in L1 C/N_0 of greater than 1 dB in 10% of the tested receivers is produced by a F5H signal broadcast at -82 dBm (top left cell in Table 10).

LightSquared's Position:

The KPIs for all elements show significant improvement in the presence of the lower 10 MHz channel (F10L) compared to deployments utilizing an upper channel.

The comparative test results in the Figure 28 below demonstrate that the High Precision GPS devices in normal operational conditions, without the presence of a LightSquared signal, have C/N_0 variability from device to device almost 10 dB for the same GPS conditions. Even devices from the same manufacturer had shown considerable difference in performance. This suggests that a 1 dB degradation of C/N_0 does not have a meaningful operational impact and that user-identifiable changes in performance would be a more appropriate indicator.

If the absolute value of C/N_0 as reported by the device is inaccurate then the calibration of the relative magnitude of C/N_0 changes caused by changes in either GPS signal power or adjacent channel interference is also highly suspect, and cannot be relied upon as a KPI.

The GPS Community believe the LightSquared position is invalid due to the following reasons:-

There is a variation of the GPS antenna gain across the different manufacturers and models as even within the High Precision class the receivers may be optimized for different applications. The difference in gain impacts both LightSquared and GPS reception, and can result in an increase or decrease in GPS C/No and LTE jammer power incident on the LNA. Only zenith receiver antenna gain was exercised in the

NAVAIR testing, antennas having high zenith gain would have reduced low elevation gain.

Manufacturers use different methods for calculating C/No. Comparing the absolute non-normalized data is meaningless. However the degree of degradation remains the same whether the data is normalized or not. Outside the chamber not impacted by the LTE signal were control units for each manufacturer, however during the test the simulator signal was conducted into the units and not radiated and so impact on the C/No of representative antenna/LNA assemblies were not tested. As each antenna will potentially have a different zenith gain, some in excess of +5dBi, and the noise figure of each LNA may be slightly different this didn't get tested in the control units. Consequently when the data was analyzed a change in the C/No of the UUT was used to form the metric and implicitly normalizes the data. The raw data was not further processed to normalize it. The cellular subteam also accepted that there were variations in computed C/No, but chose to normalize their data.

The key metric is how each individual receiver degrades and analyzing the difference in absolute reported C/No across receivers is not meaningful without normalizing the data.

11.1.4 Timing Receivers - Conclusions

The detailed results from the NAVAIR testing for Timing receivers are found in Appendix H.1.11. The results are summarized in this section.

Table 11 below shows the Timing Receiver Key Performance Indicators for the tests run in the Anechoic chamber.

	F5L+F5H			F5H			F5L			F10L+F10H			F10H			F10L			Handset		
Receivers Affected	10 %	50 %	90 %	10 %	50 %	90 %	10 %	50 %	90 %	10 %	50 %	90 %	10 %	50 %	90 %	10 %	50 %	90 %	10 %	50 %	90 %
1dB drop in L1 C/No	-77	-48	-39	-74	-36	-22	-33	-19	0	-72	-45	-35	-72	-37	-23	-39	-15	0	-19	0	0
loss of satellite lock	-63	-34	-19	-63	-23	0	-18	0	0	-58	-31	-17	-59	-25	0	-21	0	0	0	0	0
Loss of GPS-Lock	-63	-39	-22	-64	-17	0	-23	0	0	-60	-34	-25	-59	-24	0	-24	0	0	0	0	0
Sensitivity	-70	-50	-40	-70	-40	-25				-70	-45	-35				-35	-15	0			
Reacquisition GPS-Lock	-60	-45	-35	-60	-30	0				-60	-40	-25				-25	0	0			
Reacquisition L1	-75	-45	-25	-40	-25	0				-65	-40	-30				-60	0	0			

Table 11 LTE Power for Changes in Timing Key Performance Indicators (dBm)

Each cell in Table 11 represents the LTE power required to affect the KPI value. Zeros indicate that the Test Condition was not observed. For example, a drop in L1 C/N_0 of greater than 1 dB in 10% of the tested receivers is produced by a F5L+F5H signal broadcast at -77 dBm (top left cell in Table 11).

The power values needed to affect the KPI for the Phase 2 plan are very weak signals. These values can be translated into radial distances from LTE tower locations showing the areas where these types of receiver are weakened or inoperable with the use of a propagation model.

LightSquared takes the following positions:

> The test results show considerable differences between the high precision and the timing device response with respect to the lower 10 MHz channel.

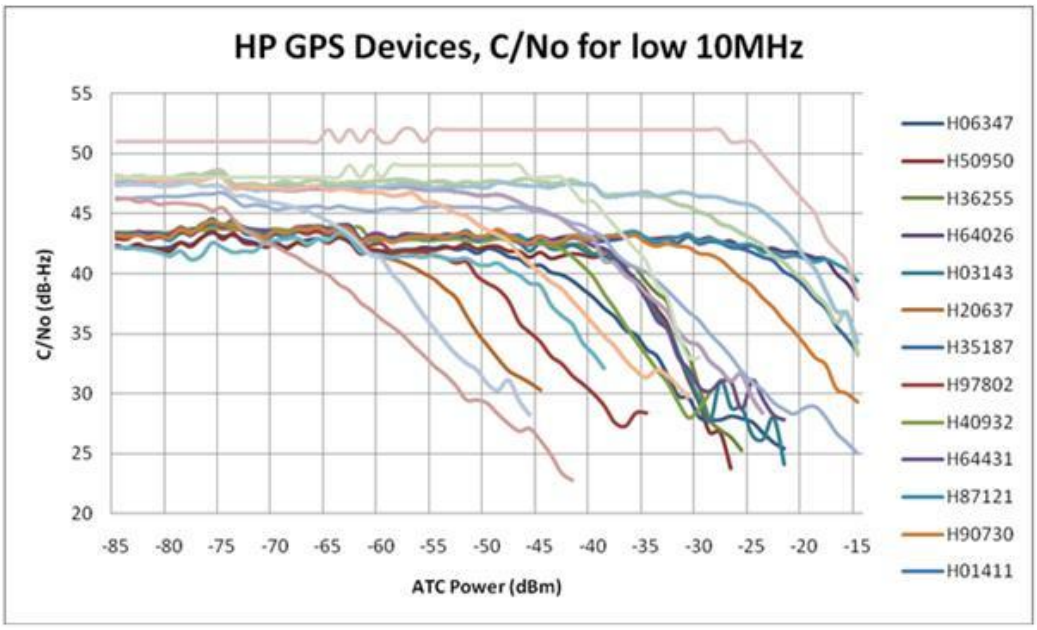


Figure 36 High Precision C/N_0 for Low 10 MHz

> It is clearly demonstrated in Figure 29 that the timing devices are generally immune to lower 10 MHz channel (with the exception of one outlier which begins to degrade at -40 dBm).

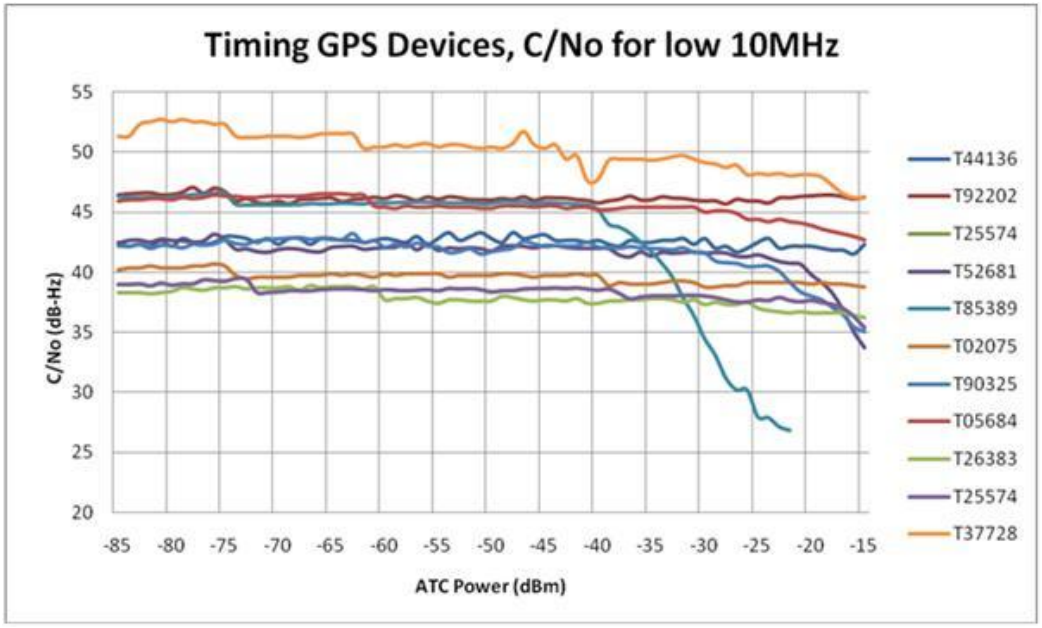


Figure 37 Timing Receivers C/N_0 for Low 10 MHz

11.1.5 PCTEL Antenna – Conclusions

The detailed results from the NAVAIR testing for the PCTEL antennas are found in Appendix H.1.12. The results are summarized in this section.

- These two receivers show no effect from either the F10L or F5L signal.
- There was slight loss of C/N_0 when the F10H signal was at high power values. However, there were no other noticeable effects in the KPI.
- For the test of the F5H signal, one of the receivers dropped more than four satellites when the power level reached -21 dBm.

The GPS Community takes the following position:

> This loss of satellites is alarming giving the modest effect (under 1dB) on the measured C/N_0 values. One possible explanation of this could be due to spectral content in the emissions interacting with the C/A codes and specific channel tracking frequencies. This alarming observation requires further research and investigation.

LightSquared takes the following position:

> The test results clearly indicate the benefits that can be attained through the use of proper filtering in narrowband GPS timing receivers. LightSquared also believes that these lessons can, and should, be applied to the assessment of mitigation options for other types of GPS receivers as well. The PCTEL antenna functioned well in the Las Vegas field tests, even in the presence of dual carriers. It further notes that intermodulation is not an issue with the

lower 10 MHz channel on a stand-alone basis. The LightSquared concluded that the PCTEL antenna completely protects the timing receivers from the potential of overload in many spectrum configurations, especially the F10L configuration.

The GPS Community takes the following position:

1 The live sky testing of the PCTel antenna did not include any measurement of the received interference power at the device under test, therefore the power level at which the performance was observed is unknown.

2 The live sky test was conducted at 3dB below LightSquared's planned power levels for deployment

3 The PCTel antenna is highly narrowband and thus will not work for wideband high precision or future modernized GPS signals, see Section 3.5

4 New designs do not work for the existing installed base without large scale equipment replacement.

- Either of the dual signal combinations (F5L+F5H) or (F10L+F10H) causes significant detrimental changes to the performance of these receivers. Acquisition of satellites is not possible if the LTE signal powers are above -25 dBm or -30 dBm depending on the receiver. The sensitivity of the receivers is impacted when the LTE signal levels are above -50 dBm.

The GPS Community takes the following position:

Some of the detrimental effects noted during dual band testing are likely due to the third order harmonic of the two combined signals.

LightSquared takes the following position:

The PCTEL antenna functioned normally (no alarms were triggered) in the Las Vegas field trials, as observed by several CMRS operators, including Sprint and Verizon. LightSquared also notes that intermod is not an issue with regard to the Lower 10 MHz channel operation on a stand-alone basis.

11.1.6 OmniSTAR and StarFire - Conclusions

The detailed results from the NAVAIR testing for StarFire/OmniSTAR are found in Appendix H.1.13. The results are summarized in this section.

- All results indicate that the LTE emissions produce significant degrading effects on the receiver's ability to track the L-Band augmentation signal.
- There appeared to be significant Third Order Intermodulation interference effects during the dual frequency tests (F5L+F5H and F10L+F10H).

11.2 Live Sky

The Live Sky testing followed too closely behind the NAVAIR testing for the High Precision, Timing, and Networks Sub-Teams to have organized a common test plan. Consequently, each company or organization participating in the Live Sky testing did so primarily on its own. The following companies and organizations from these Sub-Teams provided reports on their testing.

- Trimble – power and receiver testing
- Deere – power and receiver testing
- Verizon Wireless –cell site Timing receiver testing
- NOAA/NGS - receiver testing
- Sprint Nextel –cell site Timing receiver testing
- Topcon - power and receiver testing

These reports are included in the Appendices in full. The summary and primary conclusion from these reports are presented in the following sections, followed by a summary of the overall results.

11.2.1 Trimble Summary

Trimble personnel collected an extensive data set in the greater Las Vegas area over nine consecutive nights between May 18th through May 26th. Their attached report (Appendix H.1.2) provides a detailed account of their activities, data collection, and results.

They had several objectives:

- Establish an RF propagation model to use as part of this analysis.
- Analyze the performance of several types of GPS receivers over a range of distances and types of terrain (urban, suburban) from real-world LightSquared cell towers.
- Analyze the performance of OmniSTAR radio reception over a range of distances and types of terrain (urban, suburban) from real-world LightSquared cell towers.

11.2.1.1 RF Propagation Results Summary

See Figure 38 below.

Trimble takes the position:

> Trimble found that the free space power model worked well as a predictor of expected LTE signal power.

LightSquared takes the position:

> LightSquared notes that this model is effective at setting an upper bound for expected signal propagation. It also stresses that theoretical models such as free space are not useful for this type of application. Detailed models that are tuned to specific frequency bands and environments, that can properly account for terrain and

morphology variations, are essential to determining the likelihood of experiencing a particular signal strength at a specific location.

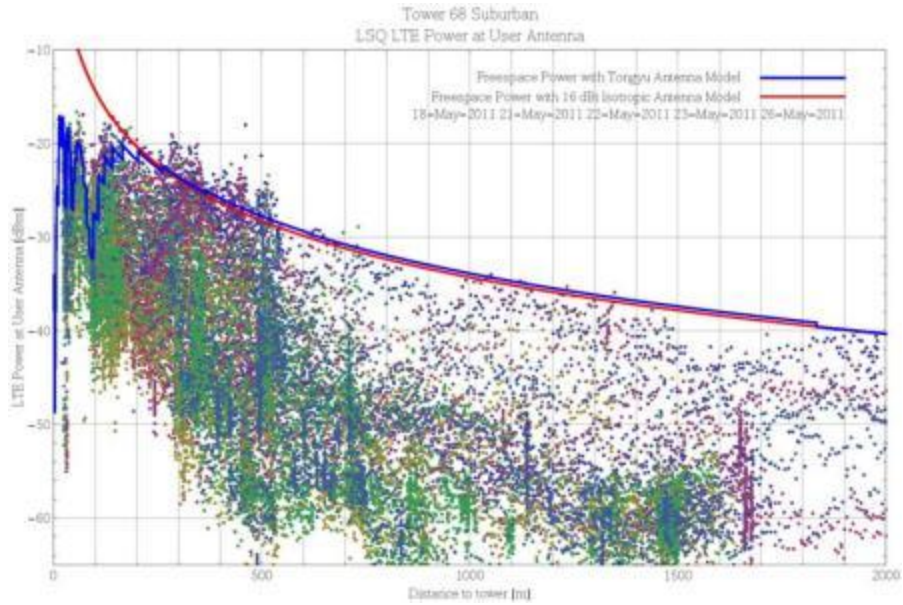


Figure 38 Las Vegas Tower 68 Measured Power vs. Range

11.2.1.2 GPS Receiver Performance Summary:

Trimble found that High Precision receivers were very susceptible to the LightSquared emissions. They found that the LightSquared emissions prevented their High Precision receiver from tracking at very long ranges from the cell tower. Figure 39 shows the dramatic effect on the C/N_0 values (red dots) when the LightSquared emissions were present compared with the C/N_0 values (blue dots) when the LightSquared signal was off.

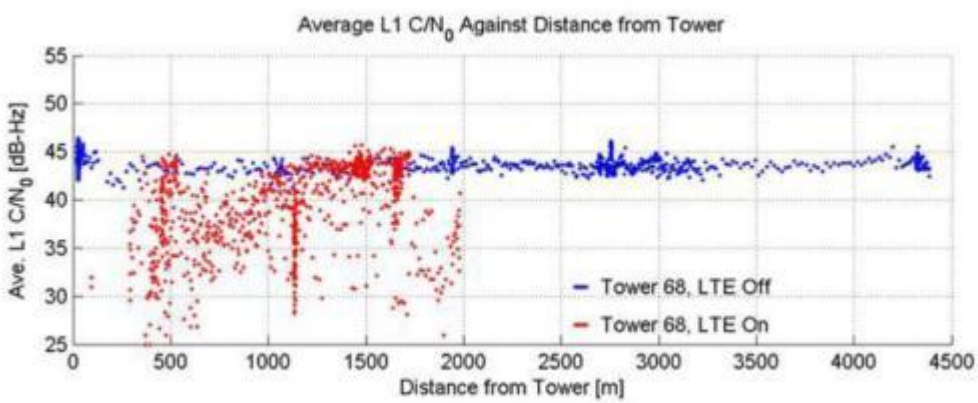


Figure 39 Las Vegas C/N_0 F5L+F5H

In the case above, the precision receiver was not able to calculate a position in any mode out to 2 km from the tower, at which point the van was turned around, so it is not known for how far the precision GPS denied zone extended.

11.2.1.3 OmniSTAR Receiver Performance Summary

Trimble found extensive interference to the reception of the OmniSTAR signal. Figure 40 below is a plot of the C/N_0 values of the OmniSTAR signal with (red) and without (blue) the presence of LightSquared signals. Note the dramatic difference with and without the LightSquared emissions.

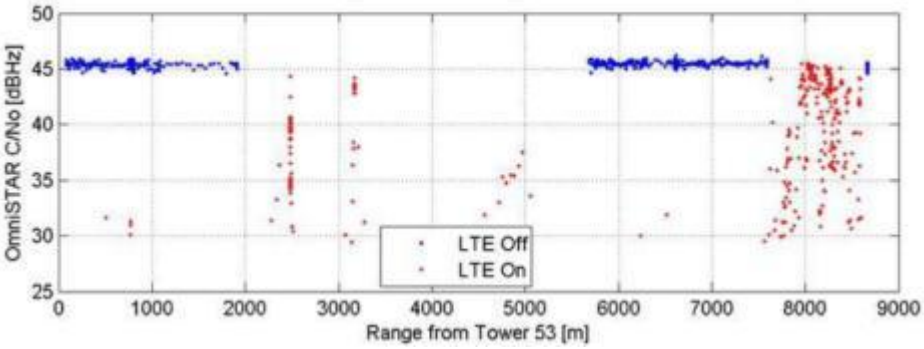


Figure 40 OmniSTAR C/N_0 Values

The OmniSTAR tracking is almost completely jammed out to 8.5 km and even out at that range the tracking is significantly degraded.

11.2.2 Deere Summary

With similar objectives to Trimble's, Deere collected an extensive dataset during the Las Vegas testing in order to verify the RF propagation model and test several of their receiver types.

Deere found that the free space model fit well with the data they collected. The red curve on Figure 41 is the free space model superimposed on the field data that they collected. Deere demonstrated that significant LightSquared power levels (over -60 dBm at greater than 15 km, and over -65 dBm at greater than 22 km) are received by GPS receivers at long ranges.

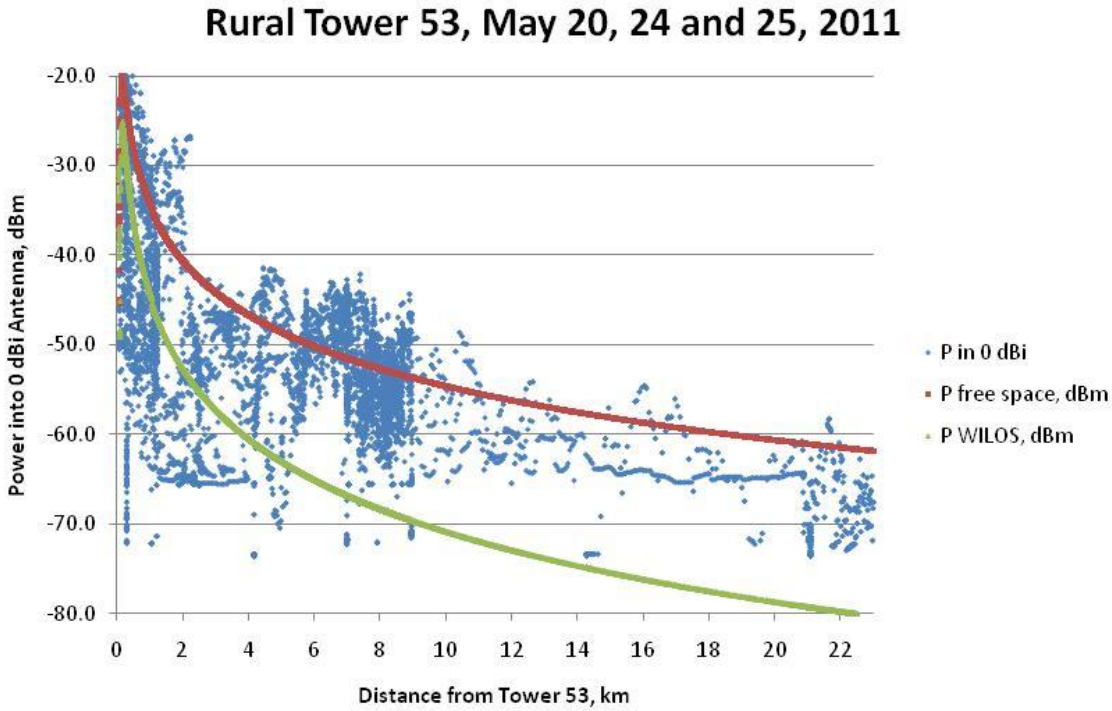


Figure 41 Las Vegas Tower 53

LightSquared notes that the while the received power for the rural site (#53) was largely between that predicted by Free Space and WILOS (the predictions are plotted incorrectly in Fig. 94 as they do not account for the antenna elevation pattern discrimination at short distances), at the other sites this was not the case. For example, in LightSquared supplied Figure 42 the following data for the urban site (#160), also collected by Trimble, shows that the received power was below the WILOS prediction for a large percent of time.

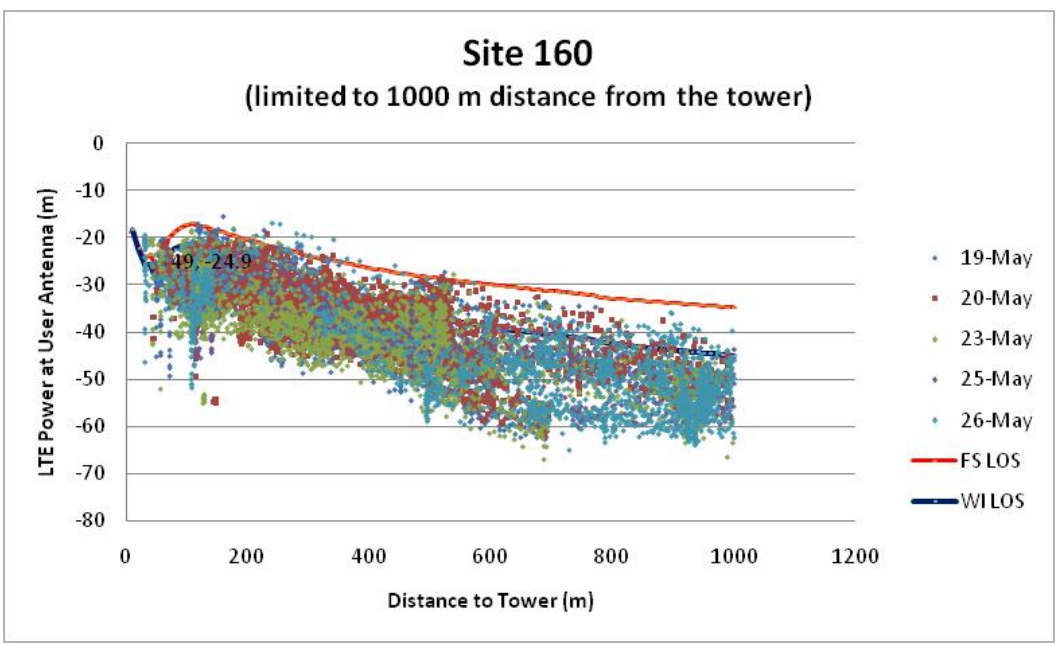


Figure 42 Site 160 Power Data

Deere also demonstrated the detrimental effect of the LightSquared emissions on their GPS equipment. Figure 43 shows C/N_0 values versus radial distance from the LightSquared cell tower, and illustrates the effect on C/N_0 when the emissions are present (blue) and not present (red). Note also the large number of blue dots along the bottom axis. These points represent places where the receiver was not able to track GPS signals at all.

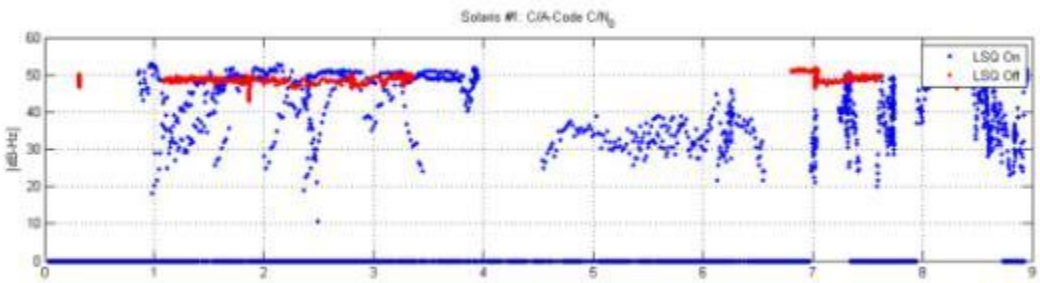


Figure 43 Las Vegas GPS Test

The Deere report documents clearly how its receivers were impacted by the LightSquared signals at very large distances away from the cell phone towers.

11.2.3 Verizon Wireless Summary

Verizon Wireless documented many Timing GPS alarms in their communications equipment during the Las Vegas tests. See Appendix H.1.4 for their field report. The report includes detailed GPS alarm logs. Verizon determined that the faults with their equipment coincided with the LightSquared emissions broadcast plan.

Six Verizon Timing GPS receivers associated with their own cell towers, all within a 1 mile radius of the LightSquared equipment, were rendered inoperable during the signal test periods.

Note: the Verizon GPS receivers are narrow band Timing receivers, not wide band receivers as are used for high precision GPS, so reduced ranges for LightSquared impacts are expected.

LightSquared notes the following:

> Verizon also field tested a PCTEL GPS timing antenna which experienced no negative effects from the LightSquared transmissions.

The GPS Community notes the following:

> Verizon had no corresponding power measurements of the interferers at their PCTEL antenna, and therefore we are unable to correlate this result with any of the other work in this report. While promising, we are unable to conclude that PCTEL would be a general fix for timing without further work.

11.2.4 NOAA/NGS Summary

NOAA/NGS also participated in the Las Vegas Field Trial. Their report is attached as Appendix H.1.5.

They reported a wide range of GPS receiver behavior at rural site 53. With some combination of GPS receivers and antennas, they experienced high amounts of GPS fix losses (33-75%). They also measured GPS fix loss out to approximately 4 km from the base station.

With other antenna choices, they were able to improve the performance to less than 10% losses. With this combination, they also only observed GPS fix losses if they were within 362 m of the cell tower. LightSquared notes that this is a very important observation, and its relevance to potential mitigation options should not be overlooked

NOAA/NGS also noticed the distinct areas on the ground where the receivers experienced a high amount of loss. They associated these areas with the cell tower antenna broadcast radiation patterns.

On May 23 stationary data was also recorded near Dense Urban Site 217 with LightSquared transmissions in the lower 5 MHz band only. The NOAA vehicle was positioned on the top level of a parking garage with a direct line of sight to Site 217 at an approximate distance of 190 m. The NOAA vehicle was 32^0 west of the north sector beam at an azimuth of 328^0. Three receivers were used in the stationary tests (Receiver H07007A w/ antenna 5, Receiver H07007B w/ antenna 2, and Receiver H41591 w/ antenna 3). Six data sets were collected for each receiver during LightSquared transmissions between 12:30 am to 3:15 am and the 95% horizontal accuracy was computed for each data set relative to the vehicle average position for each receiver. These data sets were compared with the vehicle accuracy when site 217 was not transmitting. No degradation in accuracy was noted during Site 217 transmissions and no tracking losses were observed during the six data sets for each of the three receivers. No LightSquared power measurements were recorded.

11.2.5 CORS Summary

During the NOAA/NGS testing, several nearby CORS reference stations directly in the antenna boresight in sectors 30 degrees and 270 degrees from Site 53 at 12 and 26 km experienced intermittent tracking loss and significant latitude and longitude errors. See Appendix H.1.7.

11.2.6 Sprint Nextel Summary

Sprint also documented test results from their Las Vegas testing. See Appendix H.1.8 for their field report. Eight Timing GPS receivers were chosen for evaluation, four from iDEN sites and four from CDMA Sites. Four of these sites were collocated with a LightSquared test site. All were within a 3/4 mile radius of LightSquared equipment.

Sprint found the following:

- There was little to no noticeable GPS interference seen at cell sites when LightSquared transmitted only the lower frequency, even at the Sprint sites equipped with their original GPS antennas.

- There was a high rate of failures at cell sites that were collocated or in near proximity to the LightSquared transmitting antennas, when the upper or upper+lower frequency options were tested (these sites had their original GPS antennas in place).
- When three of the original GPS antennas were replaced with PCTEL model GPS-TMG-HR-26N enhanced filtering antennas, these receivers showed no noticeable GPS interference during any of the LightSquared frequency options tested.

The GPS Community takes the following position:

> The three PCTEL antennas in the Sprint report had no corresponding power measurements of the interferer, and therefore we are unable to correlate the Sprint report results with any of the other work in this report. While promising, the GPS Community is unable to conclude that the PCTEL antenna would be a general fix for timing without further work and cannot be extrapolated to wide band receivers see section 3.5.1

LightSquared takes the following position:

> LightSquared believes that these results, combined with laboratory testing, conclusively demonstrate how additional filtering can avoid conflict between GPS and MSS ATC operations.

11.2.7 Topcon Summary

This report was received too late for analysis, but is included in Appendix H.1.9.

11.2.8 Live Sky Conclusions

The field tests conducted by Trimble and Deere established that the Free-space model is a valid choice to use for predicting worst case conditions experienced by fielded GPS receivers. Both urban and suburban environments were examined. They provided many examples where field power measurements exceeded the power that Free-space propagation would have predicted.

The GPS Community takes the following position:

> For the purpose of this report, it is recommended that the Free-space model be used to estimate the area of impact from the NAVAIR anechoic chamber test results.

LightSquared takes the following position:

> LightSquared believes that any analysis should consider worst case scenarios, as well as others, as part of a broader statistical analysis. As has been pointed out elsewhere in the document, utilizing only worst-case datapoints as a means to predict areas of specific signal strength is highly inaccurate and misleading. It has proposed elsewhere the use of tuned models such as the Korowajczuk model as a superior means of predicting areas of potential impact.

All of the companies that tested High Precision GPS receivers in Las Vegas (Trimble, Deere, NOAA/NGS, etc.) demonstrated detrimental impact to these receivers at long distances from the active LightSquared base stations. Trimble, NOAA, and Deere reports

document tracking losses at distances up to 8.5 km, 4 km, 15 km from the LightSquared base stations respectively. The approximate range of these impairment distances were predicted by the NASA/JPL report (Appendix H.1.1).

LightSquared notes the following:

> NOAA did observe improved performance in some models tested that were fitted with different antenna configurations. It stresses the importance of assessing and understanding the different types of components already available to manufacturers today that will allow GPS devices to coexist with MSS/ATC operations in the adjacent band.

Verizon Wireless and Sprint demonstrated detrimental impact on their narrow band Timing receivers. They showed Loss of Service alarms on many of their receivers that were within 1 mile (1.6 km) of the active LightSquared base station. However, receivers from both companies showed resilience to the LightSquared signal when the PCTEL antenna was used.

11.3 Laboratory

The JPL/NASA report (See Appendix H.1.1) describes their analysis of LightSquared base station interference to four high-precision GPS receivers used in NASA spaceborne and terrestrial applications (two of each type). They examined the effect of the Phase 1 signal (F5L+F5H) on four dual frequency receivers TRIG, IGOR[50], Javad Delta G3T, and Ashtech Z-12. The latter two of these receivers are common High Precision receivers and are found in many applications in the US and around the world today and are representative of receivers used in the IGS (International GNSS Service) network.

NASA, with the assistance from JPL, conducted very careful laboratory experiments to determine, among other things, the LightSquared power levels that would result in 1 dB C/N_0 degradation in GPS signal tracking. They determined that the following power levels caused 1 dB C/N_0 degradation with the F5L+F5H LightSquared signal:

- -82 dBm (TRIG)
- -57 dBm (IGOR)
- -54 dBm (JAVAD)
- -68 dBm (Ashtech)

LightSquared notes that NASA/JPL did not report results for these receivers with just LightSquared lower band signals (F10L or F5L).

They also provided an extensive analyses with these levels to determine the impact on users in practical terms. They computed the range from a typical LightSquared base station where power levels would exceed these values using several popular RF propagation models: Free-space, Hata, Extended Hata, Walfisch-Ikegami and NTIA/ITM. They found that using the Free-space model that this impairment distance equated to:

[50] The space receivers TRIG and IGOR are subjected to ground testing prior to launch, so the terrestrial interference impact has to be considered also for these receivers.

- 22 km (TRIG),
- 4 km (IGOR),
- 3 km (JAVAD),
- 14 km (Ashtech).

From their analysis of LightSquared proposed cell tower locations for Las Vegas, they have shown 100% impairment of High Precision GPS receivers within environments where this service is deployed. Figure 44 shows the area (2,008 square km) in which the -56 dBm Interference Threshold for the Javad receiver is exceeded using the Free-space propagation model. Figure 45 shows the area (3,529 square km) in which the -68 dBm Interference Threshold for the Ashtech receiver is exceeded using the Free-space propagation model.

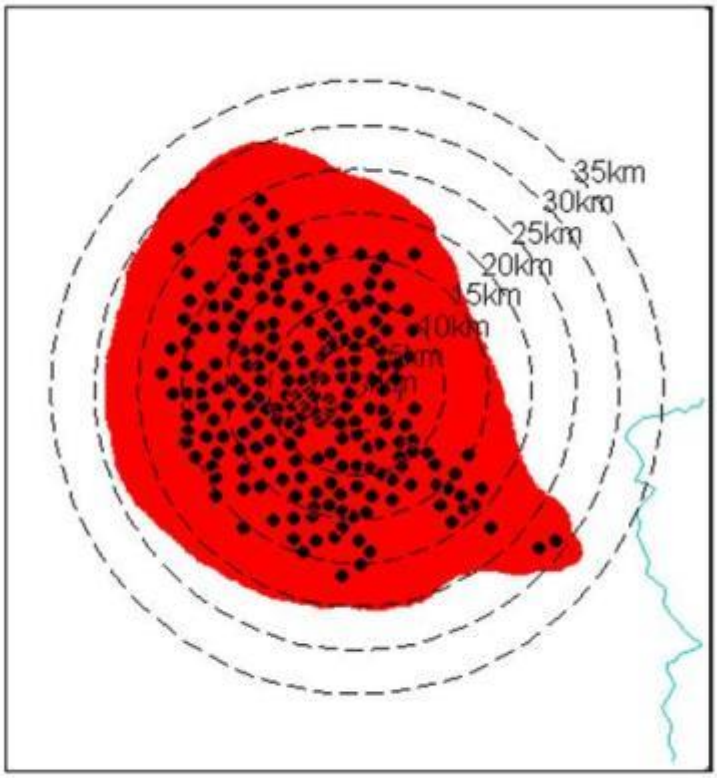


Figure 44 - 56 dBm Interference Area

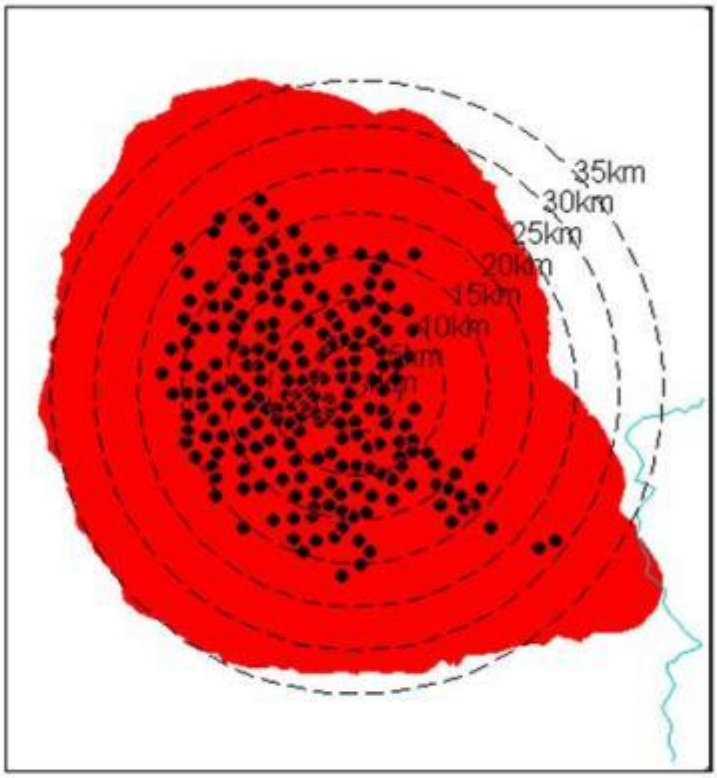


Figure 45 - 68 dBm Interference Area

11.4 Coverage Effects

The power values needed to affect the KPI for the Phase 2 plan are very weak signals. These values can be translated into radial distances from LTE tower locations showing the areas where these types of receiver are weakened or inoperable with the use of a propagation model.

The NAVAIR testing analyzed various KPIs while the receiver was subject to a LightSquared signal at boresight to the antenna. In most precision applications, with some exception in GIS, the antenna is held near vertical during precision operation. Unless the receiver is very close to the LightSquared tower the signal will enter the antenna at almost zero degrees elevation. A typical antenna may have 5 dBi of gain at zenith and -5 dBi gain at the horizon, although there is a wide spread with some classes of precision antennas having only about 5 dB spread between zenith and the horizons and antennas such as the Choke ring having substantially more loss at the horizon. The gain pattern does provide some immunity to the LightSquared signal when it enters the antenna at lower elevations, for the typical antenna it provides about 10 dB of immunity relative to the zenith NAVAIR data.

For the proposed F10L+F10H deployment, Table 10 shows that 90% of the receivers have a 1 dB susceptibility when -55 dBm is present at boresight to the antenna. Using the nominal antenna model we've defined that would translate to -50 dBm into the LNA which would be equivalent to -45 dBm at the antenna when the signal is entering the antenna within a few degrees of horizon which would occur when the user is beyond several hundred meters from the tower assuming a tower height of 30 m. For a ground level user in an area with high towers, typically seen in a dense urban environment in a city with high buildings, the user will get little benefit from the roll off of the receiver antenna gain pattern as the LightSquared signal source will always be at a high elevation to the user.

The Las Vegas power analysis has shown that the propagation is approaching free space in many cases, especially in the rural environment and close to the towers in all other environments. Therefore:

> The GPS Community believes for the purposes of receiver overload the free space model should be used.

LightSquared's position is:

> LightSquared believes that use of a WILOS propagation model is appropriate in many environments, particularly in an urban and dense-urban environment, as the Las Vegas data also shows.

A few key percentiles for the NAVAIR F10L+F10H are reviewed below in Table 12 and Table 13 using a typical antenna (antennas with less change from zenith to horizon will show increased range susceptibility). We see that 50% of the devices are impacted out to horizon about each tower while even if the more optimistic WILOS model is assumed they are still impacted to a 6.2 km radius about the tower. Even using LightSquared's preferred WILOS model, 90% of the receivers are impacted out to a radius of 1.37 km about each tower. In a rural environment the typical tower spacing will be 5-8 km, and hence the closest tower would be typically be not more than 2.5-4 km away from a user, so even with the optimistic WILOS model 50% of receivers would have at least 1 dB of degradation across the deployed area. The deployment in a city will be even more dense and hence the user will typically be closer to a tower.

Percentile	**NAVAIR Zenith [dBm]**	**Horizon[51] [dBm]**	**Free Space**	**WILOS**
90%	-55 dBm	-45 dBm	4.84 km	1.37 km
50%	-72 dBm	-62 dBm	34.3 km[52]	6.2 km

Table 12 NAVAIR 1 dB Susceptibility KPI Converted to Power on the Horizon

[51] Assuming a nominal +5dBi at zenith, -5dBi at the horizon. For some receivers in the precision class the antenna will not provide as much immunity to the LightSquared signal at the horizon.

[52] The distance to the horizon for a 30m tower is approximately 19.6 km, so for a ground user the impact would be all the way to the horizon for the free space model.

Environment	Typical distance between towers	Furthest distance from a tower
Dense Urban	0.4 – 0.8 km	0.2 – 0.4 km
Urban	1 – 2 km	0.5 – 1 km
Suburban	2 – 4 km	1 – 2 km
Rural	5 – 8 km	2.5 – 4 km

Table 13 LightSquared Typical Tower Spacing (NTIA Questions, 2011-02-24)

Figure 49 shows graphically what the impact of a single tower would be on the 1 dB C/N_0 loss KPI in a rural area for 50% and 90% of the models tested at NAVAIR. The 50% impact area is approximately all the way to the horizon for a 30 m high tower. The Las Vegas testing showed areas at 8.5 km from a rural tower -44 dBm was measured into a 0 dBi antenna.

GNSS signals are RHCP. As part of the power collection and analysis performed by Trimble, the power data was already adjusted to account for the attenuation afforded by a high precision antenna when it receives dual +/-45 degree polarized signals. This correction is shown in Figure 30 where the gain has been adjusted relative to the nominal zenith gain of +5 dBi for RCHP signals. Hence, no further adjustments to the measured power levels are necessary to assess the impact of the LTE signal on the GNSS receivers. The NAVAIR test radiated an LTE signal at zenith to GNSS antennas which typically would typically have on the order of +5 dBi zenith gain. Therefore, to convert from the near horizon measurements of -44 dBm, the equivalent NAVAIR power level would be approximately -49 dBm.

From Table 10 it can be seen that in F10L+F10H mode 50% of the receivers tested not only were degraded, but completely lost lock on all satellites at this power level, hence the free space assumption and the areas shown do correctly tie together the power observations made in the Las Vegas testing rural area with the NAVAIR results.

Figure 46 shows live sky Las Vegas power measurements collected and published by LightSquared. Only two antenna panels are loaded at this site versus the usual three and some of the power measurements were made in the null created by the missing panel. However, it is clear from a receiver overload perspective that a considerable number of data points exceed the free space model, confirming the assertion that a free space model should be used.

Figure 46 Light Squared Power Measurements at the Las Vegas Rural Site

The impact model is extended in Figure 50 which shows an ideal LightSquared deployed network based on the midpoint tower spacing for a rural network as defined by LightSquared.

The GPS Community takes the following position:

> As can be seen, at least 50% of the receiver models tested (from a sample of 34) would have at least 1 dB of degradation, with many seeing substantially more, over the entire rural deployment area, significantly degrading the ability of precision GPS to be used in agriculture and other applications.
>
> Power data measured by Trimble, John Deere and LightSquared at the rural site in Las Vegas all show that the propagation model is very close to a free space model. In fact, due to multipath, the received power is often greater than a Live Sky model would predict. The Las Vegas rural data is also under predicting the problem as only two antenna panels were loaded so some of the data was collected in the null due to the missing panel.

LightSquared takes the following position:

> LightSquared does not believe that such a broad conclusion can be made from this limited dataset. In open terrain, free space propagation can sometimes hold but, more frequently, the received power will have a median level that is even less than that predicted by the WILOS model53. Figure 47 is an example for a suburban area.

[53] It is difficult to tell if an instantaneous, high value of power collected by a moving vehicle is due to Rayleigh fading multipath, which can lead to power levels that are 10 dB higher than the local mean. Such Rayleigh peaks occur for very small areas that are unlikely to cause an operational impact to most use cases except fixed timing units.

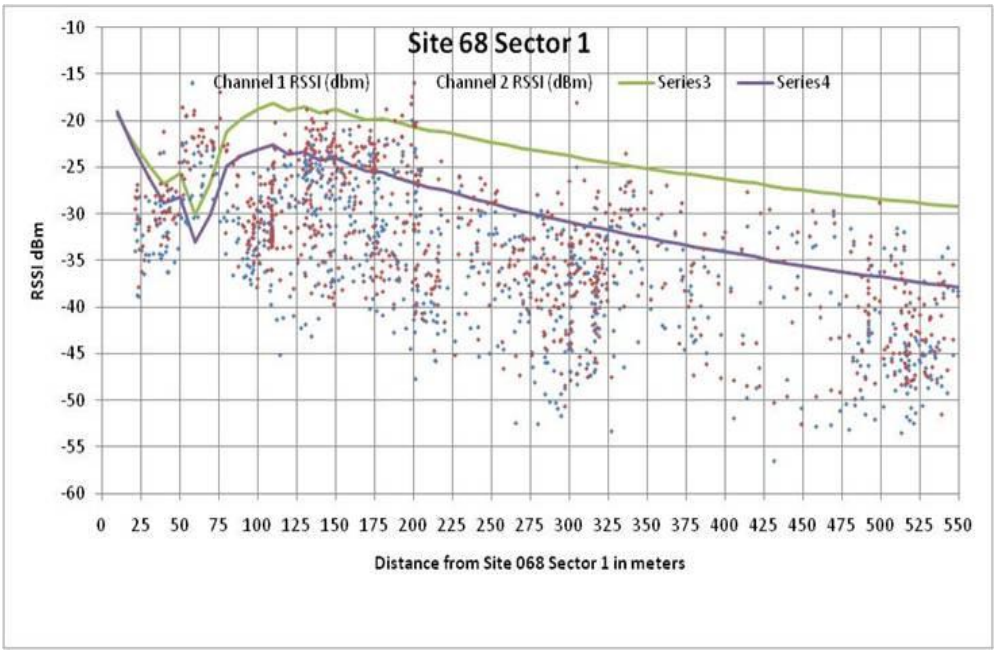


Figure 47 Site 68 Sector 1

It should be further noted that most of these measurements were performed in open areas relative to the base station antenna and for a relatively low antenna height (16.8 m). In urban and dense urban areas, where significant blockage will exist relative to the propagation of the base station signal, much lower power levels will be seen. Figure 48 below also from the TWG Final Report, is for a 71.6 m base station antenna in a dense urban setting.

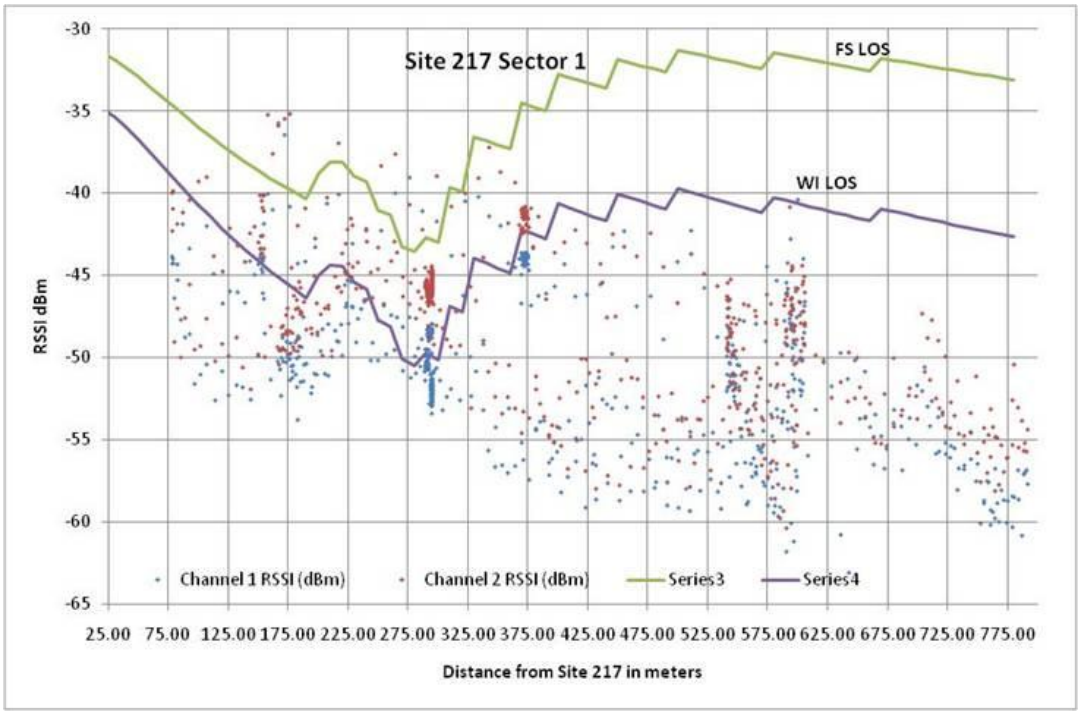


Figure 48 Site 217 Sector 1

Here the probability of the power being greater than -40 dBm was 1.5%.

These examples suggest that probabilities of receiving power levels higher than -25 dBm, when considered over the entire network, comprising a mix of tower heights and morphologies, is likely to be quite low.

While free space power levels may be encountered in individual hot spots, these will be relatively rare when considered over the entire network. Even power levels as low as -30 dBm are expected to be seen less than 1% of the time in most markets.

The GPS Community takes the following position:

While the limited data set presented in Figure 48 collected from a single antenna sector shows at some ranges a lower LTE power level, it should be noted that on some nights only 59dBm was transmitted versus the planned 62dBm per sector per LTE signal and never was the intended deployment of 65dBm per sector transmitted for dual channels. Additional power measurements that were collected and are more uniformly located around the transmitters and published by LightSquared close to the same dense urban tower (tower 217) show increased interference, see Figure 51 .Trimble results also show more significant measured power, see figure 161 and these match data collected by Deere, see. Figure 183. It also is very important to note that in the dense urban case the towers will typically be 400-800 meters apart, that means that the typical user will be no more than 400m from the closest tower and typically much closer. All the power measurements presented (measurements made by LightSquared, Deere and Trimble) show that out to approximately 500m the freespace and WILOS models are approximately bounding the received power.

Models are a convenient way to characterize the estimated power at the receiver, but are no substitute for measurements, all testing at Vegas has indicated that at the typical distances a user will experience from the closest tower in a deployed system there will significant LTE power incident on the antenna. LightSquared notes that 0.4% of the coverage area in a probabilistic model of Washington DC would experience a power level exceeding -30dBm, the NAVAIR testing results showed that in the planned final phase of deployment (F10L+F10H) at -55dBm at least 90% of the receiver models tested would be experiencing harmful interference, that's 25dB lower or 316 times less power than the provided -30dBm metric and hence much more severe outage would be shown with the probabilistic model if a more representative power level were used.

Also tower 217 was significantly higher than towers in some dense urban environments as it was on the top of a hotel on the Las Vegas strip. With a lower tower the impact close to the tower is worse as the receiver at ranges closer to the tower is in the main beam of the LTE transmitter.

The assumption has been that the downwards tilt of the LTE antenna will be 2 degrees, this is a typical value, more extreme tilts of up to 10 degrees are not unreasonable. The increased tilt angle will further reduce the range at which the user receives LTE power from the main beam of the transmit antenna. As LightSquared did not deploy towers in the Las Vegas testing with their planned network topology, only select towers were installed, it was not possible to further assess the full extent of the impact in an area that has a representative tower density, in lieu of this data we

believe that the impact studies shown in this section provide a reasonable representation of the extent of the impact in any deployment based on a comprehensive analysis of the collected data, both from multiple days of live sky testing and from a representative set of precision receivers tested in a controlled anechoic chamber environment at NAVAIR.

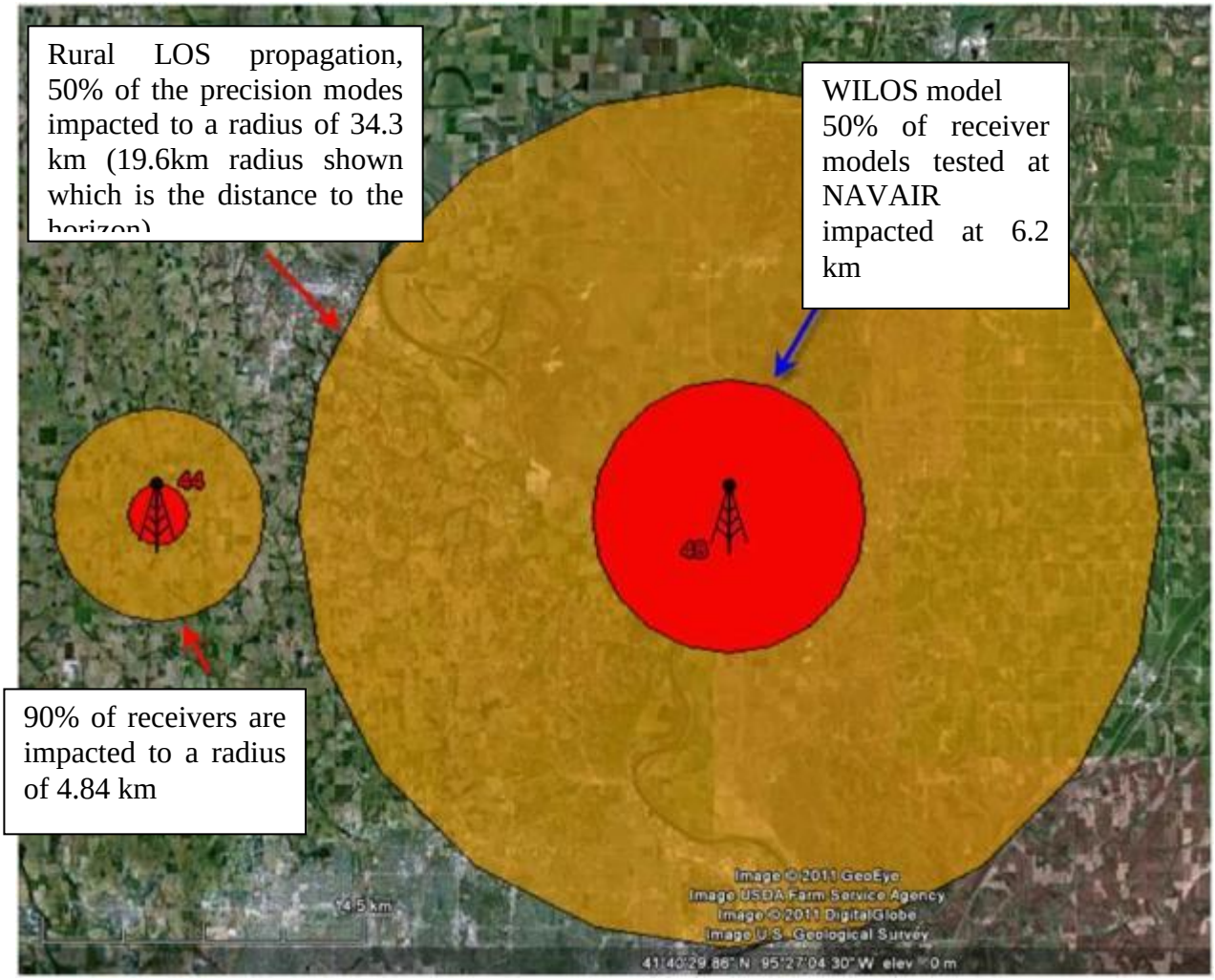


Figure 49 Agriculture Area Outside Omaha, NE - Based on NAVAIR 10L+10H Testing

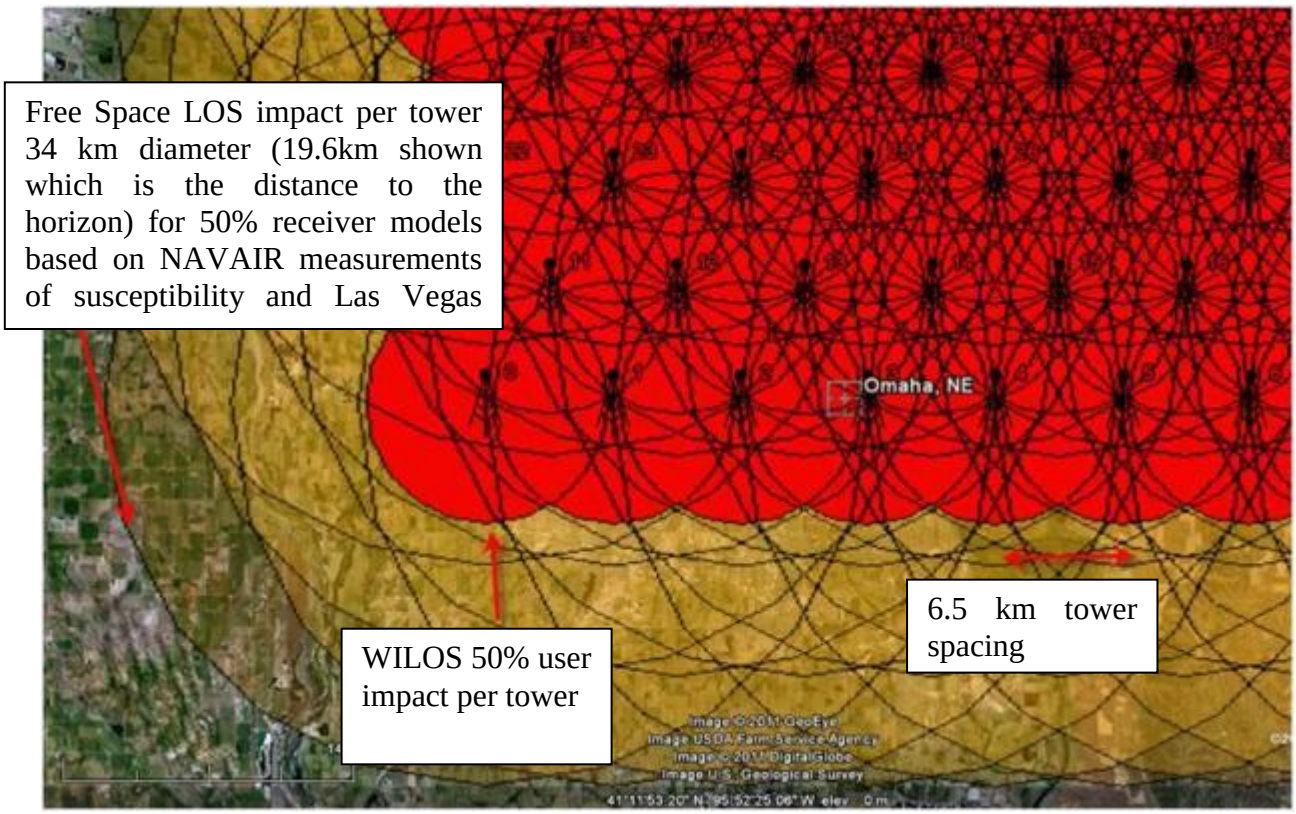


Figure 50 Rural Impact to 50% of Receiver Models with 10L+10H

Dense urban deployments will have even closer tower spacing. Figure 52 was prepared by the GPS Community and shows the minimum expected radius of impact to 90% of the precision models tested at NAVAIR on the 1 dB degradation KPI for a single tower in F10L+F10H mode transmitting the planned 65 dBm per antenna sector.

As stated elsewhere in the document, LightSquared disagrees with both the use of 1dB as the determinant for harmful interference and the use of the free space propagation model to predict LightSquared's signal.

The GPS Community takes the following position:

> A single tower in Washington DC could significantly impact the ability to use precision GPS for Survey, Construction and GIS/Mapping in a large part of the city. This is consistent with the data measured in Las Vegas, as there it was shown that in the F5L+F5H mode at a lower power level[54], that a precision receiver was unable to track at 2 km from an Urban tower. The inability to track represents much more loss that the 1 dB modeled in Figure 52. The analysis is based on LightSquared's own power measurements to adjust measured power to distance as well as the controlled NAVAIR results from 34 representative receivers. Due to the limited tower density of the Las Vegas test relative to an actual LTE deployment it was not possible to better characterize the impact.

[54] In Las Vegas between 59 dBm and 62 dBm was transmitted based on the night, tower and time of the test.

> In any built up environment it will be possible to find some very limited locations where the local geometry provides masking such that the LTE power incident on the receiver has lower impact. However, precision GPS users are not static and rely on the system working as they move around cities, towns and agricultural areas while they use precision GPS to map assets, control construction machinery, stake out subdivisions, control agricultural equipment etc. Therefore even if there are brief periods where the user is able to track the GPS satellites without harmful interference, e.g. while the LTE signal is partially masked by a building, when the user as part of his or her work flow moves, there's a high probability they will experience harmful interference. Being able to get a good position in a limited percentage of the work area provides no advantage and does not allow the user to achieve his or her work objective (e.g. map assets around a city, construct or maintain a road etc).

LightSquared takes the following position:

> LightSquared stands by its assertion that a free space propagation model is overly pessimistic for predicting signal strength through an entire coverage area. In order to begin to assess impacts on users, it is first necessary to accurately model the strength of signals at different distances from a site. To only make an assessment based on the strongest modeled frequency, using an overly pessimistic model, short-circuits an essential step in the process. The result is to paint an inappropriately large area with a signal strength that may be achieved in only a fraction of that area. Once a determination of probable signal strengths is made, only then is it appropriate to assess the impact of these signals on the devices and their end users.
>
> LightSquared also notes that Figure 42 shows deployment from a dual channel (F10H+F10L) configuration, and does not account for critical factors such as antenna patterns and loss inserted due to morphology (building clutter, etc.).

Figure 53 expands the model and shows a modeled deployment in Washington DC using the upper range of a Dense Urban network supplied by LightSquared.

The GPS Community takes the following position:

> Across the whole deployed area at least 90% of the tested receivers would be impacted. Unlike the dense urban site in Las Vegas, the height of buildings in Washington DC are limited due to the 1910 Heights of Buildings Act[55], hence the tower heights will not be particularly high and the user on the ground will not see some of the attenuation close to the transmit antenna that occurred in Las Vegas and resulted in lower received signal around the dense urban tower tested there. As the transmit is pointed down at 2 degrees and there is reduced gain outside of the main beam, lower EIRP occurs if the user is close to a tall tower, but this will not happen in Washington DC.

[55] http://en.wikipedia.org/wiki/Heights_of_Buildings_Act_of_1910 Retrieved 2011-06-13

While the GPS Community believes that free space is the best propagation model to use based on the Las Vegas power measurements, it believes that even if the WILOS model is used (impact of WILOS shown in red) the whole of the DC is impacted which will affect the use of precision GPS for Survey, Construction and GIS/Mapping applications anywhere throughout the Washington DC area.

The typical spacing of a tower in a dense urban environment is 400-800 m with a user typical user having a worst case distance of 400m from the closest tower and typically much closer. Figure 51 shows from LightSquared's dense urban measurements taken in Las Vegas that the close is much closer to free space loss than the WILOS model. This matches data collected by GPS manufacturers in Las Vegas (see Appendices H.1.2 and H.1.3).

As the F10L+10FH is the long term LightSquared planned deployment, coupled with typical industry replacement cycles of approximately 15 years, it is appropriate to analyze this configuration to show how current users will be negatively impacted as the LightSquared system is deployed. Models are no substitute for measurements and all live sky measurements from both the GPS industry and LightSquared have shown that when within typical range of a tower the power incident on the antenna of the GPS receiver is typically bounded between freespace and WILOS, even in a dense urban environment. As positioning in only limited locations around a deployment are of little value to a user who will typically move around as part of their work objective, the upper bound needs to be considered as it shows better the area in which the equipment will receive harmful interference and the users productivity will be negatively impacted. The impact plots shown in this section represent well the area around each tower in which harmful interference will be caused by a deployed LightSquared LTE transmitter. Unfortunately while data was collected at NAVAIR and has been presented in this report there was insufficient time to further model all configurations including the low only, especially as this is only a potential short term deployment. However if LightSquared's deployment plan is permanently modified to only a low band, impact simulation models could be created to show how current customers would be negatively impacted during the life span of their current equipment.

The requirement for a wide bandwidth in precision GPS receivers has been described earlier in this document (refer to section 3.5). The widest bandwidth GPS receivers are combined GPS/MSS receivers that receive augmentation signals at similar power to GPS, but in the MSS band. Unfortunately the LightSquared LTE deployment is incompatible with their own MSS satellite signals in any deployed area as demonstrated in the NAVAIR and Las Vegas live sky testing. The LTE signal causes cochannel interference to the Inmarsat provided downlinks used by StarFire, and LightSquared's own MSS downlinks which are used by the OmniSTAR system.

LightSquared takes the following position:

LightSquared disagrees with this assessment, while acknowledging that the design of high precision devices do make them susceptible to overload interference. However, Figure 45 overstates the area where such susceptibility exists due to the following factors:

- It utilizes unduly conservative propagation models that are not specifically tuned for local terrain and morphology; Figure 43 demonstrates how both the free space LOS and WI-LOS models greatly overstate signal propagation, especially as the distance from a cell site grows.
- It assumes omni-directional antennas from LightSquared cell sites.
- It does not assess the reduced area of impact due to a lower channel deployment or for the better-performing receivers tested.

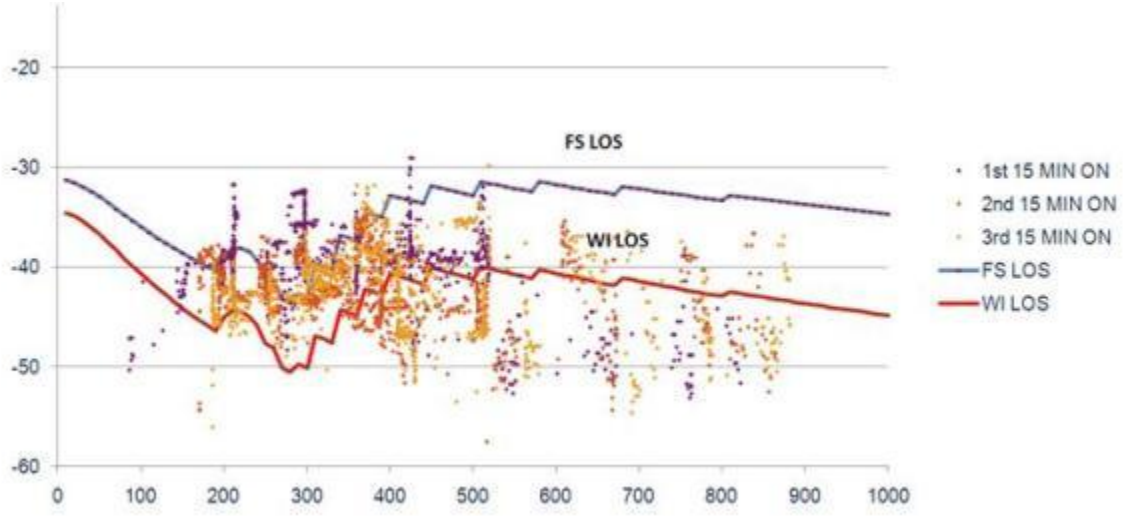


Figure 51 LightSquared Power Data from Dense Urban Las Vegas Testing

The impact radius was computed by converting the ninety percentile from the 34 receivers measured in the NAVAIR chamber to a range, so is believed to be an accurate representation of the impact area. This large denial of service area will be reflected in any region the planned LightSquared deployments are rolled out.

The analysis can be expanded to the single band deployments by converting the NAVAIR results to a distance, based on the Free Space propagation loss. Even in the Low Band only deployment the impact on a dense urban area is very significant.

LightSquared notes the following:

> This analysis is based on a dual channel configuration; it is acknowledged that GPS receivers are especially sensitive to the upper 10 MHz channel.

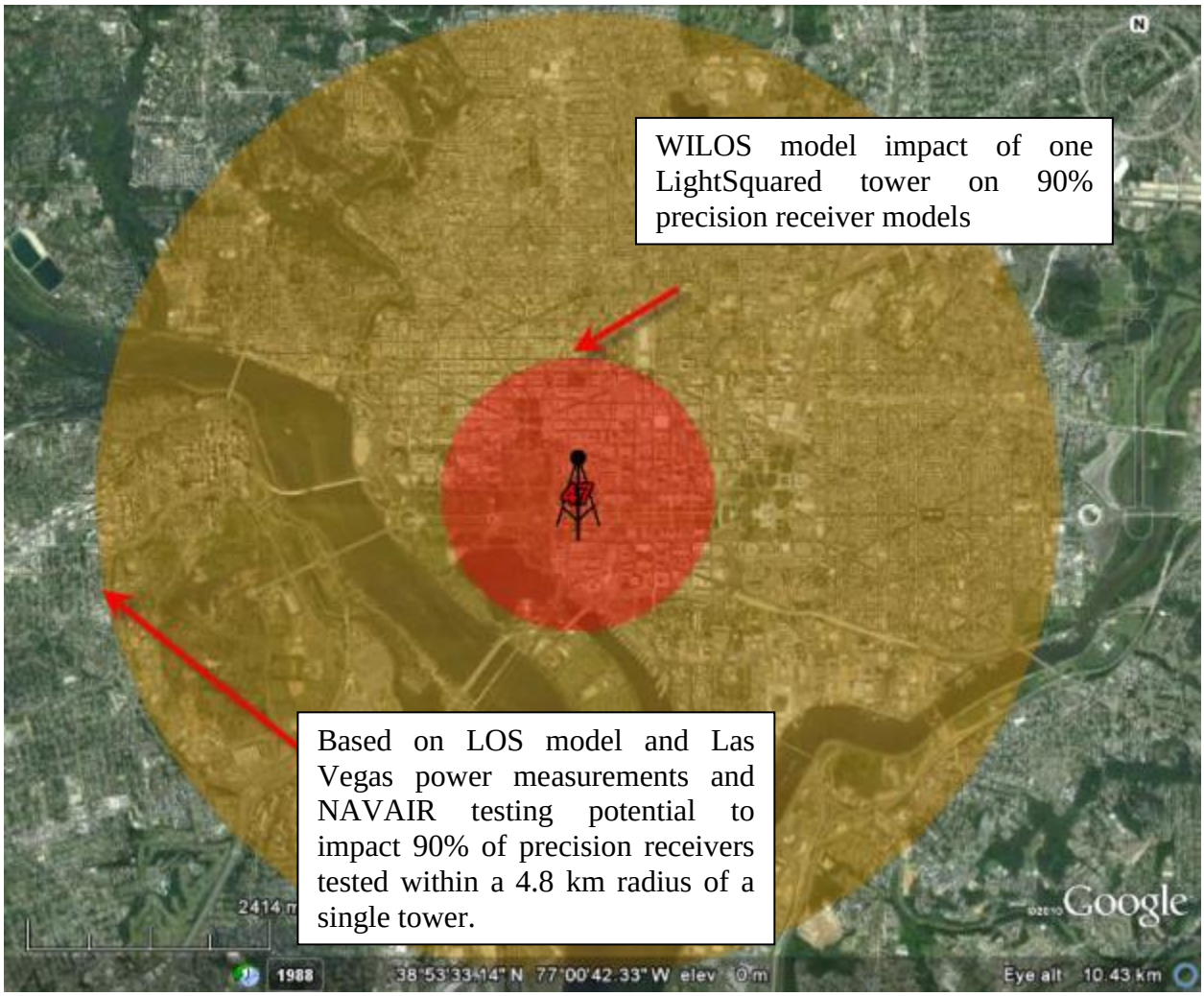


Figure 52 Impact of a LightSquared tower in 10L + 10H mode in Washington DC

Figure 53 Washington DC Network Upper Limit of Expected Tower Spacing (800 m)

11.5 Intermodulation Effects (IM3)

LightSquared notes that IM3 would not be an issue in a deployment with only a lower 10 MHz channel.

All anechoic chamber testing has shown that the C/N_0 degradation experienced when both LTE bands were transmitted was always much greater than the sum of the degradation experienced when either of the single bands was transmitted. This occurred during the testing of either the 10H + 10L or the 5H + 5L LTE configurations. This increase in degradation has been attributed to third order intermodulation products produced by the interaction between the high and low band signals. These intermod products occur in and near the GPS band. To evaluate the interference caused by the intermods, an analysis tool was created to estimate the intermod signal power. The discussion that follows concentrates on the 10H + 10L LTE configuration but is equally valid for the 5h + 5L configuration.

LTE is an OFDM multicarrier system. The 10 MHz LTE signal contains 600 subcarriers spaced every 15 kHz. Since there are many individual subcarriers, third order products are not properly evaluated using the typical two tone model since the intermods are not only produced by the (2FH – FL) interaction but also by the (FH1 + FH2 – FL) interaction. The number of intermods that are produced between 1555 MHz and 1585 MHz caused by the interaction between the 10H and the 10L LightSquared LTE signals

exceeds 100 million. Since the subcarriers in the LTE signal are spaced every 15 KHz so are the intermod products. Figure 54 shows the density function of the number of occurrences of each intermod as a function of frequency.

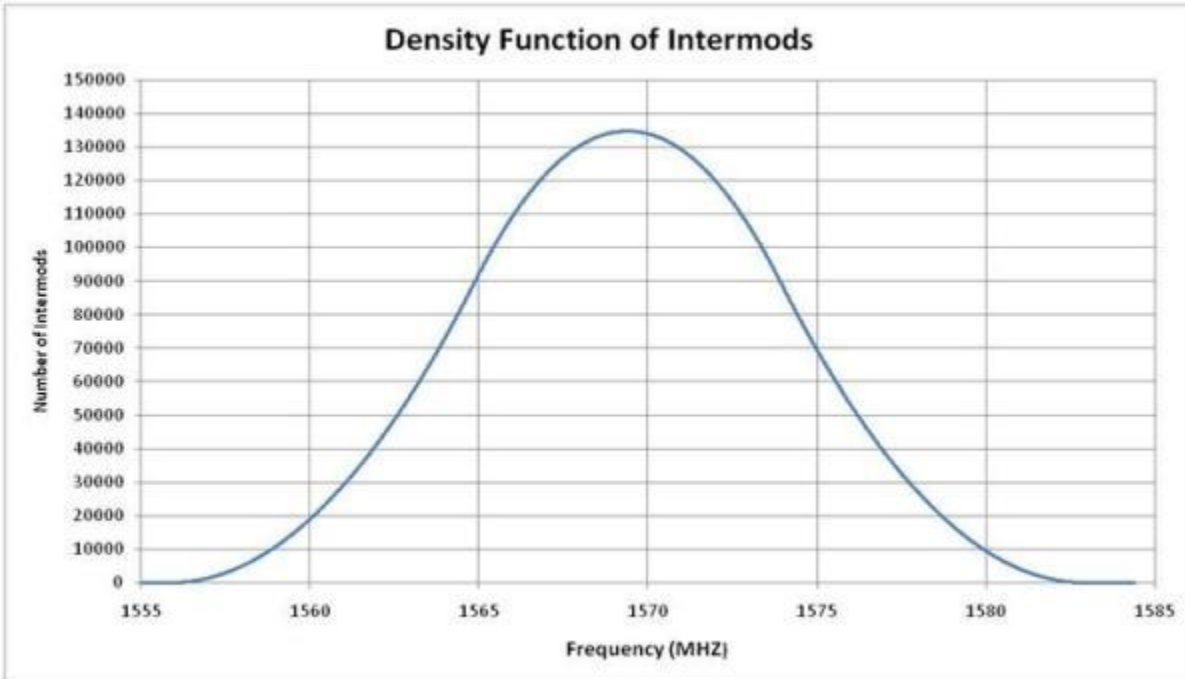


Figure 54 Intermod Density Function

The analysis tool uses a cubic non-linear gain equation of the form: $y=ax+bx^2+cx^3$ to evaluate third order products created by the cx^3 term. All possible intermods are evaluated and an intermod power density function vs. frequency is created. To evaluate the accuracy of the analysis tool's intermod power estimation, it was compared to the actual results obtained with a John Deere high precision receiver during the anechoic chamber tests. The candidate receiver has an IP3 = -55 dBm and a pre-correlation bandwidth for L1 GPS channels of approximately 30 MHz. The anechoic chamber testing indicated that C/N_0 degradation turning point (the LightSquared LTE power level at which a small increase in power quickly causes severe degradation of receiver performance) for this receiver occurred at about -70 dBm LTE power. The results obtained from the analysis tool are presented in Figure 55 and indicate that at -70 dBm the tool predicts a C/N_0 degradation of 2 dB, which is indicative of reaching the turning point of C/N_0 degradation. The conclusion of this comparison is that the anechoic chamber tests and the analysis tool are very well correlated in the level of intermod interference present in a receiver with a particular IP3 at a given input power to within a couple of dB. The total intermod power was calculated as the sum of all 15 KHz intermods present in the pre-correlation bandwidth (1560 MHz – 1590 MHz) of the receiver.

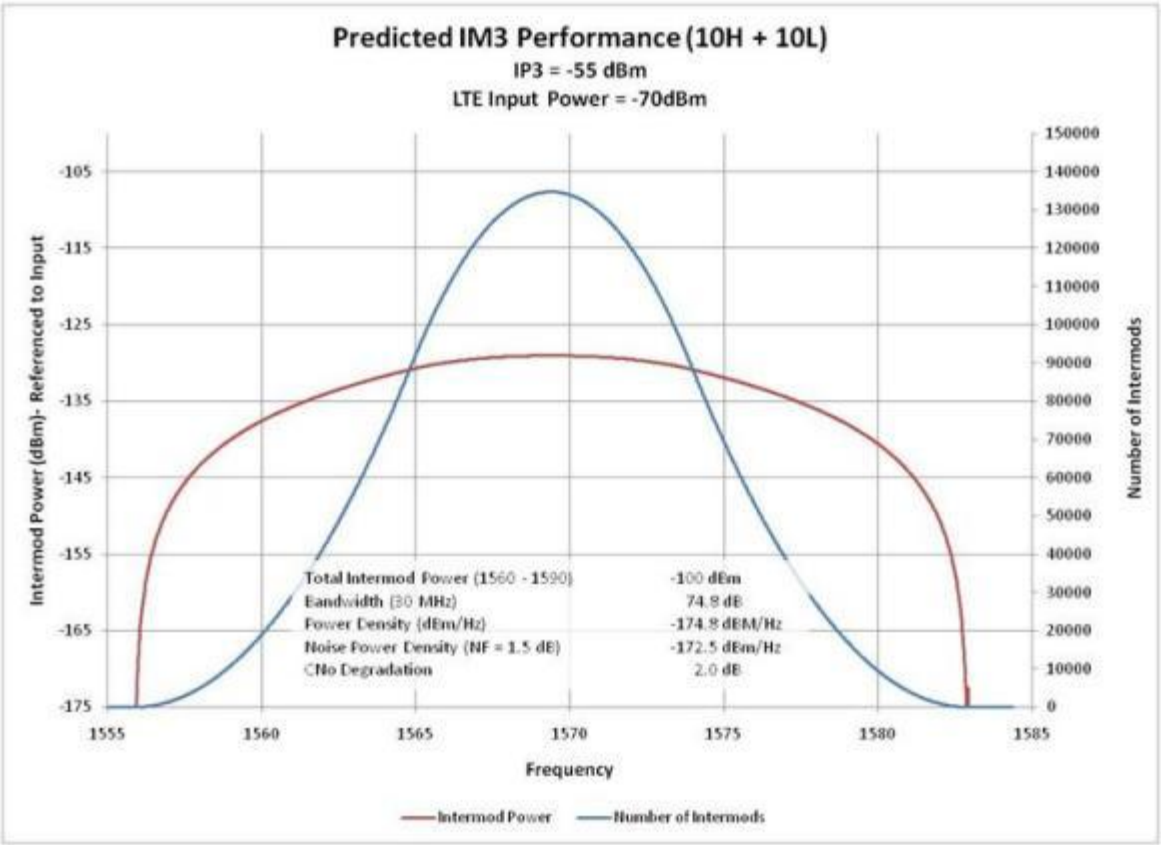


Figure 55 Predicted IM3 Performance

During the initial setup of the anechoic test chamber at NAVAIR, spectrum analyzer measurements of the signal received at the antenna wall were taken to verify that the spectrum of the received signal was free of unintentional signals. A screen capture of the measurement made when the two 10 MHz LightSquared LTE signals were transmitted is shown in Figure 56.

This measurement was made with a quad ridge horn antenna with a measured gain of 9.4 dB. The connection from the antenna to the spectrum analyzer had a loss of -15.6 dB so the power measurements levels shown on the spectrum analyzer must be increased by 6.2 dB to represent the power at the antenna wall. The power level of the LTE signal is at -43 + 6.2 = -37.8 dBm in a 100 KHz resolution bandwidth. The average power for each 15 KHz subcarrier would be -37.8 – 8.2 (10*log(100/15) = 8.2) = -46 dBm. The noise floor at marker 4 in a 15 KHz bandwidth (41.8 dB) is at a level of -145 dBm + 6.2 + 41.8 = -97 dBm.

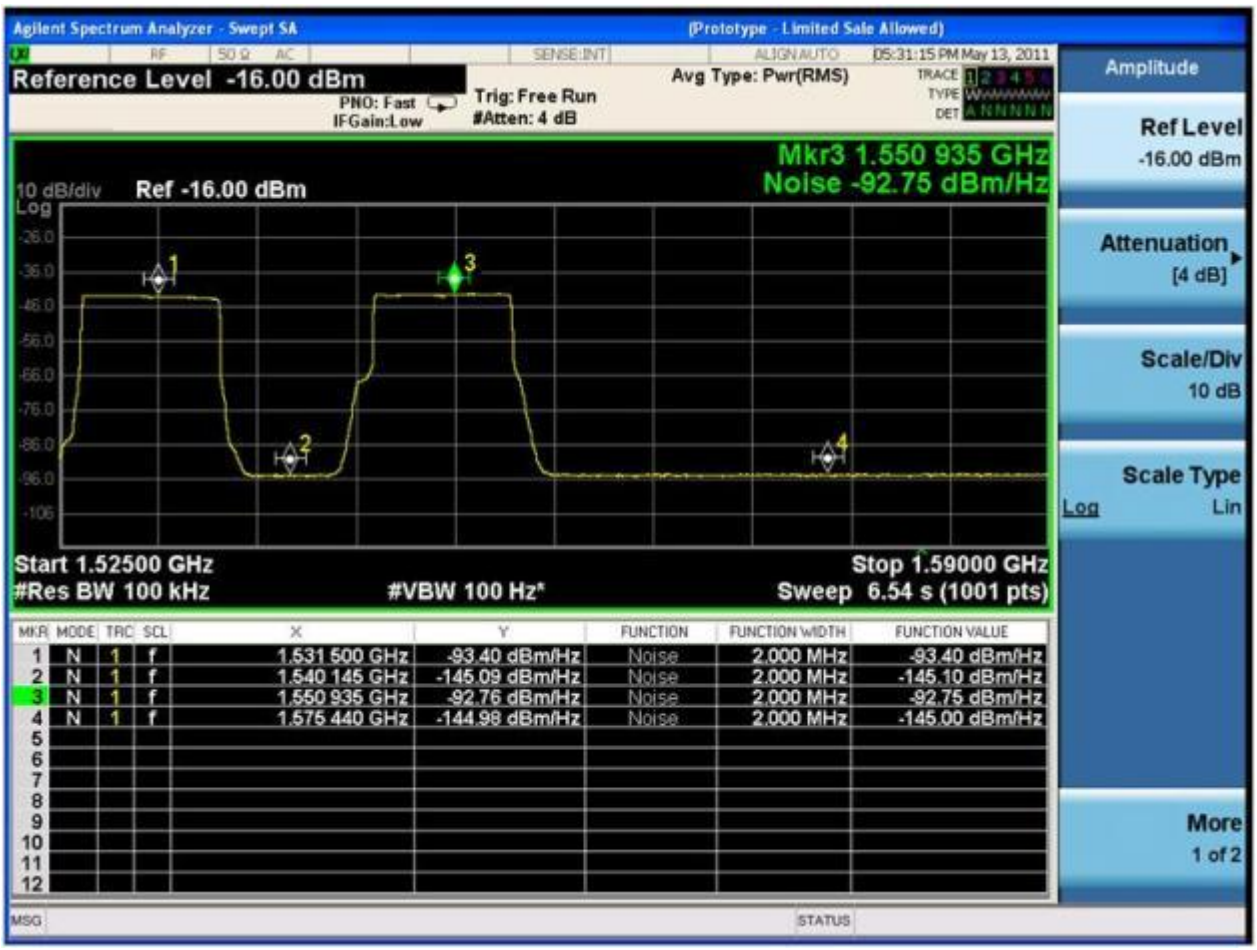


Figure 56 NAVAIR Received Signal

The question is what level of non linearity, characterized by an IP3, would create an intermod greater than that noise floor and hence begin to show up on the spectrum analyzer measurement. The IM3 analysis tool indicates that a non linearity with an IP3 of +6 dBm would be required to generate an intermod at -97 dBm, given the power level of the LTE subcarriers, as shown in Figure 57.

Since no out of band signal in the range of 1555 MHz to 1585 MHz can be seen in Figure 56, we can assume that the transmit apparatus, including the antennas and chamber, must have an IP3 greater than +6 dBm. Since all of the receivers tested had IP3 below -10 dBm, any observed degradation in C/N_0 as a result of third order intermodulation would have to have originated in the receiver circuitry, not in the transmit system.

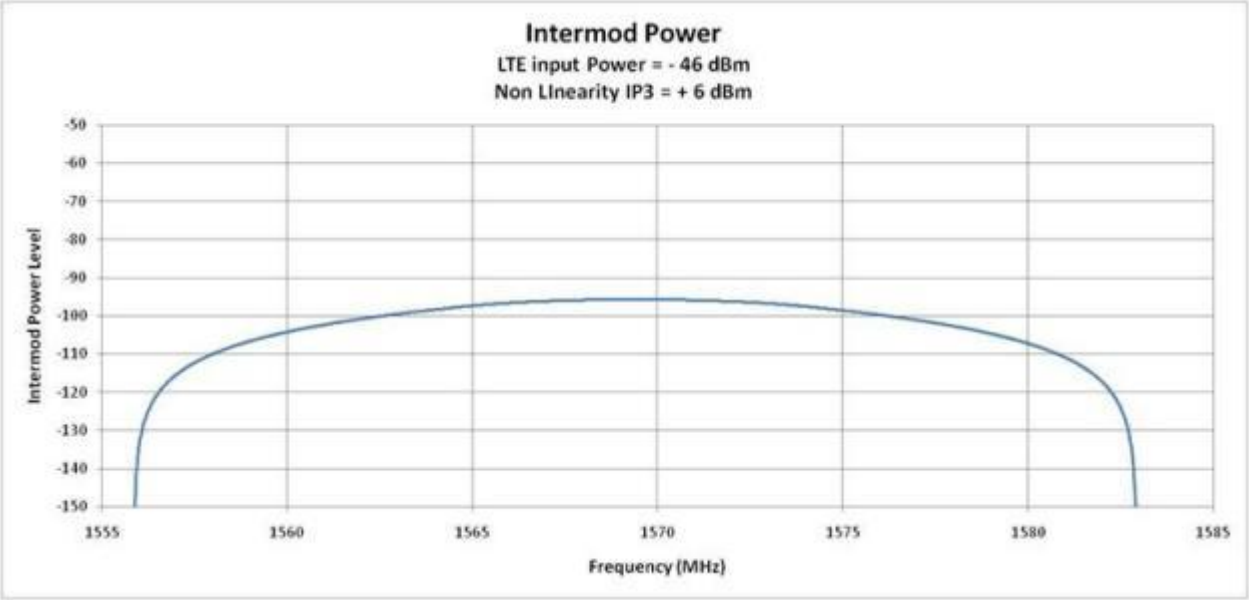


Figure 57 Intermod Power

12 Effects on Operational Scenarios

12.1 Key Performance Indicators

The operational Key Performance Indicators (KPI) for high precision applications are (1) Availability of high precision positioning, (2) Accuracy of high precision positioning, (3) Time To Initialize Real Time Kinematic (RTK) On-The-Fly (OTF), (4) Repeatability of positioning over time, and (5) Provision of reliable a posteriori statistical and stochastic data regarding the quality and precision of the position solution. This is necessary in some cases to show that legal or contractual accuracy or precision requirements have been met.

Availability of positioning (or GPS coverage) in Real Time Kinematic (RTK) or Post Processed static/kinematic mode and OTF Initialization requires a minimum of 5 GPS signals on both L1 and L2 frequencies with sufficient C/N_0 to meet the KPI required in the operational use scenario including while operating in stressed RF environments. Continuous availability of the reference station or network data is equally critical, given that high precision GPS positioning solutions are relative to the frame of reference called for by each application.

Real Time Differential (RTD) or post processed differential mode, requires a minimum of 5 GPS signals on GPS L1 with sufficient C/N_0 and acceptable Dilution of Precision measures to be used in the differential solution, along with the continuous availability of differential correction data from a reference station or network in order to provide positioning and the necessary reliable a posteriori statistical and stochastic data regarding the quality of the position.

For RTK, there must be 5 satellites in common between the mobile receiver and reference system with sufficient C/N_0 and acceptable Dilution of Precision to meet required KPI. In real time mode, both kinematic and differential positioning requires a continuously operating radio communications link for transfer of that data. This connection may be provided via a cellular or proprietary terrestrial communications link, or via a satellite communications link - typically a L-Band Mobile Satellite Service in the 1525-1559 MHz MSS band.

Table 10 in Section 11.1.3 (anechoic chamber results section) shows the 10th, 50th and 90th percentiles for a number of Key Performance Indicators across the full range of planned and unplanned LTE deployments tested. Table 14 below shows two of these KPIs, the 1 dB L1 compression point and the point at which RTK positioning is lost.

The GPS Community takes the following position:

> For high precision RTK applications, the point at which the RTK receiver is no longer able to provide centimeter level accuracy positioning is equivalent to complete denial of the high accuracy solutions critical to the economic and productivity benefits of the high precision user as explained in Section 5. Prior to this occurrence, a 1 dB drop in L1 C/N_0 as defined in Section 3.3 as harmful interference, is considered likely to impact the time or ability to initialize the RTK positioning Kalman filter, and potentially RTK accuracy. Due to the limited time available for

this mandated test, the latter points would require considerable further investigation and evaluation beyond the scope or time span of this study.

For high precision Real Time Differential (RTD) applications, harmful interference is considered to begin at the point where a 1 dB drop in C/N_0 is experienced. Again, the error propagation effects of any signal compression through the positioning filter require analysis but are beyond the scope and timeframe of this study. Loss of RTD positioning will occur when either the real time differential data stream is lost (for example, caused by in-band interference to an L-Band MSS channel) or when too many GPS satellites are lost due to interference, whichever is the first to occur. In either case the high precision position solution can no longer be calculated, which is the primary function of the device. For both RTK and RTD cases, the effect on post processed solutions will be materially the same so far as the GPS measurements are concerned.

LightSquared takes the following position:

LightSquared notes that Table 10 clearly shows the lack of correlation between the "harmful interference" criteria, 1 dB drop in C/N_0, and the actual impact to a KPI, loss of good RTK. For example, with the F10L signal, the "harmful interference" criteria occurs with 9 dB less LightSquared signal power than the actual impact to the KPI.

12.2 Antenna and Power Assumptions

In Table 14 below, the chamber results have been adjusted to account for a typical gain pattern seen in a high precision GPS receiver. These adjusted results assume +5 dB gain at the zenith and -5 dB gain at the horizon and further assume that the LTE signal will be incident at, or very close, to the horizon. At distances very close to the tower, this would not be the case, causing more severe effects than those shown.

LTE Power for Changes in Key Performance Indicators (dBm), from Anechoic Chamber Results												
	F5H		F5L+F5H		F10L+F10H		Handset		F10L		F5L	
Receivers Affected	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%	50%	90%
1dB drop in L1 C/No	-56	-49	-66	-57	-72	-55	-41	0	-43	-25	-43	-25
Loss of Good RTK	-47	-38	-58	-50	-55	-47	-27	-15	-35	-16	-21	0
Adjusted for Receiver Antenna Gain assuming +5dB zenith, -d5B Horizon incidence LTE signal												
1dB drop in L1 C/No	-46	-39	-56	-47	-62	-45	-31	0	-33	-15	-33	-15
Loss of Good RTK	-37	-28	-48	-40	-45	-37	-17	-5	-25	-6	-11	0

Table 14 Adjusted Chamber Results

The critical points highlighted essentially represent the worst case planned deployment scenario tested and an unplanned partial deployment plan of 10 MHz in the lower part of the band (also tested). These points are used to assess the operational impacts on high precision GPS users across the range of commercial and professional applications in Section 5.

12.3 Agricultural Operational Scenario

As noted in Section 5, the operational scenarios used are presented by the GPS Community.

Agricultural GPS receivers are likely to be used in rural LTE deployments. Figure 58 shows the measured received power versus range for a typical rural LTE deployment as tested by Tower 53 in the Las Vegas Live Sky testing. Note that this test assumed that LightSquared would not transmit at power levels more than approximately –62 dBm per sector per LTE signal, even in rural areas where tower spacing is much greater than in urban areas; clearly any use of higher power would significantly change these results. In Figure 58 below, the 50th percentile point of Loss of Good RTK is overlaid on the measured power levels, for both the Phase 0 LTE deployment and for the unplanned 10 MHz in the lower part of the band, F10L.

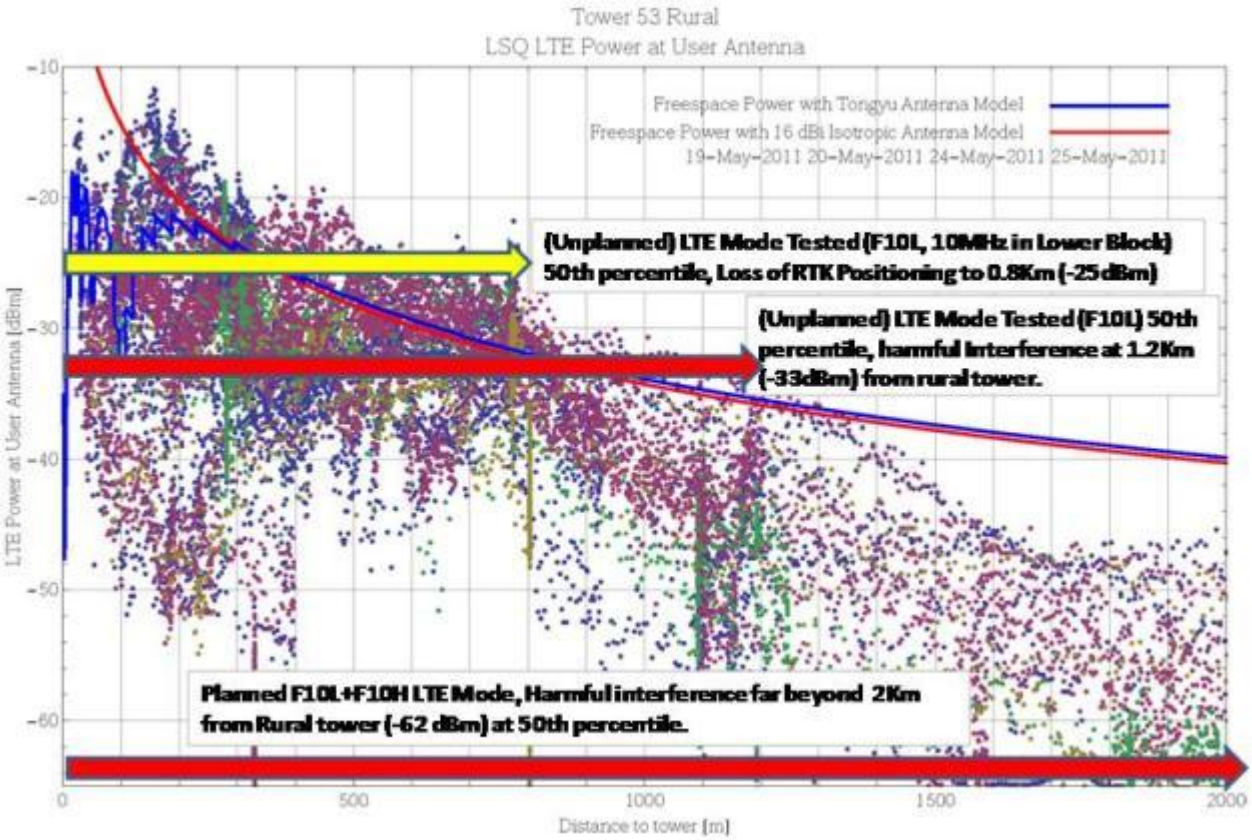


Figure 58 Las Vegas Tower 53 LTE Power vs. Range, Overlaid with RTK Loss Data

it can be seen that in the Phase 2 deployment, a typical RTK receiver as measured at the 50th percentile, would suffer harmful interference well beyond the 2 km point on this chart. Given typical rural tower spacing, harmful interference in all areas covered by this service could be expected, with complete blanket denial of RTK positioning over very large areas. In the partial LTE deployment scenario tested – 10 MHz in the lowest part of the MSS band 1526.3 MHz -1536.3 MHz at 62 dBm EIRP – a typical RTK receiver as measured at the 50th percentile would be unable to function within 800 m or half a mile of each tower and degradation of performance from harmful interference, as measured by the 50th percentile 1 dB C/N_0 loss point, could be expected up to 1.2 km or three quarters of a mile from each tower.

In addition to RTK, large numbers of agricultural GPS receivers deployed across the United States depend on delivery of continuous real time differential (RTD) GPS correction data via L-Band Mobile Satellite Services in the 1525-1559 MHz band. Due to the contractual requirements of the MSS providers, receivers in this band have to be able to receive a signal anywhere within the band, as the providers reserve the right to move at short notice the frequency within the band being used to deliver any given signal. For this reason, the in-band interference to MSS signals used by integrated MSS-GPS receivers was also tested.

This testing shows complete loss of the MSS signals at power levels of -47 dBm (-57 dBm adjusted for receiver antenna gain). It can be seen from Figure 58 above that -57 dBm would be received at distances well beyond 2 km from each tower. In a Free Space Path Loss model, this power level could be seen at more than 10 km from each tower. Given typical rural tower spacing, blanket denial of MSS delivered differential GPS correction data and thus MSS-GPS receiver function could be expected by agricultural users throughout the rural coverage areas.

Harmful interference, as defined by the GPS Community in Section 3.3, at the 1 dB C/N_0 loss point was observed at between -83 dBm and -55 dBm, best case and worst case respectively, depending on LTE configuration and receiver type. The GPS Community notes that utilizing a free space LOS model, as can be seen from Figure 41, the best case level of -55 dBm would mean harmful interference to MSS communications to approximately 16 km or 10 miles from a rural tower at 62 dBm EIRP and in the worst case, the harmful interference would extend far beyond the 22 km limit on this chart. Accordingly, harmful interference to MSS communications used for real time differential GPS systems could be expected over more than 12.5 million square miles of the United States, assuming 40,000 towers and the best case observations.

LightSquared disagrees with the calculations above as it believes they are overly general; it also notes that the information above does not account for possible mitigation options.

Based on the operational scenarios in Section 5, agricultural operations would suffer significant harm in areas where any of the following occurs:

- Satellite coverage is reduced so that there not a common set of 5 satellites between the reference station that generates corrections and the roving receiver.

- Accuracy degradation; for some applications 2 cm accuracy is required, others (particularly those using decimeter network corrections) 10 cm.
- Positioning impairment in any part of the field.
- Denial of MSS delivered differential correction data.

The following information is provided by the GPS Community. LightSquared strongly objects to the inclusion of an economic analysis in this report as it believes it is outside of the charter and work-plan of the working group that was properly focused on a technical analysis of the GPS issue.

US Dept of Agriculture census data reports that crop farm production in the United States averages $169.1B per year and input costs average $108.4B annually. The industry employs more than half a million people in the U.S. Studies[56][57][58] and published data indicate that adoption of high precision GPS in the United States crop farming industry is at 60%, with a total capital investment of $3B, producing average resulting yield increases of 10 percent and average resulting input cost savings of 15%. At the current adoption rate, the economic benefits of GPS Precision Agriculture are estimated[59] at $10.1B per year in increased yields and $9.8B per year in reduced input costs. Figure 59 below shows the estimated annual economic impact over a range of percentage denial of high precision GPS use, assuming a linear function. At higher adoption rates, these numbers would increase accordingly.

[56] National Association of Wheat Growers estimates, 2011
[57] US Dept of Agriculture Agricultural Census Data
[58] ABI Research, GPS Industry Study 2007-2011
[59] Pham et. al, GPS industry study, 2011[60] With reference to Geospatial Industry Association of America and N.A.M. Geospatial Industry Group statistics, annual reports and other sources of industry data.

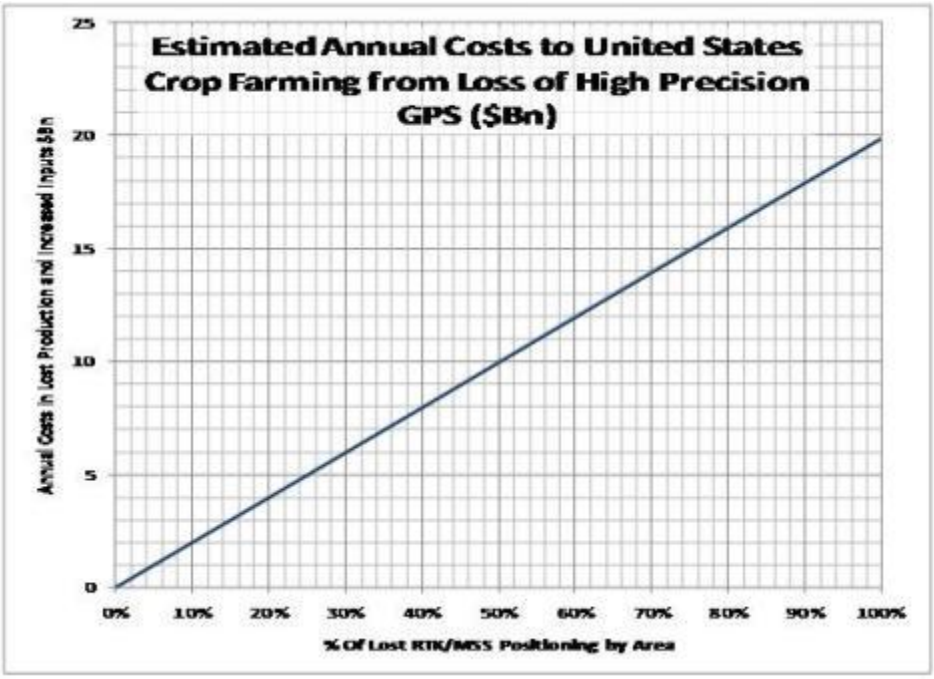


Figure 59 Estimated Annual Costs to US Farming from Loss of High Precision GPS

It can be seen that the impact to the US Agricultural Economy of the large scale denial of high precision GPS operation expected from the test results and observations is in the order of tens of billions of dollars per year. These are the operational costs and do not factor in the depreciated value of the estimated $3B of capital equipment purchased in this sector still in use. The planned deployments would tend toward the 100% denial scenario in any rural area where coverage is provided.

Given the stated intent of this network to cover 92% of the US population, this scenario would tend toward the upper right hand quadrant. Even the most favorable LTE unplanned deployment tested would deny RTK over very large rural areas and cause almost complete denial of MSS delivered differential GPS corrections within the coverage area. This is true for planned and unplanned deployments tested including 10 MHz in the lower part of the band. The linear assumption of the economic model may be questionable in that scenario, as unpredictable or partial coverage of high precision GPS positioning could render precision agricultural operations impractical in many cases. Therefore, none of the deployments tested – planned or unplanned - can be considered compatible with current large scale precision agricultural uses and the potential costs of any such deployments tested are estimated to be in the order of magnitude of tens of billions of dollars annually, , in addition to social costs caused by the aggregate resulting increases in fuel, fertilizer and chemical use.

12.4 Other Operational Scenarios

As noted in Section 5, the operational scenarios used are presented by the GPS Community.

This section considers the operational scenarios involving Construction, Engineering, Surveying, Local Government, Energy and Utilities, and Transportation and Science.

Many users of high precision GPS and integrated MSS-GPS equipment in non-agricultural applications also work in rural environments and thus would be expected to suffer the same impacts outlined above. Additionally, in terms of lost of coverage to RTK GPS users, the effects in urban and suburban areas were measured in the Live Sky tests to be different from those in rural areas; which coupled with denser cell tower spacing in urban and suburban areas creates a slightly different interference environment. Figure 60 below shows a representative suburban example of measured power versus distance from Tower 68 at the Las Vegas Live Sky testing, overlaid with the 50th percentile point of Loss of Good RTK as measured in the chamber tests, for both the Phase 0 LTE deployment and for the unplanned, partial deployment tested, 10 MHz in the lower part of the band, F10L. These overlays have been adjusted for the typical GPS antenna gain as a function of zenith angle and assume that the LTE power is incident at the horizon, which, in the opinion of the GPS Community, may be optimistic given typical urban and suburban LTE antenna siting.

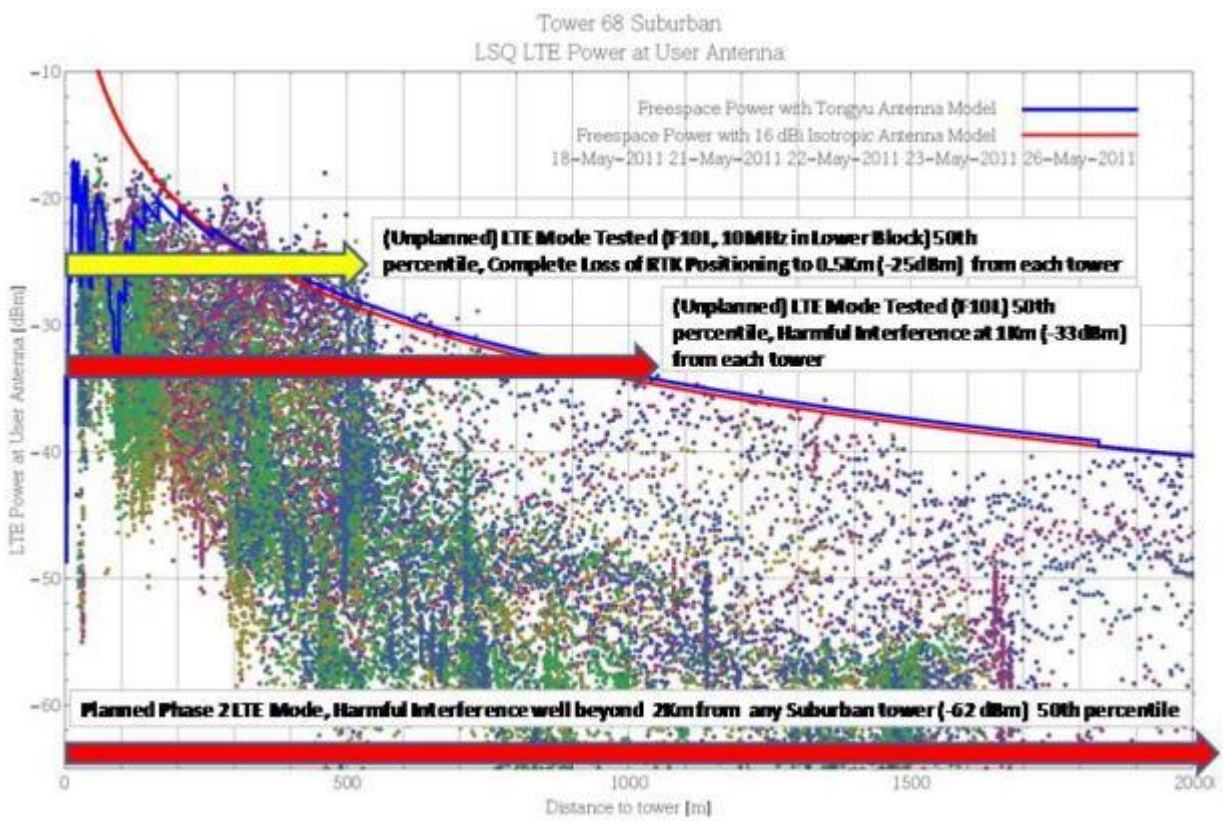


Figure 60 Las Vegas Tower 68 Power vs. Range, Overlaid with RTK Loss Data

GPS Community Position:

> It can be seen that in the Phase 2 deployment, a typical RTK receiver as measured at the 50th percentile would be unable to provide the RTK or high precision function well beyond the 2 km point on this chart. Given typical tower spacing in suburban environments, complete blanket denial of RTK positioning in areas covered by this

service could be expected. This is also true for the urban and dense urban cases; despite the higher attenuation as a function of distance observed in those configurations, the denser station spacing means that a user would never escape the -45 dBm power level at which RTK positioning is completely denied while inside a coverage area and would have to move far outside of it to do so. In the unplanned LTE deployment scenario tested – 10 MHz in the lower part of the MSS band – a typical RTK receiver as measured at the 50th percentile would be unable to function within 500 m of each tower and degradation of performance from harmful interference (as defined in Section 3.3), as measured by the 50th percentile 1dB compression point could be expected up to 1 km or three quarters of a mile from each tower. Again, due to the denser station spacing in suburban and urban environments, even this configuration would cause harmful interference over almost the entire urban and suburban area covered, and complete denial of RTK and high precision positioning over 50% or more of the area covered.

LightSquared's Position:

LightSquared does not disagree with the measurements that are shown in Figure 52, but does disagree with the assessment of the impact to high precision GPS users. Figure 52 demonstrates that the free space LOS model is an accurate predictor of the worst case signal propagation from an interference perspective. Figure 52 clearly shows how the measured signal strength is clustered well below the free space LOS line; especially as the distance from the site grows. While there is outlier data that is consistent with the free space LOS line, it should not be misconstrued as evidence that these signal strengths consistently acheived at these distances.

GPS Community's Position:

Refer to section 11.4

The following information is provided by the GPS Community. LightSquared strongly objects to the inclusion of an economic analysis in this report as it believes it is outside of the charter and work-plan of the working group that was properly focused on a technical analysis of the GPS issue.

The full extent of the economic and social impacts that would be caused by these observed levels of interference and denial across all the uses of high precision GPS described in Section 5 including Construction, Engineering, Surveying, Local Government, Energy & Utilities, Transportation and Science are almost incalculable and would certainly be beyond the scope of this study. However, as with Agriculture, the order of magnitude is estimated below to be in the tens of billions of dollars annually, not factoring the depreciated capital expenditures on high precision GPS in the United States, estimated to be more than $3B[60] excluding Agriculture for equipment still in use – with equipment replacement cycles across all high precision applications typically being up to 15 years.

[60] With reference to Geospatial Industry Association of America and N.A.M. Geospatial Industry Group statistics, annual reports and other sources of industry data.

Heavy and Civil Engineering Construction and Architectural and Engineering Services including Surveying are U.S. industries with annual revenues of $260B and $250B and employing 1.04 and 1.43 million people in the US, respectively[61] As illustrated in Section 5 through examples, the adoption of high precision GPS in these industries generates significant economic benefits including productivity increases and reduced input costs. It is estimated that the annual cost savings generated in labor, capital and raw materials alone as a result of the current levels of GPS adoption are in excess of $9B annually[62]. Expected future increased adoption rates would increase these estimates proportionally. In addition, reduced productivity caused by denial or degradation of high precision GPS would further increase the economic costs as well as the social costs caused by reversal of fuel savings and reduced environmental impact.

In one of the operational scenarios described in Section 5, surveyors and engineers routinely bid for projects throughout the State using the precise positioning information (less than 2 centimeters in 3 dimensions--latitude, longitude, altitude) in real-time, dynamic—and often stressed—environments. The resulting soft cost savings in the annual state budget, associated with these projects, range from 40-60 percent annually. For eight years to date, this network has delivered robust, high fidelity precise positioning information that enables predictable project bidding and completion. If the coverage areas where these projects are currently bid, using the precise positioning information provided by this network, becomes unreliable due to the presence of harmful interference, then current users, including surveyors and engineers, would not be in a position to reliably bid for projects. Using alternative measurement methods would significantly raise project costs in many cases.

Given the investment in high precision GPS across the other sectors and applications described in Section 5, including State and Local Government, Energy, Utilities, Oil & Gas and Transportation the economic impacts that could be expected, even in the best case unplanned deployment tested, would be of a similar magnitude, with estimated total economic costs over ten years summing to almost $1 trillion[63]. The social costs in these cases may be higher; for example the interference with high precision GPS used to monitor critical structures such as dams or used as inputs to earthquake, volcano and tsunami early warning systems; or the interference with high precision GPS used in automatic lane guidance systems or with GPS used in Positive Train Control systems all have safety of life implications.

Given the test results and the estimated economic and social impacts caused by the interference levels observed and the resulting extent of denial of high precision GPS, none of the deployments tested – planned or unplanned - can be considered compatible with current large scale high precision GPS uses across many critical sectors of U.S. public and private sector activity. The lost production and increased input costs of any such deployment are estimated to be in the order of magnitude of

[61] U.S. Census Bureau, Economic Census Data released 2010/2011.

[62] Pham et. al, GPS industry study, 2011

[63] Pham et al, 2011 estimate $96B annual economic cost of degradation to GPS, almost $1Tn over 10 years.

tens of billions of dollars annually across these sectors and could also have public safety implications. Accordingly, proceeding with any of the deployment scenarios tested - including the unplanned partial deployment in the lower part of the band - cannot be recommended and should in fact be strongly cautioned against.

12.5 Networks

12.5.1 Decimeter Networks

A representative example operational scenario for high precision GPS networks is the StarFire network, for which the impacts of interference have been analyzed. The effect of removing US StarFire reference sites (simulating LTE interference sufficient to make their measurements invalid) on global StarFire positioning has been measured using recorded StarFire data. The results show a doubling of the navigation error, which would affect Deere users substantially.

It is harder to experimentally investigate interference effects on networks than to investigate interference effects on individual receivers. Networks are usually geographically diverse, making it difficult to subject them to controlled interference, and operating networks do not want to subject themselves to interference that might degrade their performance. So networks tend to necessarily be investigated analytically rather than experimentally.

12.5.1.1 Background - StarFire

StarFire is the global differential GPS system operated by John Deere for its customers. StarFire has a network of GNSS receivers (approximately 50) distributed throughout the world that send real time measurement data to two processing centers in the US. At these processing centers, the data are used to continuously compute corrections to the clocks and orbits of all the GNSS satellites. The clock and orbit corrections are sent to Uplink sites, where they are transmitted to geostationary satellites, which broadcast the corrections to Deere receivers throughout the world. These corrections enable Deere receivers to improve the accuracy of their GNSS measurements and navigate with accuracies of a few decimeters.

12.5.1.2 Test Plan

All the data from the StarFire reference sites is recorded at the processing centers, hence is available for post processing. As it is not feasible to subject real time operational StarFire sites or data to degradation, it is necessary to use post processing techniques to study the effects of LTE interference.

The most effective way to study the effects of LTE interference on StarFire would be to degrade the measurements in a manner consistent with LTE interference, and vary the degree of interference and the sites that are subjected to interference. However, degrading the measurements would take far more effort that can be justified at present.

Consequently, it was decided to study the effects of removal of sequential US sites from StarFire. This situation corresponds to what would happen if LTE interference were severe enough to prevent measurements from these sites from being used. In this sense,

it seems to correspond to a worst case interference scenario. However, it should be noted that the processing centers look at the quality of incoming measurements and reject those that are deemed not acceptable, so losing the measurements from a reference site could occur under interference conditions less severe than that required to prevent a reference site from tracking satellites.

The test that was conducted is as follows:

1) We want to evaluate the effect on global positioning of losing reference sites in the US.
2) We will first record the performance of StarFire monitors at nine US reference sites and five other reference sites worldwide (Brazil, Australia, China, Peru, Japan). In this initial case, clock and orbit corrections are computed using measurements from all StarFire sites, including these 14 sites.
3) We will then drop one reference site in the US, compute clock and orbit corrections without this reference site, and re-observe navigation performance at all 14 sites.
4) We will next observe navigation performance at all 14 sites as we sequentially drop more US reference sites, one at a time, until all nine US reference sites have been dropped.
5) For each of the 10 cases above, we will process 24 hours of data after the orbit filters have fully settled and determine the effects on navigation accuracy.
6) The primary metric collected is standard deviation in 3D positioning.

12.5.1.3 Test Results

The results of this experiment are shown below in Figure 61.

The horizontal axis shows the number of sites removed for the purpose of computing corrections. The leftmost point shows the result with no sites removed, the rightmost with the 9 US sites removed. The vertical axis shows the <u>change</u> in 2-sigma three dimensional (North, East, Vertical) positioning accuracy. The vertical axis has been normalized by removing the initial value for each graph from its later results, resulting in all graphs starting at zero on the left and showing the change in positioning accuracy as sites are removed (the average initial 2-sigma three dimensional value is 35 cm).

Each graph shows the positioning result of the sequential removal of the nine US reference sites at a particular location.

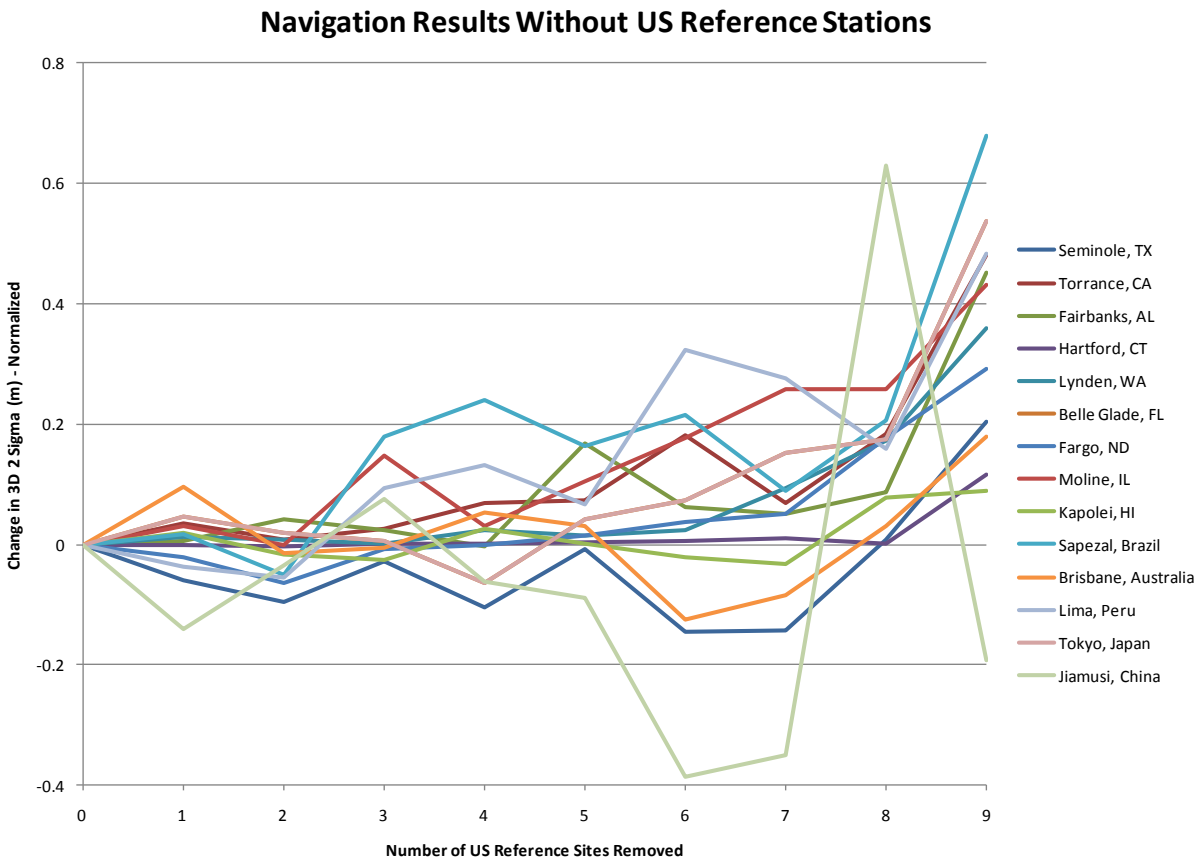


Figure 61 Removal of US Reference Sites

12.5.1.4 Analysis and Conclusions

The conclusions of this experiment are as follows:

- It is clear that the positioning variance increases as sites are removed. The average 2-sigma 3D value after the removal of all nine reference sites has increased from 35 cm to 70 cm.
- The effects are larger on sites outside the US. This is likely because the deterioration in clock and orbit accuracy occurs as the satellite is not tracked by as many sites as it traverses the US, and this deterioration then results in reduced positioning accuracy as that satellite is used by other global sites.
- The effect on Deere customers of a doubling in the 3D 2-sigma values would be severe. Multiple agricultural operations depend on the StarFire accuracy, and some equipment is now sold without mechanical attachments that previously were used for guidance.

12.5.2 Centimeter Networks

This section discusses the operation effects of interference to a single reference receiver in a centimeter network.

12.5.2.1 Discussion

Centimeter or RTK networks represent an infrastructure of fixed receivers and software that provides information about the satellite carrier phase to mobile receivers. This data enables the mobile receivers to compute positions accurate to 1.5 cm. A continuous stream of data from the network is needed for the system to operate.

One of the key elements in the data stream is information about the ionosphere. Because variations in the ionosphere are localized, the spacing of reference receivers in the network is recommended by network system providers to be no greater than 50-60 km in the temperate zone (the ionosphere being more active in the tropics and polar regions, the recommended density there is higher). Generally, the receivers in RTK networks are not any denser than the recommended level for cost reasons.

For a mobile receiver to produce a two cm (RTK) solution, it must have data from the network for at least five satellites in common with satellites that the mobile receiver is tracking. If a single reference receiver does not produce adequate data, the network will usually continue to generate and broadcast data, but the ionospheric correction content will be lacking for mobile receivers in the vicinity of the reference station.

The consequence of inadequate ionospheric information is higher position error. For RTK positioning, the L1 and L2 frequencies are used for initialization, and then the positioning is done only by L1. In the absence of adequate ionospheric information, positioning must be done (if at all) by an ionosphere-free combination of L1 and L2. This technique has noise levels 3-4 times an L1-only solution, so the accuracy of the solution is greater than 6 cm instead of 2 cm.

12.5.2.2 Operational Effects

If a reference receiver is interfered with so that it tracks fewer than five satellites at an adequate SNR, or the satellite set it does track does not have five satellites in common with rover receivers, then any rover receiver within up to a 30 km radius of that reference receiver will experience an accuracy worse than 5 cm instead of 1.5 cm. The poorer accuracy is unacceptable for most survey and construction applications, as noted in Section 5.2.3.

13 Potential Mitigations

Since the LightSquared planned rollout of terrestrial transmitters and the installed base of precision and timing receivers are largely incompatible, we now address the issue of what can be done to mitigate the lack of compatibility.

13.1 Interference Mechanisms

To understand what potential mitigations would be feasible and appropriate, it is first necessary to consider the interference mechanism. We've identified three interference mechanisms while conducting this study.

The first mechanism arises from the ability to receive a low power signal (GPS) in the presence high power signal (LightSquared) that is broadcast in an adjacent spectrum band. If the filtering in the receiver cannot adequately attenuate the LightSquared signal prior to the substantial amplification needed to see the low power signal, then the amplifiers will limit, attenuating the GPS signal and making it more difficult to receive, or blocking it entirely. This interference mechanism explains the results from upper band (Phase 0) testing.

The second interference mechanism is in-band interference to GPS. This occurs because the third order inter-modulation product between LightSquared's low band and high band signals falls directly into the GPS band (see Phase 1 and Phase 2 rollout plans, Section 3.2). The inter-modulation, or mixing product takes place whenever a non-linearity exists in the system. See Figure 62 below.

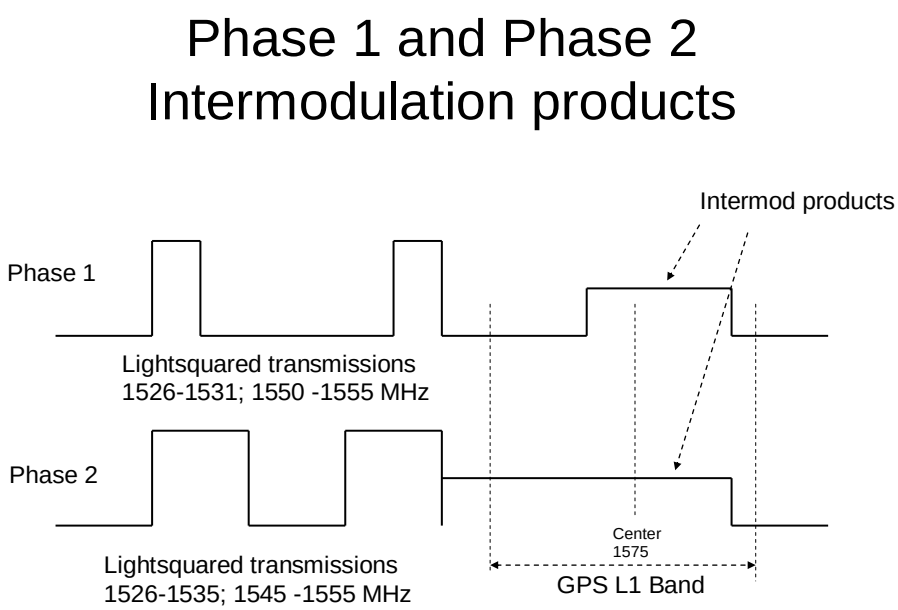


Figure 62 Intermodulation Products

Depending on the rollout configuration, this could take place in the post-filtering antenna system of the transmitter, or it could take place in a GPS receiver, particularly if the any

element in the receive chain is experiencing strong signals as described in the first mechanism above. It is not expected that it will occur at the transmitter if LightSquared meets its regulatory requirements. However it occurs, this mechanism explains why the two band testing (Phases 1 and 2) gives significantly worse results than the upper band alone (Phase 0).

The third harmful interference mechanism identified is the in-band, co-channel interference to the Mobile Satellite Services (MSS) communications component of integrated MSS-GPS real time differential receivers. This component is critical to the primary function of the device; without the data stream the unit is unable to provide the primary function of delivering real time high precision positioning. In order to provide flexibility in user operations, many fielded high precision GPS receivers offer the ability to receive such MSS signals, often through a common antenna element and Low Noise Amplifier (LNA) due to the contiguous and immediately adjacent nature of the bands being used.

13.2 Mitigation Conditions

Armed with this understanding, we now consider what can be done in each category of GPS receiver design going forward, and then also consider whether any of these approaches – or others – can meet the set of criteria below. Finally, we address how the LightSquared signal could be different to improve compatibility. In order to be practical, any potential mitigation solution must, in its entirety, meet certain conditions:

- It must be technically feasible and verifiable for the class of GPS receiver under consideration, given technology which is commercially available and technically verifiable.
- It must be technically feasible and verifiable for the deployment of a 4G LTE network by LightSquared.
- It must, in its entirety, be commercially viable and feasible in implementation for currently fielded GPS and MSS-GPS equipment and systems, within a normal replacement cycle, as well as for future equipment.
- In must, in its entirety, be commercially viable for LightSquared in terms of available bandwidth, total network capacity, network and user equipment, and in meeting its license obligations to the FCC.

LightSquared is troubled by the term “commercially available” as used in the bullets describing the mitigation conditions above. This term could be construed to imply that only components that are immediately available for order are “commercially available.” LightSquared believes a broader definition that contemplates the development of updated receiver/filter specifications by the GPS Community and the solicitation of proposals from manufacturers is appropriate. LightSquared believes it also should be acknowledged that some amount of expenditure for the research and development of these components may be both necessary and reasonable.

The GPS Community believes that the starting point for mitigation should be LightSquared's rollout plan, (see Section 3.2) which incorporates 7 dB less transmit power than the SkyTerra 2010 license of 42 dBW maximum aggregate EIRP per sector.

13.3 GPS Receiver Mitigation Analysis for Proposed Rollout

13.3.1 High Precision and Network Receivers

Precision GPS receivers utilize the entire L1 GNSS spectrum to enable GPS dual frequency operation, to gather information for multipath suppression – both needed to achieve the required accuracy for their applications – and in some cases to receive signals from the other satellite providers, such as GLONASS, Galileo, and Compass. Going forward, the GPS Community knows of no practical filtering technology that would provide the desired discrimination between the Phase 0, 1, or 2 rollouts (1550 MHz – 1555 MHz) and the GNSS band starting at 1559 MHz. Cavity filter technology could possibly meet the electrical requirements, but the physics of cavities at these frequencies result in a filter of very large size – larger and more expensive than the rest of GPS receiver – which would not be appropriate for portable equipment. Investigation of Surface Acoustic Wave (SAW) filter technology as a possible filter mitigation has shown that a state-of-the-art SAW filter design to operate in the Phase 0, 1 or 2 rollout scenarios is not feasible for a GPS receiver that uses the full GPS signal, due to both the limited transition band and the inter-modulation effects. Bulk Acoustic Wave (BAW) technology is not available in the L-Band frequency range, therefore it cannot be tested or evaluated.

LightSquared notes the following:

> LightSquared believes that more due diligence should be performed by manufacturers regarding the range of filtering options available, given different potential spectrum deployment scenarios.

Given these constraints, the GPS Community believes there is no mitigation solution for the installed base of precision receivers for LightSquared Phase 0, 1, or 2 rollouts.

13.3.2 Augmented Receivers

Some precision GPS receivers achieve their degree of precision by the reception of augmentation signals through a broadcast MSS satellite service subject to the terms of commercial service agreements. In North America, these services are currently received at approximately 1535 MHz and 1557 MHz, however these receivers have to be capable of receiving signals in the entire 1525-1559 MHz band due to the operational and contractual requirements of the MSS providers. The filtering problem for these is completely intractable due to the in-band, co-channel nature of the interference. The only possible future mitigation is to identify, develop, and install a completely different delivery mechanism for these services. No such delivery system has been identified at this time.

Since current augmented receivers are already open to the MSS band, there is no possible receiver mitigation which could work for the installed base of L-band augmentation receivers. In order to provide flexibility in user and supplier operations, many high

precision GPS receivers use a common antenna LNA which is designed to support all GNSS signals and augmentation services, even though the augmentation component of the system may not always be in use.

13.3.3 Timing Receivers

Timing receivers often use a small subset of the 32 MHz wide GPS band, sometimes as little as 2 MHz surrounding 1575.42 MHz. For these receivers, testing of the PCTEL antenna has indicated that an adequate solution may be available for Phase 0 of the LightSquared rollout, albeit with an increase in the antenna noise figure over conventional designs, typically by 2 dB. Some timing applications require the receivers to be much closer to the terrestrial transmitters than do receivers in other applications, so the success of this solution depends on the proximity of any particular installation to LightSquared transmitters. Laboratory testing has also indicated that this solution may not mitigate Phase 1 and Phase 2 interference. However, field tests did not replicate this issue for Phase 1 (Phase 2 was not tested in the field).

It should be noted that the field test results for this antenna do not include measured interference power at the devices under test. Further, the Las Vegas field tests were conducted at a power level 3 dB lower than that planned for deployment in Phases 1 and 2 in MIMO mode due to equipment limitations. Therefore, the field test results may have avoided the inter-modulation results observed in the carefully calibrated lab tests due to exposure of the antenna to lower power levels for the duration of the field test. No other mechanism is known that would account for the Phase 1 and Phase 2 problems experienced in the lab test.

In the future when the L1C signal are available, timing receivers are likely to use them due to their greater robustness and multipath resistance, and also because the C/A code is likely to be eventually phased out. Since the L1C signal is wider band, the extremely narrowband solution proposed for Phase 0 mitigation will no longer be adequate when this signal comes into general use.

The timing solution above for the Phase 0 rollout can be available in antenna form, so it is a possible solution for the installed base for Phase 0, or for a lower 10 MHz channel operating on a permanent standalone basis, subject to the caveats above. It would require existing users to replace existing units on or near their towers incurring unplanned costs. It is not certain to protect against interference from Phase 1 and Phase 2 rollouts, or to be compatible with modernized GPS signals.

A summary of the mitigation possibilities under for the proposed LightSquared rollout appears in Table 15 below.

	Receiver Mitigation for Proposed Rollout		
	Precision	MSS Comm	Timing
New Receiver Design	None known	None known	Phase 0 of rollout appears possible; phase 1 and 2 unknown; L1C would require a new

			solution
Installed Receiver Base	None known	None known	Technically feasible where the antenna is not integrated into another system. Partial or total replacement of fielded antennas or receivers for phase 0. The GPS community notes that these components typically have a 15 year life cycle. phase 1 and 2 unknown – may not be technically viable.

Table 15 Receiver Mitigation for Proposed Rollout

13.4 GPS Receiver Mitigation for an Upper Band Only Rollout

The following section reflects the position of the GPS Community. LightSquared has not commented on the information in Section 13.4 as it is not considering an upper-channel only deployment.

Due to the intermodulation interference arising from strong signals in the two bands proposed for rollout, in this section we address the concept of using only the upper band.

For precision receivers, the same spectral separation exists for an upper band-only approach as for phase 0 rollout. Thus the same limitations for precision receivers apply as discussed in the previous section. There is no practical technology to address new designs or to mitigate the installed base under this scenario.

For augmentation signals received from satellites in the MSS band, it may be conceivable to design a satellite receiver that operates in the lowest part of the MSS band and not be interfered with by LightSquared signals in the upper part of the MSS band, although this will require further technical study to verify. Should that be the case, it would require migrating all US augmentation services to the lowest part of the MSS band, near 1525 MHz, and would make any US solution incompatible with international equipment, which operate over the entire MSS band. In this scenario, the MSS augmentation signals would be spectrally separated from the GPS band by the LightSquared signals, so such a solution would be more expensive than today's integrated solution. The potential interference from the spectral neighbors below 1525 MHz has not been investigated, and would require further study. No prospective augmentation solution exists for the installed base.

Testing has demonstrated that it is possible to design a Timing receiver that mitigates an upper-band approach at a 32 dBW transmit power. Some timing applications require the receivers to be much closer to the terrestrial transmitters than do receivers in other applications, so the success of this solution depends on the proximity of any particular

installation to LightSquared transmitters. The solution tested (PCTEL) incorporates additional filtering, a higher-power consuming amplifier, and a higher noise figure, which could be suitable for a fixed-installation, line-power unit. However, much of the installed timing base is sensitive to a high-band LTE rollout and, depending on location, would have to be replaced with a different design.

As the L1C signal becomes available, it would not be compatible with the solution tested, and given the greater bandwidth needed by this signal, it is not known if an alternative solution could be developed.

As described in the proposed LightSquared rollout plan, the terrestrial broadband operations are assumed, considering all deployment phases, to require 20 MHz of downlink spectrum using two channels of 10 MHz each to deliver a commercial 4G LTE service. A deployment of 10 MHz in the upper band can only be considered in isolation as a viable mitigation option if, in its entirety, it is a commercially viable solution for an LTE deployment, or if the other 10 MHz of the required 20 MHz is to be deployed in a different band entirely. Any subsequent use of additional spectrum within the MSS L-band in question simply reverts to a re-sequencing the original planned rollout, with mitigation options as described in Section 13.3 above.

A summary of the mitigation possibilities under an alternative upper-band-only LightSquared rollout appears in Table 16 below.

	Receiver Mitigation for Upper Band Rollout Only		
	Precision	MSS Comm	Timing
New Receiver Design	None known	If possible, would require use of only the lowest MSS band for satellite comm.; requires study	Appears possible; L1C will require a new solution
Installed Receiver Base	None known	None known	May be technically viable. May not be commercially viable due to need for partial or total replacement of fielded units. The GPS community notes that these components typically have a 15 year life cycle

Table 16 Receiver Mitigation for an Alternative Upper Band Rollout

13.5 Mitigation of GPS Receivers for a Lower Band Only Rollout

As described in Section 13.3, the GPS Community believes any potential mitigation solution must, in its entirety, meet certain conditions in order to be practical. A deployment of 5 or 10 MHz in the lower band can only be considered in isolation as a

viable mitigation option if, in its entirety, it is a commercially viable solution for an LTE deployment, or if the other 10 MHz of the required 20 MHz is to be deployed in a different band entirely. The GPS Community believes that a deployment in the lower band only cannot be considered in isolation if it is subject to any subsequent use of additional spectrum within the MSS L-band in question, as in that case it simply reverts to a re-sequencing of the original planned rollout, with mitigation options as already described in Section 13.3 above.

Considering a deployment in the lower part of the band (below 1536.3 MHZ) with no subsequent deployment in any other part of the band, the GPS Community believes it is not certain that a mitigation can be found for precision receivers that maintain the bandwidth and noise figure of current technology as discussed in section 3.5.1.1. If so, it may be at a different transmit power level than originally proposed for this band of 32 dBW, and certainly less than the full authorized level of 42 dBW. No solution is available that maintains the current access to the augmentation signals over the entire MSS band, though isolation of these signals to the upper part of the GPS band is a possibility. More study is required to fully understand what is possible, both from a technical and commercially viable standpoint. Most of the installed base is not compatible with this solution, and would require replacement should a new design become available, to meet current performance requirements

LightSquared notes that a deployment in the lower part of the band provides much greater separation between terrestrial and GPS uses and affords the GPS industry an excellent opportunity to begin implementing reasonable receiver-side mitigation components into its equipment. Such a deployment by LightSquared would afford 23 MHz of separation between the top edge of its downlink spectrum and the beginning of the GNSS band. As noted by the GPS Community, there are options available for the augmentation signal as well that would allow future devices to continue to utilize L-Band augmentation signals in a common front-end. LightSquared does not believe there are any substantial technical or operational obstacles to quickly improving the resiliency of new high precision receivers so that they are no longer susceptible to receiver overload; especially when coupled with a lower band deployment by LightSquared.

The GPS Community believes that any replacement for precision receivers, even if available, would not be compatible with any subsequent LightSquared terrestrial deployment in the MSS L-Band for the reasons outlined in Section 13.3 and therefore could only be considered a viable solution if the extent of the terrestrial deployment was permanently limited to operation below 1536.3 MHz and, further, that deployment in the 1525-1536.3 band is not commenced until the necessary R&D time and normal industry replacement cycles has been achieved. The GPS Community notes that the normal industry replacement cycles for Precision and Timing receivers are on the order of 15 years.

LightSquared notes that the 15 year replacement timeframe stated GPS Community is based only on the GPS Community's assessment of the normal replacement cycle of equipment. It does not account for opportunities for prioritized upgrading of equipment (due to proximity to LightSquared network or overall susceptibility of equipment). Additional measures, such as coordination activities, could serve to further enable the

deployment of the LightSquared network without negatively affecting users of high precision equipment.

The GPS Community notes that any acceleration of this timeframe would represent a burden shift to the installed user base with too many unknowns.

For augmentation signals received from satellites in the MSS band, it may be conceivable to design a satellite receiver that operates in the highest part of the MSS band and not be interfered with by LightSquared signals in the lower part of the MSS band, although this will require further work to verify. Should that be the case, it would require migrating all US augmentation services to the highest part of the MSS band, and would make any US solution incompatible with international equipment, which operate over the entire MSS band. The GPS Community has identified no prospective augmentation solution that exists for the installed base.

Therefore, the GPS Community believes that this approach for moving MSS augmentation signals could only be considered a viable and practicable solution if deployment in the 1525-1536.3 MHz band is not commenced until the necessary R&D time and normal industry replacement cycles has been achieved. Further, any such replacement, even if or when available, would not be compatible with any subsequent LightSquared terrestrial deployment in the higher part of the MSS L-Band for the reasons outlined in Section 13.3, and therefore this could only be considered a viable solution if the extent of the terrestrial deployment is permanently limited to operation below 1536.3 MHz. LightSquared disagrees with the 15 year timeframe and believes that through proper prioritization and coordination, deployment of LightSquared's network need not be delayed.

Testing has demonstrated that it is possible to design a timing receiver that mitigates a lower-band approach at a 32 dBW transmit power; LightSquared notes that such products are already commercially available. Some timing applications require the receivers to be much closer to the terrestrial transmitters than do receivers in other applications, so the success of this solution depends on the proximity of any particular installation to LightSquared transmitters; though LightSquared notes that the Las Vegas testing showed that even co-located timing receivers utilizing commercially available resilient antennas, continued to perform their intended function without interruption in the presence of LightSquared's lower-channel signal. Some of the installed timing base are sensitive to lower-band rollout and, depending on location, would have to be replaced with a different design.

A summary of the mitigation possibilities under an alternative lower band only LightSquared rollout appears in Table 17 below.

	Receiver Mitigation for Lower Band Rollout Only		
	Precision	MSS Comm	Timing
New Receiver Design	Mitigation not certain; requires more study. Any mitigation is likely be a non-global	If possible, would require the use of only the highest MSS band for satellite comm; requires	Appears possible for current GPS signals. Modernized

	solution for inclusion of MSS augmentation delivery.	study.	GPS signals requires more study.
Installed Receiver Base	Replacement of most of the installed base if a solution new design were available- costs unknown, so may not be commercially viable. Normal replacement cycles would prevent terrestrial deployment within 15 years and in any event not above 1536.3 MHz.	None known	Appears technically possible for current GPS signals. Will require replacement of some fielded units, costs require more study. Modernized GPS signals requires more study.

Table 17 Receiver Mitigation for an Alternative Lower Band Rollout

13.6 Other Mitigation Possibilities

The satellite component of LightSquared's deployment is currently in operation and is compatible with current GPS uses. The GPS Community believes that deployment of the terrestrial component of the network in a completely different band, not in the MSS L-Band, where the transmissions would be more compatible with adjacent uses would be a technically viable solution (for example, in the S-Band or in the 700 MHz band already allocated to 4G terrestrial services). The GPS Industry believes this option requires additional study in terms of technical and commercial viability, indicating that more due diligence needs to be exercised by LightSquared regarding the range of network deployment mitigation scenarios available. The GPS community believes t is more feasible to change the frequency plan for a network yet to be deployed than it is to change the frequency plan for equipment already widely deployed, both terrestrially and in earth orbit.

LightSquared believes that both it and the GPS Community have an obligation to develop and implement mitigation measures that allow both services to operate in accordance with established FCC rules. LightSquared notes that alternate deployment scenarios inside of the L-Band have been thoroughly evaluated by the working group. It strongly disagrees with the GPS Community's assertion that LightSquared should be forced to move its operations to "a completely different band." LightSquared notes that spectrum is a critical resource and it is incumbent upon all licensees and users to manage their use of the spectrum efficiently.

The use of much lower power but higher density 'microcells' has not been investigated in terms of either technical or commercial feasibility, indicating that more due diligence needs to be exercised by LightSquared regarding the range of network deployment

mitigation scenarios available. LightSquared disagrees with this characterization and believes that ample solutions exist for it to be able to deploy its network consistent with the MSS/ATC rules currently in place, subject to the mitigation measures discussed in this report.

The GPS Community believes that:

> Spectrum is a critical resource and it is incumbent upon all licensees and users to manage their use of the spectrum efficiently. GPS is arguably the most efficient user of spectrum in use today; it is estimated that almost a billion people are currently benefitting from use of the GPS signal globally. Allowing harmful interference to GPS receivers and GPS-dependent devices from LightSquared's 4G LTE proposed operations in the 1525-1559 MHz band would be neither an efficient nor effective use of spectrum.

14. Glossary

This glossary contains definitions of acronyms used in this report.

1PPS	One pulse per second.
3GPP	3rd Generation Partnership Project, a collaboration between groups of telecommunications associations to define a globally applicable third-generation mobile phone system specification based on GSM.
4G	Fourth Generation, usually used with LTE.
ATC	Ancillary Terrestrial Component, referring to LightSquared terrestrial cell network sites.
BW	Bandwidth
C/N_0	Carrier to Noise Ratio, a measure of the quality of a signal.
Cm	Centimeters (2.54 cm = 1 inch)
Compass	The Chinese GNSS.
CORS	Continuously Operating Reference Network
CW	Continuous Wave
dB	Decibels, a logarithmic measure of relative power between two signals, defined as dB = 10 log(P1/P2).
dBi	dB isotropic, the gain a given antenna has over a theoretical isotropic (point source) antenna.
dBm	dB relative to one milliWatt (dBm = 10 log (P1/one milliWatt)
dBW	dB relative to one Watt (dBW = 10 log (P1/one Watt)
DOT	Department of Transportation.
DTM	Digital Terrain Model.

e911	Enhanced 911, a system for emergency calls.
EIRP	Effective Isotropically Radiated Power, the amount of power that a theoretical isotropic antenna (which evenly distributes power in all directions) would emit to produce the peak power density observed in the direction of maximum antenna gain.
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency.
GHz	Giga-Hertz, one billion cycles per second
GIS	Geographic Information Systems, a class of GNSS receivers used for applications involving the storage and use of precise location information.
GLONASS	The Russian GNSS.
GNSS	Global Navigation Satellite System. GPS is one instance of a GNSS. Others include GLONASS (Russia), Galileo (EU), and Compass (China).
GPS	Global Positioning System
Hz	Hertz, one cycle per second
IGS	International GNSS Service.
IM	Intermodulation.
IM3	Third Order Intermodulation.
INS	Inertial Navigation System.
ITU	International Telecommunications Union, a UN agency that coordinates frequency allocations globally.
JPL	Jet Propulsion Laboratory, operated by NASA, and a participant in the Space and High Precision Sub-Teams.
KPI	Key Performance Indicator
L1	The GPS frequency 1575.42 MHz.
L1 C/A	The GPS L1 frequency carries the C/A code, one of several codes on L1, and the one most commonly used for general GPS navigation.
L1P	A wideband GPS signal on L1.
L2	The GPS frequency 1227.60 MHz
L2C	A wideband civil GPS signal on L2.
L2P	A wideband GPS signal on L2.
L-Band	The portion of the frequency spectrum from roughly 1 GHz to 2 GHz. Part of L-band is used by GPS (1559 MHz – 1591 MHz), part by MSS (1525 MHz – 1559 MHz).
LNA	Low Noise Amplifier

LTE	Long Term Evolution, a global standard for the type of signals used for high speed broadband networks of the type envisioned by LightSquared and other data/voice providers.
MHz	Mega-Hertz, one million cycles per second
mm	Millimeters (10 mm = 1 cm)
MSS	Mobile Satellite Services, referring to portions of the frequency spectrum previously used for space to ground services, now reallocated for high powered terrestrial services, more particularly in this case the spectrum from 1525 MHz to 1559 MHz.
MW	MegaWatt.
NASA	National Aeronautics and Space Administration, under which JPL operates.
NAVAIR	Naval Air Warfare Center Aircraft Division, the US Navy facility used for anechoic chamber testing.
NGS	National Geodetic Service
NOAA	National Oceanic and Atmospheric Administration, a US Government agency.
ns	Nanoseconds (one billionth of a second)
NTIA	National Telecommunications and Information Administration, a US Government agency involved in spectrum management.
NTP	Network Time Protocol.
OFDM	Orthogonal Frequency Division Multiplexing, a frequency division multiplexing scheme used as a digital multi-carrier modulation method. A large number of closely-spaced orthogonal sub-carriers are used, with data divided into several parallel channels, one for each sub-carrier. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation or phase shift keying).
OmniSTAR	GNSS augmentation system, operated by Trimble, providing global differential GNSS corrections to increase the accuracy achieved by GNSS receivers using its signals in MSS L-band.
OTF	On-the Fly, a method of performing RTK while moving.
PC	Personal Computer.
PRS	Primary Reference System, a timing system providing a primary time reference.
PTC	Positive Train Control
RF	Radio Frequency.
RHCP	Right Hand Circularly Polarized.
RMS	Root Mean Square, a statistical measure.

RNSS	Radio Navigation Satellite Service.
RTD	Real Time Differential.
RTK	Real Time Kinematic, a GPS operational mode in which corrections from a Base Station receiver (or a network of Base Station receivers) are passed to other GPS receivers (Rovers) to enable the Rovers to navigate with very high precision (a few cm).
SNR	Signal to Noise Ratio, a measure of the quality of a signal in the presence of noise or interference.
StarFire	GNSS augmentation system, operated by Deere and Company, providing global differential GNSS corrections to increase the accuracy achieved by GNSS receivers using its signals in MSS L-band.
TIC	Time Interval Counter.
TWG	Technical Working Group
USGIC	US GPS Industry Council
UTC	Universal Time Coordinated, a global time reference
UUT	Unit Under Test
UWB	Ultra Wide Band, a technology used for various purposes, which if implemented as originally proposed, would have interfered with GPS.
WAAS	Wide Area Augmentation System, a GPS augmentation system operated by the FAA for aviation use, but used also by many non-aviation GPS receivers
WILOS	A particular RF propagation model.

3.5 Space Based Receivers

3.5.0 Executive Summary

Two different high-precision space receivers used for either Radiooccultation (RO) measurements or orbit determination/navigation were studied - a current generation receiver (IGOR) and a next generation receiver (TriG). In addition, testing was performed for two high precision GPS receivers that are representative of receivers used in the International GNSS Service (IGS) and other NASA science applications.

LightSquared notes that the next generation TriG receiver is still in development.

Conducted testing performed at NASA/JPL on four NASA GPS receivers indicated that a 1 dB degradation in carrier-to-noise density ratio (C/N_0), assuming the LightSquared signal at the output of a GPS passive receive antenna, occurred at approximately -68 dBm for one model of high precision GPS receiver and -56 dBm for another high precision receiver. For the two space-based receivers tested, 1-dB degradation to C/N_0 occurred at approximately -82 dBm for the TriG and -59 for the IGOR receiver.

LightSquared notes that these measurements were performed with dual LightSquared emissions (both the upper and lower channels). LightSquared further notes that when measured with a single LightSquared emission in the lower channel, 1-dB degradation to C/N_0 occurred at approximately -63 dBm for the developmental TriG and -13 dBm for the IGOR. This shows an improvement of 19 dB for the TriG and 46 dB for the IGOR.

Aggregate interference statistics were calculated for a LightSquared base station deployment of approximately 34940 stations distributed among 139 major cities in the US and using LightSquared base station characteristics. For the RO receiver in the 800km/72° orbit (Case 1), degradation of at least 1-dB (in C/N_0) ranged from 0.4% of the time (IGOR) to 9% of the time (TriG). For the RO receiver in the 520 km/24° orbit (Case 2), degradation was less than 1 dB for both receivers since the satellite does not pass over the US. For the navigation receiver in the 400 km/72° orbit (Case 3), degradation of at least 1-dB occurred about 3% of the time for the TriG receiver and 0% of the time for the IGOR receiver. These results assume each base station sector is transmitting 2 (5 MHz) channels at 32 dBW EIRP per channel. If base stations transmit up to their FCC authorized level of 42 dBW EIRP, then the degradation to TriG will increase to 12% of the time. In NASA's view, the interference to space-based GPS receivers used for RO would be severely disruptive to NASA's science missions based on the test and analysis conducted in the TWG. Space-based GPS receivers used for navigation and precise orbit determination would receive a lesser amount of interference, though interference would occur. Therefore, mitigation of the interference to space-based GPS receivers is necessary in NASA's view.

LightSquared notes that the peak aggregate interference levels identified by the simulations were -55.1 dBm for the COSMIC-2 satellite in a 800 km/72° inclined orbit, -88.2 dBm for the COSMIC-2 satellite in a 520 km/24° inclined orbit, and -78.1 dBm for the LEOSAT in a 400 km/72° inclined orbit.

For high-precision GPS receivers used for Earth sciences and other applications requiring precise measurements, analysis was conducted to determine the required minimum separation distance between a terrestrial high-precision GPS receiver and a single LightSquared base station where there would be a 1 dB drop in the received C/N_0. Results of the analysis showed that separation distances for the two receivers tested, assuming several different propagation models, ranged from approximately 1.5 to 4 kilometers for one receiver type to approximately 3 to 12 kilometers for the other receiver model tested. For the space based receivers, separation distances were approximately 4 km for the IGOR and 22 km for the TriG, assuming free space propagation conditions.

LightSquared notes that these measurements were performed with dual LightSquared emissions (both the upper and lower channels).

Given the ATC deployment density anticipated with the LightSquared terrestrial network, it is unlikely that such separation distances could be assured. Therefore in NASA's view, mitigation of the interference to high precision GPS receivers used for NASA's scientific purposes is necessary.

Preliminary analysis also showed that MSS handsets operating in the 1626.5-1660.5 MHz MSS band could interfere with space-based receivers at distances in excess of 200 meters during terrestrial pre-launch check-out. However, there was insufficient time to thoroughly investigate this potential interference scenario, or the possible aggregate interference effect from handsets, for either space-based receivers or high precision science receivers.

NASA is of the view that, although the TWG members worked diligently and in good faith throughout the period prescribed by the FCC, it was impossible to adequately evaluate and thoroughly investigate potential interference mitigation options for space-based and high precision science receivers. While some limited testing64 conducted by JPL at the request of the TWG towards the end of the TWG's work showed promise for one type of space-based receiver, there was minimal improvement for the second space-based receiver tested. In NASA's view, there was not sufficient time to adequately evaluate the effectiveness of this particular technique, or any other mitigation technique, for space-based or terrestrial high precision science receivers.

LightSquared believes that, based on the measured lower channel test results and the simulation calculations, restricting LightSquared emissions to the lower 10 MHz channel completely mitigates the current generation IGOR receiver with in excess of 40-dB margin between the peak aggregate power received and the received power level resulting in 1-dB C/N_0 degradation. LightSquared also believes that restricting operations to the lower 10 MHz channel reduces the impact on the next generation TriG receiver, but does not completely mitigate it. Additional mitigation would be required in the form of increased selectivity through front end filtering at the receiver. LightSquared believes that since the TriG receiver is still in development, it could be modified to achieve complete mitigation with minimal impact on NASA science missions.

[64] NASA was able to conduct limited testing of one potential mitigation technique, use of just the lowest 10 MHz channel by LightSquared, for the two space-based receivers but not for the high precision science receivers.

NASA notes that one mitigation technique that would resolve interference to both space-based and terrestrial high precision GPS receivers is to relocate high power terrestrial operations to a different frequency band. However, any potential candidate bands would need a thorough evaluation that would consider, among other issues, the implications for providing terrestrial wireless services and potential impacts to in-band and adjacent band operations for incumbent systems and services.

3.5.1 Work Plan Item 1: Establish Pertinent Analytical and Test Methodologies and Assumptions Underlying the Test Regime

The Space Based Receiver sub-team identified C/N_0 degradation as the most appropriate measure of LightSquared's emission's impact on space receivers. A degradation of 1-dB in C/N_0 was used as a measure of degradation to operational space-based receivers. It was noted that space receivers are used to conduct science, such as occultation measurements for characterizing the Earth's atmosphere, and that significant interference from the LightSquared emissions could result in loss of scientific information.

The sub-team made several assumptions based on LightSquared inputs:

- 34,939 LightSquared base stations located in 139 US cities
- 3 sectors per base station
- Two LightSquared channels per sector at 32 dBW each
- Tongyu sector pattern (16.5 dBi max gain) at bore sight with a universally applied 2 degree downtilt)
- Minimum per sector overhead antenna gain of -3.5 dBi due to ground reflections

3.5.2 Work Plan Item 2: Select the Categories of Receivers and Receivers to be Tested

The sub-team identified two space receivers for testing:

- IGOR (current generation space receiver, with dual-frequency GPS-only capability)
- TriG (next-generation space receiver currently in development for later missions with full GNSS capability)

The IGOR is the current generation radiooccultation (RO) receiver manufactured by Broadreach Engineering and is based on the NASA/JPL Black Jack space receiver. IGOR receivers have been deployed as primary science payloads on the COSMIC mission, TerraSAR-X, Tandem-X, and TACSAT-2 missions. IGOR has a wideband pre-select filter and narrowband L1 and L2 filters. IGOR can also function as a precise orbit determination (POD) GPS receiver.

The TriG is the next generation NASA/JPL RO receiver designed to work with new signals from GPS and other GNSS satellites. It can also be used for POD. It has a very wide RF pre-select filter (i.e. 3 dB bandwidth from 1100 MHz to 1660 MHz) to allow the receiver to be reprogrammed in flight to different frequencies over the full range of GNSS and augmentation signals. NASA may track TDRSS signals (2106 MHz), or INMARSAT differential correction signals, so interference with the delivery of these

augmentation signals should also be prevented. The wide bandwidth also results in lower insertion loss, less variation of signal delay and phase with temperature, and allows newer processing techniques by using a signal bandwidth much greater than the conventional 20 MHz.

The sub-team also identified two high precision receivers:

- JAVAD Delta G3T (High Precision-IGS)
- Ashtech Z12 (High Precision-IGS)

These JAVAD and ASHTECH receivers are commonly used in surveying and high precision ground networks such as the IGS (International GNSS Service) and SCIGN (Southern California Integrated GPS Network). The Ashtech Z-12 is a standard dual frequency (L1/L2) phase and pseudorange measuring instrument that can track up to 12 GPS satellites. The JAVAD Delta-G3T is a newer 36-channel receiver capable of tracking GPS L1/L2/L2C/L5 and GLONASS L1/L2.

3.5.3 Work Plan Item 3: Develop Operational Scenarios

Two space receiver operational scenarios were considered: (1) the radio occultation (RO) application which involves pointing the GPS receiver antenna towards the earth limb in order to receive GPS signals traversing the atmosphere; and (2) the more typical navigation application in which the antenna is pointed in the zenith direction towards the GPS constellation.

The IGOR and TriG receivers are designed for RO measurements but can also be used for navigation/Precision Orbit Determination (POD). In the RO technique a GPS receiver in LEO observes the propagation delay of GPS signals which travel through the atmosphere. Occultation occurs as each GPS satellite rises or sets on the horizon as viewed by the space receiver. From the changing delay, the (altitude) variation in the atmosphere's index of refraction can be measured and altitude profiles of ionosphere electron density, atmospheric density, pressure, temperature, and water vapor can be derived. Consequently, the receiver antenna main-beam is directed towards the earth limb (and also, in this case, the main-beams of the interfering base stations). JPL is planning the next generation of RO measurements with receivers onboard the COSMIC-2 constellation, which will have initial launch in 2014 and consist of six satellites in a 520 km orbit at 24 degrees inclination and six more at 800 km orbit and 72 degrees inclination. Each satellite will have actively steered array antennas with approximately +15 dBic gain directed along the limb of the earth in the forward (for rising GPS satellites) and aft (for setting GPS satellites) directions.

For the usual space navigation application, the TriG/IGOR receivers were assumed to use a zenith pointed choke ring antenna with 6.8 dBic gain. For this analysis a typical LEO altitude of 400 km was assumed and again a 72° inclination was considered which causes the satellite to pass over the entire CONUS numerous times.

3.5.4 Work Plan Item 4: Establish the Methodology for Analyzing Test Results

The primary observable identified by the Space Based Receiver sub-team was the change in C/N_0 due to LightSquared emissions during the orbital periods where satellite antenna beamwidth and orbital position will encounter aggregated LightSquared signals on a path above, approaching, or leaving the continental US. Analysis conducted by the space-based receiver sub-group indicated LightSquared signals would radiate sufficient energy close to a line of sight path coincident with signals from distant GPS satellites to negatively impact the RO receiver. When the LightSquared aggregate signal reaches a point so as to induce a 1-dB C/N_0 degradation level in the RO receiver, it is deemed to have reached an analytical interference threshold for the RO mode receiver. Other secondary observables and test results that were measured during conducted testing at Jet Propulsion Laboratory (JPL) included pseudorange and carrier phase for each GPS satellite signal, onboard position solutions including 4-D position and its time derivatives, the formal errors, and the Chi-squared statistics for the solutions.

3.5.5 Work Plan Item 5: Derive the Test Conditions Based on the Established Operational Scenarios

The Space-based Receiver Group agreed that conducted testing of the two space receivers NASA identified, as well as high precision receivers used for science applications, would be performed at NASA JPL and that LightSquared personnel would participate and provide filters and assist in ensuring the transmitted broadband signals accurately reflected LightSquared's planned emissions.

3.5.6 Work Plan Item 6: Write the Test Plan and Procedures

The Space Based Receiver sub-team focused on conducted testing because it offers the best accuracy since signal, noise, and interference levels can be carefully controlled and calibrated. The test plan, (the full version exists in Appendix S.1) was designed to observe the change in C/N_0 due to LightSquared emissions. The most important parameters to measure are the noise floor and the interference power. The signal was set high enough to provide a conveniently high level of C/N_0 to start from. In addition to C/N_0 degradation, the following parameters were collected and shared with the TWG:

- Pseudorange
- Carrier phase
- Position solution (4D, time derivatives, formal errors, and Chi-squared statistics)

The highlights of the test procedure follow:

1. Use Agilent Signal Studio for 3GPP LTE FDD to generate a full filled QPSK 5 MHz (25RB) Basic LTE FDD Downlink (v. 2009-12).

2. Load this LTE Base-Band signal onto an Agilent E4438C Vector Signal Generator and modulate it onto a 1552.5 MHz carrier.
3. Configure the E4438C to simultaneously output this same LTE Base-Band waveform onto its External I/Q Outputs.
4. Connect the E4438C RF output to a Band-Pass Filter supplied by LightSquared: Model: RMC1550B10M01.
5. Connect the external I/Q Outputs of the E4438C to the I/Q modulator inputs of a RHODE&SCHWARZ SMBV100A Vector Signal Generator set to a 1528.7 MHz carrier.
6. Connect the SMBV100A RF output of a Band-Pass Filter supplied by LightSquared: Model: RMC1531B10M01.
7. Configure a NAVLABS GPS Simulator configured for 7 satellites with constant power throughout the scenario, and L1 C/A power set 3 dB above P1 and P2 powers.
8. Terminate the "Antenna Output Simulator"" mainline with a 50 Ohm broadband shunt.
9. Couple the two LightSquared Signals onto the "Antenna Output Simulator" mainline using -10 dB directional couplers.
10. Attenuate the GPS Simulator and then couple onto the "Antenna Output Simulator" mainline using a -20 dB directional coupler.
11. Connect the Antenna Output Simulator port to a calibrated Tektronix RSA3308A Spectrum Analyzer.
12. Adjust the Amplitude Offset until the measured powers for each LightSquared channel match the Amplitude read-off on the Signal Generators.
13. Calibrate the Total Noise Temperature of the "Antenna Output Simulator" using an Agilent N8975A Noise Figure Analyzer (NFA) together with an HP 346A Noise Source for calibration.
14. Use a combination of an LNA and a Tektronix RSA3308A Spectrum Analyzer to verify the spectrum of the broadband noise floor for flatness,
15. Set the Amplitude Correction of the Spectrum Analyzer to compensate for the LNA gain.
16. Verify the Intermodulation and Distortion-Free Dynamic Range of the test setup.

3.5.7 Work Plan Item 7: Identify and Engage Appropriate Neutral Test Facility(ies) for the Testing Portion of the Work Plan

The Space Based Receiver sub-team identified NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California as the most appropriate facility for testing of the space receivers.

3.5.8 Work Plan Item 8: Perform Testing

Conducted testing was performed by NASA and LightSquared personnel at JPL on 22 March 2011. The results are shown in Table 3.5.2. The power levels are the total power at the input of the receiver unit. The results of the JAVAD and Ashtech receiver testing were shared with the High Precision sub-team.

		NASA GPS RECEIVER SUSCEPTIBILITY TO LSQ INTERFERENCE (BASED ON JPL CONDUCTED TESTING)											
		NOTE: POWER LEVEL SHOWN IS TOTAL POWER AT OUTPUT OF GPS RX PASSIVE ANTENNA (dBm)											
LSQ Signal Spectrum	Interference Criterion	TRIG			IGOR			JAVAD Delta G3T			Ashtech Z-12		
		L1 C/A	L1 P	L2 P	L1 C/A	L1 P	L2 P	L1 C/A	L1 P	L2 P	L1 C/A	L1 P	L2 P
LSQ Phase 1 (two 5 MHz channels @ 1526.3-1531.3 and 1550.2-1555.2)	1 dB C/No degradation	C: -82	C: -82	C: -78	C: -57	C: -59	C: -51	C: -54	C: -56	C: -43	C:-68		
	3 dB C/No degradation	C: -78	C: -80	C: -77	C: -53	C: -54	C: -49	C: -51	C: -52	C: -43	C:-65		
	5 dB C/No degradation	C: -75	C: -73	C: -74	C: -49	C: -51	C: -48	C: -49	C: -50	C: -43	C:-62		
	Loss of Lock	C: -67	C:-67	C: -67	C: -45	C: -45	C: -45	C: -43	C: -43	C: -43	C: -38	C: -38	C: -38

Table 3.5.18 Space GPS Receiver Susceptibility to LightSquared Emissions (dBm)

Although anechoic chamber testing and live-sky testing were also performed with these receivers, the conducted testing offers the best accuracy since signal, noise, and interference levels can be carefully controlled and calibrated.

LightSquared notes that additional testing of the IGOR and TriG receivers with just the LightSquared lower 10 MHz channel was performed at JPL in June 2011. These tests showed that the IGOR and TriG receivers experienced 1-dB C/N_0 degradation at power levels of -13 dBm and -63 dBm, respectively.

3.5.9 Work Plan item 9: Analyze Test Results Based on Established Methodology

The test results were analyzed based on the established methodology to determine the interference thresholds for each receiver as shown in the graphics below and summarized in Table 3.5.3.

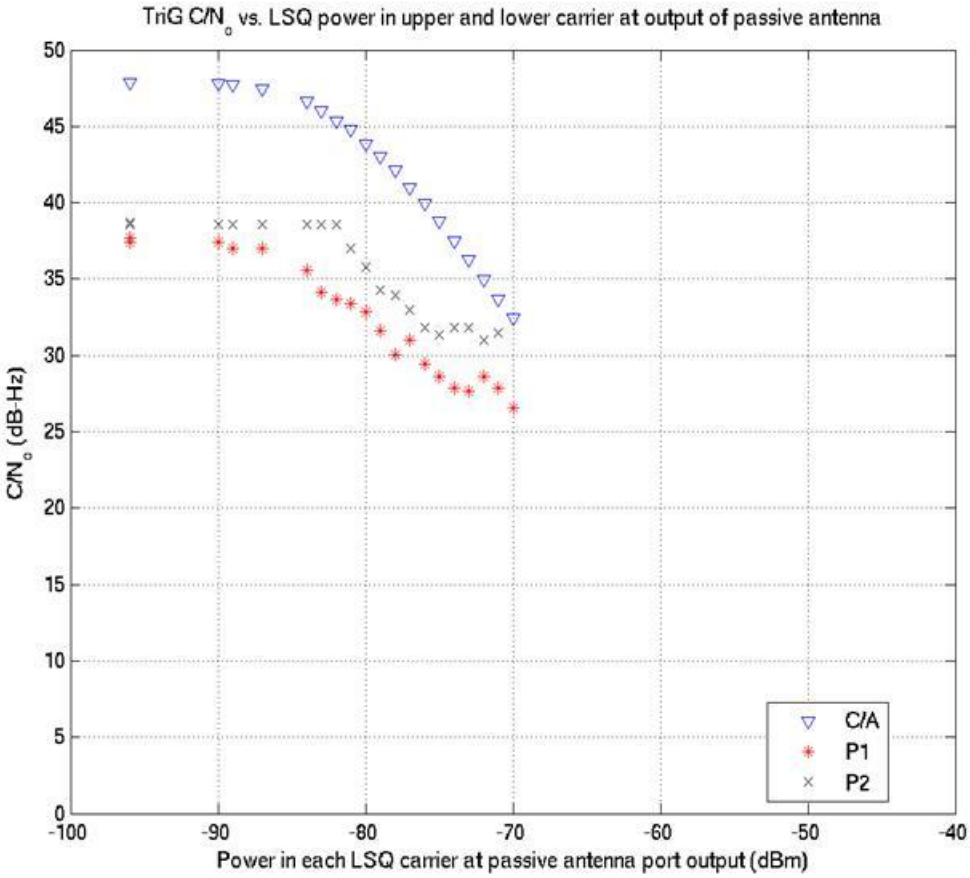

TriG C/N0 vs. LSQ power in upper and lower carrier at output of passive antenna
C/N0 (dB-Hz)
Power in each LSQ carrier at passive antenna port output (dBm)
C/A
P1
P2
50
45
40
35
30
25
20
15
10
5
0
-100
-90
-80
-70
-60
-50
-40

Figure 3.5.30

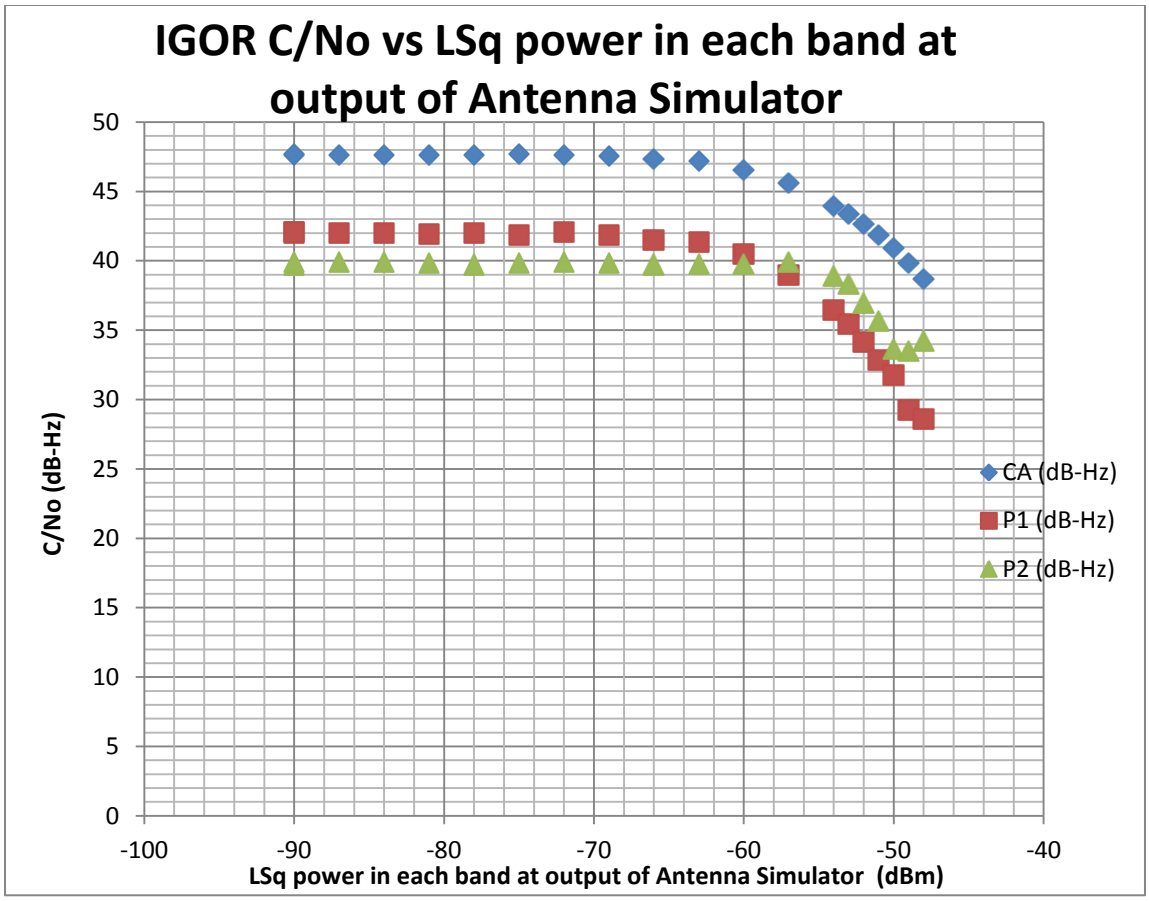


Figure 3.5.31

Emissions	IGOR	TriG
2 5-MHz LTE Signals (1526.3 to 1531.3 MHz & 1550.2 MHz to 1555.2 MHz)	-59	-82

Table 3.5.19 Space Receiver -1 dB C/N_0 Points (dBm)

LightSquared notes that for the lower 10 MHz channel, the -1 dB C/N_0 points were -13 dBm and -63 dBm, respectively.]

3.5.10 Work Plan Item 10: Assess Operational Scenarios Using Analytics and Test Results

For the spaceborne receiver analysis a MATLAB simulation program was developed to model the receiver onboard a satellite in various orbits and interference statistics calculated for a LightSquared base station deployment of approximately 34940 stations distributed among 139 major cities in the US. This city data was provided by LightSquared. The assumed EIRP of the LightSquared Base Stations was 32 dBW; however analysis was also conducted for the permissible power level of 42 dBW. Two

types of space receiver applications were considered: (1) the RO application which involves pointing the GPS receiver antenna towards the earth limb in order to receive GPS signals traversing the atmosphere; and (2) the more typical navigation application in which the antenna is pointed in the zenith direction towards the GPS constellation. In both cases interference thresholds for the TRIG and IGOR space receivers (as determined by the JPL conduction testing) were considered. The results of the analysis are shown in Table 3.5.21, Table 3.5.22, and Table 3.5.23 below.

Interference results for the RO GPS RX onboard a COSMIC-2 satellite (800 km/72° orbit) are shown in Table 3.5.22 and Table 3.5.23. Table 3.5.4 assumes a 0° elevation mask on the base stations while Table 3.5.22 assumes a 5° elevation mask on the base stations. The entries in these tables are interpreted as follows. Consider, for example, Table 3.5.19 and an aggregate interference threshold of -82 dBm (2nd column). For this row in the table, the first column indicates that an interference power level of -82 dBm at the output of the GPS receiver antenna will cause a 1 dB drop in the C/N_0 for the TRIG receiver (for both the L1 C/A-code and L1 P-code channels of the receiver). Column 3 indicates that over the 10-day simulation period, the aggregate interference (from the ~34900 base stations) at the GPS antenna output actually exceeds this level about 9% of the time (i.e. since 10 days = 240 hours, the interference exceeds -82 dBm for 0.09 x 240 = 21.6 hours total over the 10-day period). It is important to note that these analyses were only done for rising occultations, that is, ones seen from the forward antenna. The actual missions have a second aft-looking antenna that will see a similar number of interference events. In other words, for 9% of the time, the receiver C/N_0 degradation is *at least* 1 dB. In the table header, the peak interference level is shown to reach -55.1 dBm (enough for the TRIG to lose lock). Column 4 indicates that over the 10-day period, there are 268 interference events (i.e. 268 separate time intervals during which interference exceeds -82 dBm). Note that these time intervals may be very short or fairly long depending on how many interfering base stations the satellite sees on the particular orbit pass over the US. The sum duration of all 268 interference events is the 21.6 hours. Also, there can be multiple interference events for a single orbit pass as different numbers of base stations pass through the FOV of the receiver antenna. Column 5 indicates that the average duration of an interference event is about 4.9 minutes and the maximum duration from column 6 is 16.9 minutes. Table 3.5.19 also shows that for a threshold of -67 dBm (where TRIG loses lock), interference exceeds this level about 3% of the time with 152 interference events of average duration 2.9 min and max duration 10.6 min. It should be noted that the duration of an atmospheric occultation (as the signal path moves from skimming the Earth's surface to an altitude of about 100 km) is only one to two minutes. Table 3.5.22 with the 5° elevation mask ignores interference from the low elevation angle base stations, but still shows average interference event duration of 3.8 min at the -67 dBm TRIG loss of lock threshold. (Compared to Table 3.5.21 there are fewer events, 57 vs 152, but the average duration is longer.)

The impact to the IGOR space receiver is seen to be much less. Note, however, that the results for both receivers are only for the forward looking RO antenna. There will also be an aft pointing RO antenna, so interference will occur both when the CONUS is coming into the forward looking antenna FOV and when it is leaving the aft looking antenna FOV. The spatial correlation of these outages is troublesome for two reasons. First, one of the occultation products is the significant improvement of weather forecasts and loss

of data around CONUS produces poorer weather forecasting in this area. A second major product of occultation measurements is global climate benchmarking. The systematic bias due to representing different areas of the earth with unequal sampling, or sampling with systematically different C/N_0, is a serious challenge to the climate record. Further analysis is required to determine the interference statistics when both antennas are included.

For the case of RO receiver onboard COSMIC-2 satellite in the 520 km/24° inclined orbit, the peak interference was found to be -88.2 dBm. This is much lower than for the 800 km/72° inclined orbit since the satellite does not pass over the US, but only sees a few base stations on the southern border. This level of interference is expected to cause less than 1 dB of degradation to the TRIG receiver.

Interference results for the navigation mode GPS RX with zenith pointed antenna onboard a LEOSAT (400 km/72° orbit) are shown in Table 3.5.23 (0° base station elevation mask) and Table 3.5.23 (5° base station elevation mask). The majority of GPS receivers used in space are small, lightweight, low-power devices providing spacecraft 3-dimensional position and velocity as well as timing and possibly 3-axis attitude determination. Table 3.5.22 and Table 3.5.23 show that compared to the RO case, interference effects are much less.

It is also worth noting that there was insufficient time to permit a full analysis of the potential effects of the handsets operating in the 1626.5-1660.5 MHz band. In particular, the possible effects of handsets operating in this range at an EIRP of -7 dBW on the TriG receiver during the 2000 hour pre-launch testing phase (terrestrial scenario) could result in degradation of as much as a 3 dB drop in C/N_0 at distances in excess of 200 meters.

LSQ Interference Results for JPL Occultation GPS Receiver					
GPS RX Onboard COSMIC-2 Satellite in 800 km/72° Orbit					
Interference from 34939 LSQ Base Stations Located Across 139 US Cities					
Two LSQ channels per sector @ 32 dBW max EIRP per channel					
Tongyu sector antenna pattern (16.5 dBi max gain); 3 sectors per base station					
0° Elevation Mask on LSQ Base Stations					
Min overhead sector antenna gain of -3.5 dBi (16.5-20) due to signal ground reflection					
Peak Interference Level = -55.1 dBm					
RX C/No Degradation (based on JPL conduction testing)	Agg Interference Threshold **(dBm)** (int power at output of GPS RX antenna)	% Time (over 10-day period) that Interference Exceeds Threshold	# of Interference Events over 10-day sim period	Avg Duration of Interferenc e Event (min)	Max Interference Event Duration (min)
	-56.000	0.009	11.000	0.112	0.367
IGOR (1 dB; C/A)	**-57.000**	0.074	59.000	0.180	0.800
	-58.000	0.217	80.000	0.390	2.167
IGOR (1 dB; P1)	**-59.000**	0.384	93.000	0.595	3.533
	-60.000	0.595	86.000	0.996	5.550
	-61.000	0.829	105.000	1.137	5.767
	-62.000	1.154	136.000	1.222	6.033
	-63.000	1.531	156.000	1.413	7.617
	-64.000	1.918	157.000	1.760	8.233
	-65.000	2.297	158.000	2.094	8.900
	-66.000	2.652	165.000	2.314	9.783
TRIG (Lost Lock; C/A & P1 & P2)	**-67.000**	3.033	152.000	2.873	10.600
	-68.000	3.414	157.000	3.131	10.750
	-69.000	3.787	185.000	2.948	11.483
	-70.000	4.150	153.000	3.906	11.683
	-71.000	4.477	139.000	4.638	12.017
	-72.000	4.800	145.000	4.767	12.433
TRIG (5 dB; P1)	**-73.000**	5.131	147.000	5.027	12.683
TRIG (5 dB; P2)	**-74.000**	5.452	163.000	4.817	13.350
TRIG (5 dB; C/A)	**-75.000**	5.851	193.000	4.366	13.700
	-76.000	6.262	205.000	4.399	13.917
TRIG (3 dB; P2)	**-77.000**	6.696	225.000	4.285	14.167
TRIG (3 dB; C/A) ; TRIG (1 dB; P2)	**-78.000**	7.135	240.000	4.281	15.167
	-79.000	7.601	257.000	4.259	16.117
TRIG (3 dB; P1)	**-80.000**	8.084	264.000	4.409	16.717
	-81.000	8.554	279.000	4.415	16.950
TRIG (1 dB; C/A & P1)	**-82.000**	9.059	268.000	4.867	16.983
	-83.000	9.491	258.000	5.297	17.083
	-84.000	9.878	254.000	5.600	17.150
	-85.000	10.252	266.000	5.550	17.283
	-300.000	15.749	175.000	12.960	25.300

Table 3.5.30 Interference Results for JPL Occultation GPS RX Onboard COSMIC-2 Satellite (800 km/72° orbit) With Earth Limb Pointed Array Antenna (0 ° elevation mask on base stations)

LSQ Interference Results for JPL Occultation GPS Receiver					
GPS RX Onboard COSMIC Satellite in 800 km/72° Orbit					
Interference from 34939 LSQ Base Stations Located Across 139 US Cities					
Two LSQ channels per sector @ 32 dBW max EIRP per channel					
Tongyu sector antenna pattern (16.5 dBi max gain); 3 sectors per base station					
5° Elevation Mask on LSQ Base Stations					
Min overhead sector antenna gain of -3.5 dBi (16.5-20) due to signal ground reflection					
Peak Interference Level = -60.2 dBm					
RX C/No Degradation (based on JPL conduction testing)	Agg Interference Threshold **(dBm)** (int power at output of GPS RX antenna)	% Time (over 10-day period) that Interference Exceeds Threshold	# of Interference Events over 10-day sim period	Avg Duration of Interferenc e Event (min)	Max Interference Event Duration (min)
	-56.000	0.000	0.000	0.000	0.000
IGOR (1 dB; C/A)	**-57.000**	0.000	0.000	0.000	0.000
	-58.000	0.000	0.000	0.000	0.000
IGOR (1 dB; P1)	**-59.000**	0.000	0.000	0.000	0.000
	-60.000	0.000	0.000	0.000	0.000
	-61.000	0.082	18.000	0.653	1.733
	-62.000	0.236	23.000	1.478	2.983
	-63.000	0.429	41.000	1.506	3.717
	-64.000	0.684	57.000	1.727	5.933
	-65.000	0.918	52.000	2.542	6.433
	-66.000	1.210	56.000	3.111	7.033
TRIG (Lost Lock; C/A & P1 & P2)	**-67.000**	1.502	57.000	3.795	7.983
	-68.000	1.817	81.000	3.230	8.150
	-69.000	2.069	76.000	3.921	8.433
	-70.000	2.355	79.000	4.292	8.917
	-71.000	2.655	75.000	5.097	9.583
	-72.000	2.994	94.000	4.586	9.850
TRIG (5 dB; P1)	**-73.000**	3.328	95.000	5.044	10.467
TRIG (5 dB; P2)	**-74.000**	3.578	94.000	5.481	11.067
TRIG (5 dB; C/A)	**-75.000**	3.844	110.000	5.032	11.450
	-76.000	4.113	111.000	5.335	11.533
TRIG (3 dB; P2)	**-77.000**	4.420	107.000	5.948	11.533
TRIG (3 dB; C/A) TRIG (1 dB; P2)	**-78.000**	4.697	121.000	5.589	11.750
	-79.000	4.982	127.000	5.649	12.750
TRIG (3 dB; P1)	**-80.000**	5.275	128.000	5.934	13.217
	-81.000	5.562	121.000	6.619	13.717
TRIG (1 dB; C/A & P1)	**-82.000**	5.853	134.000	6.290	14.083
	-83.000	6.116	132.000	6.672	14.350
	-84.000	6.410	143.000	6.455	14.350
	-85.000	6.703	165.000	5.850	14.433
	-300.000	12.180	189.000	9.280	21.683

Table 3.5.21 Interference Results for JPL Occultation GPS RX Onboard COSMIC-2 Satellite (800 km/72° orbit) With Earth Limb Pointed Array Antenna (5 ° elevation mask on base stations)

LSQ Interference Results for JPL GPS Receiver with Zenith Pointed 7 dBic Choke Ring Antenna					
GPS RX Onboard LEO Satellite in 400 km/72° Orbit					
Interference from 34939 LSQ Base Stations Located Across 139 US Cities					
Two LSQ channels per sector @ 32 dBW max EIRP per channel					
Tongyu sector antenna pattern (16.5 dBi max gain); 3 sectors per base station					
Min overhead sector antenna gain of -3.5 dBi (16.5-20) due to signal ground reflection					
0° Elevation Mask on LSQ Base Stations					
Peak Interference Level = -78.1 dBm					
RX C/No Degradation (based on JPL conduction testing)	Agg Interference Threshold **(dBm)** (int power at output of GPS RX antenna)	% Time (over 10-day period) that Interference Exceeds Threshold	# of Interference Events over 10-day sim period	Avg Duration of Interference Event (min)	Max Interference Event Duration (min)
	-56.000	0.000	0.000	0.000	0.000
IGOR (1 dB; C/A)	**-57.000**	0.000	0.000	0.000	0.000
	-58.000	0.000	0.000	0.000	0.000
IGOR (1 dB; P1)	**-59.000**	0.000	0.000	0.000	0.000
	-60.000	0.000	0.000	0.000	0.000
	-61.000	0.000	0.000	0.000	0.000
	-62.000	0.000	0.000	0.000	0.000
	-63.000	0.000	0.000	0.000	0.000
	-64.000	0.000	0.000	0.000	0.000
	-65.000	0.000	0.000	0.000	0.000
	-66.000	0.000	0.000	0.000	0.000
TRIG (Lost Lock; C/A & P1 & P2)	**-67.000**	0.000	0.000	0.000	0.000
	-68.000	0.000	0.000	0.000	0.000
	-69.000	0.000	0.000	0.000	0.000
	-70.000	0.000	0.000	0.000	0.000
	-71.000	0.000	0.000	0.000	0.000
	-72.000	0.000	0.000	0.000	0.000
TRIG (5 dB; P1)	**-73.000**	0.000	0.000	0.000	0.000
TRIG (5 dB; P2)	**-74.000**	0.000	0.000	0.000	0.000
TRIG (5 dB; C/A)	**-75.000**	0.000	0.000	0.000	0.000
	-76.000	0.000	0.000	0.000	0.000
TRIG (3 dB; P2)	**-77.000**	0.000	0.000	0.000	0.000
TRIG (3 dB; C/A) TRIG (1 dB; P2)	**-78.000**	0.000	0.000	0.000	0.000
	-79.000	0.161	80.000	0.290	1.467
TRIG (3 dB; P1)	**-80.000**	0.601	183.000	0.473	4.717
	-81.000	1.517	364.000	0.600	8.300
TRIG (1 dB; C/A & P1)	**-82.000**	2.980	322.000	1.332	11.533
	-83.000	3.915	257.000	2.193	13.067
	-84.000	4.651	290.000	2.309	13.133
	-85.000	5.387	264.000	2.938	13.983
	-300.000	15.327	165.000	13.377	25.167

Table 3.5.22 Interference Results for JPL GPS RX Onboard LEOSAT (400 km/72° orbit) With Zenith Pointed Choke Ring Antenna (0° elevation mask on base stations)

LSQ Interference Results for JPL GPS Receiver with Zenith Pointed 7 dBic Choke Ring Antenna					
GPS RX Onboard LEO Satellite in 400 km/72° Orbit					
Interference from 34939 LSQ Base Stations Located Across 139 US Cities					
Two LSQ channels per sector @ 32 dBW max EIRP per channel					
Tongyu sector antenna pattern (16.5 dBi max gain); 3 sectors per base station					
Min overhead sector antenna gain of -3.5 dBi (16.5-20) due to signal ground reflection					
5° Elevation Mask on LSQ Base Stations					
Peak Interference Level = -81.3 dBm					
RX C/No Degradation (based on JPL conduction testing)	Agg Interference Threshold **(dBm)** (int power at output of GPS RX antenna)	% Time (over 10-day period) that Interference Exceeds Threshold	# of Interference Events over 10-day sim period	Avg Duration of Interference Event (min)	Max Interference Event Duration (min)
	-56.000	0.000	0.000	0.000	0.000
IGOR (1 dB; C/A)	**-57.000**	0.000	0.000	0.000	0.000
	-58.000	0.000	0.000	0.000	0.000
IGOR (1 dB; P1)	**-59.000**	0.000	0.000	0.000	0.000
	-60.000	0.000	0.000	0.000	0.000
	-61.000	0.000	0.000	0.000	0.000
	-62.000	0.000	0.000	0.000	0.000
	-63.000	0.000	0.000	0.000	0.000
	-64.000	0.000	0.000	0.000	0.000
	-65.000	0.000	0.000	0.000	0.000
	-66.000	0.000	0.000	0.000	0.000
TRIG (Lost Lock; C/A & P1 & P2)	**-67.000**	0.000	0.000	0.000	0.000
	-68.000	0.000	0.000	0.000	0.000
	-69.000	0.000	0.000	0.000	0.000
	-70.000	0.000	0.000	0.000	0.000
	-71.000	0.000	0.000	0.000	0.000
	-72.000	0.000	0.000	0.000	0.000
TRIG (5 dB; P1)	**-73.000**	0.000	0.000	0.000	0.000
TRIG (5 dB; P2)	**-74.000**	0.000	0.000	0.000	0.000
TRIG (5 dB; C/A)	**-75.000**	0.000	0.000	0.000	0.000
	-76.000	0.000	0.000	0.000	0.000
TRIG (3 dB; P2)	**-77.000**	0.000	0.000	0.000	0.000
TRIG (3 dB; C/A) TRIG (1 dB; P2)	**-78.000**	0.000	0.000	0.000	0.000
	-79.000	0.000	0.000	0.000	0.000
TRIG (3 dB; P1)	**-80.000**	0.000	0.000	0.000	0.000
	-81.000	0.000	0.000	0.000	0.000
TRIG (1 dB; C/A & P1)	**-82.000**	0.147	15.000	1.407	2.383
	-83.000	0.493	60.000	1.184	3.867
	-84.000	1.107	55.000	2.899	7.283
	-85.000	1.793	103.000	2.507	8.083
	-300.000	11.515	167.000	9.929	21.450

Table 3.5.23 Interference Results for JPL GPS RX Onboard LEOSAT (400 km/72° orbit) With Zenith Pointed Choke Ring Antenna (5° elevation mask on base stations

LightSquared notes that the peak aggregate interference levels identified by the simulations were -55.1 dBm for the COSMIC-2 satellite in a 800 km/72° inclined orbit, -88.2 dBm for the COSMIC-2 satellite in a 520 km/24° inclined orbit, and -78.1 dBm for the LEOSAT in a 400 km/72° inclined orbit.]

3.5.11 Work Plan Item 11: Assess Whether any Mitigation Measures are Feasible and Appropriate

3.5.11.1 Measures Applicable to LightSquared's Network

3.5.11.1.1 Confining LightSquared to the Lower Portion of the MSS L-band

Studies performed in the NPEF and the Industry Technical Working Group (TWG) indicate that for some GPS receivers, there may be sufficient receiver selectivity to prevent receiver overload if the LightSquared signal is limited to just the lower portion of the MSS allocated band at 1525-1559 MHz. Unfortunately, the advanced receivers being developed by NASA for space science are affected to a significant extent by these signals. This class of modern high-performance receiver would require the addition of filters, with the disadvantages listed under the section below describing receiver mitigations.

NASA is currently conducting testing to determine the effects of LightSquared using only the lower 10 MHz channel on the two space-based and two high precision receivers tested previously with the planned LightSquared deployment model and will provide the results of this testing to the TWG as soon as it is available. Initial results for the two space-based receivers indicate that limiting the LightSquared signal to only the lower 10 MHz channel results in improved performance for the IGOR receiver; however, the TriG receiver does not benefit substantively from this mitigation technique. Preliminary space-based receiver test results for only the lower 10 MHz channel are shown below:

IGOR:

Power in LSQ channel referenced to LNA input:	DROP in C/A SNR:
Off	0 (SNR = 522)
13 dBm	1 dB (SNR = 465)
7 dBm	3 dB (SNR = 369)
1 dBm	lost lock of all satellites.

TRIG:

Power in LSQ channel referenced to LNA input:	DROP in C/A SNR:
Off	0 (SNR = 655)
63 dBm	1 dB (SNR = 584)
57 dBm	3 dB (SNR = 463)
35 dBm	lost lock of all satellites.

Advantages: LightSquared uses part of their current conditionally approved spectrum.

Disadvantages: Performance and accommodation penalties for space based receivers.

LightSquared believes that, on the measured lower channel test results and the simulation calculations of the peak aggregate power received at the space based receiver, LightSquared on the lower 10 MHz channel alone completely mitigates the current generation IGOR receiver with in excess of 40 dB margin between the peak aggregate power received and the received power level resulting in 1 dB C/N_0 degradation. LightSquared operation on the lower 10 MHz also reduces the impact on the next generation TriG receiver, but does not completely mitigate it.

3.5.11.1.2 Power Reduction Necessary to Mitigate Interference

The amount of transmitted power reduction necessary to prevent interference to GPS receivers varies as a function of the receiver characteristics, the scenario for which the device is used (e.g., ground-based, aviation, space-based), and the level of interference that degrades receiver performance beyond a certain amount (e.g., degrades C/N_0 by 1 dB) for the specific receiver type in the scenario in which it is used. If we assume the reduced power per transmitter is compensated by an increased density of transmitters, the bulk effect on space based receivers is about the same.

Advantages: None

Disadvantages: Costly to LightSquared, no benefit to space based receivers

3.5.11.1.3 Antenna Modifications

Modifications to base station antenna patterns (e.g., through use of narrower and otherwise shaped beams) or increasing the downward

tilt angle of the antenna from the currently planned 2 degrees to reduce the area affected by LightSquared base stations, would have similar effects on coverage area as reducing the power per base station, albeit without the additional impacts on overall network performance because the assumed transmit power per base station would remain the same. Since the number of base stations needed to provide the same coverage would increase, the impact of this mitigation technique would likely be to increase the overall interference potential rather than decrease it for the majority of GPS applications.

Advantages: Decreased power to space based receivers.

Disadvantages: Decrease in main beam power to space based receivers is somewhat reduced by increase upward scattering from ground multipath.

3.5.11.1.4 Alternative Frequency Bands

Because not all of the interference mitigation techniques discussed previously would prevent interference in all GPS use scenarios, it may be desirable to relocate the LightSquared broadband operations to a different frequency band. There are numerous possibilities that could be considered for a terrestrial broadband network, including MSS bands where MSS ATC is currently permitted such as in the 2 GHz MSS bands[65]. However, under the President's Broadband Initiative, up to 500 MHz[66] will be made available for wireless broadband applications in the next 5-10 years and some of the bands already identified via the "Fast Track" process[67] may also be suitable for use by the LightSquared network and could be examined.

Advantages: Solves the problem of LightSquared interference to GPS receivers.

Disadvantages: Schedule delays and increased cost to LightSquared.

3.5.11.2 Measures Applicable to GPS Receivers

3.5.11.2.1 Filters

The primary mitigation measure applicable to GPS receivers is to increase the receiver selectivity through filtering at the front end of the receiver. Most GPS receivers in use today were designed with an adjacent band satellite service downlink in mind and thus have limited ability to attenuate the adjacent band terrestrial signal planned for the MSS band. High performance receivers use wide

[65] *See:* DA 11-929: Spectrum Task Force Invites Technical Input on Approaches to Maximize Broadband use of Fixed/Mobile Spectrum Allocations in the 2GHz Range, May 20, 2011.
[66] Presidential Memorandum: Unleashing the Wireless Broadband Revolution, dated June 28, 2010
[67] *See:* FCC DA-11-444. The bands 1695-1710 and 3550-3650 were identified by NTIA as becoming available within the next 5 years and other bands (e.g., 1755-1850 MHz) are being evaluated for possible reallocation.

frequency bands that include frequencies in the MSS band. The technology advances that made these receivers possible was developed based on the MSS band being used for space services rather than higher power terrestrial services.

Effects on Receiver Performance: Realizable analog filters will always provide some undesired attenuation of signals in the passband, which is referred to as *insertion loss* and will always increase the receiver noise level. It is desirable for any filtering prior to the first low noise amplifier (LNA) within a GPS receiver front-end to have extremely low insertion loss. Typical requirements for insertion loss range from under 3 dB to <0.5 dB for some receivers used for high precision applications.

Each filter adds a group delay. These delays are different for signals with different spectral content, and each delay changes with temperature. The changes in delay common to all frequencies map directly into the receiver clock solution, and are a concern for high-accuracy time transfer receivers. Filter delay changes that are not common for the different frequency channels affect the estimation of the ionospheric content, and increase the difficulty of various cycle ambiguity estimation schemes used for high accuracy GPS applications.

If the filters are at IF or baseband frequencies, these delay variations produce very different effects on the carrier phase and group delay observables, which reduces the effectiveness of techniques such as carrier smoothing of group delay.

Advantages: Filters out the interference from LightSquared transmissions.

Disadvantages: Narrow filters with sharp cutoffs have the following disadvantages

1. Attenuate signal
2. Add to noise floor
3. Add cost
4. Add mass
5. Increase group delay, and the slope of delay vs. frequency, which leads to
6. Phase and group delay variations with temperature
7. Reduces the opportunity of using increased bandwidth to implement narrow-correlator spacing in receivers. This precludes using narrow correlator spacing to reduce multipath effects and to provide better precision (less system noise error).