L Band Service Compatibility

Part II: Optimum GPS Receiver ABI Compatibility

Greenwood Telecommunications Consultants LLC

DOT ABC Meeting

March 12, 2015

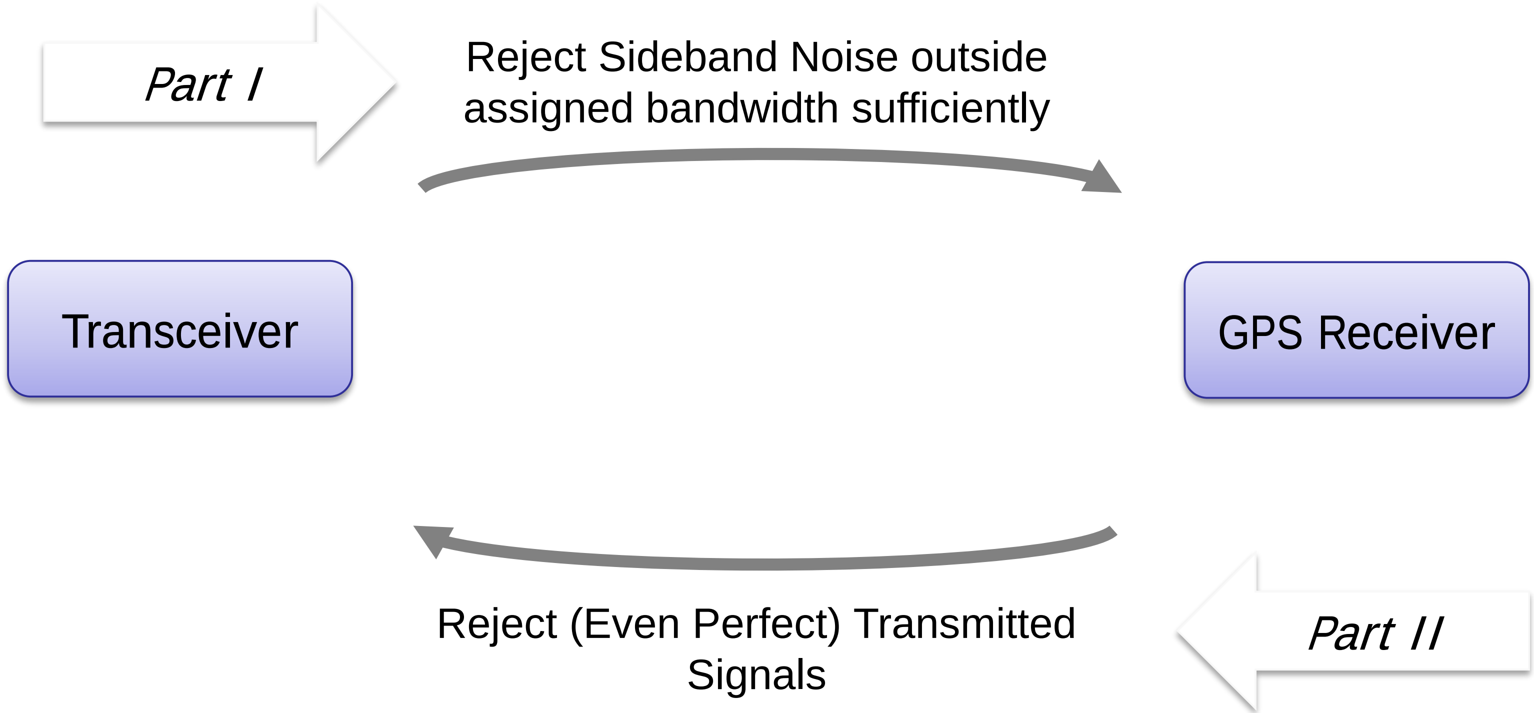
El Segundo, CA

Workshop Objectives

- This is the Second of Two Parts on Compatibility
  - Last time, OOBE. Today examine mitigation of Adjacent Band Interference, ABI.
- Apply Relevant TWG and NPEF (2011) data to engage compatibility analysis
- Assert Principle: Dr. Brad Parkinson's PTA, Protect, Toughen and Augment
- Assert Principle: OOBE and ABI are distinct but parallel forms of interference
  - OOBE = Transmitter sideband emissions that fall into GPS receive bands
  - ABI governed by GPS receiver rejection of *all* nearby transmitted signals
  - Parallel process for success: Must solve and set OOBE and ABI rules together
    - Should not forget Intermodulation once OOBE, ABI are set
- Finding: Last time we covered the first compatibility factor, OOBE...
  - We found that ATC offers optimum OOBE compatibility at **-105 dBW/MHz**
  - Uses competitive, practical commercial components
  - OOBE sets a **balanced performance threshold for ABI** performance.
    - Reaching one without the other undermines real compatibility

OOBE & ABI Parallel Forms of Interference

Spatially, Spectrally Dense, Close-In Compatibility Analysis



Object is to have Transceiver and GPS Receiver Harmlessly Operate at One Meter based on Current Standards

More Difficult to Achieve Cross-Service Compatibility

Yet GPS & Wireless Have Common Customer Base

- **GPS Most Affected (TWG)**
- GLN
- Precision
- Non-certified Aviation (GLN)
- Network

GPS Suppliers

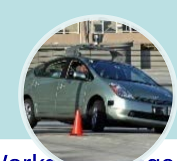
- **Closer-In COMMS**
- PCS, Cellular
- MSS Next Gen
- **L Band ATC**
- **AWS-3, AWS-1**
- **AMT**

Broadband Suppliers

- Personal, vehicle, passenger
- Intelligent transportation
- Future Communication systems
- Shared Spectrum systems
- Indoor E911

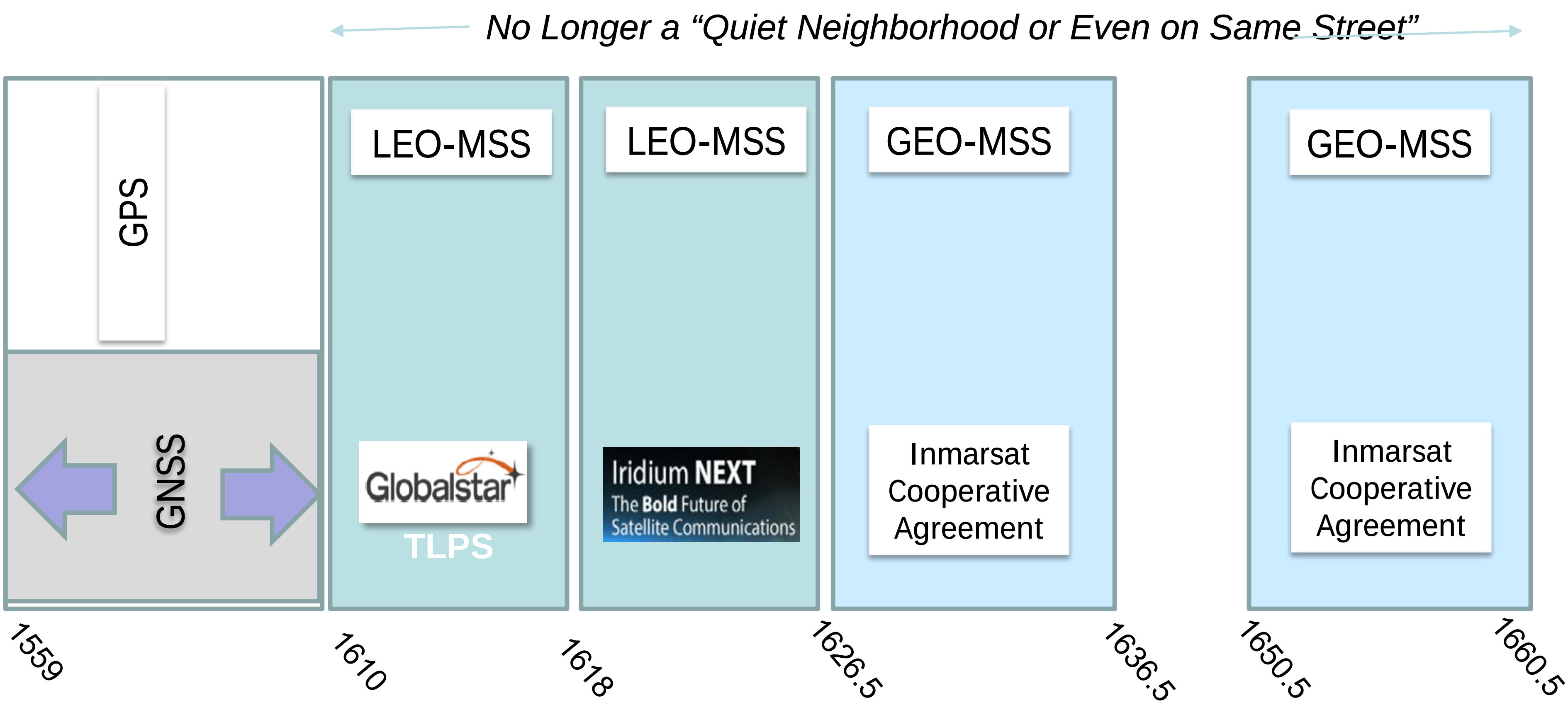
- ...

Common Customers

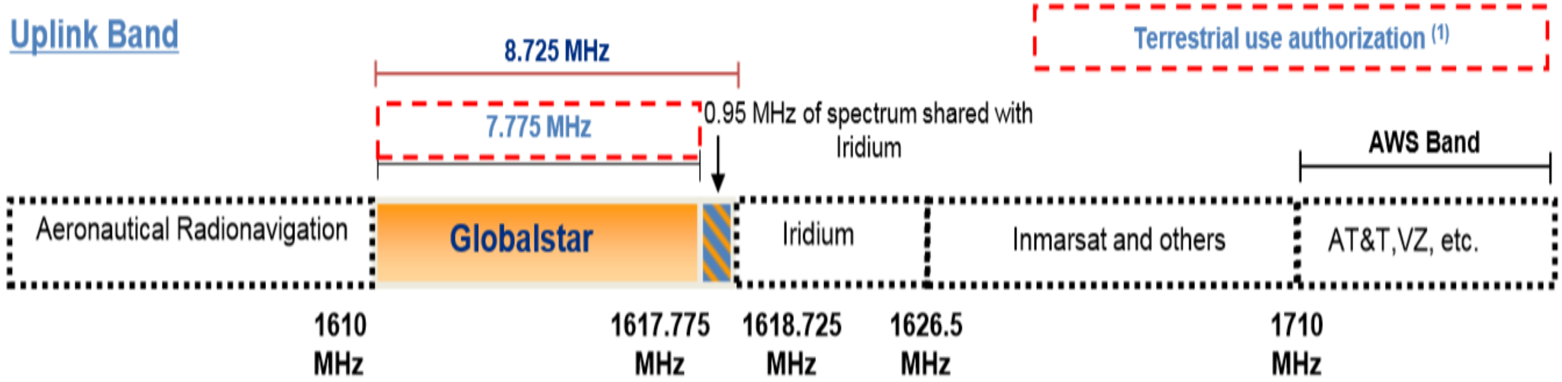


ATC & MSS Operators: More "Terrestrialization"

- Spectrum values rising
- Recent AWS-3 L Band auction prices $44.9B, >$2.50 MHz-POP average, paired
- High power neighbors inside MSS uplink and at both edges: 2000W EIRP just above near neighbors at 1670MHz, 25W EIRP airborne below 1525MHz



Latest: Globalstar Proposes Terrestrial Service in Their Existing MSS Uplink Band ("TLPS")



- Proposes 4.6dBW EIRP (2.9W)
- ~10X higher than current EIRP
- Current: November, 2014

Return Link Budget GEN2 High Speed Data AFixed 1.23 MHz

Return Link: 1.6 GHz up/7 GHz down					
	Inner		Outer		
Uplink Analysis					Units
Frequency	1.6		1.6		GHz
EIRP per user	4.6		4.5		dBW
Altitude	1414		1414		km
User elevation angle	70		25		deg
Slant Range	1486		2528		km
Path loss	-160.0		-164.7		dB
Polarization & Tracking loss	-1		-1		dB
S/C Rx Signal Strength	-156.4		-161.1		dB
Satellite antenna gain	13.09		17.78		dBi
Line loss	-2.00		-2.00		dB
User signal at transponder	-145.3		-145.3		dBW

Source: Globalstar FCC filings

Rising LEO MSS Land Mobile Services

Mostly from Transportation Segment

Current Market Research:

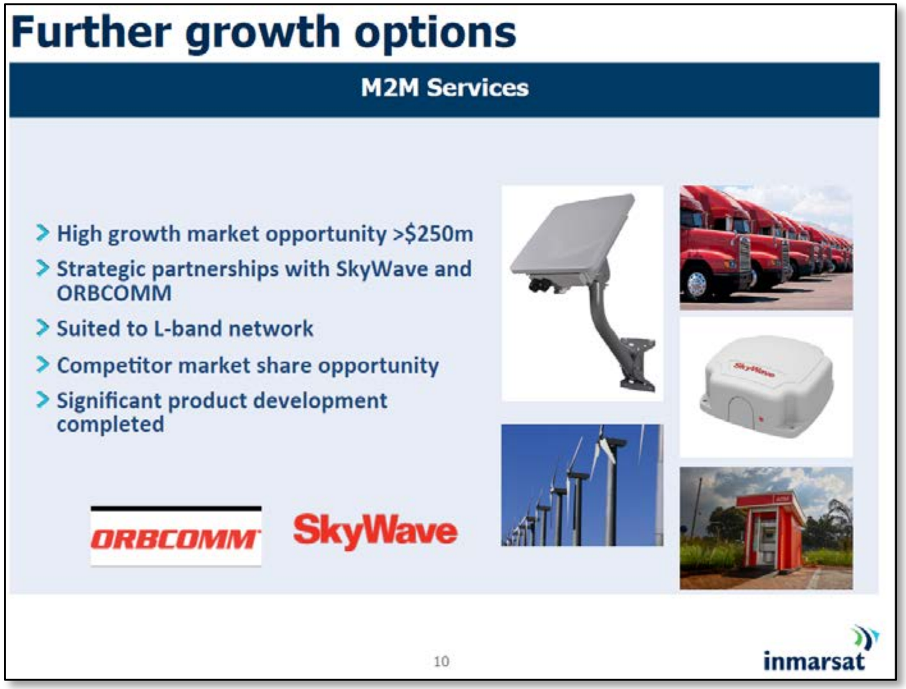
- Remote MSS becoming smaller %
- IoT, M2M applications dominating
- Higher bandwidth growing
- N. American leads all regions
- L Band remains as is today 90% of satellite revenues out to 2023
- 2023: 3.5M units in N. American transport segment alone, $1.2B/yr
- Coverage critical market segment
- Hybrid terrestrial/satellite also developing
- $20-25 ARPU by 2020
- 6M Global systems by 2023

Source: NSR market Research (Feb 2015)

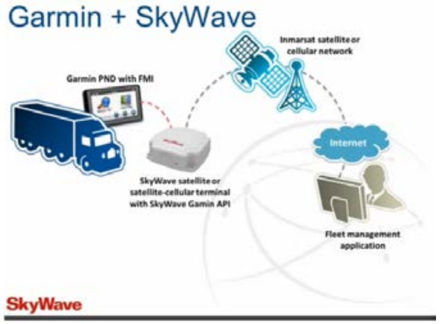
GEO-MSS Services Also Growing Land Mobile

Note: Common Customers of MSS, GPS, Cellular Technologies

- Off-shore, aviation low growth segments
- Land Mobile Growth areas:
  - Automatic Vehicle Location (AVL)
  - SCADA
  - M2M/IoT
  - Precision Mining, Construction
  - Energy, Critical Infrastructure
  - Remote Field Communications
- 7-46W EIRP MSS Uplink transmitter power
  - Integrated or on-board, antennas, but in field, on road as well, so MSS uplink signals ubiquitous



Source: June 2014 Inmarsat Corporate Presentation



Source: SkyWave website

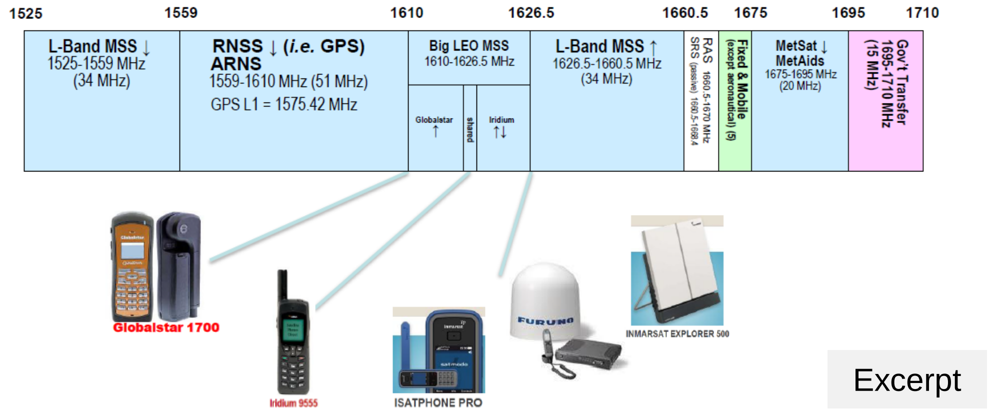
NTIA & FCC December EXCOMM Presentation:
Are GNSS & MSS Uplink Maintaining Compatibility?

Excerpt

Uplink MSS Neighbors

- MSS UPL Separation: 0-50MHz
- MSS UPL EIRP: 1-40W
- New Broadband EIRP: 10-350W

Big LEO and L-band MSS Terminals



Excerpt

Terminal Types	MAX EIRP	Notes
Satellite Phones (Sat Mode)	26-29.5dBm EIRP	29.5dBm with car kit
Broadband Data Terminals	40-55dBm EIRP	Based on the Inmarsat product catalog and FCC Authorization
MET/MES	37-46dBm EIRP	

Source: NTIA/FCC Spectrum Management Perspectives Presentation to the Fourteenth Meeting of the U.S. Space-based Positioning, Navigation and Timing (PNT) Advisory Board, Dec. 10, 2104, slides 19-20

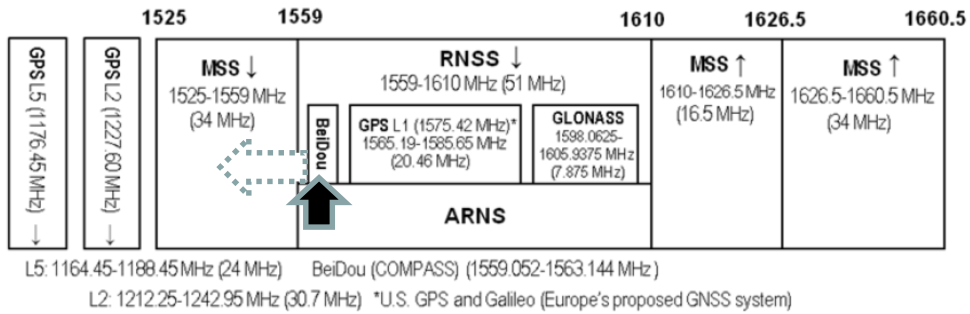
NTIA & FCC Quandary: GNSS & MSS Compatibility

RF Front-End Bandwidth

Excerpt

- GNSS is a wideband resource
- Wideband signals are precious
- Imperative: Advocate for right-sizing GNSS spectrum

GPS/GNSS Systems and Neighboring Bands Allocations
(not to scale – for illustration purposes only)



GPS/GNSS mode	Minimum RF Front-End BW
Narrowband GPS Only	2 MHz
Wideband GPS Only	20 MHz
Wideband GPS + GLONASS	41MHz
Wideband GPS + GLONASS + BeiDou + Galileo	47 MHz

Actually, wider BW
(Beidou: 8 or 16MHz ½ BW?)
(Galileo: 40 or 41MHz BW?)

More recent Requirements

GPS L1C	4 MHz
GPS new SV's	32 MHz

Source: NTIA/FCC Spectrum Management Perspectives Presentation to the Fourteenth Meeting of the U.S. Space-based Positioning, Navigation and Timing (PNT) Advisory Board, Dec. 10, 2104, slides 19-20

MSS Economics: Fill Satellite Pipeline

Data-Centric, Higher Usage Applications, Low Cost Terminals

<u>Example: Iridium NEXT</u>

- LEO-MSS, 7MHz from edge of GNSS L1
- Replenishing all 66+ satellites, $3B CAPEX
- 3M subscriber on-line global capacity
- 1.5Mbps data versus current 128kbps
- Launch in June, begin service 2017
- Inexpensive modems, service plans
- Ubiquitous coverage, omni antennas

Source: Iridium

2011 FCC TWG Focused Exclusively on ATC

Thus Drew Attention Away from Other Existing Sources of ABI

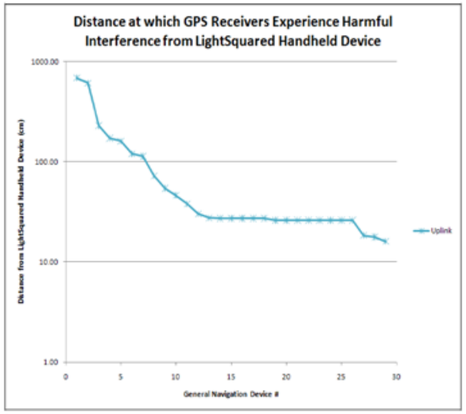


Figure 3.3.8

TWG Report, GLN section:

- "Figure 3.3.8 above shows the interference from a single LightSquared (ATC) handset."
- "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 (GLN)** 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**."

However….

- *No assessment of MSS devices in proximate bands closer to GPS, many with 15-35 times more power than ATC.*
- *No assessment given why such large differences in GLN receiver ABI immunity exist.*
- *No assessment given what receiver performance trade-offs are necessary to protect GLN narrowband receiver from adjacent band signals.*

ABI Susceptibility Results by Category

TWG Test of ATC Uplink Impact: Stand-off Distances by Receiver Category (1dB C/No criterion)

ATC (TWG tested)
LTE 10MHz
Centered at 1631MHz

MSS (not tested)
LEO, GEO .25-45W
1610-1636 MHz

Aviation

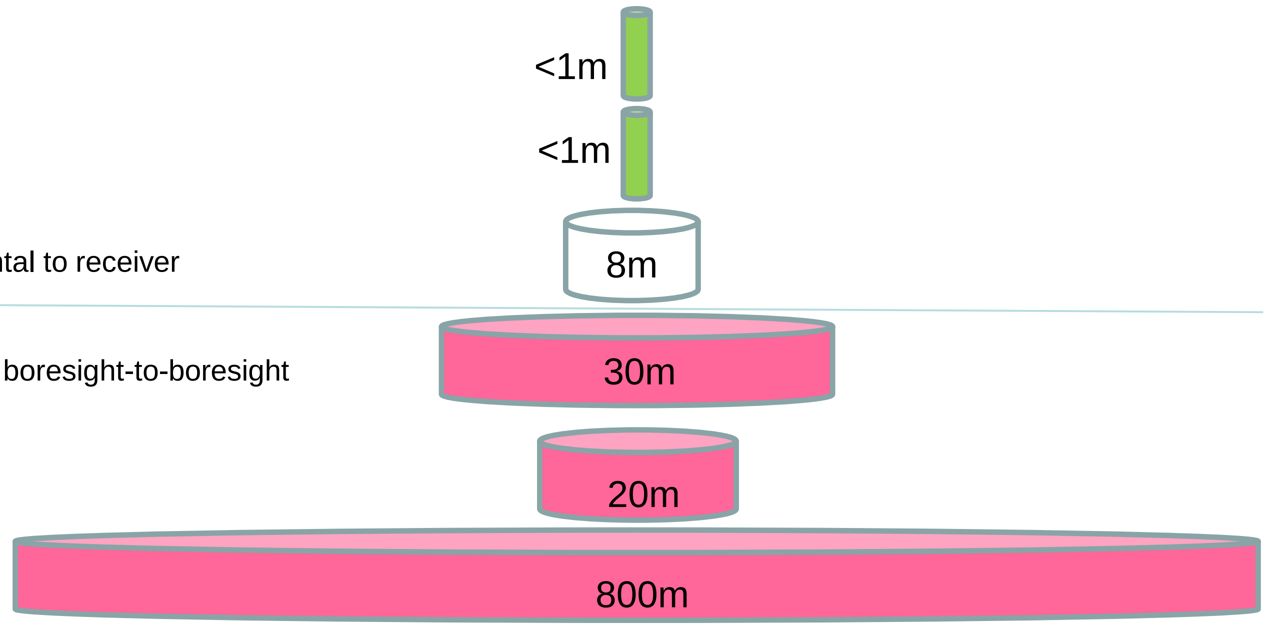
Cellular

Precision*
Mobile is horizontal to receiver

Precision*
Antennas tested boresight-to-boresight

GLN
Minimum

GLN
Maximum



No Change

No Change*

56+ times (LOS)

56+ times (LOS)

56+ times (LOS)

56+ times (LOS)

GLN narrowband receivers exhibit significantly less ABI rejection relative to other GPS receiver categories, narrow and wideband.

* 50% result (TWG); ** GPS not GNSS/GLONASS

TWG Cellular Tests Showed Robust Compatibility

Robust with either GEO-MSS or ATC Uplink Transmissions

- At least 8dB greater compatibility margin
- Cellular and GLN are narrowband receivers
- Thus GLN could benefit from similar low cost front end filter devices.
- Cellular GPS arguably has the most demanding L Band compatibility requirement…
  - Higher acquisition sensitivity (minimum std: -147 dBm)
  - E911 mandate
  - Must reject several on-board transmitters, multitude of licensed f’s.
  - Cellular is very cost sensitive
- Cellular deploys inexpensive SAW or BAW solid state filters to protect GPS front end
- Given claim of “substantial harm” by the GLN community, questions must be posed…

TWG (2011) Test Result Excerpt

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.

Source: FCC TWG Final Report, p. 114, 2011.
Note: The TWG Cellular test capability was limited to -10dBm incident blocker interference power. Based on results, actual cellular mobile blocker resistance was likely greater than test range allowed..

TWG GLN ATC versus MSS Uplink Profiles

Taken at Face: Under-designed for "Quiet Neighborhood" MSS

Global Product Compliance Laboratory
PN: 2011-0080
Report Number: GPCL-2011-0080-LS
R3.0

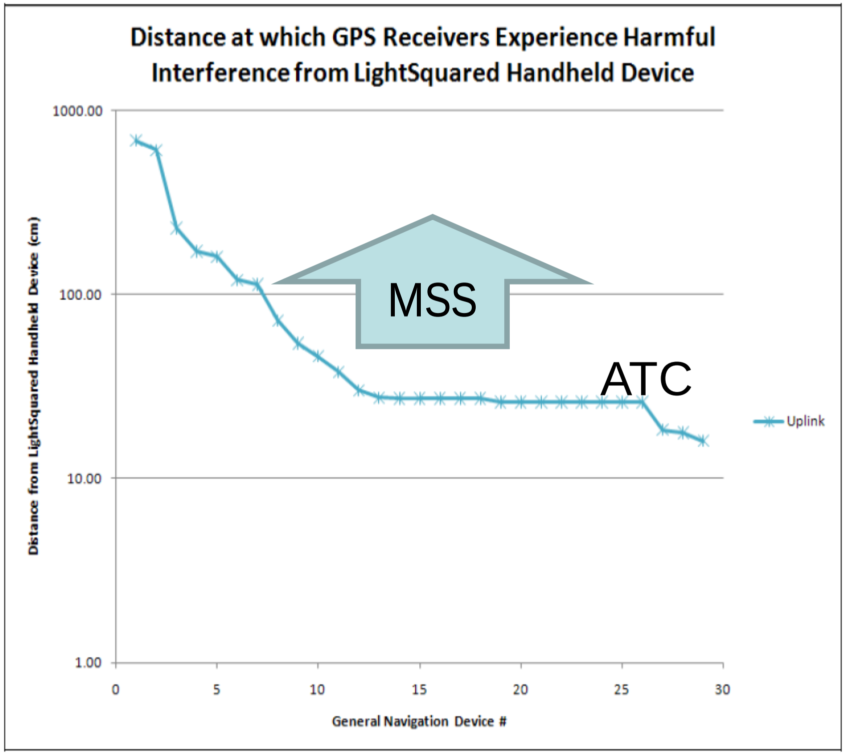


Figure 3.3.8

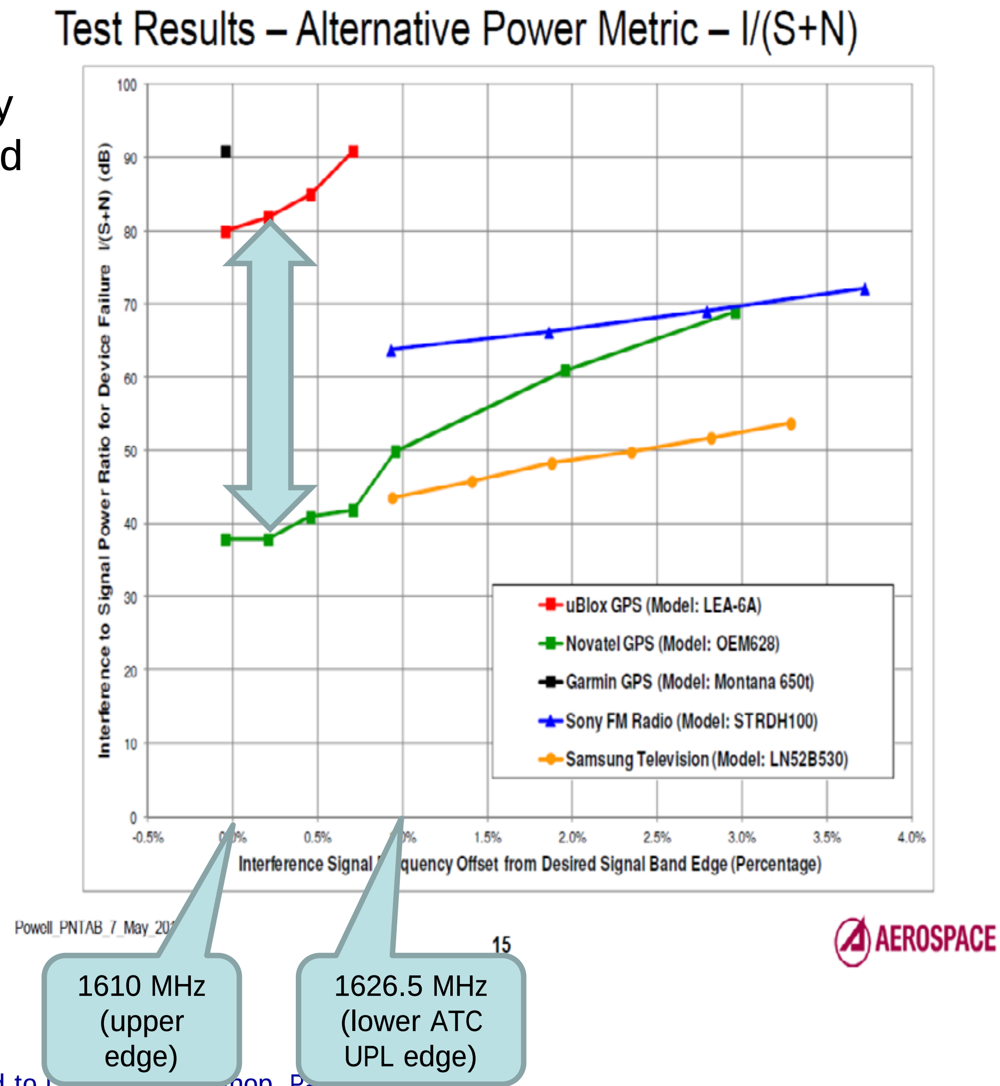
	Phase 3							
	TEST:	Static InterferenceSuceptibility, uplink 1630.3 (5 MHz BW)						
	Power at Device (dBm) vs C/N degradation							
	Device	1 dB	3 dB	6 dB	10 dB	20 dB	LOF	
1	P14949	-30.4	-23.4	-18.4	-10.4	*MPNE*		
2	G18161	-29.4	-24.4	-18.4	-13.4	-2.4	*MPNE*	
3	G15028	-20.9	-18.0	-15.6	-14.2	lof	-11.1	
4	G16382	-18.4	-9.4	-3.4	*MPNE*			
5	G10195	-17.8	-14.4	-14.6	-4.2	lof	-0.1	
6	G12867	-15.3	-3.0	*MPNE*				
7	G14298	-14.8	-9.7	-6.7	-2.7	*MPNE*		
8	G15343	-10.9	-7.9	-2.4	*MPNE*			
9	P15427	-8.4	-4.4	-2.4	*MPNE*			
10	G12559	-7.0	*MPNE*					
11	G17783	-5.3	*MPNE*					
12	P14730	-3.3	*MPNE*					
13	G12586	1.0	*MPNE*					
14	G10968	1.3	*MPNE*					
15	G10607	*MPNE*						
16	G11207	*MPNE*						
17	G13445	*MPNE*						
18	G14188	*MPNE*						
19	G14666	*MPNE*						
20	G15448	*MPNE*						
21	G16449	*MPNE*						
22	G16534	*MPNE*						
23	G17169	*MPNE*						
24	G17641	*MPNE*						
25	G18062	*MPNE*						
26	G18696	*MPNE*						
27	P13275	*MPNE*						
28	P17655	*MPNE*						
29	P18892	*MPNE*						
		lof	loss of fix					
		MPNE	Maximum Power reached with No Effect (> 0 dBm)					

(Above) Page 142 of TWG Report;
(Right) Page 30, Appendix 2, TWG Report June 2011

Another Study Suggests Some Narrowband GPS Receivers Designed with Sufficient ABI Resistance

Compares to Inexpensive Broadcast Receivers

- Top of graph, 100dB I/S, is approximately the ATC receiver rejection margin required
  - **115+ dB required** to reject MSS uplinks
- Comment: A similar test using openly available, representative receivers could have been conducted 5-15 years ago



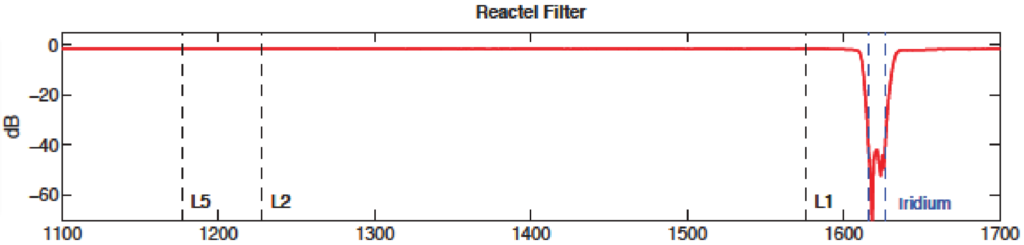
Precision & Geodesy Applications:

Customers Adapt their Precision GPS Receivers without Loss of Performance

Problem: Precision Tier I brand precision receiver susceptible to nearby MSS SATCOMM uplinks at ranges of 30-100+ meters from GPS receiver.

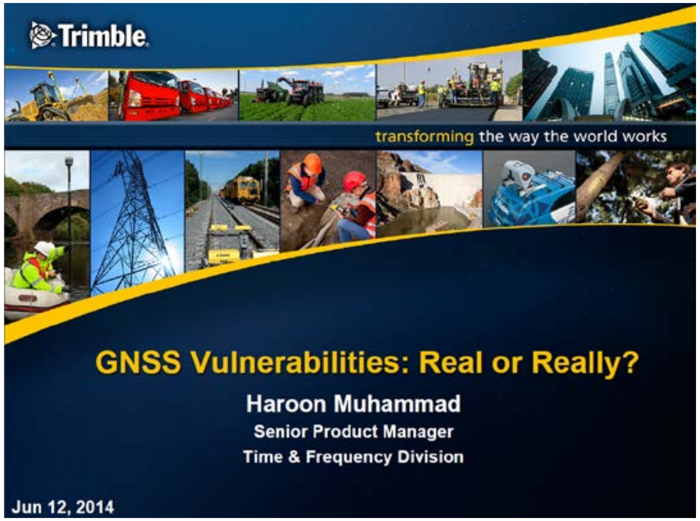
Solution: Customers inserted their own receiver design upgrade. Add either a band-pass or band-reject filter to reject MSS uplink transmissions. Sub-mm precision carrier phase measurements were retained.

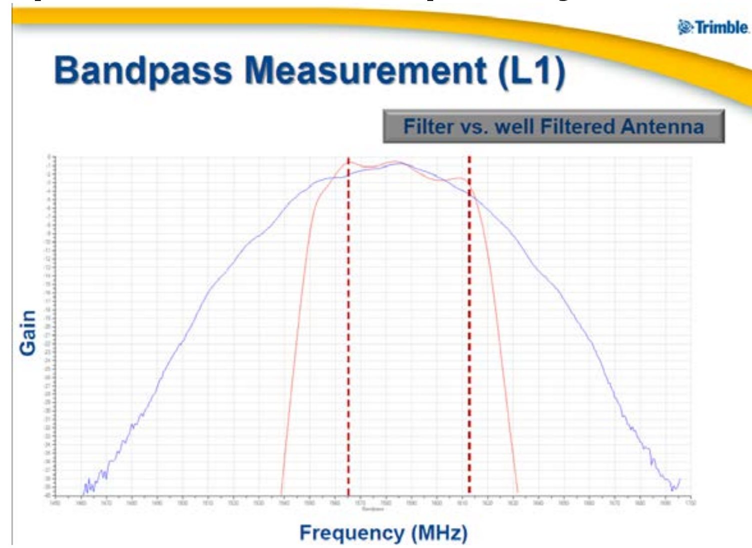
Aviation also attends to ABI… MOPS airworthiness mask rejects ground or on-craft MSS uplinks.



Source: https://www.**unavco**.org/...and.../Berglund-**GPS**-GNSS.pdf last retrieved 12/6/14. *Also presents a separate filter solution for Lower 10 compatibility consistent with Greenwood Telecom ION ITM January 2012 report adapting three precision receivers.*

One Major Supplier’s Message:
Plan for Close-In Adjacent Spectrum Occupancy





How many spoofing events?

- Trimble has shipped/deployed over 3 million GNSS timing receivers since 2000
- We have only received one report of a limited area “potential” spoofing incident in early 2000’s reported by a network next to Chinese military installation
- The U.S. Department of Homeland Security assessed jamming disruptions to be more likely than spoofing incidents*

* DHS: National Risk Estimate, released November 2012

Conclusion

- GNSS reference is still the only solution for distributed time
  - IEEE-1588 is based on GNSS (PRTC)
- Multi-constellation, multi-band provides the most robust solution
- The application and end-use case will determine the selection of timing source, but in some cases GPS is the only primary reference source

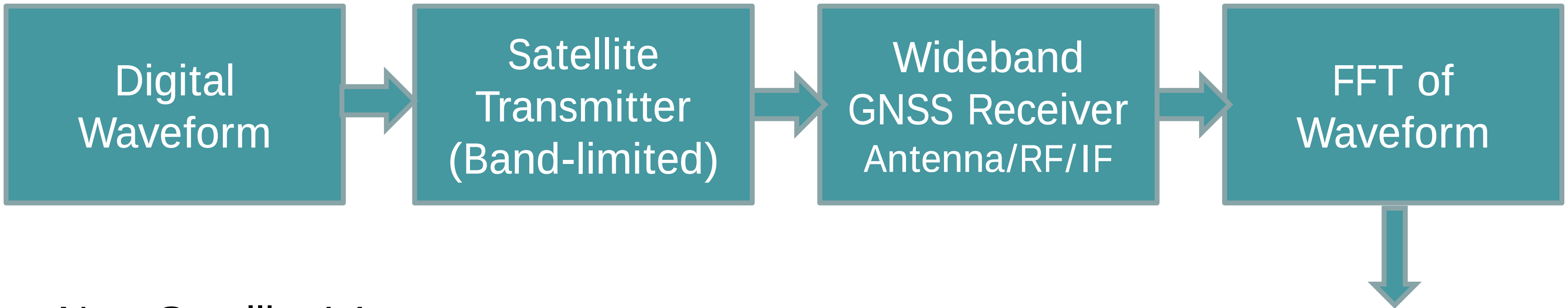
Source: http://www.atis.org/WSTS/papers/6-2_Trimble_Haroon_mohd_GNSS_vulnerable.pdf
Retrieved 2/12/15

Blocking Analysis

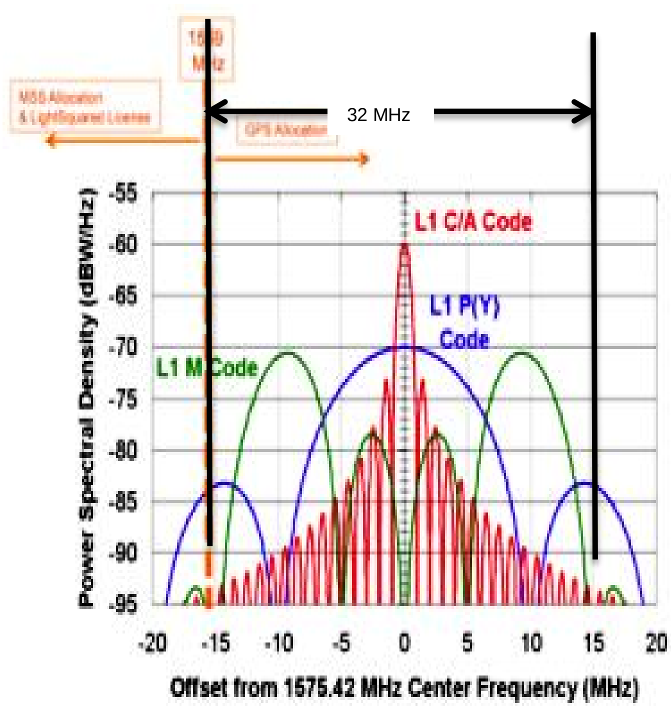
GPS Receiver Blocking

- Blocking requirements calculation
- L1 CA code filter impact-quantify
- L1 C code filter impact-quantify
- Precision Rx simulations and measurements
- Conclusions and recommendations

GPS Spectrum to Be Protected



- New Satellite L1 BW=32MHz Due to L1 M code
  - Formerly 24MHz for P(y) code
- Band to be protected
  - High end=1591.42 MHz
  - Low End=1559.42 MHz
- C/A and L1C code recovered by RX with BW much less than 32MHz
- GPS Spectrum now requires 32MHz



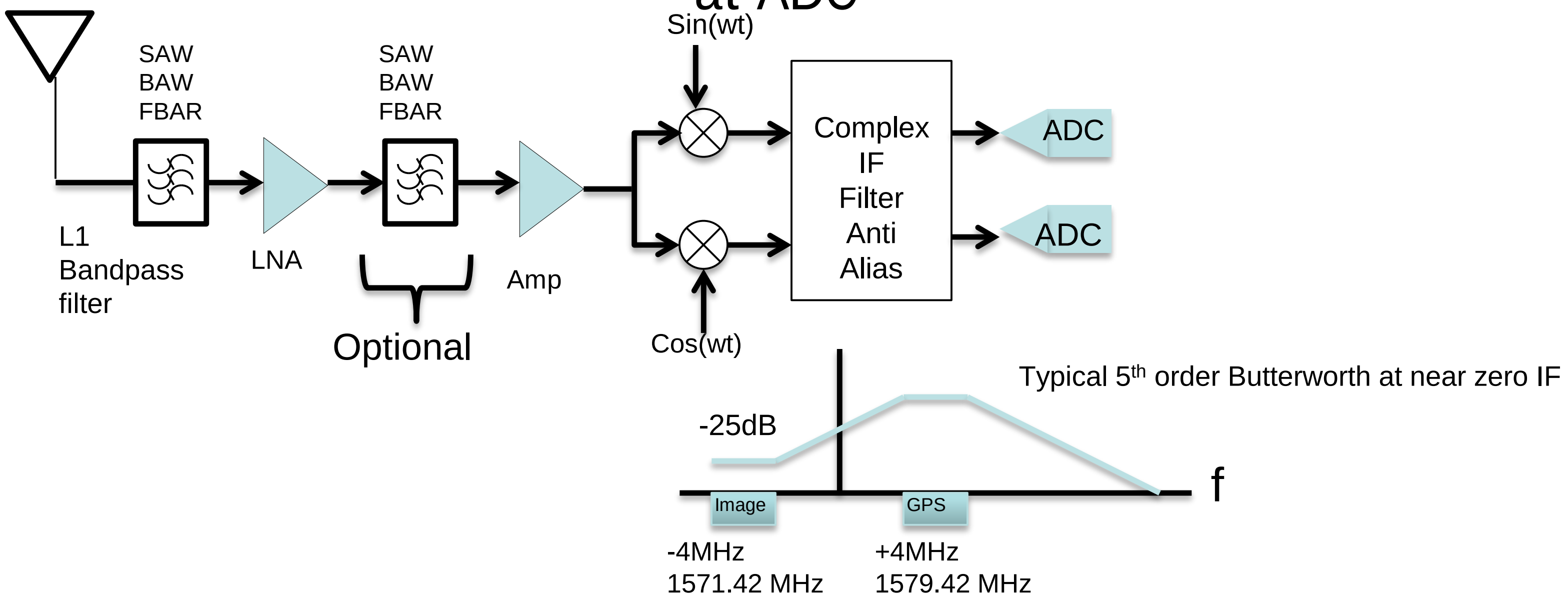
Blocking Calculation Vs Interfering System

Reciprocal to Tx OOBE method CA code analysis

Determination of Blocking for 1dB loss in GPS C/No, handset to handset						
Interfering System ->	**Big LEO MSS 1**	**Big LEO MSS 2**	**LTE**	**Inmarsat**	**units**	**Comment**
Modulation	CDMA 1.23MHz	QPSK 25KHz	OFDM 10MHz	QPSK		
Tx Burst Power	27.8	38.5	23.0	46.6	dBm	
Gain of Tx ant at Horizon	-5	-5	0	-10	dBi	Gant Likley less
Gain of GPS antenna (From TWG report)	-5	-5	-5	-5	dBi	Gant Likley less
Body blockage	2	2	2	2	dB	
Free Space Path loss at 1 m (1575MHz)	36	36	36	36	dB	
Blocking rejection to -1dB	**-20.6**	**-9.9**	**-20.4**	**-6.8**	dBm	
Freq offset from 1575.42	34.58	45.58	51.08	51.08	MHz	
Freq offset from 1575.42 +16	18.58	29.58	35.08	35.08	MHz	

- Blocking rejection ranges from -20.6dBm to -6.8dBm
  - Can be converted to Handset to Precision GPS by adding path loss from Handset to Precision GPS likely much greater than 1 m
  - Inmarsat 47dBm Tx uses directive high gain antenna with much lower gain at all other directions

Low Cost Rx Architecture and Focus on Filtering to Protect Noise Floor at ADC



- Assume interference adds like noise and is aliased onto the channel
- Total filtering must protect noise floor from input interference
  - Distortion is IF + RF filtering, IF is usually bigger issue due to narrow bw and high filter order
- This analysis "drives interference" to 6dB below kTBF for 1 dB loss in C/No
- Typical GPS RFIC IF at +40MHz provides 60dB rejection
- Other impairments of less concern are
  - Reciprocal mixing with LO sbn- Protected by RF filters and SBNR
  - Mixer IP2 protected by near zero IF and RF filters
  - 1dB compression of all stages-protected by upstream filters

Rx Filter Requirement

Total filter rejection based on noise equivalent analysis

Interfering System ->	Global Star	Iridium	LTE	Inmarsat	
Modulation	CDMA 1.23MHz	QPSK 25KHz	OFDM 10MHz	QPSK	
Modulation BW	1.23	0.0315	9	2	MHz
Tx Power at GPS Rx	-20.6	-9.9	-20.4	-6.8	dBm
Equivalent noise in GPS 2MHz BW	-20.6	-9.9	-26.9	-6.8	dBm
GPS RX typical noise figure	2	2	2	2	dB
GPS Rx noise floor	-172	-172	-172	-172	dBm/Hz
Power allowed for 1dB C/No loss	-178	-178	-178	-178	dBm/Hz
Power allowed for 1dB C/No loss 2MHz BW	-115	-115	-115	-115	dBm
Total filtering required	94.4	105.1	88.1	108.2	dB
RFIC IF selectivity-example	60	60	60	60	dB
RF filter rejection required	**34.4**	**45.1**	**28.1**	**48.2**	dB
Frequency offset from 1575.42	**34.6**	**43.3**	**51.1**	**51.1**	MHz

Total filter rejection based on other impairements

Interfering System ->	Global Star	Iridium	LTE	Inmarsat	
P1dB 1st LNA - example	-13	-13	-13	-13	dBm
RF filter rejectiion required	-7.6	3.1	-13.9	6.2	dB
Mixer P1dB- example spec	-34	-34	-34	-34	dBm
Jammer - example spec	-13.4	-24.1	-13.6	-27.2	dBm
Max RF Filter rejection	13.4	24.1	13.6	27.2	dB

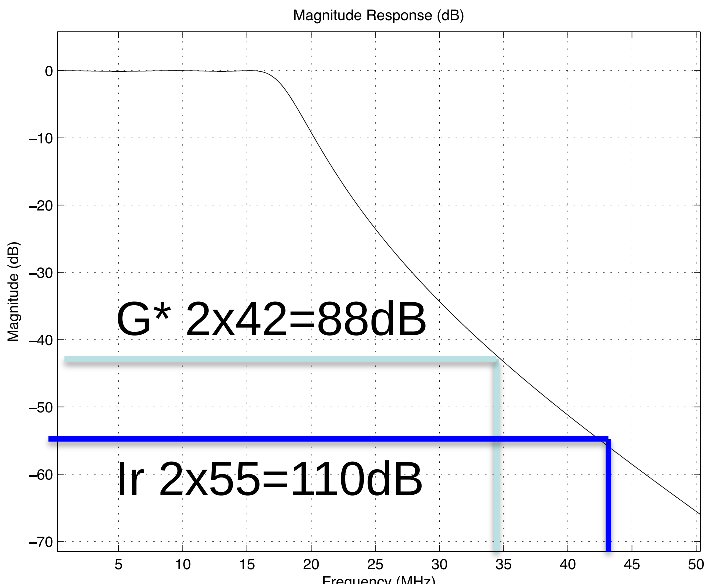
Filter requirements driven by Noise equivalent analysis

Filters

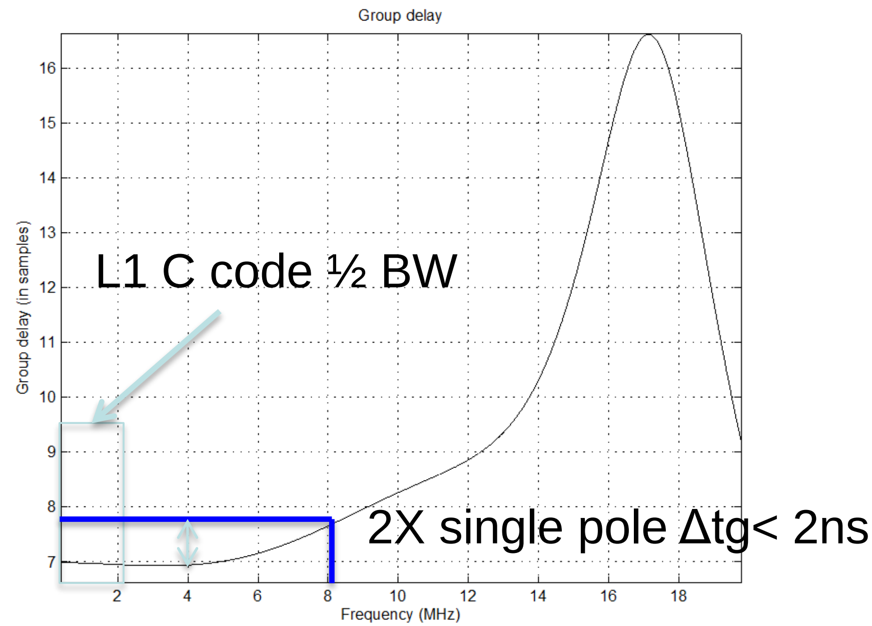
- Modeled 3 filters in Matlab all .1dB Tcheb
  - L1C code (null to null BW=4MHz)
    - Bssb=16MHz 5pole IIR
      - Used to stress filter performance
    - FIR equivalent of IIR modeled as same Bssb 3dB
  - CA code (null to null BW=2MHz)
    - Bssb=1MHz 4pole IIR
    - Bssb=2 MHz 4pole IIR
  - Filter model to simulate the IF filter + RF filter is a cascade of two filters denoted by 2x filter_type

L1 C code waveform and wideband filter

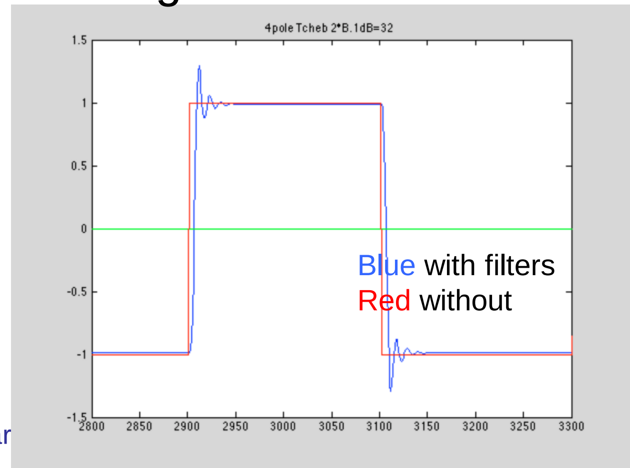
Single filter Bssb=16MHz



Single filter Bssb=16MHz



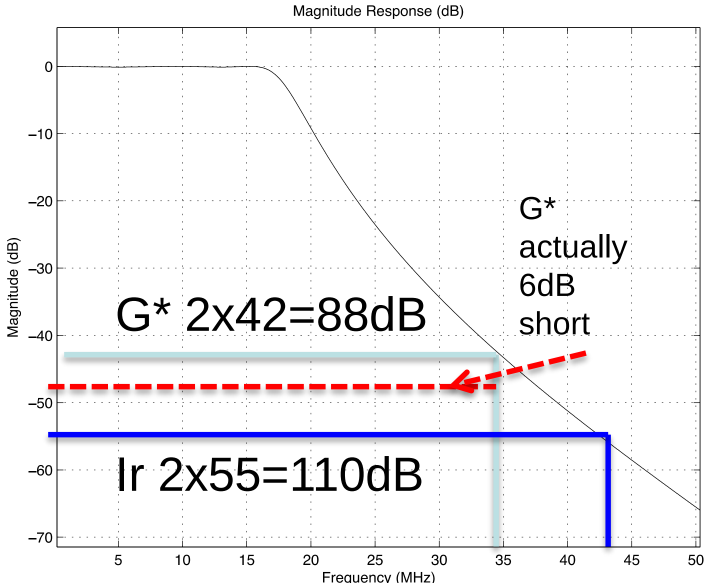
2X Single filter Bssb=16MHz



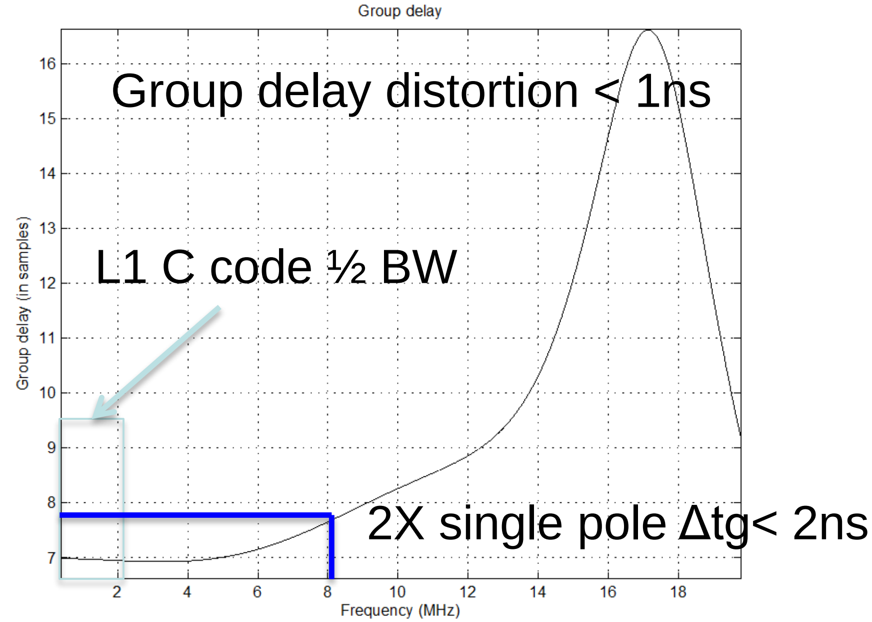
- Filter appears to have little distortion impact
- In keeping with Phil Mattos linear group delay distortion over 2MHz for sine waves Jan 2012

L1 C code waveform and wideband filter

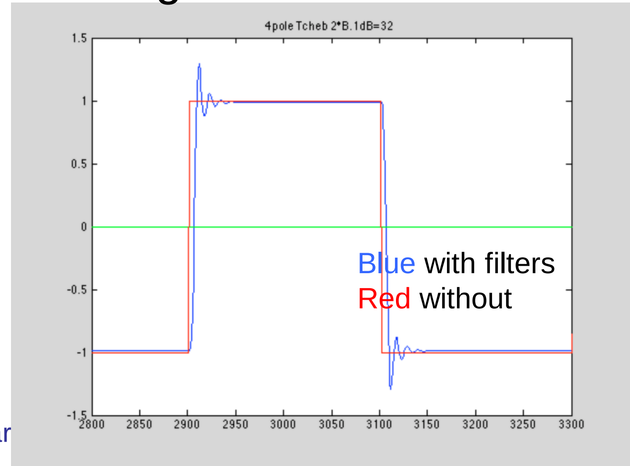
Single filter Bssb=16MHz



Single filter Bssb=16MHz



2X Single filter Bssb=16MHz

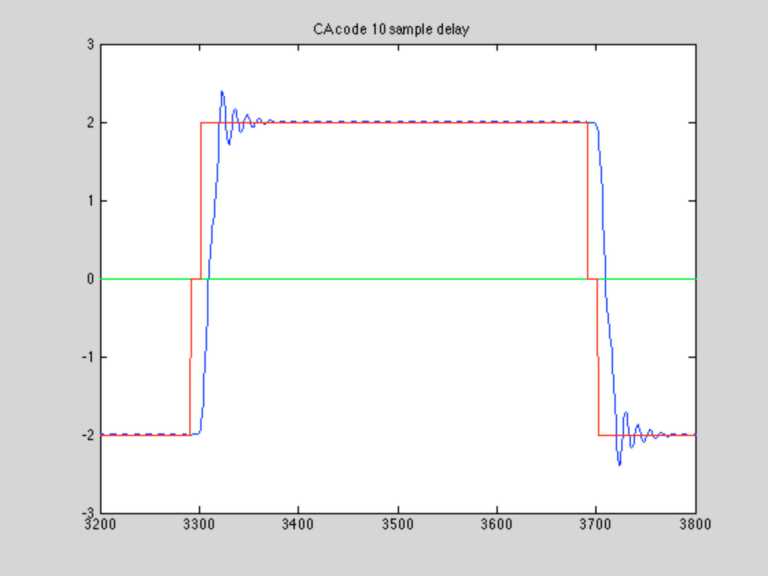


- Filter appears to have little distortion impact
- In keeping with Phil Mattos linear group delay distortion over 2MHz for sine waves Jan 2012
- Post evaluation revealed that G* rejection was short 6dB but change of filter design from 5 pole to 6 pole is likely pretty low

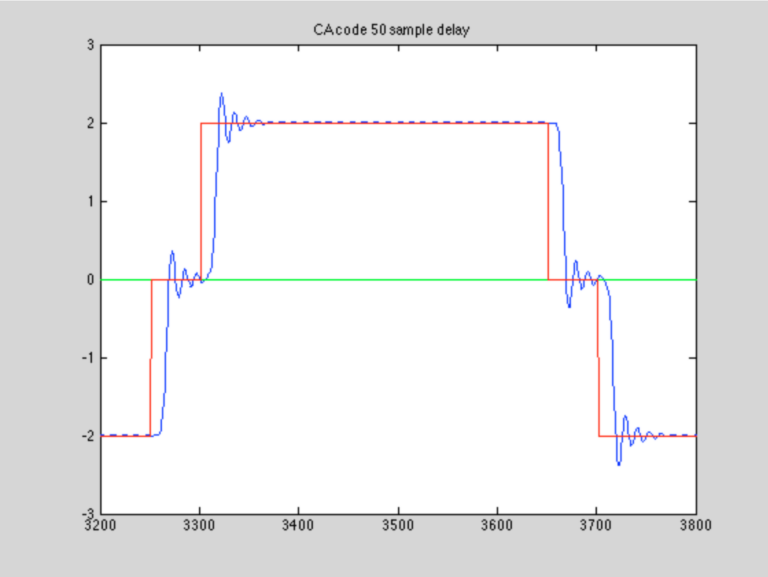
CA Code multipath delayed ray time domain

Sample time 4.88 ns

10 sample delay 2s 16_5p



50 sample delay 2s 16_5p



What is the significance?

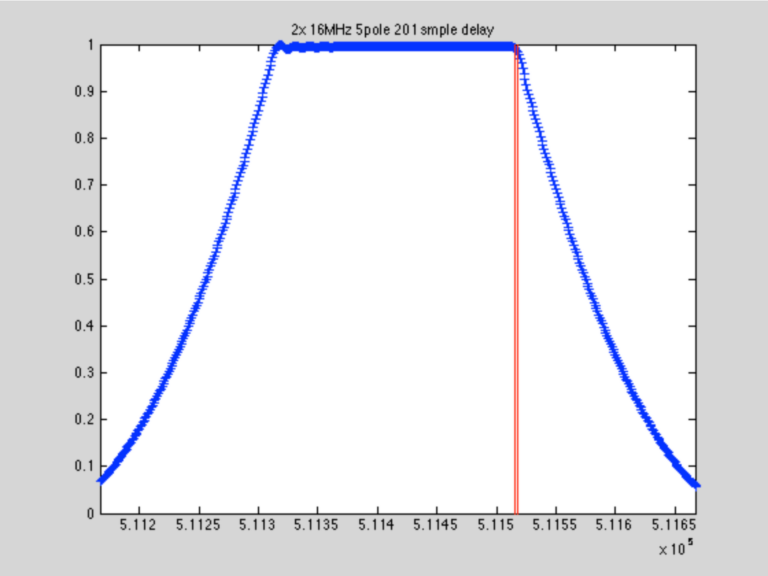
- Real filters have overshoot if they have fast roll off- red trace is impossible
- Can't identify that delayed signal is present with filter at 10sample (49ns) delayed ray.
- May be detectable at 50 sample error if at equal power
- Filter BW of 16MHz does affect low sample time delayed signal in the time domain
- Since the GPS SV has limited BW these limitations likely already exist so doubtful this filter set has any real impact to Multipath performance

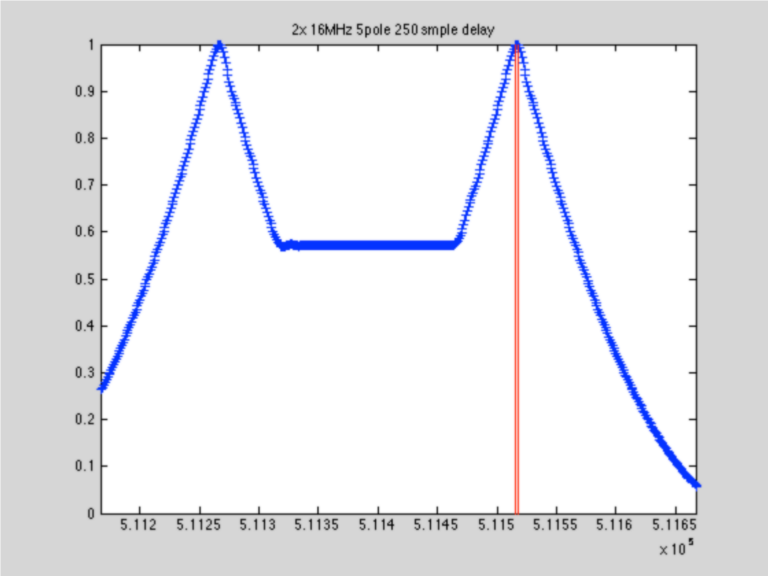
CA Multipath Delayed Ray Detection Bssb=2x16MHz filter

Sample time 4.88 ns

Second ray delayed 201 samples
201/200 chips

Second ray delayed 250 samples
1.25 chips





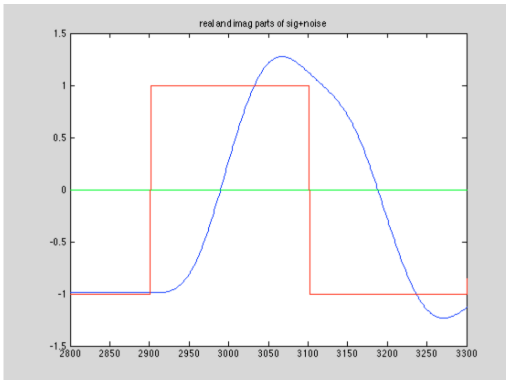
What is the significance?

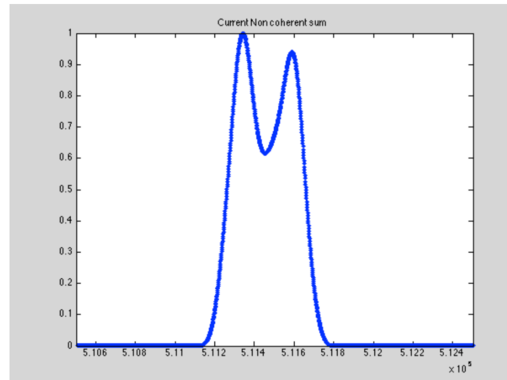
- No real difference from filter less, do filters really matter if you can’t detect < 1 chip anyway?

CA code 2XBssb=1&2MHz

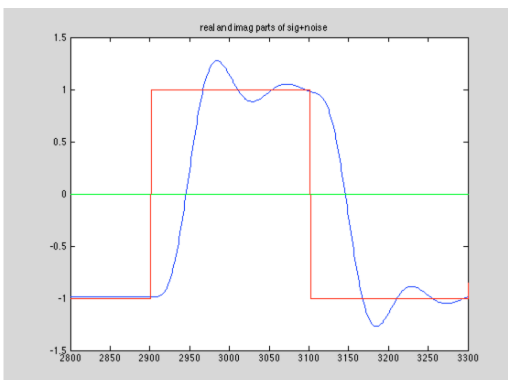
Single Ray   Second ray delayed 250 samples 1.25 chips

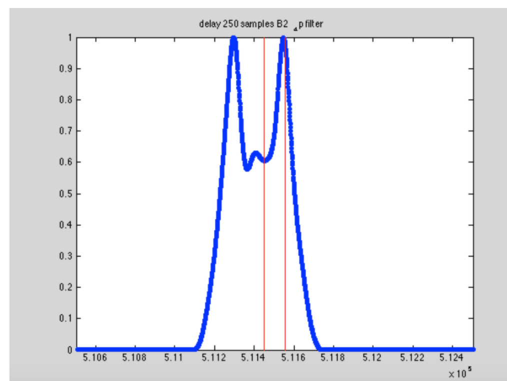
1MHz Bssb

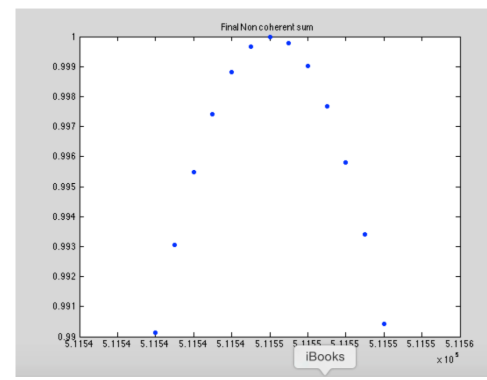




2MHz Bssb





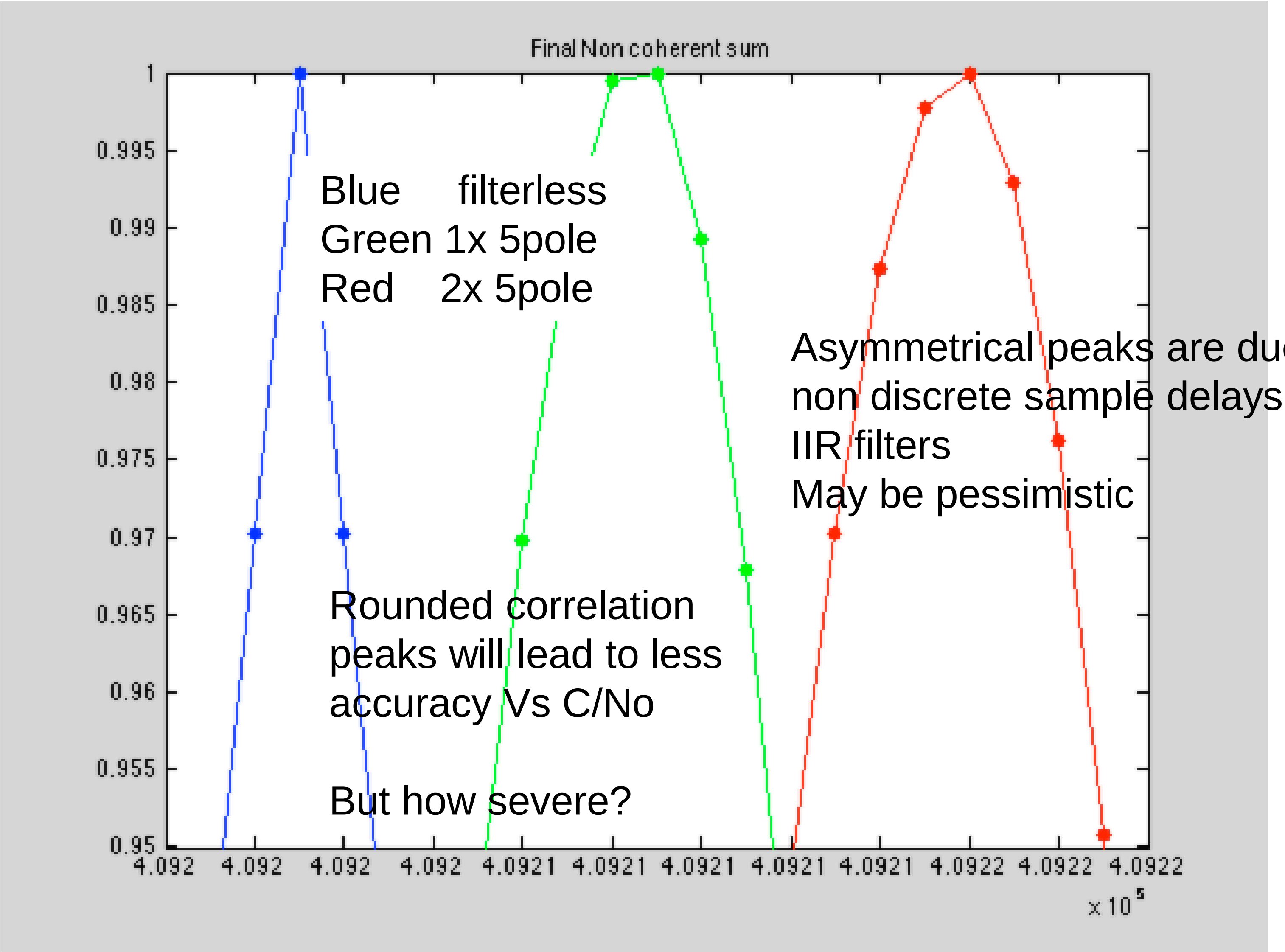


What is the significance?

- Still detect second ray at 1.25 chip
- Filter has little impact on multipath identification
- Rounded correlation will affect sensitivity

Sample time 4.88 ns

L1C correlation Vs Filter Zoom Bssb=16MHz



L1C Sensitivity Vs. Filter (1ms CI)

- L1C evaluated at tight time criteria Vs BW of ideal sample and 2 sample error
    - Results for CA will be more favorable due to lower BW

L1C sensitivity C/No dB_Hz for given time error

Time error	No filter	.1dB TCh_5p_16MHz ssb	2X .1dB TCh_5p	FIR eq 3dB
<2.5ns	51.25	75.25	65.25	58.5
<12.5ns	45.25	46.25	47	45.25

Sensitivity defined as Probability of detection to time error =0.95 over 50μsec search window

L1C C/No Delta dB from no Filter for given time error

Time error	No filter	.1dB TCh_5p_16MHz ssb	2X .1dB TCh_5p	FIR eq 3dB
<2.5ns	ref	24	14	7.25
<12.5ns	ref	1	1.75	0

Due to dual flat peaks

Due to narrower filter

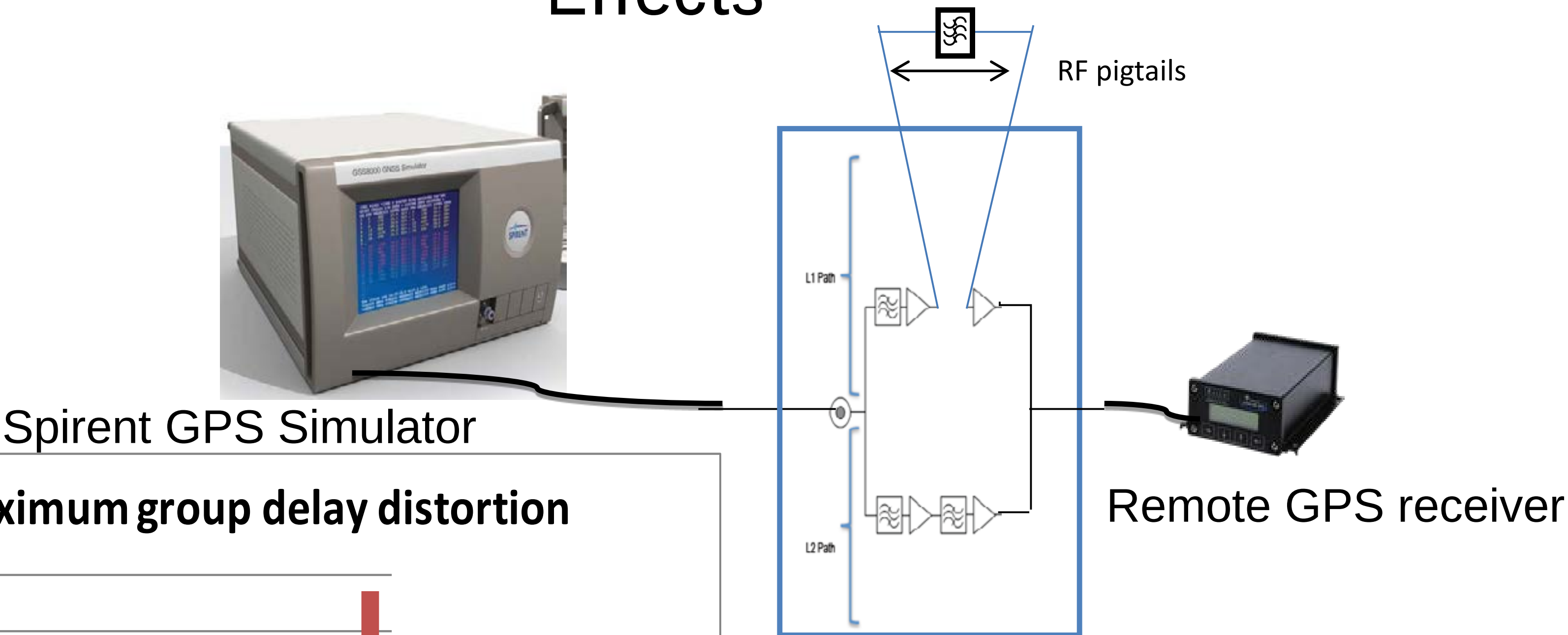
L1C Standard Deviation of time error at C/No=44 dB_Hz 10000 Monte Carlo trials

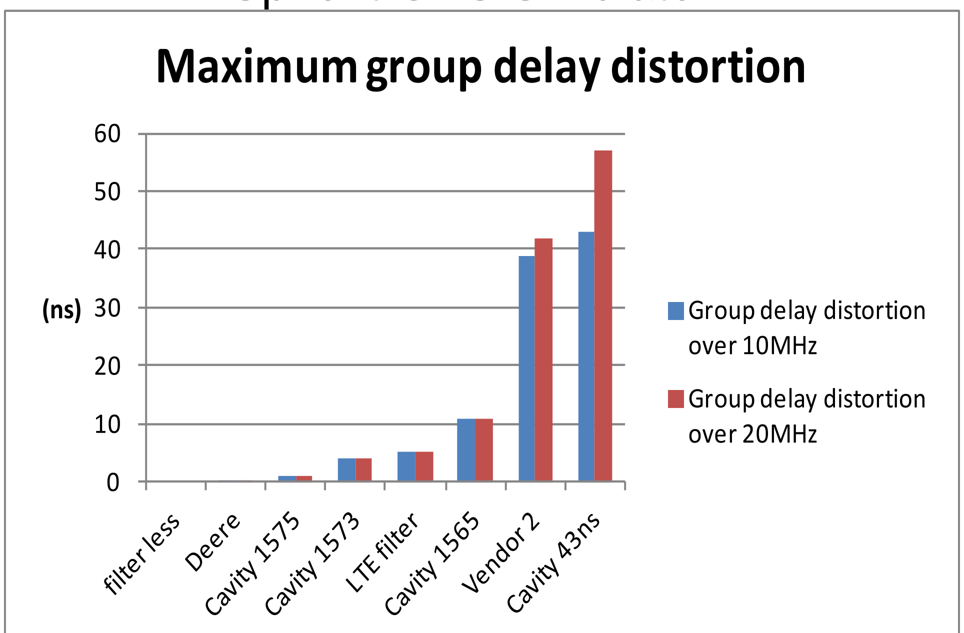
	No filter	.1dB TCh_5p_16MHz ssb	2X .1dB TCh_5p	FIR eq 3dB
Time error (ns)	8.39	8.96	10.33	8.37

-128dBm from satellite provides about C/No = 44dB-Hz

- Filters will affect optimum sample correlation at ideal sample (<2.5ns)
- Increasing error allowance to 12.5 ns shows minimum impact
- Time domain detection like tracking loops may be better than single correlation
- This does not directly relate to RTK phase tracking
- Filters can provide protection to Big LEO MSS for most applications requiring moderate accuracy at least from single correlation
- **RMS time error virtually unchanged with all filter combinations**

Precision Receiver Testing Front End Filtering Effects



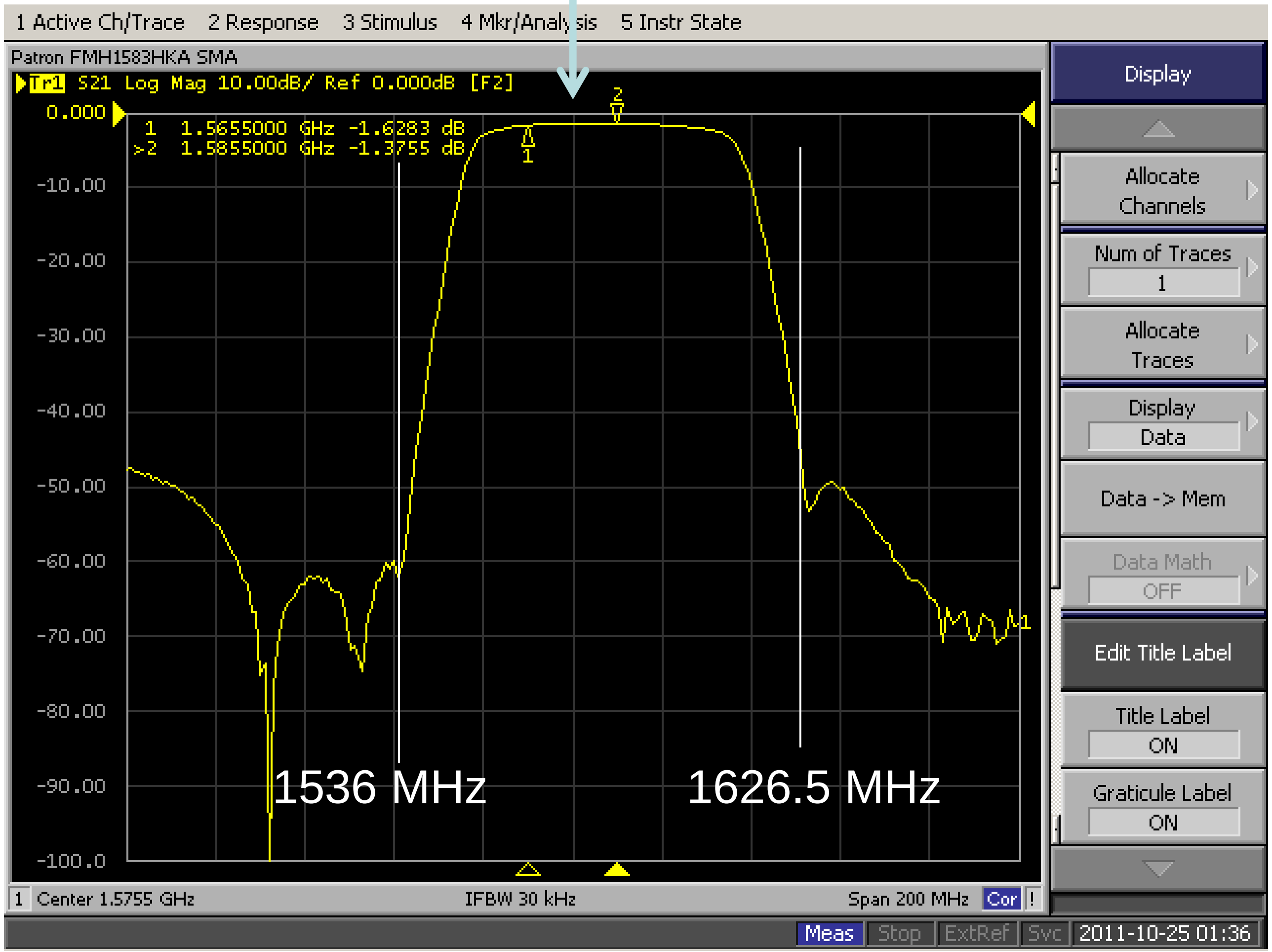


- Filters cabled in between active stages, i.e. LNA's, for testing

Cavity Surrogate Front End filter

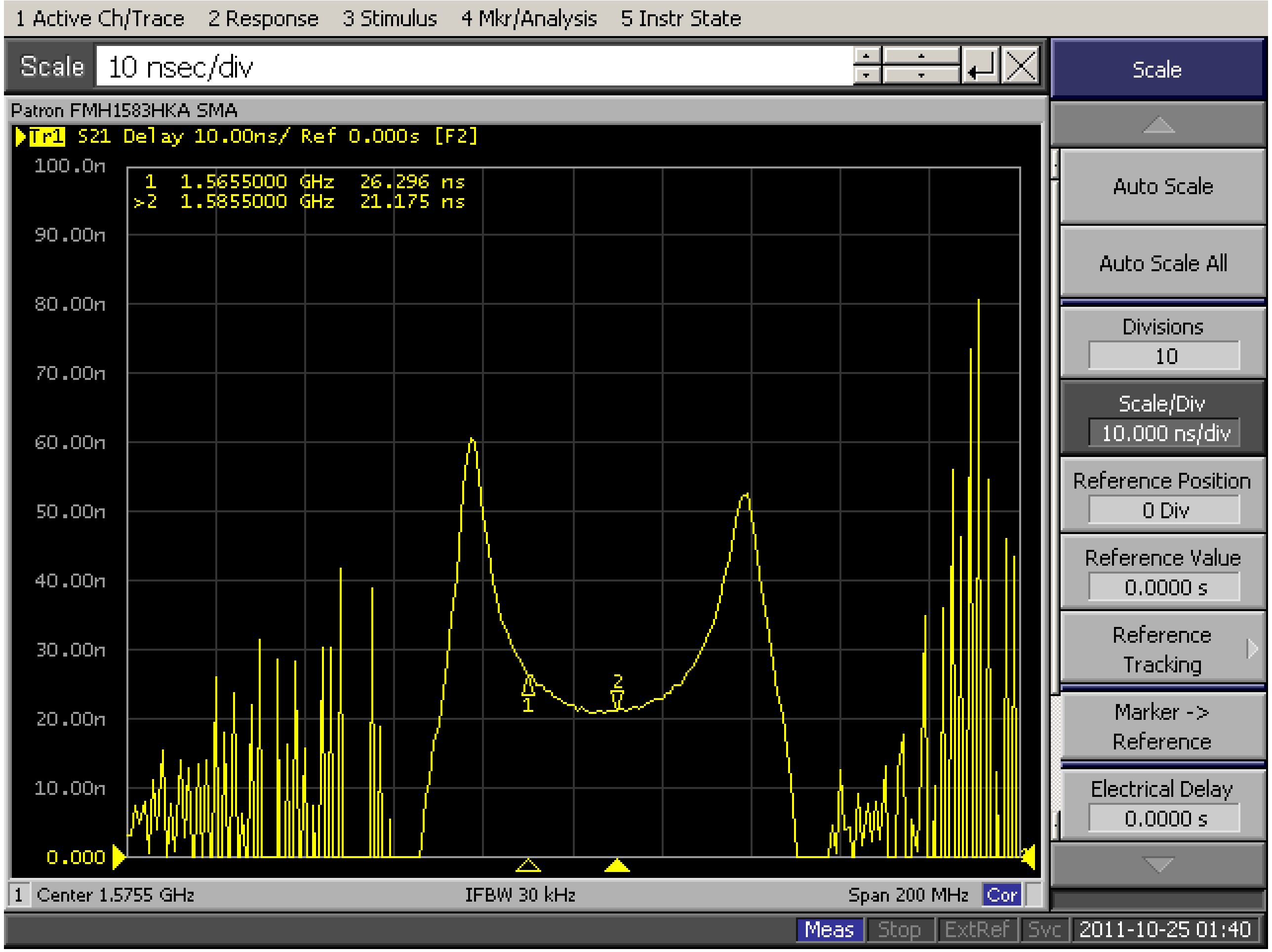
1575.5MHz

BW>50MHz



Filter group delay distortion

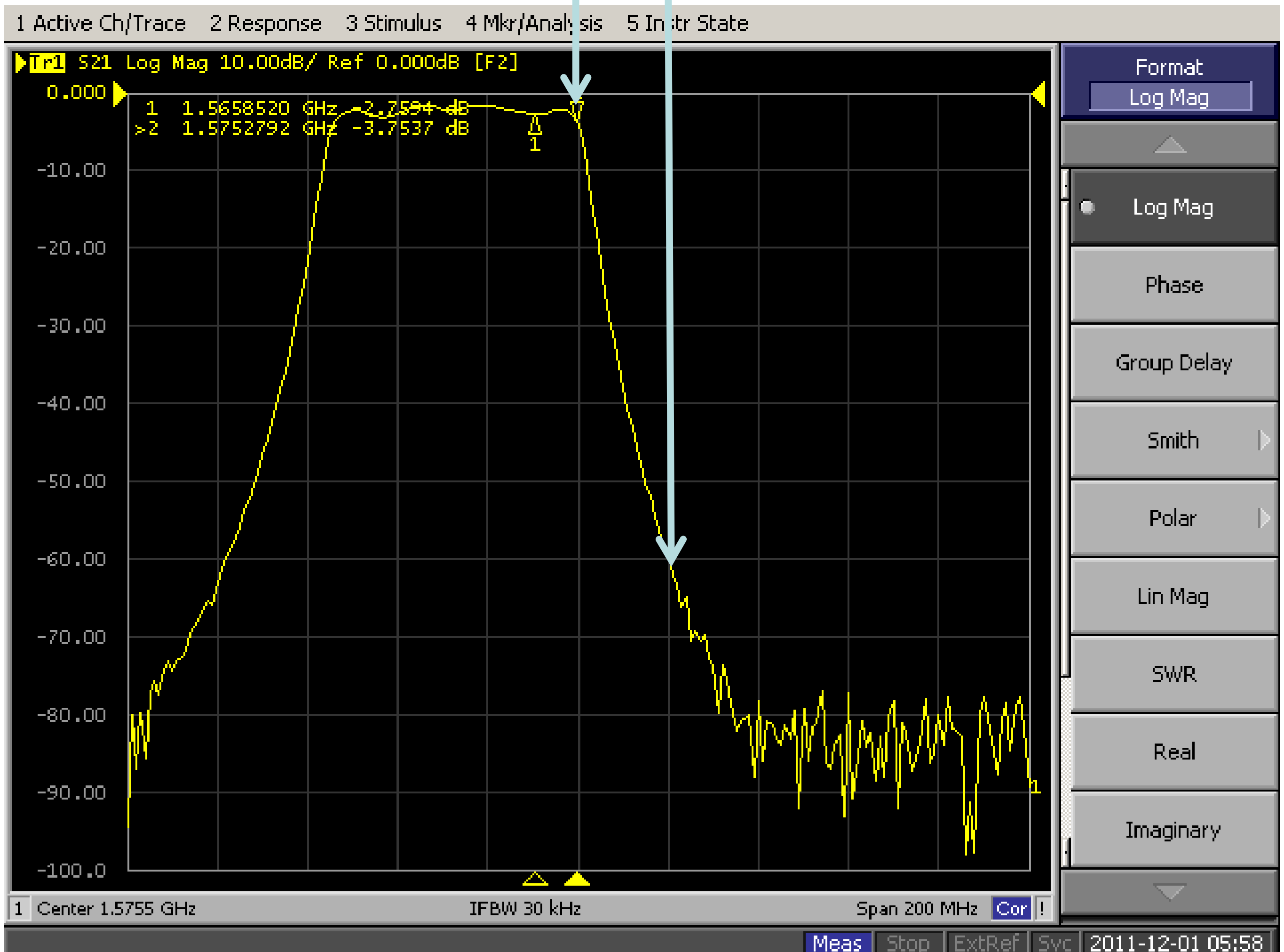
Group delay
Distortion
=5.1ns over 1565 to 1585 MHz



Cavity Retuned An Extreme 25 MHz Lower

1575.5MHz

1595.5MHz



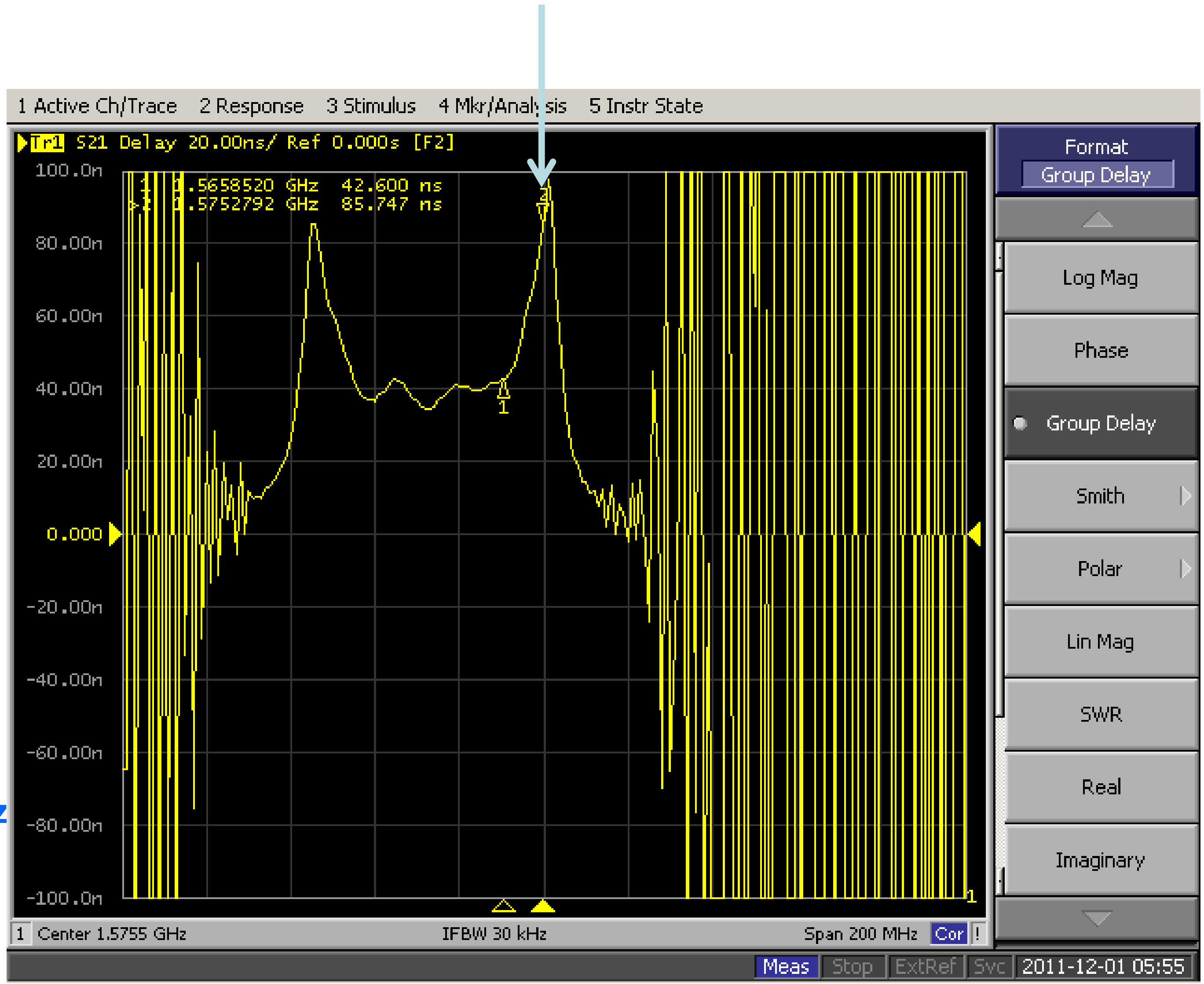
Cavity Retuned An Extreme 25 MHz lower

1575.5 MHz

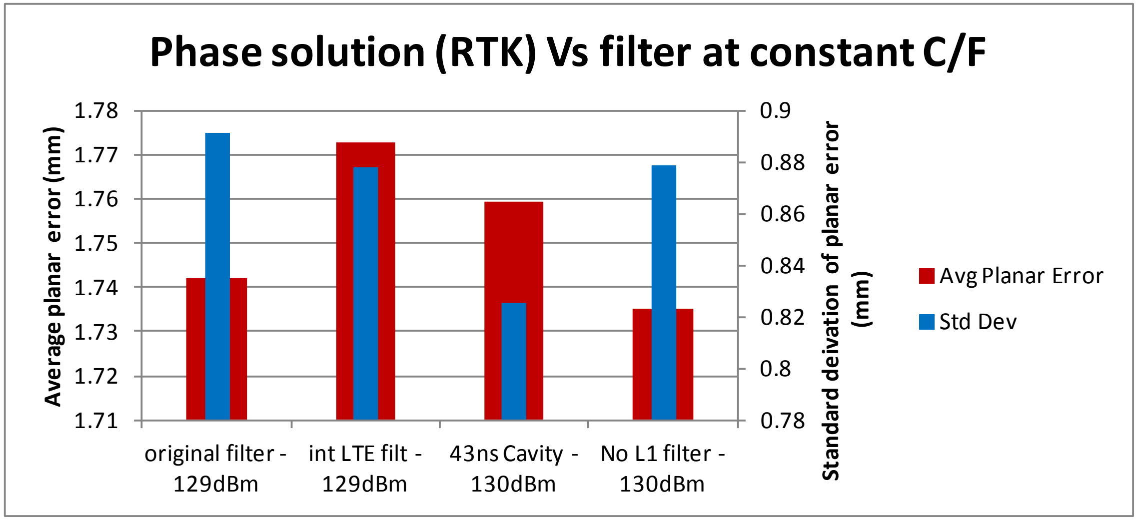
Group delay distortion 1565.5 to 1575.5
=85.75-42.6
=43.1ns

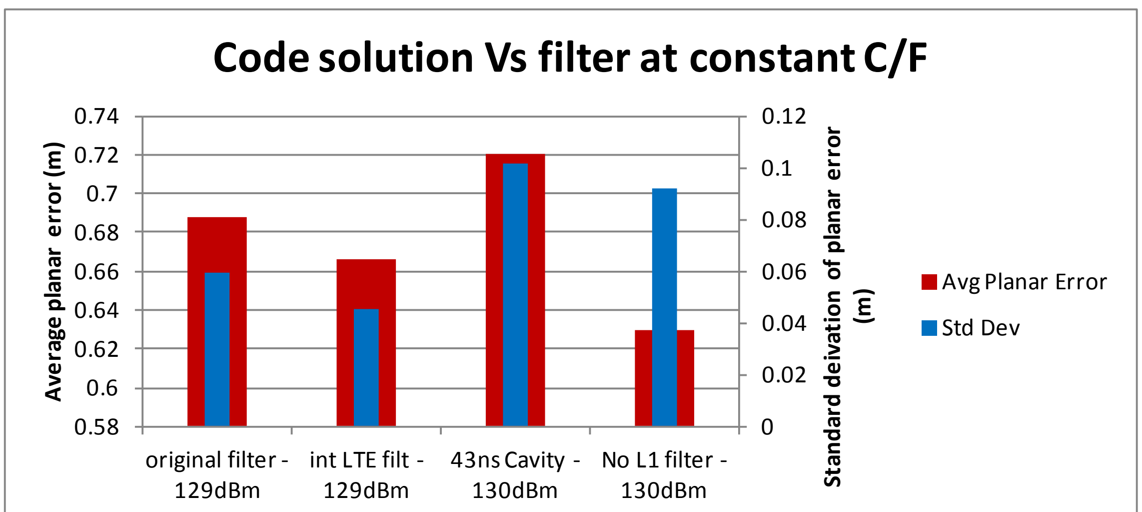
Group delay distortion 1565.5 to 1585.5
=99-42.6
=56.4ns

Seems linear over + / - MHz



Tests with Same Constellation





- Same constellation temporal geometry ,we rewind the constellation
- GPS satellite powers set to provide same C/No as determined by receiver measured noise figure F
- No significant impact for either code or phase solutions
- 43ns Cavity may have slight increase in error statistics for ***Code*** solution

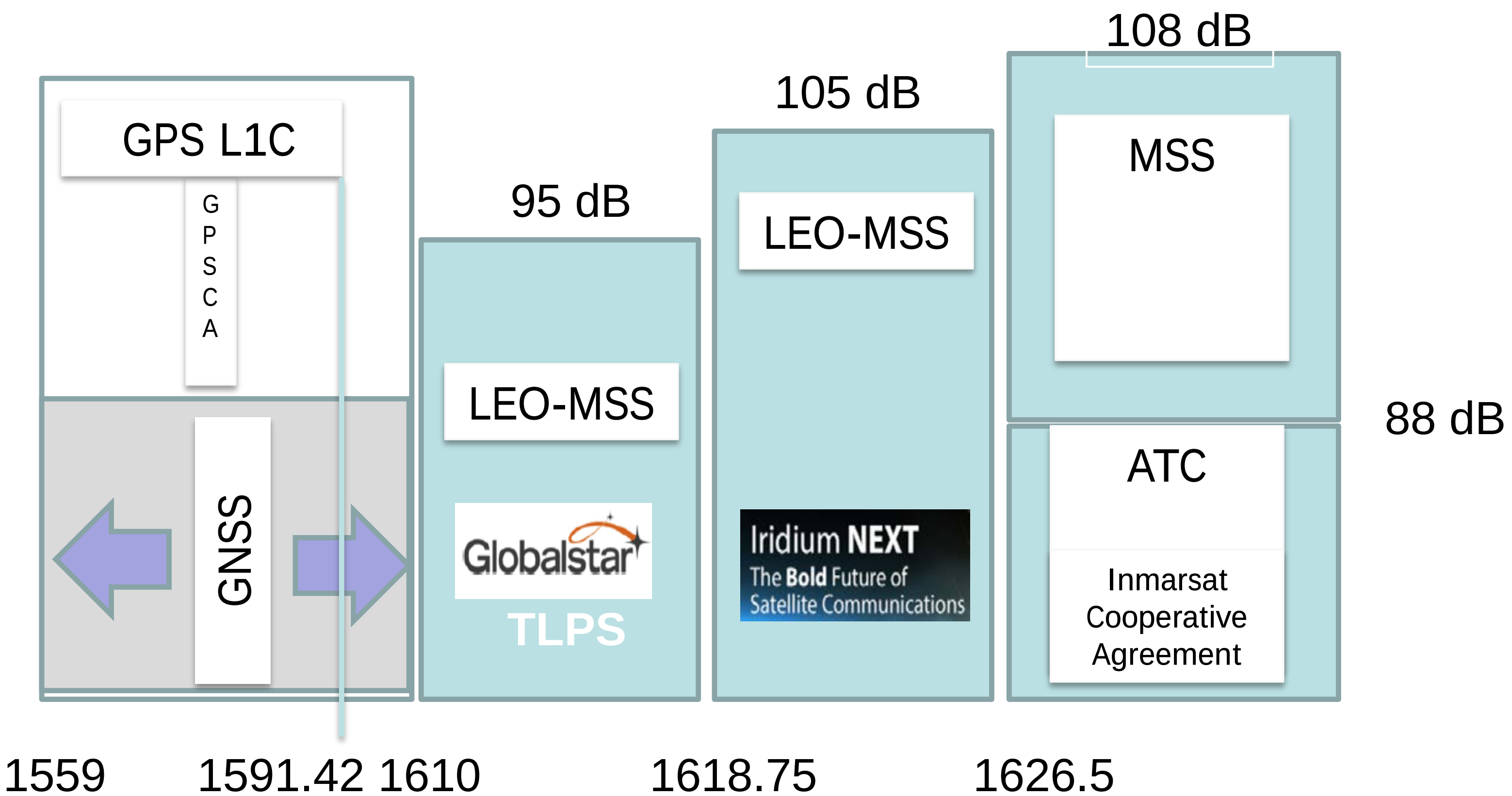
C /CA code Conclusions

- Filters
  - All filters round correlation peaks and affect absolute minimum ***time resolution*** for single 1ms correlation even with zero group delay distortion
  - Zero group delay distortion (symmetrical FIR) have symmetrical correlation response and provide enhanced time resolution at the finest resolution
  - At resolutions of 12ns even narrow filters do not affect performance for C/A code even with very high group delay distortion and non linear group delay
  - Averaging techniques can improve performance
    - RMS time error is the same for all filters analyzed at 44dB C/No at 1ms
    - Discriminator detection can be used in PLL as averager
- Precision
  - High Group delay distortion associated with narrow filters has minimum impact to code and RTK systems.
- Blocking
  - No barriers identified that prevent achieving blocking performance calculated for C/A code receivers
  - C code needs more simulation as a bandpass model but linear Grp Delay <2ns likely needed over +/-1 MHz. Bssb=16MHz should be fine if centered at GPS
- Recommendation
  - Invite all manufactures to explore filter impacts further

Thank you

Supplemental

Total Filter Requirements Vs Interferer

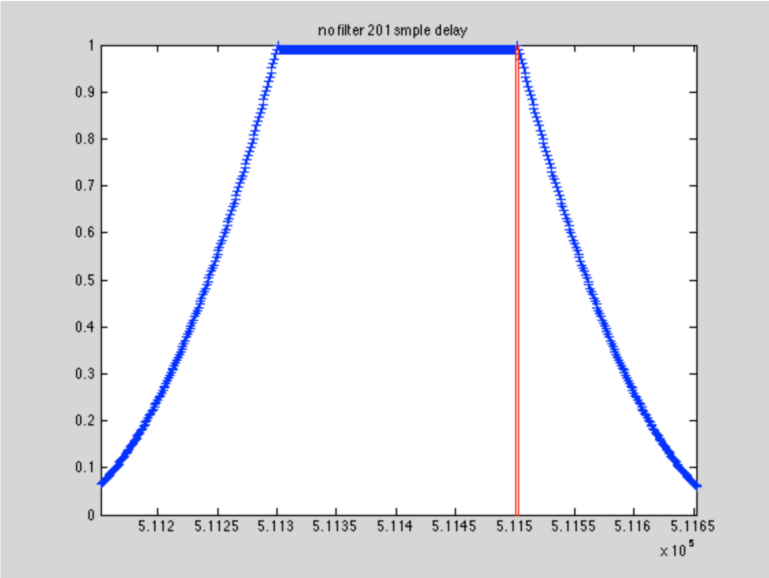


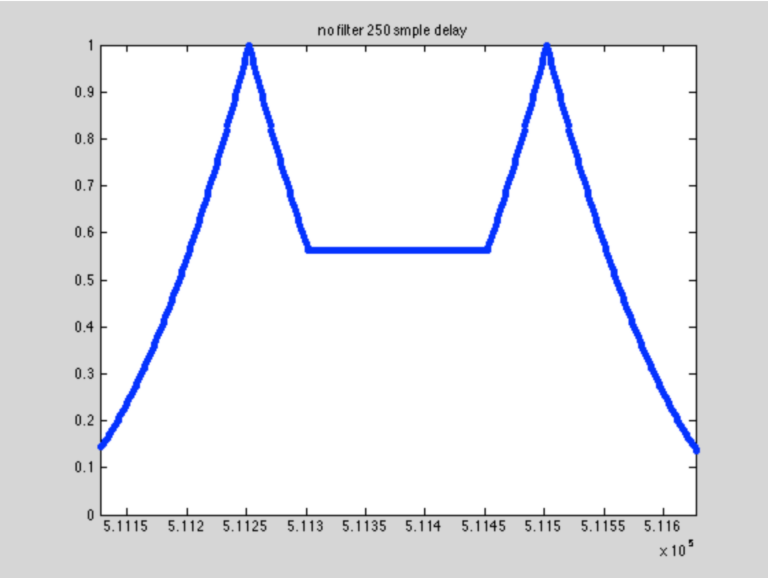
CA Multipath Delayed Ray Detection No filter-Single Correlation result

Sample time 4.88 ns

Second ray delayed 201 samples
201/200 chips

Second ray delayed 250 samples
1.25 chips

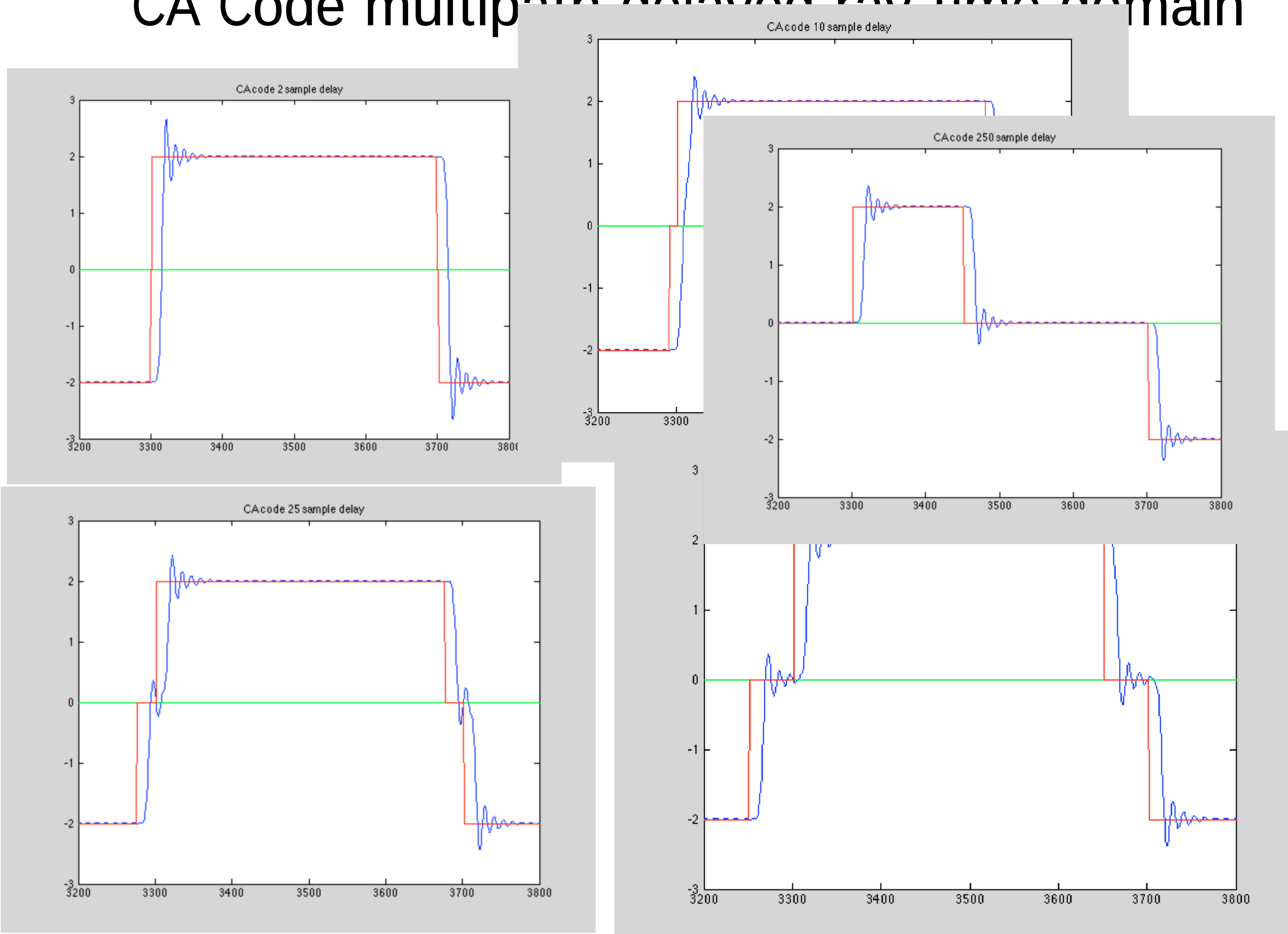




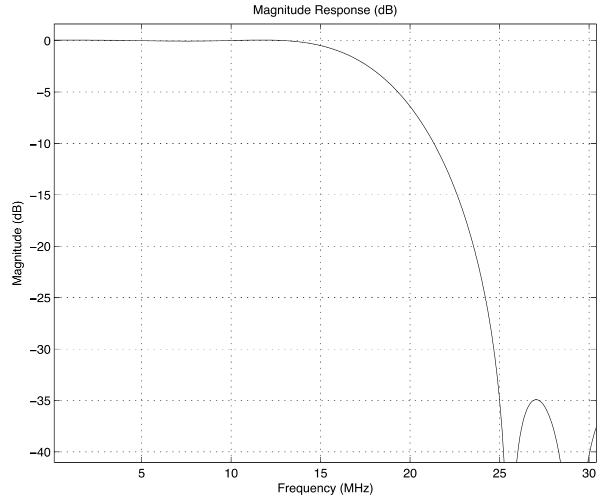
What is the significance?

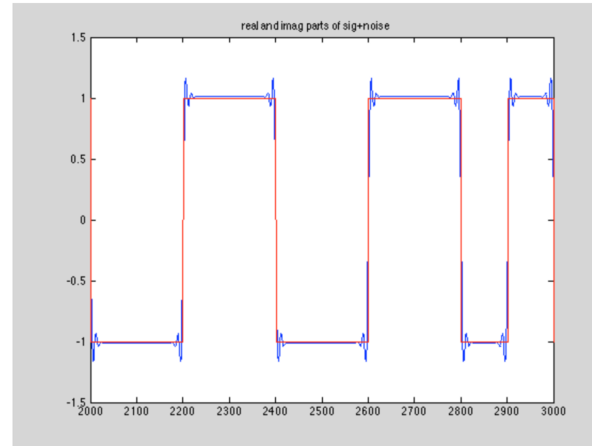
- No matter what the RF/IF BW is multipath cannot be distinguished less than 1 chip

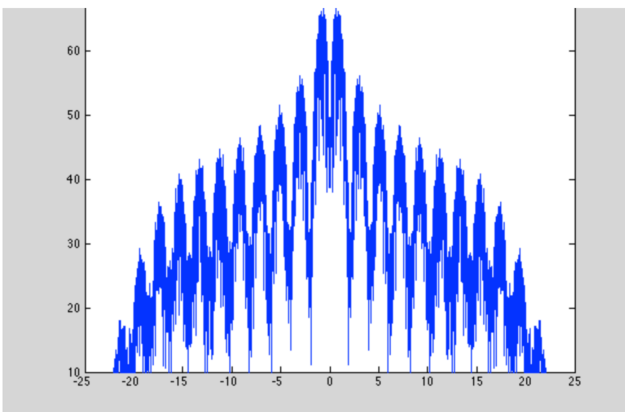
CA Code multipath delayed ray time domain

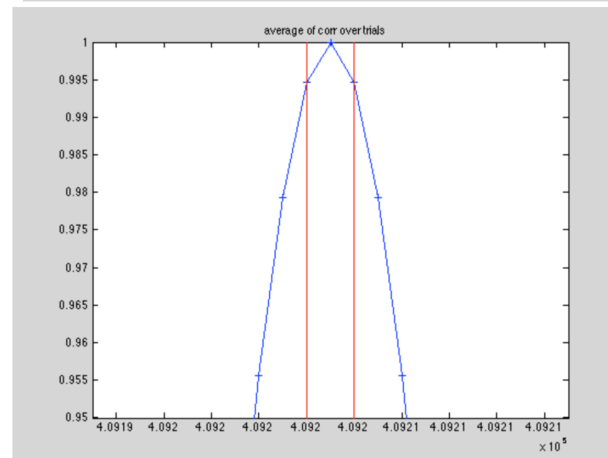


FIR Equivalent Tcheb .1dB TCH 3dB Bssb=18 MHz



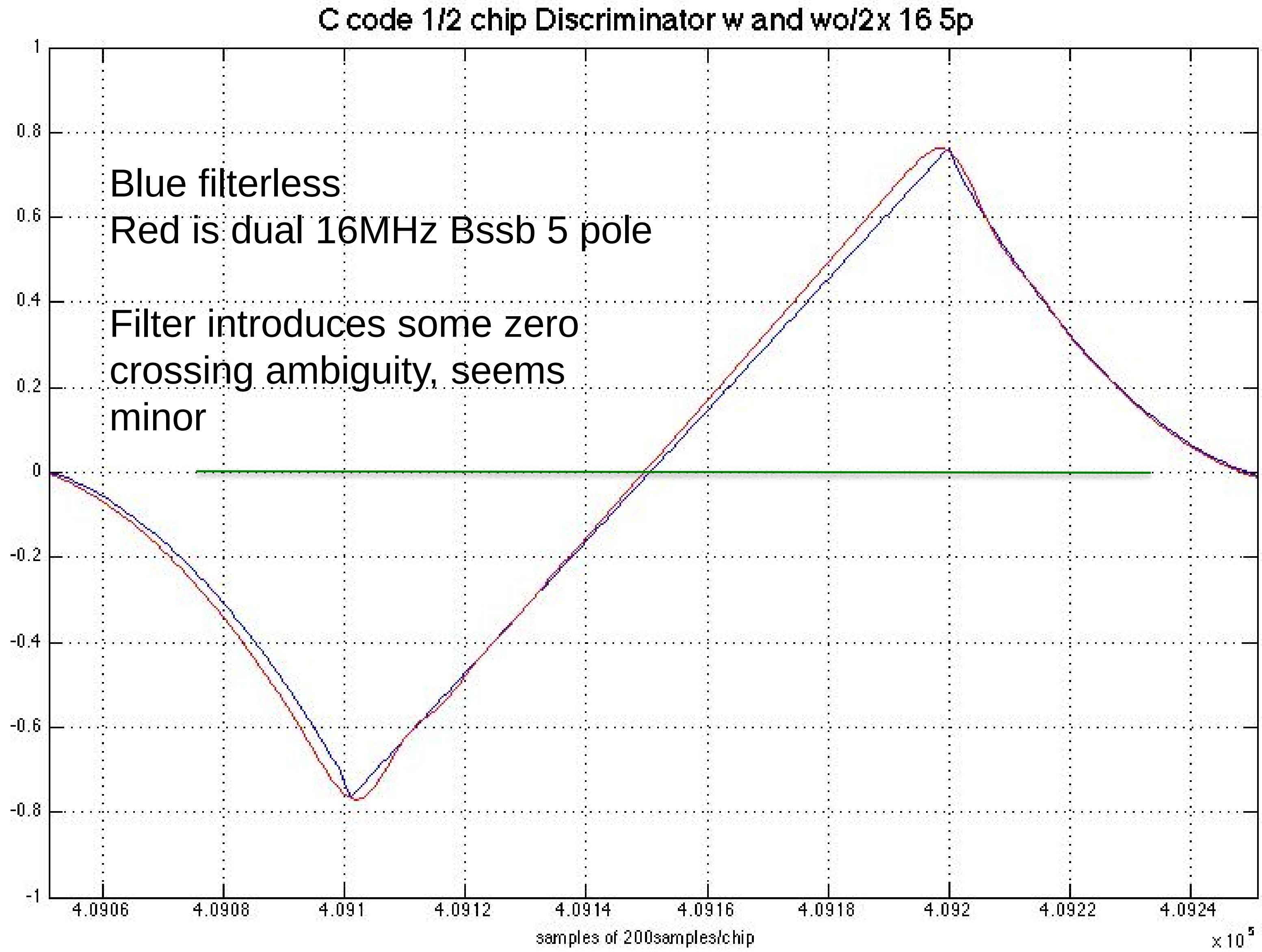






Zero group delay distortion FIR filter has clear peak but is also perfectly synchronous with sample clock since delay is discrete sample time. May exaggerate performance at very low time error criteria

L1 C code ½ chip discriminator



CA Sensitivity Vs Filter (1ms CI)

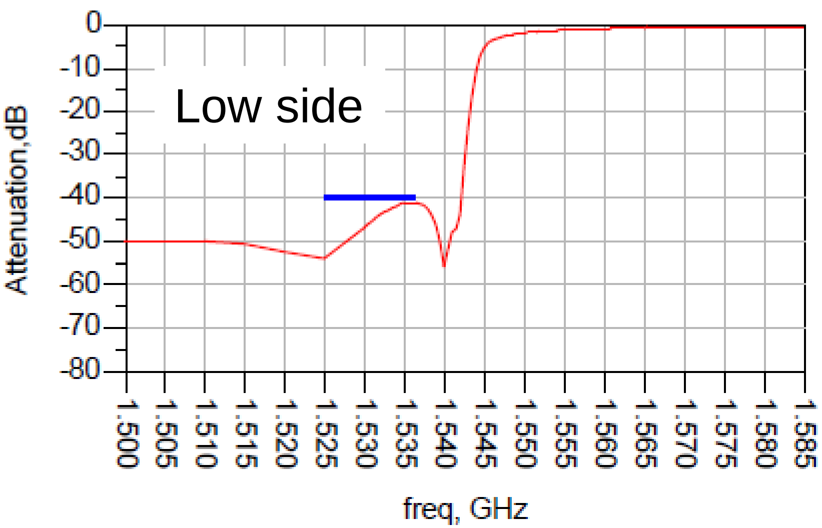
- Typical sample rate for CA code is 4 samples per chip, this implies 244ns sample to sample time
- All filters tested showed virtually the same probability of detection at for +/- 122ns

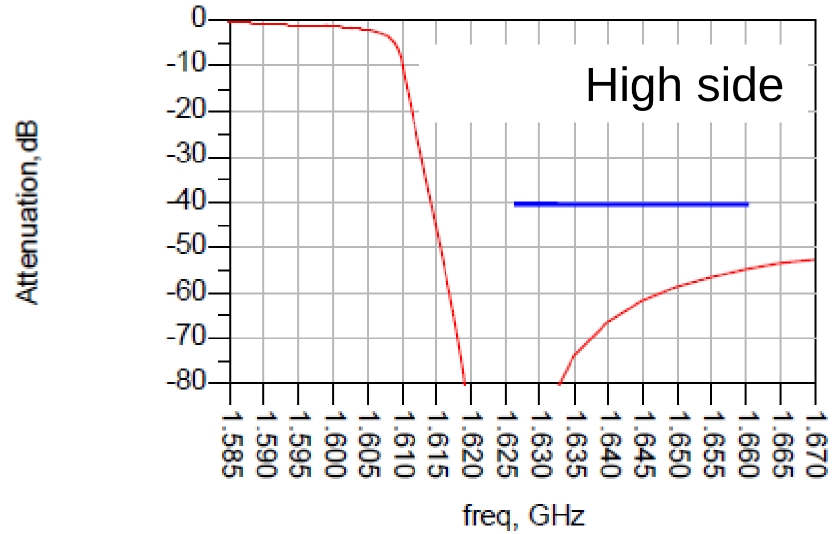
	L1 CA code Probability of Time error +/- 122ns			
C/No (dB-Hz)	**no filt**	**16Bssb_4P**	**1Bssb_4P**	**2Bssb_4P**
41.75	0.95	0.942	0.932	0.941
42	0.955	0.96	0.951	0.969

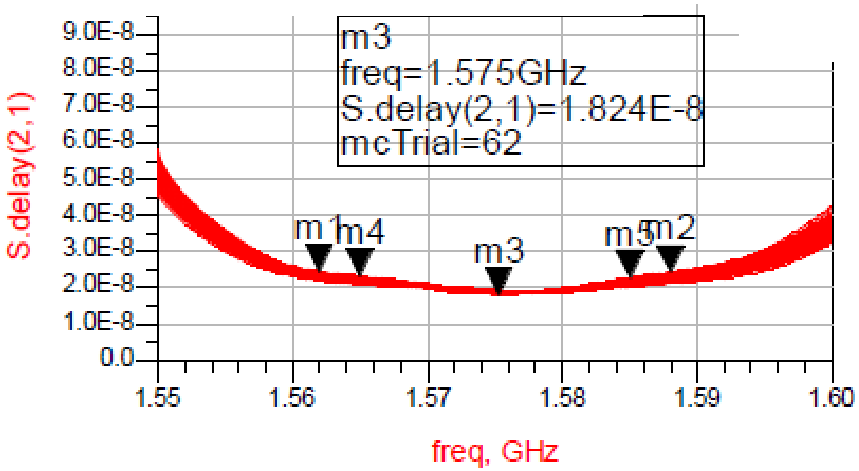
- Little difference between filters
- Narrow Filters can provide protection to Big LEO MSS for most applications requiring moderate accuracy at least from single correlation

Sensitivity defined as Probability for detection to time error =0.95over 50μsec search window

Avago FBAR GNSS filter







- Group delay distortion over 16MHz about 8 ns

Max. group delay variation at Room Temperature incl. production variation ~5ns
Max. group delay variation incl. Temperature and production variation ~7ns