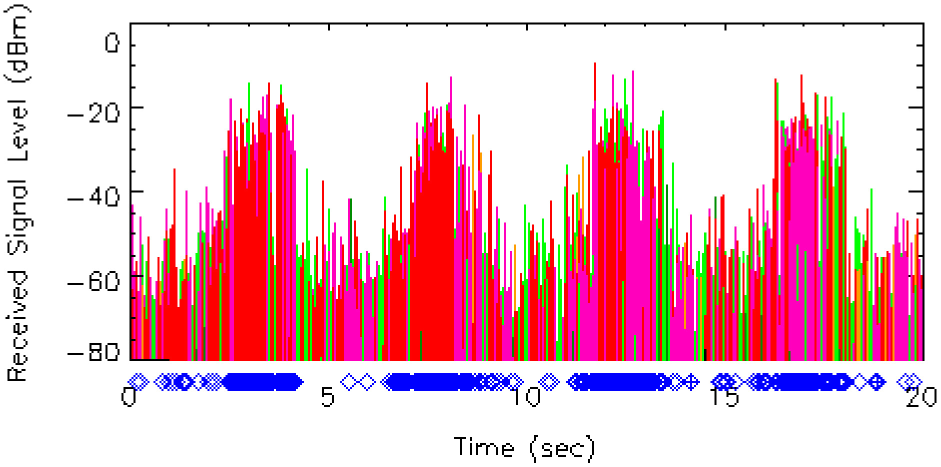
TASC TECHNICAL REPORT TR-9454-02-01

THE 1030/1090 MHZ INTERFERENCE SIMULATOR TECHNICAL DESCRIPTION AND INITIAL RESULTS



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ES. EXECUTIVE SUMMARY

ES-1. BACKGROUND

Several interoperable beacon-based aeronautical surveillance systems presently use the frequency bands at 1030 MHz and 1090 MHz:

- Military Identification Friend or Foe (IFF)
- Civil Air Traffic Control Radar Beacon System (ATCRBS)
- Civil ATCRBS Mode S (discrete-addressed)
- Terminal-Area Collision Avoidance System (TCAS)

Several new systems based on the communications capabilities of Mode S are presently under development, and will also operate in these bands. These will provide uplink data transmission to enhance pilots' situational awareness, and downlink transmission of position and status information, under the Automatic Dependent Surveillance-Broadcast (ADS-B) concept. Multilateration-based systems for airport surface surveillance are also being developed for use in these bands, and are currently undergoing evaluation.

These closely-related systems share common frequencies to allow them to interoperate, and so must rely on means other than frequency separation to avoid interference in situations where multiple aircraft and ground sites operate in proximity. All employ very short transmissions and low duty factors to minimize the probability that multiple signals arrive simultaneously at receivers and interfere, and redundant transmission to tolerate instances where they do.

Current interference levels in the bands are tolerable, indeed significantly lower than they were in the 1960s and 1970s, before the operation of all the systems was as effectively coordinated as it is today. However, with increasing air traffic and the proposed new services, interference levels will increase.

The FAA is concerned that an untenable situation will result, and so has a strong interest in quantifying the interference effects of the new services in future high-density situations before those situations actually arise. Several recent and ongoing modeling and simulation efforts have addressed this issue, but were limited in the ability to explore the many situations and cases involved in a timely and economical manner. Accordingly, the FAA Office of Spectrum Policy and Management (FAA/ASR) asked the Volpe National Transportation Systems Center in March 1999 to develop a modern graphically-intensive object-oriented means of beacon-band interference simulation. This simulation can be used in a closed-loop manner to investigate interference mechanisms. With it, answers to "what if?" questions can be obtained rapidly and efficiently, and alternative means of controlling and correcting them can be readily explored.

The 1030/1090 MHz Interference Simulator has been under development since March 1999, and currently replicates the interference production and operation of the existing surveillance systems and several proposed new Mode S applications. Efforts are ongoing to add new features and extend Simulator capabilities in additional directions.

This report describes the Simulator structure, procedures for its use, and details of its key features. The Simulator has been used already to explore several current interference issues, and the results of those analyses are also included.

ES-2. SIMULATOR STRUCTURE

The Simulator has three principal components:

- A ***scenario development tool***, on which scenarios involving multiple aircraft and interrogators are laid out geographically, and the parameters and characteristics of these components are selected and adjusted.
- A ***runtime infrastructure***, on which simulation of all interrogations and replies generated in the scenario is managed and executed.
- A ***display tool*** which presents executed results to the analyst, who can examine them in depth and collect a variety of pertinent statistical information.

The ***scenario development tool*** permits the analyst to construct a complicated scenario from a variety of system components. Currently available components (individual "objects" in the object-oriented Simulator infrastructure) include ATCRBS and Mode S transponders in aircraft, ATCRBS and Mode S ground-based interrogators, the airborne TCAS interrogator, and a "victim" receiver, at which the interference is measured. Several additional objects can be used to explore new concepts, including ground-based surface surveillance interrogators and modified ATCRBS transponders that output multipath-corrupted replies, and ADS-B squitter. The analyst can display a plan view of the location around the victim receiver, populate it graphically with these objects, and adjust the parameters of each of them.

When the scenario is complete, the analyst executes it in the ***runtime infrastructure*** for a selected time period, and generates output products. The principal product is a display of the video timeline that the victim receiver would see, accompanied by a wide variety of summary statistics. The analyst can interact with this information using the ***display tool*** to expand the timeline for detailed examination, or to elicit supporting information. A printout of selected data can also be obtained, or a computer file of the interference timeline can be generated for input to simulated receivers.

Instances of particular interference mechanisms can be examined in detail to determine their specific characteristics, and various criteria can be applied to evaluate receiver performance in the interference environment. Different types of replies are color-coded in the video timeline, and the analyst can readily determine which aircraft produced each reply, and to which radar the reply was made. The uplink (interrogation) environment seen by a selected aircraft can also be examined graphically.

ES-3. KEY CHARACTERISTICS

The Simulator executes the chosen scenario in time-sequence, in 1-ms steps. During each interval the timing of each interrogation or reply generated or received is calculated to sub-microsecond accuracy, and its power level is determined using freespace pathloss propagation characteristics and diffraction-based terrain loss calculations. (The Simulator employs a terrain elevation database to determine which aircraft are fully or partially blocked from the view of each of its radars.) Variability in power level is introduced using (optional) antenna models that incorporate random fading due to multipath and obstruction. Pertinent RF link parameters (power, sensitivity, the nature of the fading) can be adjusted individually for each aircraft and interrogator.

The Simulator models the full functionality of present and future Mode S transponders to generate squitter (unelicited information-containing replies). Several types of squitter can be produced: current TCAS ID squitter and the several new types being developed for ADS-B and defined in the most recent version of the draft ADS-B MOPS [1]. ADS-B reporting functions can also be associated with ATCRBS-equipped aircraft.

Mode S interrogator scheduling is modeled in detail, consistent with the particular Site ID selected. A variety of interrogation sequences can be selected to simulate various modes of operation (e.g., the Terra fix), and parameters can be modified to emulate specially-tailored sites (e.g., extended-range). ATCRBS interrogator modeling incorporates all of the types of interrogation stagger currently in use.

The interrogation sequences generated by TCAS with version 7 software are incorporated into the model. Prior to execution, the model calculates the environments surrounding the individual TCAS interrogators in the scenario and adjusts the interrogation sequence and power level of each accordingly, consistent with the full interference-limiting methodology incorporated into Version 7.

ES-4. CALIBRATION AND VALIDATION

Accurate replication of future interference situations by the Simulator requires its careful and ongoing calibration, and refinement of its operation whenever new data pertinent to the interference situation in the actual system is obtained. Calibration involves adjustment of system parameters to produce individual component performance in accordance with applicable MOPS and other documentation, in idealized hypothetical situations. Several such scenarios were employed in initial calibration.

Only limited data on actual system interference levels is available with sufficient detail to simulate the actual situation in which the interference was measured. The best recent source of such data is the experimental effort that was conducted by MIT Lincoln Laboratory and others in June 1999 in the Los Angeles Basin. That effort was focused on ADS-B performance, but also included airborne measurements of the incidence of several types of asynchronous interference (fruit). Enough information was obtained to replicate the aircraft population at the time of measurement in the Simulator.

The Simulator produced fruit rates consistent with what was actually measured:

- ATCRBS fruit rates were within ten percent of those measured, throughout the range of power levels greater than –80 dBm. At the two levels of most interest, -74 dBm and -79 dBm, cumulative fruit rates were within two percent of mean measured values. At greater sensitivities, measured and simulated rates diverged because the model did not include distant aircraft. (The Simulator scenario included only those aircraft that were visible to the ground-based interrogator that was directly under the instrumented aircraft on which fruit rates were measured.)
- Mode S ground interrogator fruit was within twenty-four percent of the measured value, consistent with uncertainties about how the ground sites were operating.
- ATCRBS interrogation rate was within ten percent of the measured value.
- The amount of Mode S fruit elicited by TCAS was significantly lower than measured. This was in part due to the Simulator's use of Version 7 interference limiting, which most aircraft did not use at the time the measurement was made. In addition, Lincoln Laboratory found several indicators in the measured data that components of the actual system were not operating properly.
- The amount of TCAS ID squitter was also significantly lower than measured. This type of squitter should be generated at a rate of one squitter per aircraft per second. The rate actually measured was six times higher. Again, Lincoln Laboratory believes that this is due to problems in actual system operation.

While the quality and quantity of available measured data fell short of what would be necessary to fully validate the Simulator, this validation effort underscored an important potential Simulator application: highlighting problems in actual system operation.

ES-5. INITIAL SIMULATOR APPLICATIONS

At the time of this report, the Simulator has been used to address several issues of interest to the FAA, and is currently being employed in the analysis of several others. It was first applied to the question of whether the additional squitters generated by ADS-B equipped aircraft will contribute noticeable interference to ground-based radars.

ES-5.1 Airborne ADS-B Squitter Interference to Radars

A scenario containing 743 airborne aircraft was used to address this issue. Of those, 186 were Mode S equipped, generating ADS-B extended squitter at a net rate of 6.2 per second each. The 52 interrogators within 200 nm of LAX were also included. This particular scenario was developed originally by MITRE and JSC and has been in use for over a decade in the evaluation of this and other related issues.

The ATCRBS fruit rate resulting from this scenario was 1552.4/sec, primarily received through the mainbeam. The number of elicited replies from the 743 aircraft averaged 834 per second, of which 286.7 were overlapped by other replies (primarily synchronous garble). 6.6 replies per second were overlapped by ADS-B squitter. Of those, 3.4 had relative levels and overlap durations resulting in their loss. Thus, the Simulator showed a reduction in reply probability of 0.4% resulting from the ADS-B squitter, a negligible amount relative to the high degree of synchronous garble present in this high-density scenario. A smaller scenario with 474 aircraft, 112 of which were squittering, produced a reply probability reduction of 0.27%.

ES-5.2 Surface ADS-B Squitter Interference to Radars

A different mode of ADS-B extended squitter with slightly lower transmission rates is being considered for surface surveillance at large airports. To determine its interference effects, an additional 200 aircraft squittering in this mode were placed on the LAX surface, and instances of their squitter overlapping replies from airborne aircraft were tabulated. (For this analysis, airborne ADS-B squitter was suppressed.) It was found that 200 surface aircraft reduced the reply probability for airborne aircraft by 3%. Other scenarios with fewer airborne and ground aircraft were also examined, and the reply probability reduction was seen to be directly proportional to the number of surface squittering aircraft, and independent of the number of airborne aircraft.

At airports with large amounts of general aviation traffic, the surface surveillance process will also entail interrogation of ATCRBS transponders, and multilateration calculations on the resulting Mode A replies. That situation was analyzed by changing the equipage of the 200 aircraft to ATCRBS, and placing six special-purpose ground interrogation sites around the airport periphery. It was found that the additional fruit due to this process was negligible, but that because the aircraft on the airport surface had active ATCRBS transponders, interrogation of these (primarily by nearby airborne TCAS-equipped aircraft) increased the amount of fruit seen by the ASR by 776%, from 965 to 7488/sec.

This amount of fruit is still well below the level at which its effects degrade system performance; it reduced reply probability by only 1.8%. The high fruit resulted from the combination of two extreme worst-case assumptions in the scenario: Many ATCRBS transponders active in surface aircraft, and many nearby airborne TCAS interrogators. These two situations would only occur together in the case of a large general-aviation airport located directly under the approach path of a large commercial airport.

ES-5.3 ADS-B Extended Squitter Surveillance Performance

The 474 and 743 aircraft scenarios were also used to measure the interference effects on ADS-B extended squitter reception. A ground-based six-sector ADS-B receiving site near LAX lost between 20% and 36% of the extended squitter replies it received when pointing east, and between 22% and 50% when pointing 60 degrees south of east, the direction of the maximum traffic concentration. Lost replies were randomly distributed in time, and of course occurred with higher incidence in weaker targets.

These gross statistics are of secondary importance in this application. What is of concern is the distribution of lost squitter replies from individual aircraft, especially the maximum duration of outage sequences. Even in the worst cases examined, interference effects did not produce outage runs of more than a second or two. In actuality, longer outages will result from the combination of interference and prolonged fading due to antenna gain degradation. (Other organizations are analyzing these effects in the work described in paragraph ES5-5, below.)

ES-5.4 ATCRBS Fruit Arrival Statistics

In previous analyses, the arrival of asynchronous replies (fruit) at a victim receiver has been modeled as a Poisson process, with the timing of each individual fruit reply independent from the others. That was not found to be the case with the fruit produced by the Simulator. Rather, far greater numbers of fruit-free intervals were noted than Poisson statistics predict. Additionally, very large numbers of fruit (over sixty in some instances) were noted to arrive coincidentally in some cases. This behavior is favorable to extended squitter ADS-B operation, resulting in an extended squitter detection rate in high-density cases more than twice what is predicted using Poisson statistics.

To determine the mechanism leading to this surprising result, several instances of coincidental arrival of large numbers of fruit replies were examined. It was found that often an interrogation from a single radar would elicit replies from many aircraft simultaneously within its mainbeam. In cases where the aircraft lay close to the line between the eliciting radar and the victim radar, these replies were received almost simultaneously. Because so many fruit replies exhibited this very high degree of bunching, many more empty intervals occurred.

ES-5.5 Support of TLAT

The Technical Link Assessment Team (TLAT) was established by RTCA to assess the relative merits of three proposed ADS-B data link alternatives, one of which is Mode S extended squitter. As part of that effort the TLAT developed several futuristic LA Basin and European scenarios, containing large numbers of aircraft operating over wide areas (e.g., 2694 aircraft within 400 nm of LAX). The Simulator was used to model these situations and generate the interference they would produce, as seen by representative aircraft receiving ADS-B transmissions from other aircraft. Interference, in the form of a data file, was transferred to personnel at the Applied Physics Laboratory of Johns Hopkins University, who then applied it to their simulation of the new extended squitter receiver developed by Lincoln Laboratory. Their simulation also accounted for motion of the originating and victim aircraft, and the temporal effects of antenna pattern variations on the received signal level. The TLAT effort is still underway and results will be reported by the TLAT upon its completion.

ES-6. CONCLUSIONS

The Simulator is a valuable tool for examining and understanding future interference problems in the beacon radar bands. Its value will increase as additional objects are developed, and as new opportunities arise to calibrate it more accurately.

In its first year of existence, it has already been used to investigate several potential beacon interference issues:

- It confirmed that the amount of additional interference to existing radars resulting from widespread use of ADS-B position reporting in a future high-density traffic situation would be negligible.
- It established that use of Mode S and ATCRBS multilateration techniques for airport surface surveillance caused greater amounts of asynchronous interference, but that these were still well below problematic levels. Most of the additional interference resulted from the requirement to operate ATCRBS transponders on the airport surface, which made them susceptible to other (mainly TCAS) interrogations.
- It established that worst-case interference to ADS-B extended squitter air-ground transmissions, while as high as 50%, was nonetheless low enough to allow acceptable operational performance, since interference events were uncorrelated. We noted that correlated reductions in received signal level (as caused, for example, by antenna fading) would be far more problematic, and recommended detailed examination of this mechanism.
- It found that fruit arrival statistics in high-density situations with wide-beam fixed receiving antennas depart significantly from Poisson: the incidence of very large numbers of simultaneous fruit overlaps was far higher than what Poisson statistics predict, and conversely, there are far more instances of non-overlapped replies. These effects occur when large numbers of aircraft are simultaneously present in the mainbeam of a radar that is causing fruit, and are related to high levels of synchronous garbling.
- It produced files of interference events, used to generate accurate interference timelines. These were useful in measuring the performance of actual receivers.

The Simulator can provide far more than gross statistics to characterize an interference situation. Its capabilities to investigate the details of the interference-producing mechanisms can also shed light on some of the fundamental workings and interactions of the many complex systems that share the 1030 and 1090 MHz bands. It will be of value in understanding and analyzing many problems that are likely to arise in these bands as they become more crowded, and contain more new systems and services.

1. INTRODUCTION

1.1 BACKGROUND

The frequency bands at 1030 and 1090 MHz have been used for civil aeronautical radionavigation (surveillance) since shortly after World War II, when the military IFF (Identification Friend or Foe) system operating in them was adopted for civil Air Traffic Control (ATC) use. In the fifty years in which these bands have served that purpose, the number and diversity of ATC-related services operating in them has grown enormously:

- IFF was developed by the US military during World War II as a primary radar overlay, to convey friendly aircraft identity information to radar operators. Since that time, it has evolved through several modes with varying levels of security, and further development is ongoing. IFF employs 1030 MHz for (uplink) interrogation and 1090 MHz for (downlink) response.
- The ATC Radar Beacon System (ATCRBS), the civil aviation variant of IFF, was first used in the 1950s to provide aircraft identity information to controllers. Now used worldwide, it also telemeters pressure altitude information, and is the primary source of aircraft position information for civil ATC. ATCRBS is the ICAO standard air surveillance system, and its modes remain very similar to military IFF modes.
- Mode Select (Mode S) is a variation of ATCRBS in which individual aircraft are uniquely and separately interrogated, to avoid garbling (overlapping interference) of replies from aircraft in close proximity. Mode S signals also contain short data fields that have been proposed for various types of communications. Mode S is also an ICAO standard surveillance means.
- The Traffic Alert and Collision Avoidance System (TCAS) is the ICAO standard air-derived collision-avoidance system, based on the interrogate-response concepts employed in ATCRBS and Mode S. TCAS-equipped aircraft interrogate ATCRBS and Mode S-equipped aircraft to determine their proximity, and communicate using Mode S to coordinate evasive action with one another.
- The communications capability of Mode S has prompted its proponents to propose its use for a wide variety of additional aviation-related services, including GPS-derived position reporting, weather and traffic information data exchange, navigation support information transfer, and command and control.
- ATCRBS and Mode S have also been proposed as the basis for airport surface traffic surveillance concepts employing multilateration.

These closely-related systems share common frequencies to allow them to interoperate, and so must rely on means other than frequency separation to avoid interference in situations where multiple aircraft and ground sites operate in proximity. All employ very short (tens of microseconds) transmissions with inherently low duty factors (generally well below 1%) to minimize the probability that multiple signals arrive simultaneously at receivers and interfere, and redundant transmission to tolerate cases where they do. Several major improvements in the systems over their lifetime have actually significantly decreased interference levels, despite increases in the numbers of aircraft and interrogators, and in the diversity of services provided:

- Improved interrogation sidelobe-suppression techniques have minimized the incidence of improper replies from aircraft close to an interrogator responding to ATCRBS interrogations broadcast through its antenna sidelobes. Such erroneous responses can increase the total amount of interference from close aircraft by almost a factor of 100.
- Improved assignment and control of interrogation rates, and the use of irregular ("staggered") interrogation patterns, has reduced total numbers of interrogations and replies, and randomized the incidence of interference when it occurs. The FAA manages an aggressive program to control and coordinate interrogation rates and patterns of all interrogators, military and civil.
- The introduction of monopulse antenna technology has reduced the need to elicit many replies from each aircraft as the radar antenna scans past it. Prior to this technology, azimuth accuracy was degraded by low numbers of replies. Now, accurate azimuth determination (typically 0.1°) can be made from as few as one or two replies, and the total number required is driven only by detection reliability considerations. Three to four hundred interrogations per second were once transmitted by radars that now transmit 125.

While these advances have reduced the incidence of interference in the beacon bands almost fourfold, increases in numbers of aircraft and interrogators, and the new services now provided in the bands (especially TCAS) have counteracted much of that reduction. The additional new services being proposed for the bands would aggravate the situation. The FAA is concerned that anticipated traffic growth will someday result in an untenable situation, and so has a strong interest in quantifying the effects of the new services in future high-density situations before those situations actually arise.

Several recent and ongoing modeling and simulation efforts have addressed this issue [2,3]. These efforts were limited in their ability to explore the many situations and cases involved in a timely and economical manner. Accordingly, the FAA Office of Spectrum Policy and Management (FAA/ASR) asked the Volpe National Transportation Systems Center and its contractor, TASC, Inc., to develop a modern object-oriented graphically-intensive beacon-band interference simulation. This simulation can be used in a closed-loop approach to the investigation of interference mechanisms. In this approach, answers to "what if?" questions can be obtained rapidly and efficiently, and alternative means of controlling and correcting them can be readily explored.

1.2 SIMULATOR DEVELOPMENT AND STATUS

The 1030/1090 MHz Interference Simulator has been under development since March 1999, and currently replicates the interference production and operation of IFF Modes 1-3, ATCRBS, Mode S, TCAS and several proposed new Mode S applications, in a variety of future scenarios. It recently was upgraded to include a topographical data base, and calculation of losses due to diffraction and obstruction from that terrain information, specified radar elevations, and aircraft altitudes. In a recent application, the Simulator produced an interference timeline, which was used (by the Johns Hopkins University Applied Physics Laboratory) in the evaluation of a new ADS-B receiver which uses knowledge of the characteristics of interfering signals in its processing. It has been successfully employed with scenarios involving as many as 300 radars and 2700 aircraft.

The Simulator was developed on a Silicon Graphics Indigo workstation, using a TASC-developed simulation infrastructure previously developed for military applications, and a commercial display product (PV-Wave [4]). It executes on a Personal Computer, enables efficient scenario construction and editing, and allows detailed analysis of the results.

1.3 REPORT OVERVIEW

This report describes the structure of the simulation and the procedures by which scenarios are built and executed in Section 2. Details of its key features and options are amplified in Section 3. The report also describes efforts made to calibrate and validate the simulation by comparing its results with measured real-world data (Section 4), and several initial results in the investigation of future high-density interference situations (Section 5).

2. SIMULATOR STRUCTURE

The 1030/1090 MHz Interference Simulator is comprised of three major components:

- A ***scenario development tool***, on which scenarios involving multiple aircraft and interrogators are laid out geographically, and the parameters and characteristics of these components are selected and adjusted.
- A ***runtime infrastructure***, on which simulation of all interrogations and replies generated in the scenario is managed and executed.
- A ***display tool*** which presents executed results to the analyst, who can examine them in depth and collect a variety of pertinent statistical information.

Developed scenarios and their associated results can be stored within a Windows folder. The scenario development tool automatically stores all the components of each developed scenario as files in a folder specified and labeled by the analyst. Upon execution, the resulting interference pattern can also be stored in that folder, associated with the scenario that produced it. Subsequently, either can be examined and modified as desired, and the simulation can be re-executed to produce updated results.

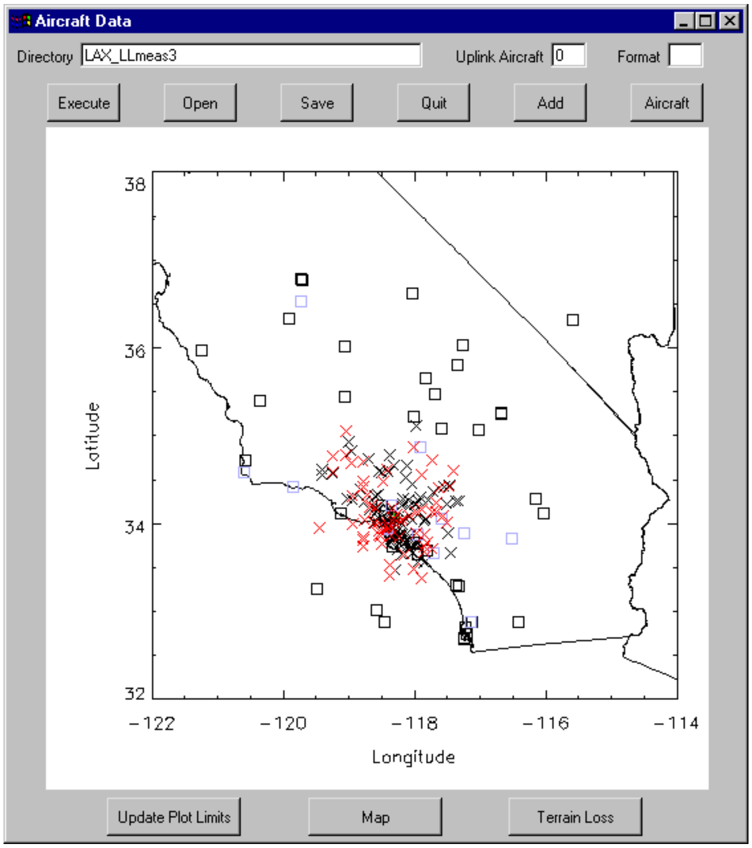
2.1 SCENARIO DEVELOPMENT TOOL

Scenarios are developed graphically on a plan-view display, or from stored elements of other scenarios. To develop a new scenario, the analyst first defines the geographical region, and then populates it with objects: various types of interrogators and transponders and the “victim” receiver (ground or airborne) at which the interference is to be measured. Figure 2-1 shows a typical display screen, associated with the geographic region around the Los Angeles Basin. Table 2-1 describes the display functions and parameters. Boxes signify interrogators and Xs are aircraft. A background map can be included, and the geographical coordinates and size of the region can be easily modified.

Any number of interrogators and aircraft can be placed graphically anywhere within the region. Alternatively, their numerical coordinates can be specified or they can be transferred from an existing file. Each object also has an associated set of parameters and characteristics that can be edited or transferred from a file. Subsections 2.1.1 through 2.1.7 describe the current set of objects available to the analyst, and the adjustable parameters and characteristics of each.

2.1.1 Aircraft

An aircraft can be placed anywhere within the region simply by clicking on the desired location. A pop-up menu then appears (Figure 2-2), automatically identifying the aircraft with a sequence number and allowing the analyst to edit the aircraft parameters (described in Table 2-2) and to specify the type of equipment it contains. (During scenario execution, aircraft locations remain fixed; velocity and heading are specified in the pop-up menu only to allow the simulation to determine TCAS directional antenna



Directory LAX_LLmeas3

Uplink Aircraft 0

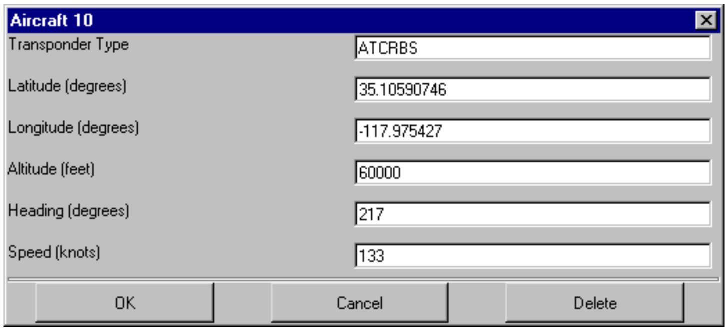
Format

Figure 2-1. Typical Scenario Plot

Window/Button	**Function**
Directory	Selects the directory to be opened or saved into
Uplink Aircraft	Selects an aircraft for which uplink interrogation display is generated
Format	Selects the format of the file to be read into the simulation. Previous versions of the code used a older file version which the new code can still read if the appropriate version is chosen. (Choices are “old”, “ver1”, and current.)
Execute	Executes displayed scenario
Open	Opens and displays contents of the selected directory
Save	Saves displayed scenario into selected directory
Quit	Stops display and editing without saving
Add	Merges content of selected directory with displayed objects
Aircraft/ Radar/ Ground/ Victim/Receiver/ATCRBS/ Mode S/TCAS	(Toggles through all object types) Used to determine what object type is instantiated or modified by left- or right-clicking (respectively)
Update Plot Limits	Allows changes to the limits of the area covered
Map	Enables the selection of a background map
Terrain Loss	Initiates a pop-up window that can be used to calculate the additional propagation loss due to terrain between a radar-aircraft pair and to display the terrain profile of that pair.

Table 2-1. Functions of Windows/Buttons on Scenario Display

orientation and threat. The pop-up menu for each aircraft can be recalled, to check or edit parameters, by right-clicking on it. Subsections 2.1.2 - 2.1.4 describe the choices available for the type of equipment the aircraft contains.


Aircraft 10

Transponder Type: ATCRBS
Latitude (degrees): 35.10590746
Longitude (degrees): -117.975427
Altitude (feet): 60000
Heading (degrees): 217
Speed (knots): 133

Figure 2-2. Aircraft Parameter Menu

Window/Button	**Function**
Transponder Type	Selects whether ATCRBS, Mode S, or TCAS
Latitude/Longitude	Specifies location (degrees and fractions)
Altitude	Specifies altitude (feet)
Heading/Speed	For use by TCAS threat evaluation logic
OK/Cancel	Attach (don't attach) displayed/edited parameters
Delete	Remove aircraft from scenario

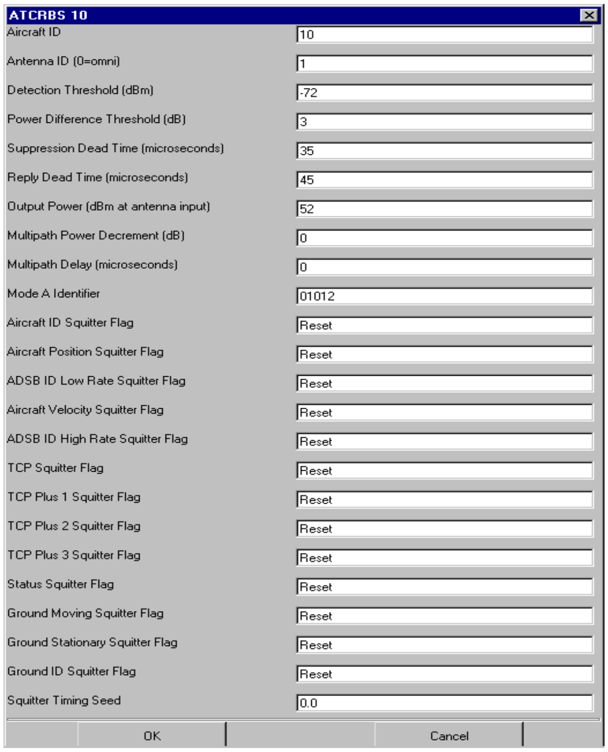
Table 2-2. Functions of Aircraft Menu Windows/Buttons

2.1.2 ATCRBS Transponder

When an aircraft is specified to have an ATCRBS transponder, the pop-up menu shown in Figure 2-3 appears, showing typical ATCRBS transponder parameters, which can be edited as desired (Table 2-3). The transponder performs all standard ATCRBS transponder functions: P1/P2 comparison, suppression, and reply rate limiting. Associated ID is properly coded into Mode A replies, as is the proper Mode C code for the pressure altitude of the aircraft. Additionally, a hypothetical squitter option is included for ATCRBS transponders, allowing ATCRBS equipped aircraft to participate in ADS-B reporting. (This capability is purely hypothetical and is only used in examining future case scenarios.)

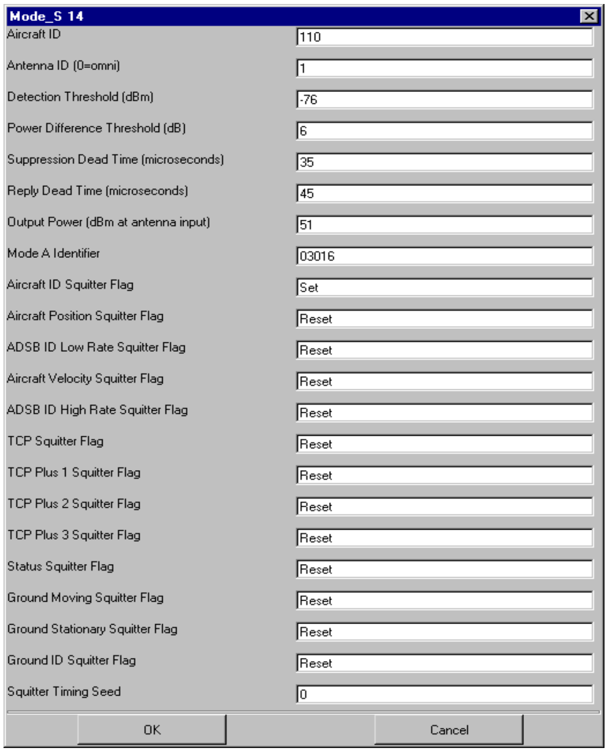
2.1.3 Mode S Transponder

When an aircraft is specified as Mode S-equipped, the pop-up menu shown in Figure 2-4 appears, allowing the characteristics of the Mode S transponder to be edited (Table 2-4). The Mode S transponder model includes the full functionality of the ATCRBS transponder. It also replies to Mode S interrogations addressed to it, but does not reply to ATCRBS interrogations with P4 set. It obeys the appropriate ATCRBS suppression rules, and produces "squitter" (unelicited replies) in accordance with the several rules that govern its generation (Sect. 3.2).



Aircraft ID	10
Antenna ID (0=omni)	1
Detection Threshold (dBm)	-72
Power Difference Threshold (dB)	3
Suppression Dead Time (microseconds)	35
Reply Dead Time (microseconds)	45
Output Power (dBm at antenna input)	52
Multipath Power Decrement (dB)	0
Multipath Delay (microseconds)	0
Mode A Identifier	01012
Aircraft ID Squitter Flag	Reset
Aircraft Position Squitter Flag	Reset
ADSB ID Low Rate Squitter Flag	Reset
Aircraft Velocity Squitter Flag	Reset
ADSB ID High Rate Squitter Flag	Reset
TCP Squitter Flag	Reset
TCP Plus 1 Squitter Flag	Reset
TCP Plus 2 Squitter Flag	Reset
TCP Plus 3 Squitter Flag	Reset
Status Squitter Flag	Reset
Ground Moving Squitter Flag	Reset
Ground Stationary Squitter Flag	Reset
Ground ID Squitter Flag	Reset
Squitter Timing Seed	0.0

Figure 2-3. ATCRBS Transponder Parameter Menu



Aircraft ID	110
Antenna ID (0=omni)	1
Detection Threshold (dBm)	-76
Power Difference Threshold (dB)	6
Suppression Dead Time (microseconds)	35
Reply Dead Time (microseconds)	45
Output Power (dBm at antenna input)	51
Mode A Identifier	03016
Aircraft ID Squitter Flag	Set
Aircraft Position Squitter Flag	Reset
ADSB ID Low Rate Squitter Flag	Reset
Aircraft Velocity Squitter Flag	Reset
ADSB ID High Rate Squitter Flag	Reset
TCP Squitter Flag	Reset
TCP Plus 1 Squitter Flag	Reset
TCP Plus 2 Squitter Flag	Reset
TCP Plus 3 Squitter Flag	Reset
Status Squitter Flag	Reset
Ground Moving Squitter Flag	Reset
Ground Stationary Squitter Flag	Reset
Ground ID Squitter Flag	Reset
Squitter Timing Seed	0

Figure 2-4 Mode S Transponder Parameter Menu

Table 2-3. Functions of ATCRBS Transponder Menu Windows/Buttons

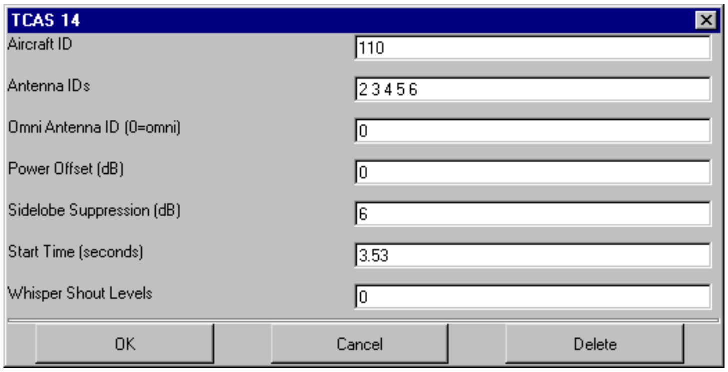
Window/Button	Function
Aircraft ID	Sequence number of aircraft (as shown on aircraft menu)
Antenna ID	Specifies whether omni (0 dB) (0), variable (random) (1) or otherwise
Detection Threshold	Transponder Minimum Usable Signal Level (MUSL) (dBm)
Power Difference Threshold	P1/P2 ratio at which sidelobe suppression occurs (dB)
Suppression Dead Time	Sidelobe suppression deadtime (from end of interrogation) (µs)
Reply Dead Time	Reply deadtime (from end of interrogation) (µs)
Output Power	Power into antenna (dBm)
Multipath Power Decrement/ Delay	Relative multipath signal power levels and timing are entered in order to simulate signal reflections from ground based objects (will accept up to 6 multipath signals at various relative levels and delays)
Mode A Identifier	Assigned Beacon Code (octal); must be preceded by 0
Aircraft ID Squitter Flag	"set" = Generate random (nom. 1/sec) Aircraft ID (short) squitter
Aircraft Position Squitter Flag	"set" = Generate random (nom. 2/sec) Aircraft position squitter
ADSB ID Low Rate Squitter Flag	"set" = Generate random (nom. 1/5 sec) ADSB Low Rate ID squitter
Aircraft Velocity Squitter Flag	"set" = Generate random (nom. 2/sec) Aircraft Velocity squitter
ADSB ID High Rate Squitter Flag	"set" = Generate random (nom. 2/ 5 sec) ADSB High Rate ID squitter
TCP Squitter Flag	"set" = Generate randomly-timed (nom. 1/1.7 sec) TCP squitter
TCP Plus 1 Squitter Flag	"set" = Generate randomly-timed (nom. 1/1.7 sec) TCP+1squitter
TCP Plus 2 Squitter Flag	"set" = Generate randomly-timed (nom. 1/1.7 sec) TCP+2 squitter
TCP Plus 3 Squitter Flag	"set" = Generate randomly-timed (nom. 1/1.7 sec) TCP+3 squitter
Ground Moving Squitter Flag	"set" = Generate random (nom. 1/0.5 sec) Position/velocity squitter (for moving aircraft on the ground)
Ground Stationary Squitter Flag	"set" = Generate random (nom. 1/5 sec) Position/velocity squitter (for stationary aircraft on the ground)
Ground ID Squitter Flag	"set" = Generate randomly-timed (nom. 1/10 sec) Aircraft ID squitter (for stationary aircraft on the ground)
Squitter Timing Seed	Input to the squitter timing randomization process
OK	Associate edited/displayed parameters with aircraft/transponder
Cancel	Don't accept edited changes to parameters (never mind)

Window/Button	Function
Aircraft ID	The sequence number of the aircraft with the Mode S transponder
Antenna ID	The type of antenna: 0 = omni (0 dB); 1 = random gain; 2 = custom
Detection Threshold	Transponder MUSL (same for Mode S and ATCRBS interrogations)(dBm)
Power Difference Threshold	ATCRBS sidelobe suppression minimum P1/P2 ratio (dB)
Suppression Dead Time	ATCRBS sidelobe suppression deadtime (from end of interrogation) (µs)
Reply Dead Time	ATCRBS reply deadtime (from end of interrogation) (µs)
Output power	Power into antenna (dBm)
Mode A Identifier	ATCRBS Assigned Beacon Code (octal); must be preceded by 0
Aircraft ID Squitter Flag	“set” = Generate random (nom. 1/sec) Aircraft ID squitter
Aircraft Position Squitter Flag	“set” = Generate random (nom. 2/sec) Aircraft position squitter
ADSB ID Low Rate Squitter Flag	“set” = Generate random (nom. 1/5 sec) ADSB Low Rate ID squitter
Aircraft Velocity Squitter Flag	“set” = Generate random (nom. 2/sec) Aircraft Velocity squitter
ADSB ID High Rate Squitter Flag	“set” = Generate random (nom. 2/ 5 sec) ADSB High Rate ID squitter
TCP Squitter Flag	“set” = Generate randomly-timed (nom. 1/1.7 sec) TCP squitter
TCP Plus 1 Squitter Flag	“set” = Generate randomly-timed (nom. 1/1.7 sec) TCP+1squitter
TCP Plus 2 Squitter Flag	“set” = Generate randomly-timed (nom. 1/1.7 sec) TCP+2 squitter
TCP Plus 3 Squitter Flag	“set” = Generate randomly-timed (nom. 1/1.7 sec) TCP+3 squitter
Ground Moving Squitter Flag	“set” = Generate random (nom. 1/0.5 sec) Position/velocity squitter (for moving aircraft on the ground)
Ground Stationary Squitter Flag	“set” = Generate randomly-timed (nom. 1/5 sec) Position/velocity squitter (for stationary aircraft on the ground)
Ground ID Squitter Flag	“set” = Generate randomly-timed (nom. 1/10 sec) Aircraft ID squitter (for stationary aircraft on the ground)
Squitter Timing Seed	Input to the squitter timing randomization process

Table 2-4. Functions of Mode S Transponder Menu Windows/Buttons

2.1.4. TCAS Interrogator

An aircraft that has been defined to be Mode S-equipped can be further specified to contain a TCAS interrogator, whose parameters (Table 2-5) can also be edited using the pop-up menu shown in Figure 2-5. Such aircraft, as well as having full Mode S transponder functionality, also transmit Mode S and ATCRBS TCAS interrogations in accordance with whisper/shout rules, applicable tracking rules, and TCAS interference-limiting procedures as defined in Version 7 of the TCAS software specifications [5] and elsewhere [6]. TCAS operation is discussed in more detail in Section 3.5.



Aircraft ID	110
Antenna IDs	2 3 4 5 6
Omni Antenna ID (0=omni)	0
Power Offset (dB)	0
Sidelobe Suppression (dB)	6
Start Time (seconds)	3.53
Whisper Shout Levels	0

Figure 2-5. TCAS Interrogator Parameter Menu

Window/Button	**Function**
Aircraft ID	Assigned sequence number of the aircraft with the TCAS Interrogator
Antenna IDs	Numbers denoting patterns of whisper/shout directional antennas
Omni Antenna ID	Refers to file containing pattern of TCAS omni antenna
Power Offset	Correction factor between Mode S interrogations and power into the antenna (dB)*
Sidelobe Suppression	Transmitted P1/P2 ratio (determines beamwidths of directional antennas)
Start Time	Timing of first whisper-shout sequence relative to run start time (sec)
Whisper Shout Levels	Correction factor between max. whisper-shout level and antenna input power

* Correction factors are set automatically by Interference-limiting logic, but can be overwritten.

Table 2-5. Functions of TCAS Interrogator Menu Windows

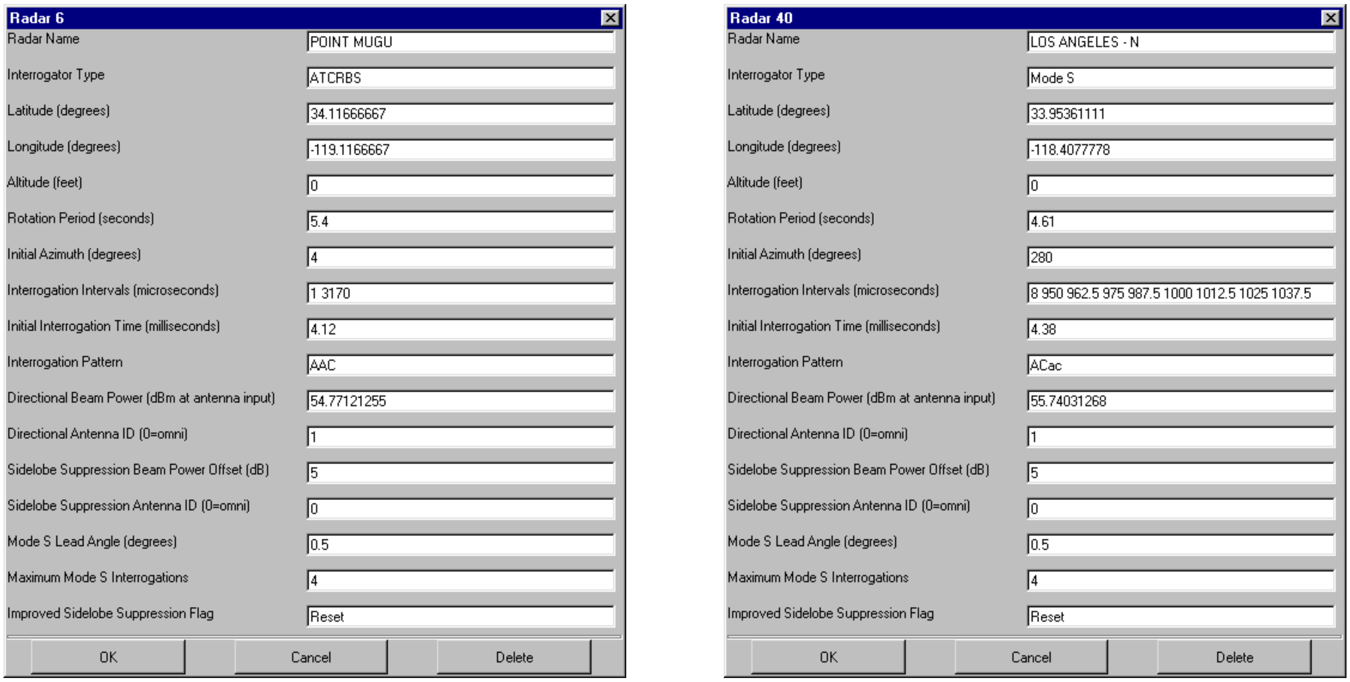
2.1.5 Ground Interrogator

Ground-based (radar) interrogators can be defined either with or without Mode S capabilities. An interrogator can be instantiated by pointing and clicking, and its parameters specified or modified from the standard (default) values (Table 2-6) by editing the pop-up menu that appears. Figure 2-6 shows pop-up menus pertaining to typical ATCRBS and Mode S interrogators; two of the parameters are pertinent only to Mode S. A single value can be placed in the pulse repetition interval (PRI) menu field, to specify a non-staggered interrogation pattern. Conversely, a sequence of n values can be specified to denote and characterize n-pulse stagger. Directional antenna pattern can be selected from a variety of available options, or custom-specified. (Antenna ID denotes the file number in which the antenna pattern is stored.)

The Mode S interrogator produces ATCRBS interrogations, interlaced among its Mode S all-call and discrete interrogations in accordance with current terminal-area Mode S scheduling algorithms. Mode S interrogator timing is specified by one of fifteen standard interrogation schedules (one of which is shown in the “Interrogation Intervals” window below, right); all interrogation schedules produce ATCRBS interrogations at a 125/sec average rate, but employ different stagger patterns to minimize synchronous interference. Any of the fifteen standard schedules can be selected, or a custom interrogation sequence can be defined (for example, with longer dwell-time to provide longer range). ATCRBS interrogations with or without P4 pulses can be specified; those with P4 are denoted by a lower-case a or c (in the “Interrogation Pattern” window below, right).

2.1.6 Victim Receiver

The Simulator generates an interference sequence that a hypothetical “victim” receiver sees. The location and characteristics of the victim must also be specified to the Simulator (Figure 2-7, Table 2-7). The victim can be associated with a selected Mode S or ATCRBS interrogator, in which case it employs the directional antenna of that radar, and replies elicited by that radar are identified by color-coding them. Alternatively, the victim can be specified as “stand alone” (for instance, to emulate a Mode S ADS passive ground receiver), by specifying the Radar ID to be zero. In that case, it can use an isotropic omnidirectional antenna or a fixed antenna with a specified directional pattern.



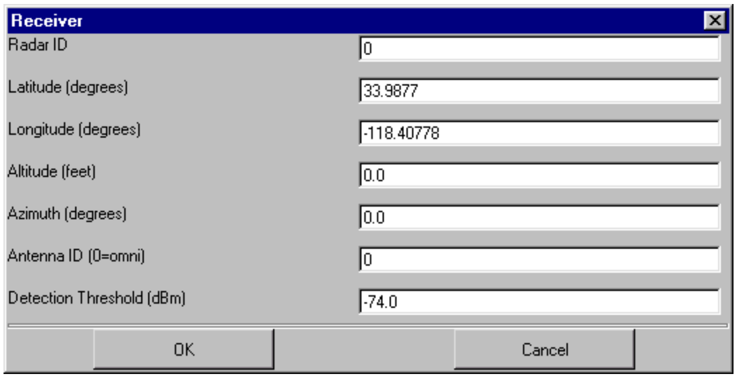
Radar 6	
Radar Name	POINT MUGU
Interrogator Type	ATCRBS
Latitude (degrees)	34.11666667
Longitude (degrees)	-119.1166667
Altitude (feet)	0
Rotation Period (seconds)	5.4
Initial Azimuth (degrees)	4
Interrogation Intervals (microseconds)	1 3170
Initial Interrogation Time (milliseconds)	4.12
Interrogation Pattern	AAC
Directional Beam Power (dBm at antenna input)	54.77121255
Directional Antenna ID (0=omni)	1
Sidelobe Suppression Beam Power Offset (dB)	5
Sidelobe Suppression Antenna ID (0=omni)	0
Mode S Lead Angle (degrees)	0.5
Maximum Mode S Interrogations	4
Improved Sidelobe Suppression Flag	Reset

Radar 40	
Radar Name	LOS ANGELES - N
Interrogator Type	Mode S
Latitude (degrees)	33.95361111
Longitude (degrees)	-118.4077778
Altitude (feet)	0
Rotation Period (seconds)	4.61
Initial Azimuth (degrees)	280
Interrogation Intervals (microseconds)	8 950 962.5 975 987.5 1000 1012.5 1025 1037.5
Initial Interrogation Time (milliseconds)	4.38
Interrogation Pattern	ACac
Directional Beam Power (dBm at antenna input)	55.74031268
Directional Antenna ID (0=omni)	1
Sidelobe Suppression Beam Power Offset (dB)	5
Sidelobe Suppression Antenna ID (0=omni)	0
Mode S Lead Angle (degrees)	0.5
Maximum Mode S Interrogations	4
Improved Sidelobe Suppression Flag	Reset

Figure 2-6. Interrogator Parameter Menus (ATCRBS and Mode S)

Button/Window	Function
Radar Name	The place name of the radar
Interrogator Type	ATCRBS (ASR or ARSR) or Mode S
Latitude/Longitude	Radar location (degrees and fractions)
Altitude	Radar altitude (feet)
Rotation Period	Antenna scan period (seconds)
Initial Azimuth	Antenna pointing direction at beginning of run (degrees)
Interrogation Intervals	Stagger pattern (first number denotes number of intervals)
Initial Interrogation Time	Timing of first interrogation at beginning of run (ms)
Interrogation Pattern	ATCRBS mode interlace (ac = P4 present)
Directional Beam Power	Power into directional antenna (dBm)
Directional Antenna ID	File number containing directional pattern (several available)
Sidelobe Suppression Beam Power Offset	Relative P1/P2 power level (before antenna gains) (dB)
Sidelobe Suppression Antenna ID	0 = omni; other options available
Mode S Lead Angle	Beam angle relative to target of first Mode S interrogation
Maximum Mode S Interrogations	Maximum number of Mode S interrogations per scan
Improved Sidelobe Suppression Flag	“set” = P2 power also fed into directional antenna

Table 2-6. Functions of Interrogator Menu Windows



Radar ID	0
Latitude (degrees)	33.9877
Longitude (degrees)	-118.40778
Altitude (feet)	0.0
Azimuth (degrees)	0.0
Antenna ID (0=omni)	0
Detection Threshold (dBm)	-74.0

Figure 2-7. Victim Receiver Parameter Menu

Button/Window	Function
Radar ID	Sequence Number of associated radar (0 = stand-alone)
Latitude/Longitude	Location in degrees/fractions (same as associated radar)
Altitude	Altitude in feet (same as associated radar)
Azimuth	Pointing direction of antenna (if directional)
Antenna ID	Antenna Pattern Identifier (several options)
Detection Threshold	Minimum displayed reply level

Table 2-7. Victim Receiver Parameters

2.1.7 Scenario Construction

Scenarios are constructed graphically using the plan-view plot shown in Figure 2-1. The plot normally has a black background for ease of visibility, but a reversed (white) background can be used to generate a more legible paper copy. Plot size is adjustable, and the analyst can “zoom” in on a selected region (by clicking on its center). Additionally, plot size can be changed by specifying latitude/longitude limits using the “Update Plot Limits” button. Any selected menu or plot can be passed to the Windows clipboard for subsequent capture in Word or Power Point.

Aircraft (depicted by the symbol X) are colored white if ATCRBS-equipped, light blue if Mode S equipped, and red if Mode S and TCAS-equipped. With white-background plots, the ATCRBS-equipped aircraft appear black. Consistent with current regulations, a TCAS aircraft must also be Mode S-equipped. Ground interrogators (boxes) are white (black if reversed background) for ATCRBS, light blue for Mode S. The victim interrogator appears as a green cross.

Objects can be placed manually, or an existing file containing one or more objects can be added to the scenario. Once the analyst is satisfied with all scenario details, depressing the “execute” button on the scenario plan-view plot causes the Simulator to execute, generating the resulting composite signal time line that the victim would see.

2.2 RUNTIME INFRASTRUCTURE

When a scenario is executed, the runtime infrastructure collects and compiles the associated files (aircraft and radar locations, associated parameter files), pre-calculates additional propagation loss due to terrain and TCAS interrogation characteristics, and steps through the specified time period (default value 20 seconds). Up to 8 files can be input to the execution process, depending on the diversity of objects in the scenario. Results are written to a file called “reply.dat”, which is then passed to display software for viewing and analysis.

The simulation executes in 1-ms time steps. During each, all interrogators are examined to determine whether they produce any interrogations (in accordance with their scheduling algorithms). The timing (to better than 0.1 μs) and characteristics of each interrogation are processed to determine the arrival timing and power level of the interrogation, as seen by each aircraft in the scenario, and a list of all interrogations seen by each aircraft is created. Those interrogations that are received within the 1-ms time step after the one in which they were generated are appropriately delayed and fed to it.

The interrogation sequence seen by each aircraft is then examined, and the resulting reply sequence determined, with appropriate transponder suppression action and threshold level determination. The analyst can capture the <u>interrogation</u> sequence seen by a specific aircraft for subsequent examination, by specifying that aircraft in the “Uplink Aircraft” window of the plan-view display (figure 2-1) prior to execution. Currently the interrogation sequence for only one aircraft per simulation run is allowed.

Levels and arrival timing of all replies so generated are then calculated at the location of the victim receiver, and written to the “reply.dat” file for subsequent display. Each entry includes the following parameters:

- Arrival timing and signal level of the reply
- Type of reply (Mode A, Mode C, Mode S, squitter)
- ID or altitude codes associated with ATCRBS replies
- Identities of the aircraft that produced it and the radar that elicited it.

The process for generating Mode S transponder “squittering” is slightly different. “Squitters” are Mode S replies that are not associated with any interrogations, but are rather produced spontaneously by Mode S transponders in accordance with random generation algorithms. Several types of squitters are modeled, each separately selectable, with timing determined by its own random process. The Simulator establishes squitter timing in each Mode S transponder and merges them with the elicited replies from that transponder in accordance with the appropriate prioritization/delay rules. ATCRBS equipped aircraft were given a hypothetical capability to squitter for the purpose of ADS-B reporting. This capability is only used in future case scenarios. Squittering is discussed in more detail in Section 3.2.

2.3 DISPLAY TOOL

Reply sequences that are generated by the Simulator and stored in the "reply.dat" file are subsequently fed to the display process. That process presents the information to the analyst in three forms:

- A plot of received signal level versus arrival time, showing all received replies, appropriately color-coded (Figure 2-8)
- Associated statistical data (Figure 2-9)
- Printout of a specified subset of replies (for example, all those that are overlapped) and their associated characteristics (Figure 2-11)

The statistical data is provided to allow the analyst to quantify what happens in a particular scenario. The display allows determination of why it happened, and analysis of the (optional) associated printout enables more detailed estimation of performance in complex situations (for example, to determine the likely success rates of various proposed detection schemes).

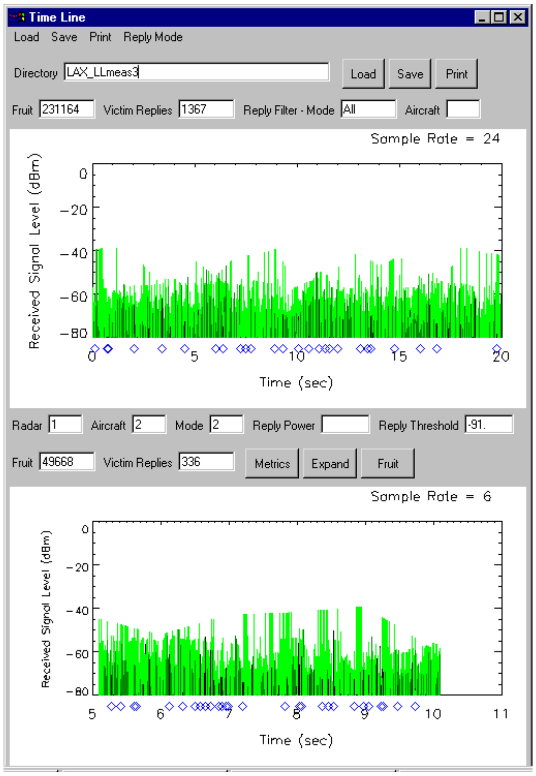
2.3.1 Pulse Data Display

The Pulse Data Display (Figure 2-8) displays the arrival timing and level of each reply, so the analyst can examine interactions of multiple replies in detail. Plot timescale can be varied from the full execution time (nominally 20 seconds) to the width of an individual reply pulse (a fraction of a microsecond), by clicking and dragging (repeatedly, if necessary) on the portion of the timeline the analyst wishes to expand. The expanded time scale is displayed in the bottom window of the display while the top remains unchanged. Statistics pertinent to the displayed data (Figure 2-9) can be presented by clicking on the "fruit" and "metrics" buttons.

The time resolution of the plot is severely limited because of the limited number of pixels in the display. Close examination of even the worst-case interference situation reveals that reply pulses occupy only a small fraction of the timeline. Yet, the minimum width of a displayed reply is typically at least 1/500 of the timeline, since that is the width of the individual pixel. Thus, when many replies are displayed at the larger timescales, the timeline appears totally full. As the selected time interval is made smaller, the display process employs the following procedures:

- At longer time intervals with many replies, only every nth reply is depicted, by a single vertical line, appropriately color coded. When such decimation is in effect, the value of n is presented by message on the display.
- As the displayed timeline is shortened, decimation ceases and every reply is represented as a single vertical line. In this situation, the decimation message disappears from the display.

- As the timescale is further expanded, the depiction of each reply changes to a sequence of vertical lines, associated with the individual pulses within the reply. The time location of each of these is in accordance with the ID or altitude for ATCRBS replies. (Mode S preamble and data pulses are displayed with their proper timing, but the data content of the Mode S reply is random.)
- When timescale is so expanded that individual reply pulse width exceeds a pixel, the pulse is represented by a rectangle of the appropriate width.



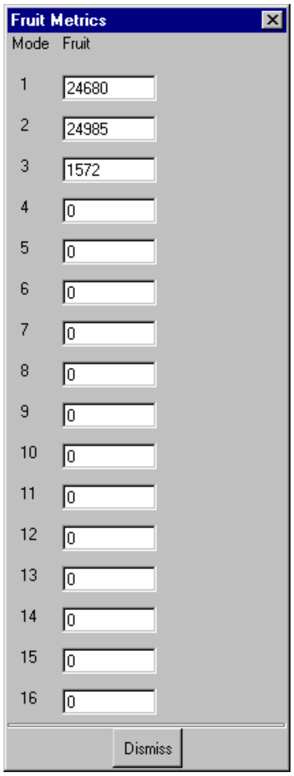
Directory LAX_LLmeas3

Fruit 231164 Victim Replies 1367 Reply Filter - Mode All Aircraft

Radar 1 Aircraft 2 Mode 2 Reply Power Reply Threshold -91.

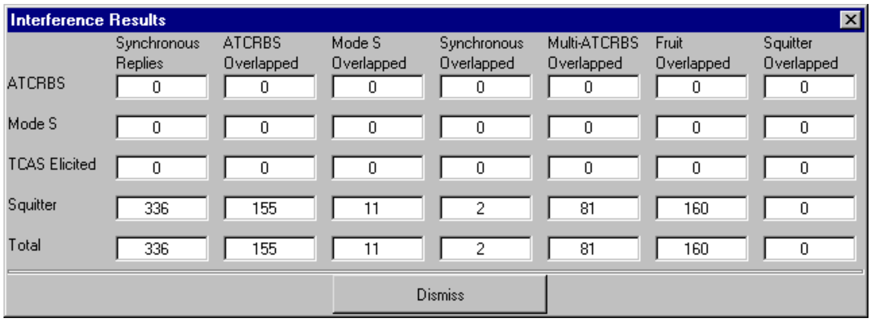
Fruit 49668 Victim Replies 336

Figure 2-8. Typical Pulse Data Display



Mode	Fruit
1	24680
2	24985
3	1572
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0
13	0
14	0
15	0
16	0

a) Fruit



	Synchronous Replies	ATCRBS Overlapped	Mode S Overlapped	Synchronous Overlapped	Multi-ATCRBS Overlapped	Fruit Overlapped	Squitter Overlapped
ATCRBS	0	0	0	0	0	0	0
Mode S	0	0	0	0	0	0	0
TCAS Elicited	0	0	0	0	0	0	0
Squitter	336	155	11	2	81	160	0
Total	336	155	11	2	81	160	0

b) Interference

Figure 2-9. “Metrics” Windows: Fruit and Interference

The pulse data display shows the full timeline executed at runtime in the top plot, and the expanded timeline selected by the analyst in the bottom plot. The fidelity of the expanded timeline display at the higher levels of expansion allows the analyst to determine the relative timing and power levels of multiple overlapping replies, and to differentiate between overlapped and interleaved ATCRBS replies. At intermediate timescales, the sets of replies elicited from individual radars can be identified, and when timescale is sufficiently long, scans of individual radar antenna beams past groups of targets can be recognized. Changing the timescale to examine situations of interest is simple, quick, and readily reversible (using the "expand" button).

Replies are color-coded as follows:

- RED replies are ATCRBS Mode A, elicited by the victim
- PURPLE replies are ATCRBS Mode C, elicited by the victim
- ORANGE replies are Mode S, elicited by the victim (and include aircraft ID)
- GREEN replies are asynchronous ATCRBS replies (fruit) (either Mode A or C)
- DARK GREEN replies are Mode S fruit
- WHITE (BLACK if background color is white) replies are Mode S or hypothetical ATCRBS squitter

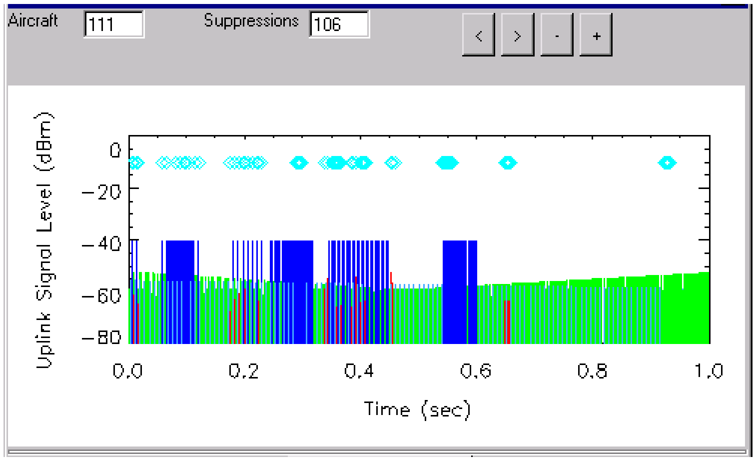
Pointing and right-clicking on an individual reply provides the analyst with its signal level (to 0.01 dBm), and the identities of the aircraft and radar that produced it. This process is effective only when the timescale is expanded sufficiently so pointing differentiates properly between closely spaced adjacent replies.

Different types of replies can also be highlighted, by selecting them in the ***Reply Filter*** window. The replies associated with a particular ***Aircraft*** can also be highlighted, to assist the analyst in tracking the behavior of individual aircraft. (Those replies not highlighted are faded into the background.) The display also identifies replies that are overlapped by other replies by placing a small blue diamond below each. Cases in which squitter overlaps an elicited reply contain a green cross within the blue diamond. In scenarios in which the victim receiver is coupled to an interrogator, only the replies elicited by that interrogator are examined for overlap. (A fruit reply overlapped by another fruit reply is not labeled as overlapped.) In the converse case, where the victim receiver is stand-alone, squitters are presumed to be the replies of interest, and are flagged if overlapped. In the stand-alone case, no red or purple (ATCRBS Modes A and C) replies are displayed, since the victim does not elicit replies.

2.3.2 Uplink Interrogation Display

If a particular aircraft is selected in the "Uplink Aircraft" window of the scenario plot (Figure 2-1) prior to execution, the uplink interrogation environment at that aircraft is saved during execution to a file that can also be displayed (Figure 2-10). This display shows all interrogations (sidelobe and mainbeam) that are seen by the aircraft, and their associated levels. It denotes those interrogations to which the aircraft replies, with blue lines. This display is obtained by pointing at the desired portion of the timeline in the pulse data display (Figure 2-8), and can be shifted to the left and right or expanded/diminished with buttons. Interrogations are color-coded as follows:

- GREEN interrogations are from other than the victim radar
- LIGHT BLUE interrogations are from the victim
- DARK BLUE denotes interrogations to which the aircraft replies
- RED interrogations occur while the aircraft transponder is suppressed



Aircraft 111

Suppressions 106

Figure 2-10. Typical Uplink Interrogation Environment Display

2.3.3 Associated Statistics

The pulse data display windows also present several gross statistics pertinent to the selected time periods:

- The ***fruit*** windows present the total amounts of ATCRBS fruit (Mode A and Mode C replies elicited from ATCRBS, Mode-S or TCAS interrogators) seen in the entire execution time (top) and the selected expanded portion (bottom). When the victim is associated with a radar, received squitter is also counted as fruit.
- The ***victim replies*** windows show totals of elicited ATCRBS and Mode S replies (if the victim receiver is associated with a radar), or of squitters (if it is not).

Additional information pertinent to individual replies is also available, by right-clicking on the particular replies (when the timescale is expanded sufficiently to capture them):

- The ***Radar*** window presents the sequence number of the radar that elicited the reply (0 if the reply is an unelicited squitter). If the reply was elicited by TCAS, the window presents a number that consists of the TCAS interrogator sequence number plus 1000.

- The ***Aircraft*** window presents the sequence number of the aircraft that produced the reply.
- The ***Reply Power*** window presents the received power level of the reply, with greater precision than can be read from the display.
- The Mode window tells what type of reply it is, in accordance with Table 2-8. (Table 2-8 also pertains to entries in the Reply Filter window.)

Mode	Reply Type
1	ATCRBS Mode A
2	ATCRBS Mode C
3	Mode S
4	Aircraft ID Squitter
5	Aircraft Position Squitter
6	ADS-B ID Squitter (low rate)
7	Aircraft Velocity Squitter
8	ADS-B ID Squitter (high rate)
9	TCP Squitter
10	TCP+1 Squitter
11	TCP+2 Squitter
12	TCP+3 Squitter
13	Status Squitter
14	Ground pos/vel Squitter (moving)
15	Ground pos/vel Squitter (stationary)
16	Ground ID Squitter (stationary)

Table 2-8. Mode Types

The Metrics button and the Fruit button produce subsidiary windows that display additional statistics, as shown in Figure 2-9. The “Interference Results” window (on the left) presents gross overlap statistics for the selected expanded portion of the timeline. The rows present total numbers of overlapped replies of various types: elicited ATCRBS and Mode S replies (when the victim receiver is associated with the eliciting radar), TCAS replies, and squitter (when the victim is stand-alone). The columns present breakdowns of these based on what types of replies are overlapping them:

- ***Synchronous Replies***: Total number of elicited replies of the type shown for each row that occur during the selected time interval, whether overlapped or not. (When the victim receiver is not associated with a radar, the column displays the total number of squitters received, as shown in Figure 2-10.)
- ***ATCRBS Overlapped***: Portion of those that are overlapped by one or more ATCRBS replies of any type
- ***Mode S Overlapped***: Portion overlapped by Mode S replies elicited by other radars

- ***Synchronous Overlapped***: Portion overlapped by other replies elicited by the victim radar (i.e., synchronously garbled).
- ***Multi-ATCRBS Overlapped***: Portion overlapped by two or more ATCRBS replies.
- ***Fruit Overlapped***: Portion overlapped by ATCRBS or Mode S fruit.
- ***Squitter Overlapped***: Portion overlapped by squitter.

All instances of overlap are counted, regardless of the amount of overlap and the relative signal power levels. To determine what subset of the total overlapped replies fails detection (because the amount of overlap is excessive and the S/I is insufficient), the analyst can selectively print out all instances of overlap, with these parameters included.

There is presently some contention about the interference conditions under which various receiver types fail to detect desired signals. When this has been resolved, the appropriate criteria for successful decoding will be incorporated into the Simulator, and a column presenting "successfully decoded" replies will be added to this window.

The "Fruit Metrics" window breaks down the fruit count associated with the expanded pulse data display according to the various reply mode types (as presented in Table 2-8).

2.3.4 Printout

The analyst can selectively print out replies that are overlapped, their associated characteristics, and the characteristics of the replies that overlap them. Figure 2-11 presents a typical printout for a case involving a stand-alone victim, where squitters are the replies of interest. Each line pertains to an individual overlapped reply of interest (sometimes folded over into two or more lines when multiple replies overlap the reply of interest). The line lists the arrival time of the reply of interest, its associated characteristics (the aircraft that produced it, the radar that elicited it, the reply mode type (per Table 2-8), and its received level), and the characteristics of each interfering reply (those same items, preceded by its arrival timing delay relative to the reply of interest).

From this raw data, the analyst can determine which of the replies of interest are successfully received and decoded by a receiver with whatever detection capabilities are chosen. As noted above, when an agreed set of capabilities are chosen, the process of counting overlapped replies that meet/fail those criteria will be automated.

```
            Signal Interfered with                    First Interfering Signal                  Second
Arrival time    A/C      Interr   Type    Level    Rel. time   A/C     Interr   Type   Level       Rel. time  A/C
0.007820  660    0   7  -78.6  -19.2  393   10   1  -62.2   -9.5  395
10   1  -61.1   -2.8  614   10   1  -65.9   -0.4  396   10   1  -60.2
9.3  377   10   1  -62.4   19.2  459   10   1  -65.1   24.4  374   10
1  -69.1   57.0  265   43   1  -63.0   84.6  173   30   1  -73.9   92.8
238   30   1  -72.4  101.1  267   30   1  -75.2  114.8  601   43   1  -
64.8
  0.008221  623    0   7  -67.4  -13.1  311   43   1  -70.0  -10.1  672
30   1  -65.5
  0.008723  602    0   5  -75.5   18.3  443    7   1  -68.0   48.9  673
7   1  -65.7   50.8  623    7   1  -67.4   67.0  304    7   1  -64.1
80.7  305    7   1  -60.5   96.1  605    7   1  -72.3  115.7  298    7
1  -68.0
  0.013617  674    0   7  -62.0  112.6  311   47   2  -70.0
  0.022696  676    0   8  -69.2   56.7  169   30   2  -67.5   95.9  239
30   2  -66.3   99.9  173   30   2  -73.9  105.8  246   30   2  -71.0
108.1  238   30   2  -72.4  116.4  267   30   2  -75.2
  0.027214  576    0   8  -57.3   -4.9  605   10   1  -72.3    5.7  289
10   1  -63.8    7.8  255   10   1  -62.3   11.4  275   10   1  -73.5
12.2  392   10   1  -61.7   13.8  390   10   1  -63.2   19.1  391   10
1  -61.4   20.9  389   10   1  -61.8   22.9  366   10   1  -70.5   54.8
377   10   1  -62.4   54.8  211   10   1  -75.5   64.6  459   10   1  -
65.1   69.8  374   10   1  -69.1
  0.027557  609    0   5  -67.4   62.2  235    4   1  -70.7   66.0  219
4   1  -62.4   66.3  619    0   5  -73.7   68.2  205    4   1  -57.2
69.2  197    4   1  -76.1   70.4  195    4   1  -54.8   71.0  196    4
1  -56.9   72.0  194    4   1  -76.5   75.0  330    4   1  -65.7   81.7
691    4   1  -49.4   83.5  319    4   1  -54.3   89.1  192    4   1  -
66.3
  0.027624  619    0   5  -73.7  -66.3  609    0   5  -67.4   -4.1  235
4   1  -70.7   -0.4  219    4   1  -62.4    1.9  205    4   1  -57.2
2.8  197    4   1  -76.1    4.1  195    4   1  -54.8    4.7  196    4
1  -56.9    5.7  194    4   1  -76.5    8.6  330    4   1  -65.7   15.3
691    4   1  -49.4   17.2  319    4   1  -54.3   22.8  192    4   1  -
66.3
  0.037842  629    0   4  -77.4   23.4  601    0   8  -65.0
  0.037865  601    0   8  -65.0  -23.4  629    0   4  -77.4
  0.038980  598    0   8  -73.2  -13.6  377    3   1  -62.4    0.5  556
3   1  -65.4   30.3  365    3   1  -66.4
  0.039217  609    0   7  -67.5  -15.1  334    5   1  -68.7
  0.040080  688    0   8  -61.8  -18.0  298    7   1  -68.0  -14.6  297
7   1  -67.9  -12.8  434   30   2  -67.3   69.2  445   30   2  -64.9
74.3  306   43   1  -76.7   79.2  151 1671   2  -56.9   82.6  225 1671
2  -59.2   83.9  109 1671   2  -66.1
  0.041498  629    0   8  -77.4   -8.5  556    3   2  -65.4   21.3  365
3   2  -66.4
  0.043122  677    0   8  -70.6   37.1  162 1671   2  -61.5   38.5  156
1671   2  -55.2   45.2  158 1671   2  -63.9   50.8  152 1671   2  -61.9
96.3  167 1671   2  -71.9
  0.045940  684    0   7  -68.1  -12.3  208    3   1  -60.0    0.6  683
3   1  -59.2    3.8  345    3   1  -64.8   11.3  165   30   1  -74.7
19.5  615    3   1  -62.4   30.6  223   30   1  -68.3   32.8  373    3
1  -65.4   34.4  658    0   8  -68.8   42.2  220   30   1  -53.9   51.6
```

Figure 2-11. Sample Printout

3. MAJOR SIMULATOR FEATURES

The previous section of this report discussed the overall structure of the Simulator and its components. This section amplifies the details of how some of the more complex surveillance-related processes are modeled within the Simulator. These include the determination of received signal power levels, the squitter-generation process, the Mode S Interrogator scheduling algorithm, ATCRBS Interrogation staggering, and TCAS interrogator operation.

3.1 SIGNAL POWER LEVEL CALCULATION

The Simulator models in detail signal level variations due to propagation-related effects, on both uplink and downlink. Neglecting these variations would erroneously lead to the conclusion that interference (overlapping replies) is the primary cause of secondary surveillance system performance degradation, when in fact it is quite common for target misses to occur even when interference is low or non-existent, because of signal fading.

Primary (skin-paint) radar uplink and downlink propagation losses are identical, and combine to establish the signal strength measured at the radar receiver. Unlike that situation, propagation phenomena on beacon radar uplinks and downlinks are usually analyzed separately, and are not tightly correlated since the links operate at different frequencies. Either link can fail independently of the other. Such failures determine the probability that a reply is received in response to an interrogation (the “round reliability”) through the probabilistic relationship:

$$\text{RR (round reliability)} = (1 - p_{\text{uplink miss}})\,(1 - p_{\text{downlink miss}}).$$

The two links are discussed separately in the following sections. The focus is on ATCRBS, since in this area it is more complicated than Mode S. The concepts readily apply to Mode S as well.

3.1.1 Uplink

The interrogator transmits over this link at 1030 MHz to the aircraft transponder. Nominal link parameters are as shown in Table 3-1:

Link Parameter	Symbol	Typical Value
Transmitter Output Power (pk)	P_T	55 dBm (300 watts[1])
Directional antenna gain (nominal)	G_T	21 dB[2]
Freespace pathloss (@100 nm)	$L = (\lambda/4\pi R)^2$	-138 dB[3]
Excess propagation loss due to terrain	L_T	0 to -35 dB[4]
Receiving antenna gain (nominal)	G_R	0 dB[5]
Received signal power @ 100 nm	P_R	- 62 dBm
MUSL (transponder detection threshold)		-74 dBm[6]

Table 3-1. Typical ATCRBS Uplink Parameters

Notes for Table 3-1:

1. Typical peak power for newer terminal-area interrogators; some older ones have as much as 1 Kw. Cable losses included.
2. Gain at the peak of the interrogation beam, for terminal radars (ASRs). En route radar antennas have higher gains (25 dB), to support their greater range. Actual gain varies from nominal due to effects of multipath propagation (these effects are lumped together with similar effects on the airborne antenna).
3. Varies with range as R^{-2}. Other propagation path losses (e.g., atmospheric absorption) are negligible. Terrain obstruction causes additional loss for aircraft at low elevation angles.
4. Depends on profile of terrain along line-of-sight path between radar and aircraft. Varies from 0 dB when aircraft is well above radar horizon to –35dB when at edge of second Fresnel zone below. Calculated using simplified diffraction loss model, discussed in Section 3.1.3.
5. Actual gain varies considerably with direction, due to blockage and multipath reflection by the aircraft fuselage. See the discussion below.
6. The minimum peak signal power level at which the transponder will trigger on an incoming interrogation. Nominal tolerance = ± 3 dB. (The Simulator models the detection process somewhat simplistically, assuming that all interrogations above this level will elicit a response, and all received below it will not.)

From Table 3-1, we would predict that an aircraft at 100 nm would be interrogated with a signal whose maximum level (when directly on-boresight, well above the horizon) is nominally 12 dB above threshold. Thus, with a typical interrogator antenna, aircraft replies should persist through 4.2 deg. (the –12 dB beamwidth of the antenna). Three factors complicate this situation:

- *Additional signal loss results when terrain is close to (or in) the line-of-sight path between the radar and the aircraft.* When an aircraft is well above the horizon of the radar, uplink propagation loss results entirely from spherical spreading (freespace pathloss). As the aircraft approaches the radar horizon so the line-of-sight path comes close to (or is blocked by) the terrain that establishes the horizon, additional loss is incurred. This additional loss depends on details of the terrain profile, becomes excessive (causing loss of the target) as the aircraft drops well below the horizon, and can be difficult to calculate in many ground-to-ground propagation situations. The Simulator calculates it individually for each aircraft-radar pair, using a terrain database and several simplifying approximations (mainly that obstruction is by a single dominant feature). Details of this process are described in Section 3.1.3.

- *Actual aircraft antenna gain varies considerably from the nominal.* Typical installed aircraft antenna patterns resemble porcupines more than the 0 dB spheres implied by the term “omnidirectional”. This variation is due partly to phase interference caused by multipath reflection from aircraft surfaces, and partly to obstruction by portions of the fuselage and wings. At the 1030 MHz wavelength (29 cm), small changes in angle (or frequency) can result in large changes in relative phase, producing rapid variation in resulting signal level with aspect angle.

  While the effects that cause departures from nominal antenna gains are completely deterministic, they are quite often modeled probabilistically, in terms of the statistical distribution of actual gain values. Figure 3-1 presents the typical statistical characterizations used in the Simulator. The various curves equate to different aircraft types, and are consistent with the common rough rule-of-thumb that there is a 10% likelihood that a nominal omnidirectional aircraft antenna will have an actual gain below -10 dB, and a 1% likelihood that it will be below -20 dB.

- *Uplink sidelobe suppression limits the maximum runlength.* To prevent a close transponder from replying improperly while in the interrogator antenna sidelobes, the interrogator transmits an omnidirectional pulse within each interrogation (the "P2 pulse"). When the received level of that pulse comes within 0 to 7 dB of the other pulses, the transponder suppresses. Thus, a typical interrogator antenna should elicit replies over at most about 3.4 degrees (the points where this sidelobe suppression threshold is reached).

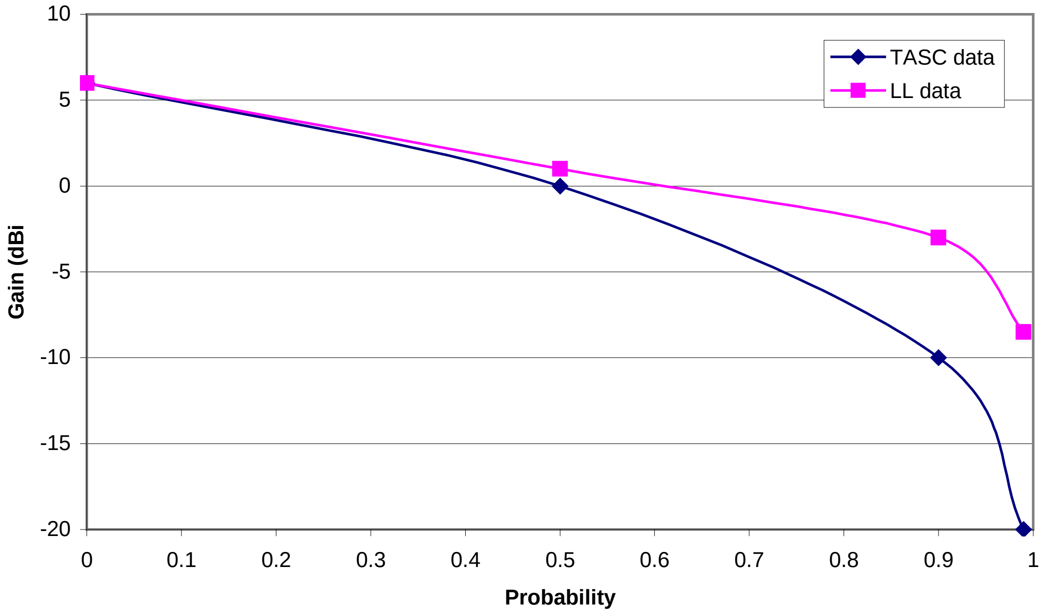


Figure 3-1. Antenna Gain Statistics (Typical)

To account for the variations in airborne antenna pattern, the Simulator calculates a gain degradation factor for each aircraft as follows:

- It generates a random variable, uniformly distributed between 0 and 1.
- It enters that factor into a lookup table (such as those plotted in Figure 3-1)
- Finally, it applies the table output to the link power budget to determine the resulting received signal power level.

The antenna degradation factor depends on aspect angle, which changes slowly. Correlation times on the order of several seconds are typical of most commercial and private aircraft. The Simulator models the antenna fading process by repeating the process described above periodically (nominally every four seconds) for each aircraft-radar pair, and linearly interpolating (in dB) the results. The resulting value is passed to the link power budget calculations for each interrogation.

The following processes are performed on each interrogation of each aircraft:

- Calculation of nominal received signal power level from range and link parameters (including excess losses due to terrain) indicated in Table 3-1.
- Calculation of off-boresight angle from antenna direction and aircraft location
- Determination of interrogator antenna gain degradation due to the aircraft being off boresight (using a lookup table containing the antenna pattern)
- Adjustment of nominal received signal power level by the amount of gain degradation
- Determination of whether the resulting received signal power level exceeds the MUSL of the transponder
- Determination of whether that value exceeds the sidelobe-suppression threshold (as established by the received omni (P2) power and the SLS offset value)
- Determination that the transponder is not suppressed (due to recent receipt of another mainbeam or sidelobe interrogation)
- Generation of a downlink reply only if the three previous conditions are met.

3.1.2 Downlink

The downlink, which operates at 1090 MHz, is characterized by the typical parameters shown in Table 3-2:

Link Parameter	Symbol	Typical Value
Transmitter Output Power (pk)	P_T	54 dBm (250 watts[1])
Aircraft Antenna Gain (nominal)	G_T	0 dB[2]
Freespace Pathloss (@ 100 nm)	$L = (\lambda/4\pi R)^2$	-138 dB[3]
Excess propagation loss due to terrain	L_T	0 to -35 dB[4]
Receiving Antenna Gain (nominal)	G_R	21 dB[5]
Received Signal Power	P_R	- 63 dBm
MUSL (Interrogator Receiver Threshold)		- 79 dBm[6]

Table 3-2. Typical ATCRBS Downlink Parameters

Notes for Table 3-2:

1. Varies ± 3 dB. Includes cable losses.
2. Actual gain varies considerably, as does aircraft antenna gain on the uplink
3. Negligible difference from uplink value: $(1030/1090)^2$ = - 0.4 dB
4. As calculated for the uplink; see section 3.1.3.
5. Gain at the peak of the beam; difference from uplink again negligible, in opposite sense.
6. Minimum level for successful detection of replies.

Note that these values result in an aircraft at 100 nm generating a reply that is nominally 16 dB above threshold (as opposed to the 12 dB margin on the uplink). Again, the effects of variations in aircraft antenna gain must be taken into account, in the same manner as for the uplink. Downlink fading characteristics are in fact only partially correlated with those of the uplink, since the multipath interference situation differs due to the different frequencies. The Simulator calculates antenna gain degradation factor independently for the uplink and the downlink. Received signal power levels associated with all replies (even those received in the antenna sidelobes) are preserved in the reply.dat file, to allow examination of interference-to-signal ratio on a reply-by-reply basis.

3.1.3 Calculation of Excess Losses due to Terrain

At the beginning of each simulation run, the Simulator determines whether, and by how much, the propagation paths between all radar-aircraft pairs are attenuated or obstructed by terrain. This entails several steps, performed for every radar-aircraft pair:

- *Calculation of Terrain Profile Along Line of Sight Path.* The Simulator determines the path along the earth's surface between radar and aircraft locations, and queries a terrain database (DTED) for terrain elevation data along that path, from which it forms the vertical terrain profile. It also forms the straight line in that vertical plane that connects the radar and the aircraft. (The 4/3-earth propagation model is used in these calculations.)
- *Determination of Maximum Penetration/Closest Approach Point.* The Simulator then determines the point along the path at which the terrain crosses the straight line by the greatest amount (or comes closest to it, if it does not cross it). It measures the distance between the terrain and the path (negative if penetration occurs, positive if the terrain does not block the line of sight) and the distance along the path at which this worst case occurs.
- *Calculation of Δ/Δ_o.* The quantity Δ_o is calculated from the expression:

  $$\Delta_o = (\lambda d_T d_R/(d_T + d_R))^{1/2}$$

  and is divided into the penetration distance, Δ, to form the ratio Δ/Δ_o. Here, d_T and d_R are the distances from the maximum penetration point to the radar and aircraft, respectively (such that $d_T + d_R$ = total distance between radar and aircraft), and λ is the wavelength (29 cm).
- *Determination of excess loss amount.* The functional relationship between the parameter Δ/Δ_o and the excess loss is presented in [7], for various types of terrain. We approximate it for this application by the linear relationship:

  $$F\ (\text{dB}) = 14(\Delta/\Delta_o - 0.5) \text{ over the range } (-2 < \Delta/\Delta_o < 0.5).$$

The excess loss amount calculated in this manner is added to the freespace pathloss to determine received signal level. These calculations produce zero excess loss when the terrain closest to the line of sight path is further from it than $\Delta_o/2$, and 35 dB excess loss when the penetration amount equals $2\Delta_o$. Variation is linear between those points, so that excess loss when the terrain just grazes the path is 7 dB, consistent with classical diffraction theory. When penetration is greater than $2\Delta_o$, excess loss is so great that the link is presumed to be broken.

These calculations are a simplified version of the more general knife-edge/cylindrical diffraction propagation loss calculations presented in [7]. That work focused on radar detection of very low altitude targets, and so was concerned with a wide variety of situations, from a completely smooth earth to multiple diffracting hills along the propagation path. The loss calculations it presents become quite complex as the hills become smaller and greater in number. They reduce to the process used by the Simulator when the following simplifying assumptions are made:

- A single terrain point dominates the propagation effects along each path (the point that establishes the optical horizon seen by the radar).
- Terrain roughness is characterized by a roughness factor of 0.2. This parameter depends on the radius of curvature of the hill, and its value here corresponds to smoothly rolling hills. Very jagged hills, more like classical knife edges, would have roughness factors close to 0, and would produce slightly lower losses (perhaps reducing the 21 dB calculated when penetration equals Δ_o to 18 dB).

Note that this method of calculating excess loss due to terrain was incorporated into the Simulator in August 2000, subsequent to the initial applications presented in Sections 5.1 through 5.3. It supersedes the desensitization approach to uplink modeling that was applied initially to the LA Basin scenario.

3.2 SQUITTER GENERATION

The Simulator models the generation of TCAS ID squitter (which current Mode S transponders produce) in accordance with Mode S MOPS. Several new squitter types intended for use with ADS-B have also been defined; the Simulator allows selection of any combination of these. There are thirteen different types of squitter:

- Acquisition (TCAS ID) Squitter - short (64 μs) Mode S replies, once per second
- Airborne Position Squitter - long (120 μs) replies, nominally twice per second
- Airborne Velocity Squitter - long replies, twice per second
- Aircraft ID Squitter (high rate) - long replies, once every 2.5 seconds
- Aircraft ID Squitter (low rate) - long replies, once every 5 seconds
- Trajectory Change Point (TCP) Message - long reply once per 1.7 seconds
- Subsequent Point Messages (TCP+1, +2, and +3) - long, each every 1.7 sec
- Status Message - long reply, once every 1.7 sec
- Surface (Moving) Position/Velocity Squitter - long, twice per second
- Surface (Stationary) Position/Velocity - long, once every 5 sec
- Surface (Stationary) ID - long, once every 10 sec

All Mode S-equipped aircraft currently transmit acquisition (TCAS ID) squitter. In the future those equipped for ADS-B will transmit some or all of the others as well, depending on their type and status. The Mode S and ATCRBS menus allow selection of any combination of squitters for each aircraft.

Transmission of each type is “nominally periodic with standard rates [as shown above, with the timing of each squitter transmission] uniformly distributed over a ±100 [or 200] ms interval” centered on the nominal transmission time. Timing of each squitter of a particular type is based on the timing of the previous squitter of the same type, in a “random walk” fashion. (This was judged preferable to random departures from periodic times, since it fully randomizes timing more rapidly upon initial turn-on.)

Each acquisition (TCAS ID) squitter is transmitted at a time following the previous one by between 0.8 and 1.2 seconds, uniformly distributed. The short all-call reply format (DF=11) is used. All the other squitter types use the long reply (DF=17) format, and are differentiated by the contents of one of the fields (ME) contained within it. (The Simulator does not include fields and format types, but does generate squitters of the appropriate lengths at the appropriate times.)

Nominal separation times are between 0.4 and 0.6 sec for airborne position and velocity (each operating independently of the other). Separation times for ground position/velocity and for identification depend on whether the aircraft is moving or not. If it is stationary, it transmits ground position/velocity at a nominal 5 sec interval and identity at a nominal 10 sec interval. If it is moving it transmits ground position/velocity at intervals of between 0.4 and 0.6 sec, and ID at 5 sec intervals. (The ground position/velocity squitter compresses both velocity and position into a single 56-bit message.)

Airborne aircraft transmit various combinations of TCP, TCP+1, TCP+2, TCP+3, status and ID squitter, depending on equipage. A fully-equipped high-performance airborne aircraft transmits all five types, plus high-rate ID, position, velocity, and acquisition, for an average squitter rate of 8.4 per second. In the worst case it could produce as many as three positions, three velocities, two acquisitions, five TCP and status, and an identification squitter (14 total) in a given second. At the other extreme, there could be as few as one each position and velocity, and no ID, acquisition or TCP/status squitters within a given 1-second interval.

Some less fully-equipped aircraft will transmit only acquisition, position, velocity, and TCP squitter, and low-rate ID (average total rate 6/sec), while others will not transmit TCP (average total rate 5.2/sec).

If the time at which a squitter should be transmitted coincides with the transmission of another squitter or of a reply to an interrogation, the squitter is delayed until that transmission is completed, plus 10 μs. If it falls shortly before the time an interrogation is received, it prevents reception of the interrogation, and so the associated reply is lost.

3.3 MODE S INTERROGATOR SCHEDULING

Terminal-area Mode S interrogators operate at a common low PRF (125 Hz), interlace Mode S and ATCRBS functions, and employ stagger patterns that repeat every eighth ATCRBS interrogation. Three types of interrogation intervals occur in regular sequence: Mode S All Call, Mode S Roll Call, and ATCRBS. All Call ordinarily employs a 1 ms period, to cover a range out to about 75 nm. Roll call occupies a 6 ms period, allowing several interrogate-respond transactions to occur. ATCRBS also occupies a nominal 1 ms period, but the exact size of this period is varied slightly to provide the staggering, to minimize the incidence of synchronous interference. An additional 450 µs period is inserted immediately preceding every eighth ATCRBS interrogation period, during which a fixed ground-based test target is interrogated. Thus, there are on average about 8 ms between successive ATCRBS interrogations, which results in the nominal 125 Hz ATCRBS PRF. (Exact PRF varies between 124.13 and 124.32 Hz.)

The duration of the ATCRBS interrogation interval varies between 912.5 and 1087.5 µs. Fifteen different interval sizes are possible, varying between these values in steps of 12.5 µs. Eight intervals of various sizes are arranged in sequence to define each of fifteen possible stagger patterns, associated with the fifteen possible Mode S "Site IDs". For example, the stagger pattern used by a Mode S interrogator with site ID 5 is:

937.5 µs
1000 µs
1062.5 µs
1062.5 µs
1087.5 µs
937.5 µs
912.5 µs
975 µs.

All fifteen patterns contain both long and short intervals, mixed together so the average interval duration for each pattern falls close to 1 ms (between 987.5 and 1000 µs). The patterns are listed in Table 3-3. Note that 7000 µs of Mode S processes follow each of these ATCRBS interrogation intervals, and that the test target interrogation interval of 450 µs occurs once during each cycle of eight ATCRBS interrogations.

Successive ATCRBS interrogations are alternated between Mode A and Mode C. All ATCRBS interrogations from Mode S interrogators were originally planned to include P4 pulses (which Mode S transponders sense and therefore inhibit replies). It was found that these interrogations also inadvertently inhibit replies from certain (Terra) ATCRBS

Site ID	1	2	3	4	5	6	7	8
1	950 µs	962.5	975	987.5	1000	1012.5	1025	1037.5
2	987.5	987.5	1025	1050	1075	912.5	937.5	962.5
3	1050	1000	925	962.5	1000	1037.5	1062.5	912.5
4	962.5	962.5	1012.5	1062.5	925	975	1025	1075
5	937.5	1000	1062.5	1062.5	1087.5	937.5	912.5	975
6	987.5	1075	950	1025	912.5	1000	1050	925
7	1050	937.5	1025	925	912.5	1087.5	975	1062.5
8	937.5	1025	937.5	1037.5	962.5	1050	962.5	1062.5
9	1037.5	1025	1012.5	1000	987.5	975	962.5	950
10	1000	987.5	962.5	912.5	912.5	1075	1050	1025
11	1075	1037.5	1000	950	912.5	925	1050	1012.5
12	1075	1025	975	925	925	1012.5	962.5	1075
13	987.5	937.5	1050	987.5	925	1062.5	1075	937.5
14	1012.5	937.5	1062.5	987.5	912.5	1025	950	1075
15	1062.5	975	1087.5	962.5	925	937.5	925	1025

Table 3-3. Mode S Stagger Sequences Implemented in the Simulator

transponders, and so P4 pulses are not presently transmitted by operational Mode S interrogators. (P4 pulses are included in the ATCRBS Mode C transmissions of TCAS interrogators.) The Simulator models both types of ATCRBS interrogations (i.e., with/without P4 pulses), and allows the analyst to specify how they are used. For example, ATCRBS interrogations can be made to alternate between those with P4 present and those with P4 absent, by setting the interlace pattern (as shown in Figure 2-6) to ACac. This results in the sequence:

> ATCRBS Mode A (no P4); Mode S All Call; Mode S Roll Call
> ATCRBS Mode C (no P4); Mode S All Call; Mode S Roll Call
> ATCRBS-only Mode A All Call (P4); Mode S All Call; Mode S Roll Call
> ATCRBS-only Mode C All Call (P4); Mode S All Call; Mode S Roll Call
> ATCRBS Mode A (no P4); Mode S All Call; Mode S Roll Call
> ATCRBS Mode C (no P4); Mode S All Call; Mode S Roll Call
> ATCRBS-only Mode A All Call (P4); Mode S All Call; Mode S Roll Call
> ATCRBS-only Mode C All Call (P4); Mode S All Call; Mode S Roll Call
> Test Target Interrogation.

The eight ATCRBS interrogation intervals between successive test target periods are assigned the eight different time durations (i.e., the stagger pattern) associated with the particular Mode S site ID, in the order given in Table 3-3.

Some Mode S ASRs have extended coverage, out to 120 nm. Assigned 1ms ATCRBS and Mode S All Call intervals are insufficient for that range, so longer intervals are used with these radars, necessitating reduction of their ATCRBS interrogation rate to around 110-115 Hz. For example, the prototype Mode S sensor recently in operation at Lincoln Laboratory had a Mode S All Call period increased to 1504 µs, and ATCRBS interrogation intervals with four values, varying in length between 1440 and 1488 µs in steps of 16 µs. The Simulator can also accommodate these interrogators.

3.4 ATCRBS INTERROGATION STAGGER

While ATCRBS interrogators transmit at assigned nominal pulse repetition rates, the actual timing of each interrogation is usually varied slightly ("staggered") to preclude synchronous interference among interrogators, and to eliminate second-time-around targets (due to range ambiguity). Many stagger patterns are used in today's military and civil ATC radars. To provide additional protection against synchronous interference, radars are also assigned different average PRFs. ATCRBS/IFF PRFs range from 200 to 360 or so interrogations per second (ips) for long-range radars, and from 380 to 450 ips for terminal-area radars. Newer terminal radars (e.g., ASR-7, 9) employ 8-pulse stagger with interval variations of as much as 2:1; older ones use 4 or 5-pulse stagger whose intervals depart only slightly from the nominal.

No specific stagger pattern information was available (other than nominal PRFs), so most of the information that follows was derived from surveys of the 1030/1090 MHz environment that were conducted by MIT Lincoln Laboratory in the late 1970s [8]. The only major change since then has been the introduction of Mode S, so that data is still pertinent to those radars (most of the population) that have not yet been upgraded to Mode S.

3.4.1 8-Pulse Stagger

Terminal radars employing 8-pulse stagger were found by Lincoln Lab to have PRIs varying between 0.804 and 1.393 of their nominal (listed) PRIs. Lincoln did not determine the sequences in which these were sent, but it is reasonable to presume that the longer and shorter intervals were intermixed. The Simulator employs the following sequence (fractions of the nominal PRI):

0.804 1.393 0.820 1.278 0.840 1.020 0.850 0.996

This stagger pattern was applied to the listed nominal PRIs of all ASRs more recent than (and including) the ASR-7.

3.4.2 5-Pulse Stagger

Lincoln also noted that many of the older (pre-ASR-7) terminal radars employed a 5-pulse stagger pattern in which successive interrogations departed from their nominal transmission times by ± 3.6 and ± 7.2 µs. Some also used ± 2.5 and ± 5.0 µs. Again, the orders in which these variations were applied were not measured; the Simulator uses:

0 + 3.6 - 7.2 +7.2 - 3.6 or 0 + 2.5 - 5.0 + 5.0 -2.5.

(Note that these are not percentages but rather departures from nominal times in µs.) The first pattern was applied to all terminal radars predating the ASR-7.

3.4.3 4-Pulse Stagger (ARSR-4)

The ARSR-4 Long Range Radar employs optional 4-pulse stagger with recommended variations from the nominal of 0, 0.853, -42.62, and 43.5 µs [9]. Its nominal PRI varies between 2800 and 3150 µs. Note that these stagger values are site-adjustable parameters that can be changed at will.

3.4.4 No Stagger

Most older long-range radars, military and civil, do not employ stagger, since their PRFs are so low (for long unambiguous range) that second-time-around targets are highly unlikely. The only new long-range radar that has come into the inventory in the past twenty years is the ARSR-4, whose 4-pulse stagger is optional.

3.5 TCAS INTERROGATOR MODELING

TCAS is the air-derived collision-avoidance system that is presently mandated for use in essentially all U. S. commercial aircraft. It operates in the 1030 and 1090 MHz bands, in conjunction with ATCRBS and Mode S, and so is an important component of the overall activity on 1030 and 1090 MHz. Our concern here is more with the interference it produces than with how well it performs its mission. Thus, the Simulator presently only models the signals it produces (and elicits from other aircraft) and the logic by which it produces them. It does not presently model the traffic alerting and collision-avoidance functions the TCAS set performs based on reception of those signals, nor the (few) additional (maneuver coordination) signals it produces in conjunction with those functions.

TCAS II is in widespread use today, and provides both traffic alerting and coordination of (vertical) evasion maneuvers. Its software has been through several revisions. Version 6 is most widely used, but a new version 7 with improved interference-control has recently been coordinated, and TCAS units are being updated to that version presently. The Simulator models only TCAS interrogators that use software version 7. (Several variations, in particular one for smaller aircraft that provides alerting only, are also proposed or in use; their inclusion in the Simulator is presently under consideration.)

TCAS II detects and tracks multiple Mode S and ATCRBS aircraft, and coordinates evasive maneuvers with the Mode S aircraft using special-purpose Mode S messages. It is thus tightly tied to Mode S: every TCAS II-equipped aircraft must also have a Mode S transponder. It performs many functions: Mode S surveillance and communication, ATCRBS surveillance, threat evaluation, threat alerting, calculation of evasive maneuver recommendations, and display of the threat situation and recommended evasion to the pilot. As noted, the Simulator models only two of these functions: Mode S surveillance and ATCRBS surveillance.

Mode S surveillance entails initial detection and regular interrogation of (and communication with) all nearby Mode S-equipped aircraft. ATCRBS surveillance involves periodic transmission of sequences of Mode C interrogations (called "whisper-shout" sequences) designed to mitigate garbling. An interference limiting procedure adjusts the transmitted power levels used in these processes, based on density of other nearby TCAS-equipped aircraft. The two surveillance processes operate sequentially at a 1-second rate; interference limiting adjusts power levels slowly as the aircraft geometry changes. (Since aircraft remain stationary during Simulator runs, the Simulator software calculates interference-limiting parameters for each TCAS interrogator only once, preceding each run.)

3.5.1 Mode S Surveillance

The TCAS II transceiver interrogates Mode S transponders over an omnidirectional antenna on the 1030 MHz uplink, and monitors their replies on the 1090 MHz downlink. Mode S transponders "squitter" acquisition (TCAS ID) messages randomly (Section 3.2), which the TCAS transceiver receives and uses to determine which aircraft are within its vicinity. (Low omnidirectional antenna gain limits transmission and reception range to a nominal 30 nm.) It then periodically interrogates each of these aircraft discretely to determine its altitude, and measure its range and range rate. It determines whether an aircraft is close enough in altitude to constitute a threat, by examining its altitude and altitude rate. For those potential threat aircraft sufficiently close in altitude (within 10,000 ft), it divides range by closing velocity (range rate) to determine time to closest point of approach (CPA). If either range is less than three miles or time to CPA is less than a minute, the aircraft is deemed potentially threatening and is interrogated once a second. Other potentially threatening aircraft within 30 nm and 10,000 ft. in altitude that do not meet this criterion are interrogated once every five seconds. When range and time to CPA fall below lower thresholds (that depend on many additional factors), TCAS warns the pilot and uses additional Mode S message transmissions to plan and coordinate whatever evasive maneuvers it advises him are necessary.

Note that when two aircraft in proximity are TCAS-equipped, each interrogates the other. (Since they have unique addresses, they are able to correlate the resulting resolution processes.) When two aircraft are so close that TCAS commands evasive maneuvers, their interrogation rates increase above once per second, and certain interrogations are repeated to ensure reliable responses. (This process occurs infrequently enough that the interference impact is small; the Simulator does not presently model it.)

3.5.2 ATCRBS Surveillance

TCAS-equipped aircraft also transmit sequences of ATCRBS Mode C interrogations, once per second, to sense the proximity of aircraft that are equipped only with ATCRBS transponders, and determine what unilateral actions they should take to evade them. In dense airspace, replies from multiple ATCRBS-only aircraft to these non-discrete interrogations are likely to overlap ("garble"), so complex interrogation patterns and multibeam antennas are employed, in an effort to limit the number of aircraft responding to each interrogation. The Mode C interrogations include P4 pulses, so Mode S transponders do not reply to them.

TCAS transceivers use two antennas for ATCRBS interrogation: a top-mounted phased-array that generates four beams (forward, aft, left and right) with nominal 90-degree SLS-limited azimuthal beamwidths, and a bottom-mounted antenna. (The patterns of these are specified to the Simulator in the sequence shown in the "Antenna IDs" window of the TCAS menu, Figure 2-5.) The bottom antenna is intended to detect aircraft underneath the TCAS-equipped aircraft, and has limited effectiveness because of multipath from the ground; only a short low-power portion of the whisper-shout sequence is broadcast over it. The Simulator models it as illuminating only the cone-shaped region 45° below the aircraft. All traffic above that angle are contained in one of the (top) directional beams.

Depending on the potential ATCRBS garbling situation in each beam, different interrogation sequences are used. (Power levels given below assume that antenna gain is 5 dB and that the interference-limiting parameter α is set to 1; when α is lower than 1 power levels can be higher.)

3.5.2.1 Single Interrogation

If there are no ATCRBS targets in a beam, a single Mode C interrogation is radiated in it at high power, to detect whether any targets enter it. (Table 3-4 shows the nominal power level radiated into each of the beams.)

Forward Beam	Suppr. Pwr	Interrog. Pwr	**Right Beam**	Suppr. Pwr	Interrog. Pwr	**Left Beam**	Suppr. Pwr	Interrog. Pwr
	None	49 dBm		None	45 dBm		None	45 dBm

Aft Beam	Suppr. Pwr	Interrog. Pwr	**Bottom Beam**	Suppr. Pwr	Interrog. Pwr
	None	40 dBm		None	31 dBm

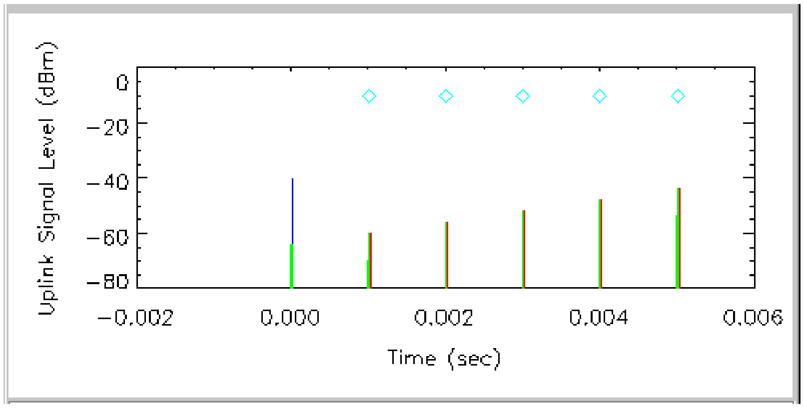
Table 3-4. Power Levels Used for Single Interrogations

3.5.2.2 Minimum Basic Whisper-Shout Sequence

When one or more targets are sensed within a beam, and no two of them garble one another, the TCAS interrogator transmits a sequence of Mode C interrogations within that beam as follows:

> In the ***forward beam***, six interrogations are transmitted, separated by 1-millisecond intervals (Figure 3-2). The first interrogation is transmitted at minimum power (29 dBm), and each subsequent interrogation is increased by 4 dB from the preceding one (so the last one is at 49 dBm if interference limiting is not in operation). A suppression pulse precedes each interrogation (except the

first one), with a level 10 dB lower than the P1, P3 and P4 pulses. (The power levels of these interrogations are enumerated in Table 3-5.)



(Note: Each interrogation includes P1 through P4 pulses)

Figure 3-2. Minimum Basic Whisper-Shout Sequence (Forward Beam)

Forward Beam	Suppr. Pwr	Interrog. Pwr	**Right Beam**	Suppr. Pwr	Interrog. Pwr	**Left Beam**	Suppr. Pwr	Interrog. Pwr
Interrog #1	None	29 dBm	**#7**	None	29 dBm	**#12**	None	29 dBm
#2	23	33	**#8**	23	33	**#13**	23	33
#3	27	37	**#9**	27	37	**#14**	27	37
#4	31	41	**#10**	31	41	**#15**	31	41
#5	35	45	**#11**	35	45	**#16**	35	45
#6	39	49						

Aft Beam	Suppr. Pwr	Interrog. Pwr	**Bottom Beam**	Suppr. Pwr	Interrog. Pwr
Interrog. #17	None	28 dBm	**#21**	None	25 dBm
#18	22	32	**#22**	24	27
#19	26	36	**#23**	26	29
#20	30	40	**#24**	28	31

Table 3-5. Power Levels Used with Minimum Basic Interrogation Sequence

The effect of the suppression pulses and the changing power levels is to subdivide the population of nearby ATCRBS transponders, so different transponders reply to different interrogations, and thus do not garble one another. Closer or more sensitive transponders will respond to the first interrogation, and will suppress on later interrogations since they will detect the suppression pulses preceding them. More distant or less sensitive transponders will reply to those two or three interrogations that are strong enough for them to see, but weak enough that they do not see the leading suppression pulses.

Note that since successive interrogations are separated by 1 ms, transponder reaction to each of them is independent of the one that preceded it. Hence, it does not matter whether interrogation power increases or decreases from one interrogation to the next. Some TCAS transceivers increase power from one interrogation to the next; others decrease it. The Simulator models it as increasing from one interrogation to the next, as in Figure 3-2.

> The ***left and right beams*** employ five interrogations each, starting at 29 dBm and increasing in 4 dB steps to 45 dBm (i.e., 9 dB below maximum power). Suppression pulses are again10 dB below the P1 pulses that follow them, and no suppression pulse is transmitted before the first interrogation.
>
> The ***aft beam*** uses four interrogations, starting at 28 dBm, and again increasing in 4-dB steps (to 40 dBm), with suppressions 10 dB below the following P1s.
>
> The ***bottom beam*** contains four interrogations, at levels of 30, 32, 34 and 36 dBm, with preceding suppression pulses 3 dB below the P1 pulses that follow. These parameters are different to cope with the more severe multipath environment of the bottom antenna.

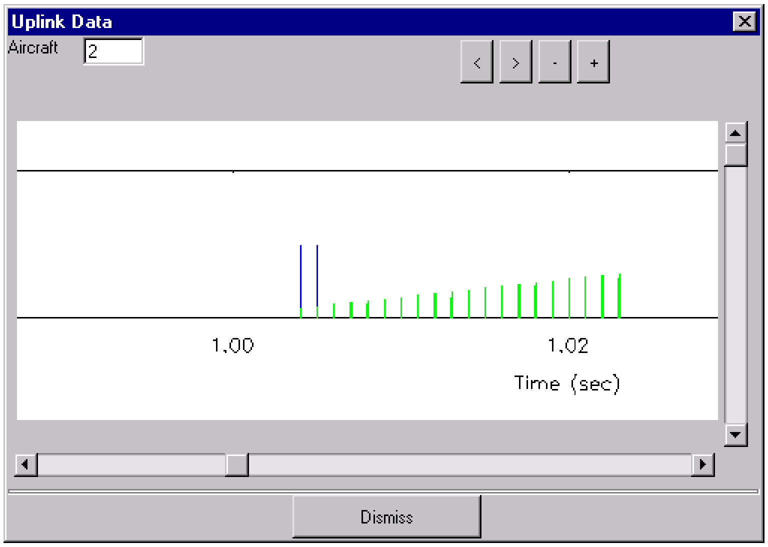
3.5.2.3 High-Resolution Whisper-Shout Sequence

When the TCAS transceiver detects garbling in a beam with the minimum basic sequence, it switches to transmission of this longer sequence in that beam, employing the same basic concepts, but far more extensively:

> The ***forward beam*** employs a sequence of 24 interrogations (Figure 3-3), again spaced 1 ms apart, starting at 26 dBm, and increasing in 1-dB steps to full power (49 dBm) when interference limiting is not in effect. Suppression pulses alternate between 2 and 3 dB lower than the P1s that follow them (except for the first interrogation, which has no suppression).
>
> The ***left and right beams*** use 20-interrogation sequences, starting at 26 dBm and increasing to 45 dBm (4 dB below full power) in 1-dB steps. Suppression pulses alternate between 2 and 3 dB lower than the P1s. Again, no suppression pulse precedes the weakest (first) interrogation.
>
> The ***aft beam*** contains a 15-interrogation sequence, with power level increasing from 26 to 40 dBm in 1-dB steps, and suppressions alternating between 2 and 3 dB below the P1s.

The ***bottom beam*** has four interrogations with levels of 30, 32, 34, and 36 dBm. Suppression pulse levels are 3 dB below the levels of the second, third and fourth interrogations.

The levels of these high-resolution sequence interrogations are summarized in Table 3-6.



Note: the first four interrogations in the sequence were below the receiver threshold.
The receiver responded (blue lines) to the first two interrogations received above its threshold.

Figure 3-3. High-Resolution TCAS Interrogation Sequence (Forward Beam)

Since each TCAS II-equipped aircraft has five antenna beams, and can employ either a single interrogation, the appropriate portion of the minimum basic sequence, or the appropriate portion of the high resolution sequence in each of them, it can generate anywhere from five to 83 Mode C interrogations per second. Examination of whisper-shout interrogation sequence simulation results reveals that a typical ATCRBS-equipped aircraft can reply to as few as one of these interrogations, or as many as three or four, depending on its location and sensitivity.

The Simulator determines which sequence to use in each antenna beam prior to each run by the numbers of aircraft present within that beam, and their range differences. It uses the single interrogation when it determines that no aircraft are in the sector. If one or more aircraft (up to 13) are within the beam, but no two of them are within 1.7 nm (garbling range) of one another, it uses the minimum basic sequence. Otherwise, it uses the full high-resolution sequence. The Simulator performs this determination only once at the beginning of the simulation run (since the geometry doesn't change during it).

Forward Beam	Supp. Pwr	Interr. Pwr	**Right Beam**	Supp. Pwr	Interr. Pwr	**Left Beam**	Supp. Pwr	Interr. Pwr
Interrog. #1	None	26 dBm	**#25**	None	26 dBm	**#45**	None	26 dBm
#2	24	27	**26**	24	27	**46**	24	27
#3	26	28	**27**	26	28	**47**	26	28
#4	26	29	**28**	26	29	**48**	26	29
#5	28	30	**29**	28	30	**49**	28	30
#6	28	31	**30**	28	31	**50**	28	31
#7	30	32	**31**	30	32	**51**	30	32
#8	30	33	**32**	30	33	**52**	30	33
#9	32	34	**33**	32	34	**53**	32	34
#10	32	35	**34**	32	35	**54**	32	35
#11	34	36	**35**	34	36	**55**	34	36
#12	34	37	**36**	34	37	**56**	34	37
#13	36	38	**37**	36	38	**57**	36	38
#14	36	39	**38**	36	39	**58**	36	39
#15	38	40	**39**	38	40	**59**	38	40
#16	38	41	**40**	38	41	**60**	38	41
#17	40	42	**41**	40	42	**61**	40	42
#18	40	43	**42**	40	43	**62**	40	43
#19	42	44	**43**	42	44	**63**	42	44
#20	42	45	**44**	42	45	**64**	42	45
#21	44	46						
#22	44	47						
#23	46	48						
#24	46	49						

Aft Beam	Supp. Pwr	Interrog. Pwr	**Aft Beam (Cont'd)**	Supp. Pwr	Interrog. Pwr	**Bottom Beam**	Supp. Pwr	Interrog. Pwr
Interr. #65	None	26 dBm	**#73**	32	34	**#80**	None	25 dBm
#66	24	27	**#74**	32	35	**#81**	24	27
#67	26	28	**#75**	34	36	**#82**	26	29
#68	26	29	**#76**	34	37	**#83**	28	31
#69	28	30	**#77**	36	38			
#70	28	31	**#78**	36	39			
#71	30	32	**#79**	38	40			
#72	30	33						

Table 3-6. Power Levels Used in High-Resolution Whisper-Shout Sequence

The key to correctly setting TCAS power levels is that the EIRP of the strongest interrogation in the whisper-shout sequence should equal 55 dBm at the peak of the forward antenna beam. All other interrogation power levels are scaled relative to that. The TCAS antenna patterns used by the Simulator have maximum gain of 5 dB at the nose of each beam, and the nominal power-limiting adjustment factor is 1 dB. Therefore the transmitter output power of the strongest pulse in each sequence is 49 dBm (49 dBm + 5 dB + 1 dB = 55 dBm). That reasoning results in the individual pulse transmitter power output levels shown in Tables 3-4 through 3-6.

3.5.3 Interference Limiting

TCAS can cause three different problems to ground-based surveillance radars:

- It can unduly suppress transponders (so their reply probabilities are lowered)
- It can unduly suppress its own co-located transponder (which is unlikely with version 7 software, if the transponder is properly designed)
- It can generate an overabundance of ATCRBS Mode C fruit.

Logic is implemented in all TCAS interrogators to prevent these problems, by limiting total power transmitted in all interrogations, thereby reducing the volume of airspace and number of times per second in which the TCAS unit affects other aircraft. This logic depends on the densities and distributions of other nearby TCAS-equipped aircraft. Every eight seconds, each TCAS interrogator announces its presence by broadcasting a single interrogation on 1030 MHz. Other TCAS sets, detecting these signals through their associated Mode S receivers, continually maintains track on each TCAS aircraft to determine its range, and use this range information in their interference limiting calculations.

3.5.3.1 TCAS Interrogator Interference-Limiting Processes

To limit suppressions of other transponders, each TCAS interrogator adjusts its transmitted power to comply with the equation:

$$\sum_{\substack{\text{all interrogations} \\ \text{in one second}}} \left(\text{Power of each}/250\text{ W}\right)^{\alpha} \leq \text{smaller of } (280/(\text{NTA}+1),\ 11/\alpha^{2}).$$

This expression is intended to ensure that no ATCRBS transponder will ever detect more than 280 TCAS interrogations per second from the total TCAS interrogator population around it. That results in a 1% reduction in suppression rate, on the assumption that each interrogation suppresses the transponder for 35 μs. This was determined to be the maximum additional degradation due to TCAS operation that could be tolerated by the ground surveillance system. In addition, when TCAS density is low, this expression allows a TCAS interrogator to increase its power (and thus its range).

The parameter α characterizes the degree of uniformity of the distribution of TCAS-equipped aircraft; its calculation procedure is described in Sect. 3.5.3.2. When $\alpha = 1$ (which denotes a uniform distribution), the inequality limits the TCAS interrogator to 11 full power interrogations per second if TCAS density is low. When density increases to more than 24 TCAS aircraft, that number reduces (e.g., to 5 when 55 other TCAS aircraft are within range). The interrogator copes with this constraint by reducing the power of its interrogations to bring their total power down to that of the required number of full-power interrogations.

Close to the airport, if $\alpha = ½$ (which denotes a distribution that is uniform in range to the airport), the interrogator is not so highly constrained. It can radiate higher power if density is low. If, for example, there are ten TCAS aircraft within range (distributed uniformly in range), it can radiate the equivalent of 25 full-power interrogations.

An exception is made for fast-flying aircraft operating above 18,000 ft altitude, since such aircraft have high velocities and need all the surveillance volume they can get. For them, eleven full-power-equivalent interrogations are always allowed, regardless of the densities of other TCAS units.

Several types of interrogations contribute to the total number per second:

- The announcement of the TCAS interrogator's presence (once every 8 sec)
- Discrete interrogations of Mode S aircraft deemed threatening (once per sec)
- Discrete interrogations of other aircraft close in altitude (once every 5 sec)
- Whisper-shout interrogations.

Adding the power contained in an entire 83-interrogation high-resolution whisper-shout sequence results in a total equivalent to three high-power interrogations. Thus, in uniformly distributed low-density TCAS operation, the TCAS interrogator can interrogate up to 8 Mode S targets per second and still radiate an entire high-resolution whisper-shout sequence. When there are more targets, or when TCAS density is high enough to reduce the allowed number, the power of individual Mode S interrogations of nearby targets is reduced. If that does not suffice, the maximum Mode S interrogation power is reduced, thereby reducing the coverage volume. In that circumstance, whisper-shout power is also reduced to maintain the Mode S and ATCRBS coverage volumes to the same size.

To limit the generation of ATCRBS Fruit, the TCAS interrogator satisfies a different constraint, that applies only to its whisper-shout interrogations:

$$\sum \text{(Power of each/250 w.)} \leq \text{smaller of } (80/(\text{NTA} + 1), 3)$$

As noted, the total power in the full high-resolution whisper-shout sequence is equivalent to three full-power interrogations; the expression above constrains it to that when TCAS interrogator density is low. It constrains it to a smaller value when there are more than 25 TCAS interrogators within 30 miles. This can be modeled in many ways, some more effective than others. The Simulator models this by calculating a power-reduction factor (the ratio of 80/(NTA + 1) to 3), and applying it to all transmissions in the whisper-shout sequence. Again, high flyers above 18, 000ft altitude are exempted, and can always transmit a full-power high-resolution sequence.

3.5.3.2 Simulator Interference-Limiting Processes and Calculations

To determine the proper interference-limiting parameter settings for each TCAS-equipped aircraft, the Simulator performs the following sequence of functions.

- It first examines the ATCRBS, Mode S and TCAS populations in the vicinity of each TCAS-equipped aircraft to determine what (ATCRBS) whisper-shout sequences to use, how many 1-sec and 5-sec Mode S aircraft are to be interrogated, and how many TCAS aircraft are present within 30 nm (NTA), within 3 nm (NTA3) and within 6 nm (NTA6).

    - It orients a 30-nm circle around the TCAS interrogator, and draws lines at ± 45° and ± 135° relative to its heading (which is included in the scenario data for this purpose),
    - It forms a 45° cone beneath the aircraft to model its bottom antenna.
    - It counts the ATCRBS-only aircraft within the five regions that are formed, and orders them by range within each region.
    - It calculates the differences in successive ranges.
    - It determines the whisper-shout pattern to be used in each sector
        - If there are no aircraft, it uses a single high-power interrogation.
        - If there are from one to thirteen aircraft, and the minimum range difference is greater than 1.7 nm, it uses the minimum basic sequence associated with the sector.
        - Otherwise, it uses the high-resolution sequence.
    - It calculates range and relative velocity of each Mode S aircraft within 10K ft of the TCAS altitude
    - If range divided by relative velocity is less than one minute or if range is less than 3 nm, the target is a threat and is put onto the list of aircraft to be tracked at a once-per-second rate.
    - Otherwise, the target is put onto the once-every-five-seconds list.
    - It calculates ranges to all nearby TCAS interrogators
    - It counts those within 3, 6, and 30 nm. (NTA3, NTA6, and NTA)

- It then calculates the parameter α (from NTA, NTA3 and NTA6), which describes the way other TCAS-equipped aircraft are distributed around the aircraft of interest. If they are uniformly distributed in area, $\alpha=1$; if uniform in range (as might be the case when approaching a busy airport) $\alpha= ½$. If it is below 2000 ft altitude, these counts include all TCAS-equipped aircraft, even if they are on the ground. If it is above 2000 ft, only airborne aircraft are counted.

    - It forms:
      $\alpha_1 = ¼ \ (\text{NTA6} / \text{NTA3})$ and $\alpha_2 = \log_{10} (\text{NTA} / \text{NTA6}) / \log_{10} 25$
      (If distribution is uniform in area, both of these will equal 1)

    - It further constrains α_1 against unusual distributions by setting it to 1 if:

$(NTA6 \leq 1)$ or $(NTA6 \leq 4$ and $NTA3 \leq 2$ and $NTA > 25)$,

and to ½ if:

$(NTA3 > 2)$ and $(NTA6 > 2NTA3)$ and $(NTA < 40)$.

- It finally sets α to the lesser of the two: $\alpha = \min(\alpha_1, \alpha_2)$.

- It then examines the selected whisper-shout sequences to see how many full-power interrogations they equate to, and if that amount exceeds what the fruit-rate limit allows, their power levels must be reduced:

  - A number is chosen from Table 3-7 for each beam that pertains to the sequence type being used in that beam.

Sequence Type:	**Single Interrogation**	**Minimum Basic**	**High-Resolution**
Forward Beam	0.32	0.53	1.54
Right Beam	0.13	0.2	0.61
Left Beam	0.13	0.2	0.61
Aft Beam	0.04	0.06	0.19
Bottom Beam	0.04	0.04	0.02

Table 3-7. Whisper-Shout Sequence Equivalent Power Values

  - These numbers are totaled (The total will be 3 if long sequences are used in all beams, and less than that when some short sequences are used.)
  - The value: $\min(80/(NTA+1), 3)$ is calculated from the number of TCAS aircraft in the vicinity.
  - If this calculation results in a number less than that which resulted from summing the sequence types, the ratio is calculated, and converted to dB.

- It then calculates the total number of Mode S and ATCRBS interrogations, compares it to what suppression-limiting constraints allow, and adjusts it as necessary:

  - The Simulator takes the number of 1-second Mode S interrogations, and raises it to the α power (recall $½ < \alpha < 1$). Next, it takes one-fifth the number of 5-second interrogations, and raises that to the α power. Next, it raises the number 1/8 to the α (to account for the broadcast identifier which is transmitted every eight seconds). It then adds to this total the full-power equivalent number of whisper-shout interrogations calculated above, also raised to the α. The result is the total number of full-power equivalent interrogations that the TCAS would broadcast

  per second if no interference-limiting were required, adjusted to account for the non-uniform aircraft distribution. This must comply with the constraints of the suppression-limiting equation.
  - It then calculates the expression: min $(280/(NTA + 1), 11/\alpha^2)$
  - If this calculation exceeds the sum calculated previously, no interference-limiting correction is required. If it is less, the Simulator divides it by the sum, takes the $1/\alpha$ power of the result, and converts that to dB.

- Finally, the Simulator determines the dominant constraint and applies it to both ATCRBS and Mode S processes (since the coverage regions must be adjusted to remain equal):

  - It takes the larger of the two power reduction values calculated (in dB) in the processes above, and subtracts it from the 1dB nominal interference-limiting factor. It then applies the result to the interrogator output power (and shows it in the "Power Offset" and "Whisper-Shout Levels" windows pertinent to the TCAS aircraft).

4. SIMULATOR CALIBRATION AND VALIDATION

Results produced by the Simulator for future high-density scenarios will be credible only if those produced in smaller scenarios are consistent with what is actually observed in those situations. Thus, a major portion of the development effort is adjustment of the many Simulator parameters to ensure that it closely tracks actual ATC radar system operation. Such "tuning" has occurred continually since the Simulator was first able to replicate idealized one-on-one situations, and will continue into the foreseeable future as more measured performance data becomes available from the actual system. Initially, most of the tuning involved idealized one-on-one or few-on-few situations whose behavior could be predicted accurately from MOPS and other known system characteristics. More recently, focus has shifted to large-scale system performance data gathered in connection with ADS-B testing. In the future, we hope to participate in planning experimentation with the ATC radar system, to ensure that sufficient data is collected to support further validation and refinement of the Simulator.

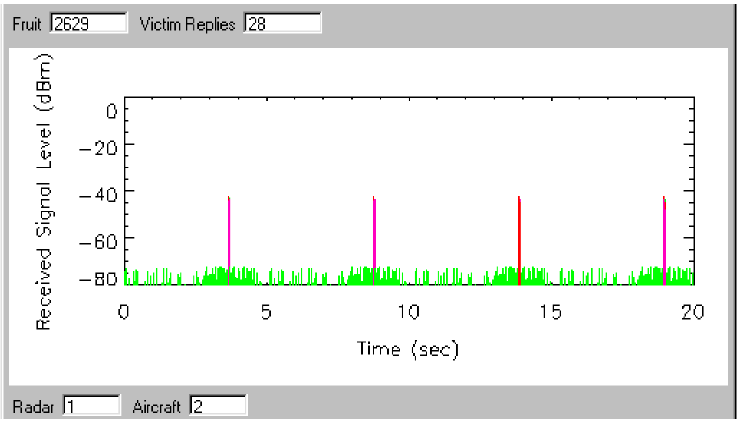
4.1 CALIBRATION USING IDEALIZED SCENARIOS

Several small-scale contrived scenarios were used during early Simulator development to verify that its performance was consistent with what would be expected. These scenarios verified proper power-level calculation, antenna behavior, and interrogation pattern generation.

4.1.1 Power Level Calculations

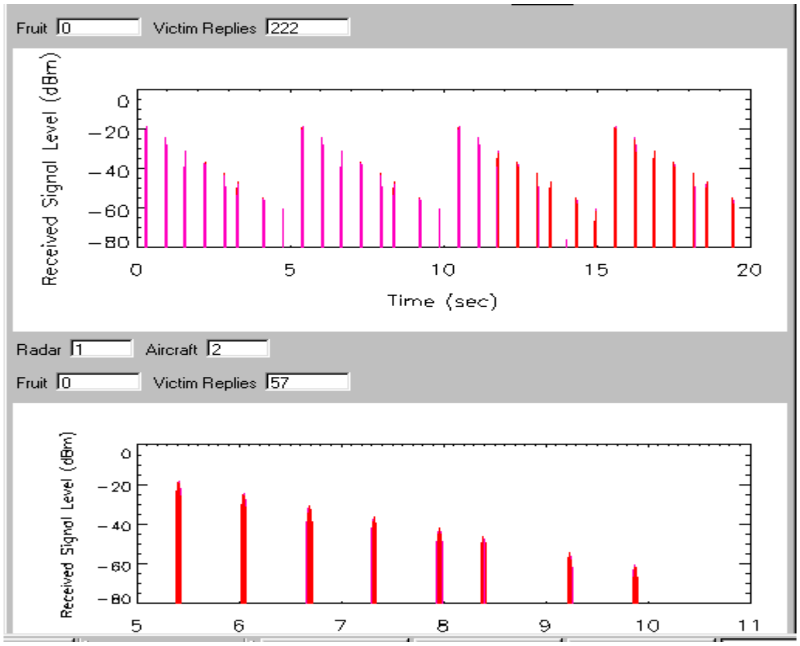
To verify that power levels were being properly calculated, a single ATCRBS-equipped aircraft was placed exactly eight miles due south of a victim receiver coupled to a Mode S interrogator. (Aircraft latitude was 33.9078°, that of the victim interrogator was 34.0411°, and both had the same longitude. The latitude difference, .1333°, equals 7.998 nm.) Calculated freespace pathloss at 1090 MHz and 8 nm is - 116.6 dB. Aircraft power output was + 54 dBm, aircraft antenna gain was 0 dB, random fading of the aircraft antenna was disabled, and radar antenna gain (at peak of beam) was 21 dB. From these values, peak received signal level should equal 54 - 116.6 + 21 = - 41.6 dBm. A plot of the signals seen by the radar over a twenty-second interval was generated (Figure 4-1), from which it can be seen that the simulated signal level is consistent with this value. A second interrogator with an omnidirectional antenna and a high PRF was placed close to the aircraft, to cause it to continuously produce fruit as well. The fruit also appears in Figure 4-1, and its level traces out the shape of the victim receiver's antenna pattern.

To verify proper variation of received power level with range (i.e., as R^{-2}), seven additional aircraft were placed around the interrogator. Each had azimuth greater than the previous by 45º and range a factor of two greater than the previous, varying from 1/2 nm to 64 nm. Fruit generation was suppressed, and aircraft antenna variation remained disabled. Figure 4-2 presents the reply sequence observed over a twenty-second interval in the upper window, and an expansion of a single scan in the lower window. It can be seen that level drops regularly by 6 dB from one aircraft to the next, as it should.


Fruit 2629 Victim Replies 28

Radar 1 Aircraft 2

Figure 4-1. Reply Sequence From a Single ATCRBS Aircraft at 8 nm.
(Aircraft is also producing fruit)

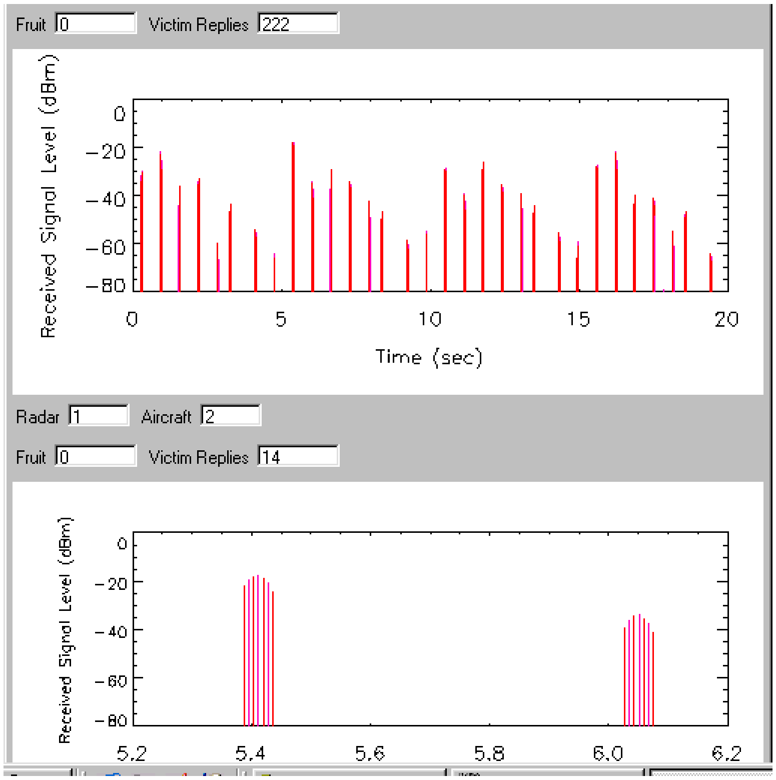

Fruit 0 Victim Replies 222

Radar 1 Aircraft 2

Fruit 0 Victim Replies 57

Figure 4-2. Reply Sequence from Eight-Aircraft Spiral
(each aircraft has twice the range of the previous)

Finally, the spiral scenario was repeated, but with random aircraft antenna gain enabled. Figure 4-3 resulted. Examination of the levels of the reply sequences from the several aircraft showed them to be consistent with the nominal values and with the gain distribution used in the randomization process.



Fruit 0 Victim Replies 222

Radar 1 Aircraft 2

Fruit 0 Victim Replies 14

Figure 4-3. Reply Sequence from Spiral, with Antenna Gain Variation Enabled

4.1.2 Directional Antenna Characteristics

The Simulator presently contains two directional antenna patterns, either of which can be selected for any interrogator. One was measured at the FAA Oklahoma City antenna range facility, on a new ASR beacon antenna. The other has sidelobes and backlobes which were synthesized from data collected at Philadelphia International Airport by the airborne measurement system operated by MIT Lincoln Laboratory [8]. That data shows occasional high sidelobes due to multipath reflections from objects on the airport surface – the same process that produces false targets – and is therefore more representative of an operational installation than is idealized pattern range data.

The synthesized as-installed pattern includes the mainbeam gain/beamwidth characteristics that were measured at the pattern range. Its sidelobe levels and occurrence rate are consistent with the airborne measurements: peak sidelobes as high as -30 dB below the mainbeam peak occur over about eight percent of the sidelobe region and three percent of the backlobe region. That pattern is shown in Figure 4-4.

The single aircraft scenario was used with the second fruit-producing interrogator present and random antenna gain variation disabled, to confirm proper relationships between antenna beamwidth, scan rate, dwell time, and the number of replies elicited (runlength).

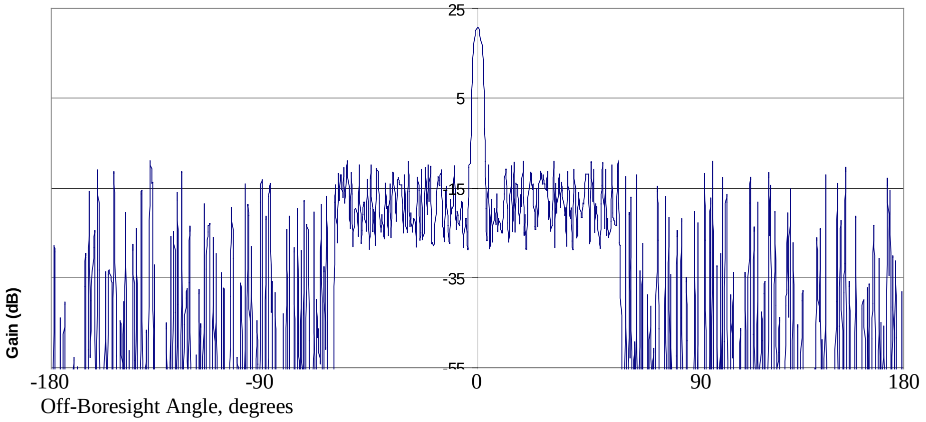
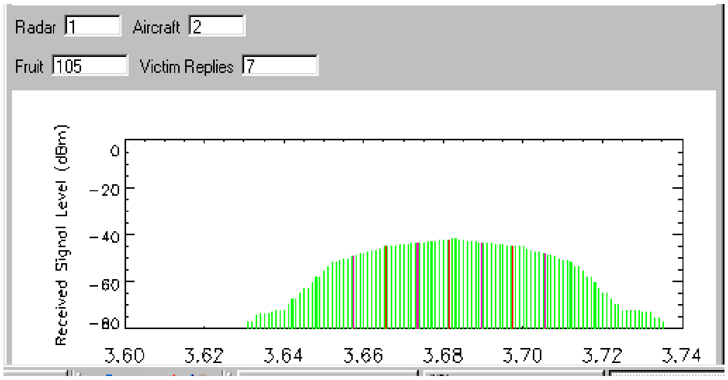


Figure 4-4. Synthesized ASR Antenna Pattern

Figure 4-5 shows a single scan past the aircraft. The victim radar antenna made a complete revolution in 5.1 sec, so a degree equates to 0.0142 sec. The angles corresponding to the timing between the first and last synchronous replies, the - 10 dB points, and the -20 dB points are 3.4°, 4.0°, and 5.1°, respectively. The beamwidth at the sensitivity threshold of the victim receiver (-79 dBm) is about 8°. (That threshold is 38 dB below peak here, consistent with the 8nm range to the aircraft.)



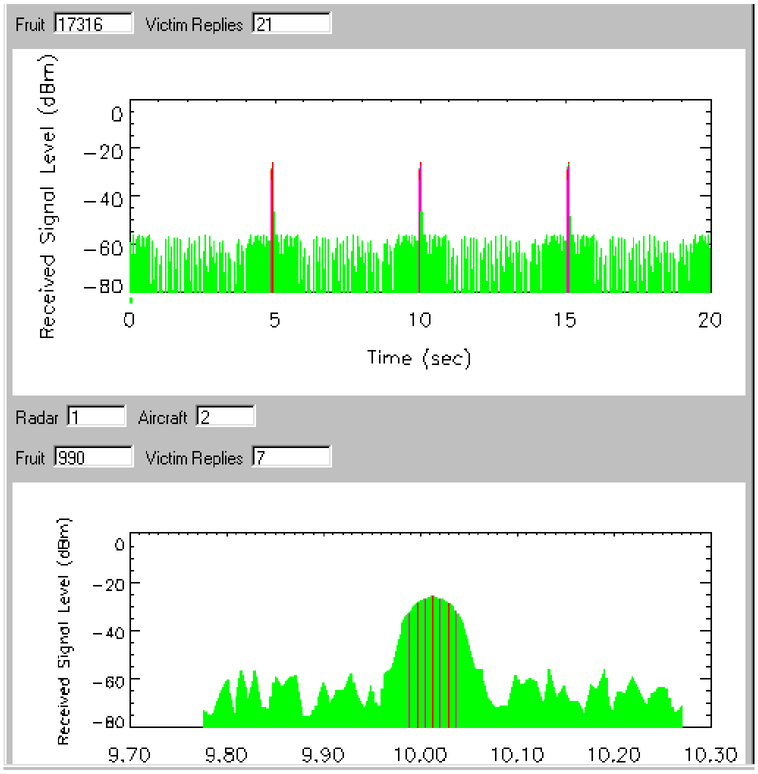
Radar 1 Aircraft 2

Fruit 105 Victim Replies 7

Figure 4-5. Single Mainbeam Scan Past Aircraft at 8 nm

These beamwidths agree with the ASR antenna mainbeam pattern provided by FAA. The first value, 3.4°, is slightly less than the antenna beamwidth at the - 9 dB point, where SLS operation inhibits replies. (In this instance, seven synchronous replies were received. Depending on the relative phasing of the antenna scan and the PRF, eight replies are occasionally observed. These values are consistent with the PRF and scan rate of the victim interrogator.)

Antenna sidelobe level distribution is also of interest, since it determines the amount of fruit received from nearby aircraft. To examine the sidelobe pattern, the scenario with the single fruit-producing aircraft was used, with the range reduced to 1 nm to raise sidelobe reply levels above the victim receiver threshold. The aircraft produced fruit at a rate of 2000/sec. (It also produced seven legitimate replies per scan when within the mainbeam, at a peak rate of 125 replies per second). As the victim interrogator antenna rotates, its directional pattern, including the sidelobes, modulates the received fruit level. Figure 4-6 shows the received reply sequence over four full scans (top), and during an expanded ½ sec interval (bottom), centered on a mainbeam dwell.



Fruit 17316 Victim Replies 21

Radar 1 Aircraft 2

Fruit 990 Victim Replies 7

Figure 4-6. Antenna Sidelobe Characteristics, as Determined by Received Fruit

The 2K/sec fruit generation rate produced 40,000 total fruit during the 20sec period shown in the top plot of Figure 4-6. Of these, 17316 were received above the victim receiver threshold, -79 dBm. At 1 nm, that threshold level is exceeded when antenna gain is greater than -35 dBi. Thus, directional antenna gain is greater than -35 dBi over 43.3% of the entire 360° of azimuth. This test was repeated at a number of different distances to produce the data presented in Figure 4-7. A shorter runtime was used in these cases, so only 20K fruit were generated during each run, and the 10K received fruit point on the ordinate equates to 50% of the total fruit generated (received when the aircraft is approximately ½ nm from the antenna). The plot shows that some sidelobe fruit will be received from aircraft within about 20nm. Beyond that range, fruit is received almost entirely through the mainbeam.

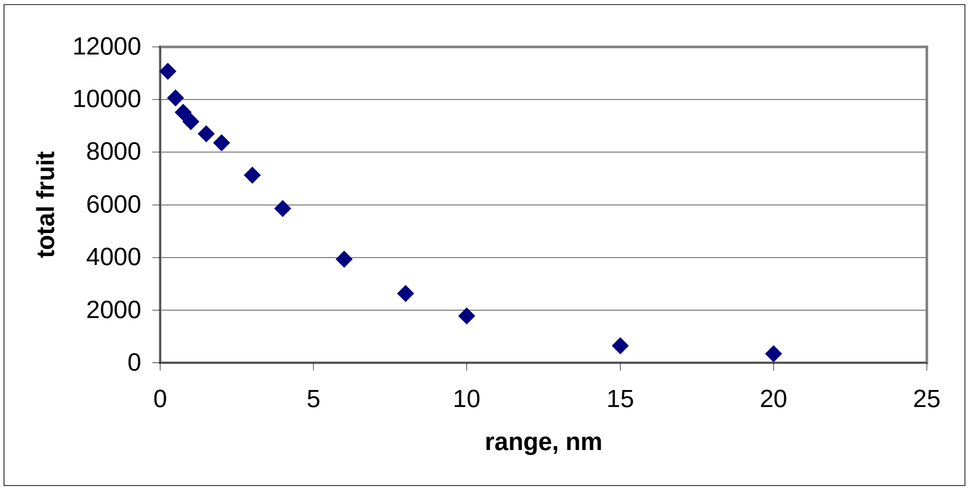


Figure 4-7. Received Fruit vs. Distance
(of 20K total possible)

4.1.3 TCAS Operation

To confirm that TCAS whisper-shout interrogation sequences were producing proper numbers of replies, a scenario was used (Figure 4-8) that contained a single TCAS interrogator heading north, surrounded by four aircraft, two ATCRBS-equipped (to the left and right of the TCAS aircraft) and two Mode S (above and below). The victim receiver was located near the TCAS aircraft but not associated with it. The reply sequence seen by the victim receiver is shown in Figure 4-9. The top window shows that groups of replies occur at nominal 1-sec intervals, slightly randomized. The bottom

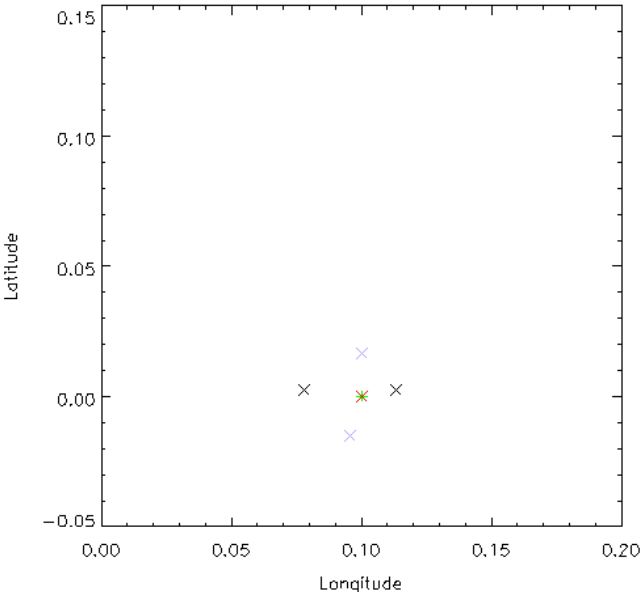
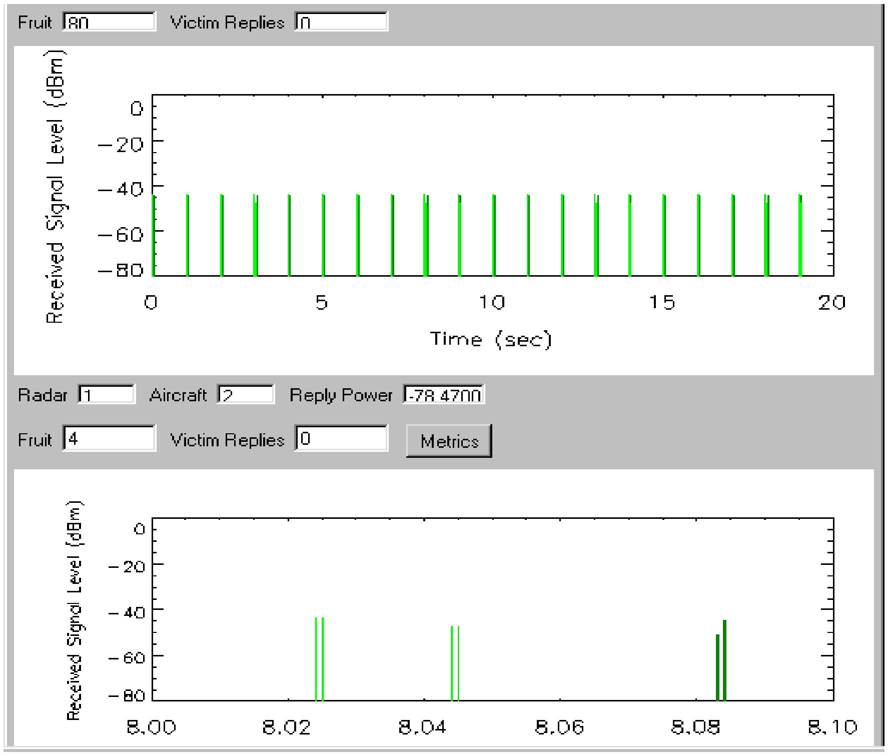


Figure 4-8. 4-Aircraft TCAS Scenario


Fruit 80 Victim Replies 0

Radar 1 Aircraft 2 Reply Power -78.4700

Fruit 4 Victim Replies 0

Figure 4-9. Replies Elicited by TCAS in 4-Aircraft Scenario

window expands one of the groups, and shows first two stronger ATCRBS replies from the aircraft to the right coinciding with the timing of the right beam, then two ATCRBS replies from the left aircraft, again coincident with the left beam. The two replies from each aircraft are separated by 1 ms, showing they were elicited by adjacent whisper-shout interrogations. After the 84 ms whisper-shout time period is completed, the TCAS scheduling algorithm interrogates Mode S targets at 1 ms intervals, since they are at close range. Replies from the two Mode S targets are seen at 8.084 and 8.085 seconds.

The test scenario was then expanded to verify proper operation when multiple (32) ATCRBS targets are present, arrayed uniformly in azimuth (Figure 4-10).

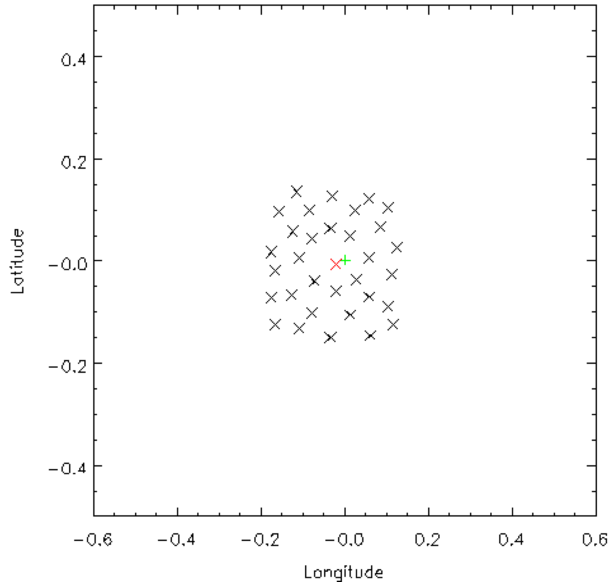


Figure 4-10. Multi-Target TCAS Test Scenario
(Single TCAS Interrogator denoted by red X at center; victim receiver at cross)

In this situation, each beam elicits multiple replies at several whisper-shout levels (Figure 4-11). The responses to the four beams can be identified in the figure. Thirty-two ATCRBS aircraft were interrogated, with High-Resolution Whisper-Shout sequences on all beams; a total of 108 replies resulted, an average of 3.4 per aircraft.

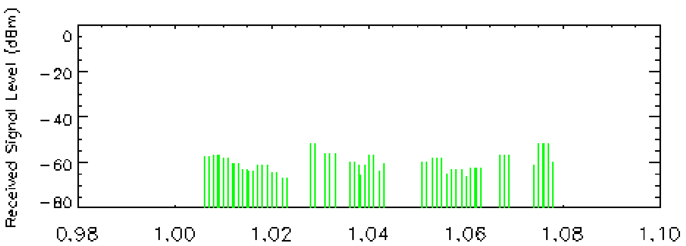


Figure 4-11. Replies from 32 ATCRBS Aircraft to a Single TCAS

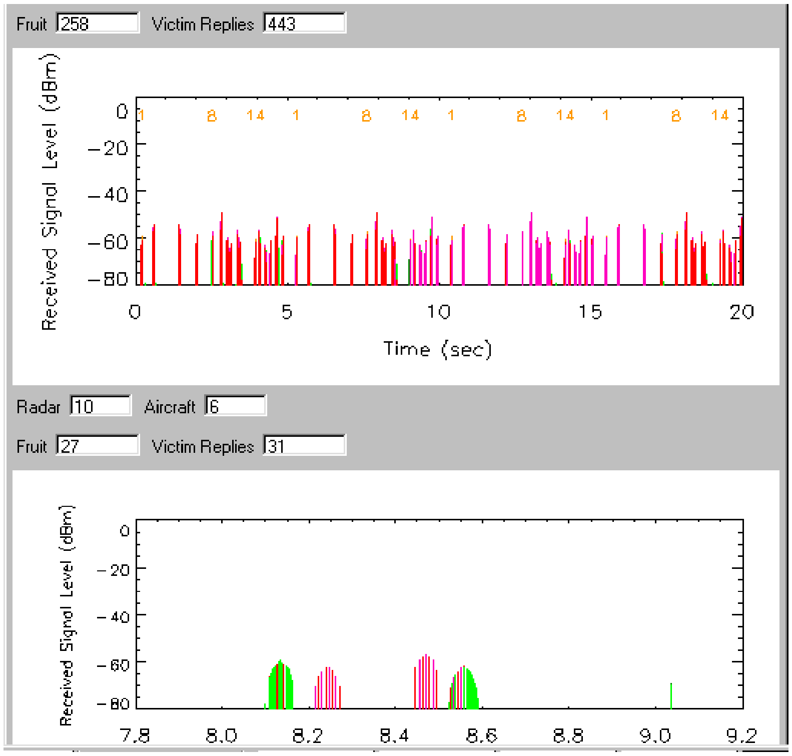
This is higher than the two replies generated by each aircraft in the previous scenario, because in this case many of the aircraft were in regions covered by two beams, and so replied to both. Detailed examination of the replies shown in Figure 4-11 showed that aircraft centered in the beams produced two replies, while those near beam intersections produced four, occasionally five.

4.1.4 Multi-Aircraft, Multi-Interrogator Scenario

To verify proper operation in a multi-aircraft, multi-interrogator situation, a scenario was used that contained sixteen aircraft, uniformly arrayed in a 4x4 grid, superimposed on the fifteen interrogators in the Los Angeles area that are closest to LAX. Seven of these were Mode S equipped; one was an ARSR. The LAX North interrogator was designated as the victim. The closest aircraft was sixteen nm from it, the next closest was 20 nm, and the furthest was 80 nm away.

Actual radar parameters were used. The average PRF of the 14 non-victim interrogators was determined to be 226 Hz, a low value since many of them were Mode S, with 125 Hz PRF. Interrogation beamwidths were all 3.6°. We would therefore expect the fruit elicited from each aircraft by all of them to be 14 x 226 x3.6/360 = 31.75 per sec. In this scenario, not much of that would be seen since no aircraft were within 15 nm, the range at which sidelobe fruit becomes significant (Figure 4-7). Rather, we would expect a total fruit count around 200 (31.75 f/s/ac x 16 ac x 20 sec x 7/360), on the assumption that the beamwidth at which replies from a target at the “average” range are received above threshold is around 7º. A total fruit count of 258 was actually observed (Figure 4-12).

The top window of Figure 4-12 shows 63 target reports, one less than what four full scans of 16 aircraft would produce. This is because a radar scan period of 5.1 sec was used, resulting in slightly less than four full revolutions in the 20-sec period, and one aircraft was missed.


Fruit 258 Victim Replies 443

Radar 10 Aircraft 6

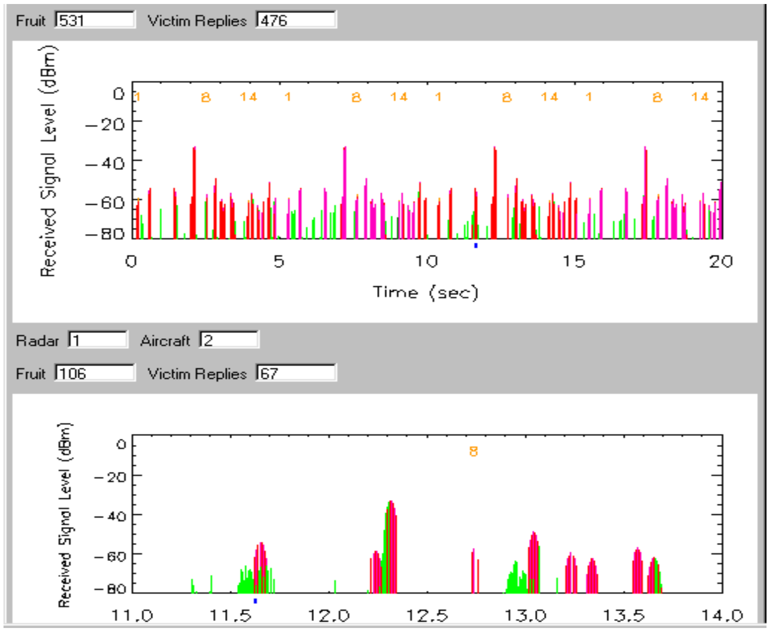
Fruit 27 Victim Replies 31

Figure 4-12. Replies Observed in 16 Aircraft, 15 Interrogator Case

Examination of individual reply sequence timing and levels was consistent with ranges and azimuths estimated from the radar and target positions. There were 443 total synchronous replies, an average of 7.03 per target. Essentially no sidelobe fruit was noted. The lower window shows several mainbeam dwells during which the aircraft were illuminated by other interrogators, and produced mainbeam fruit.

To see the effect of sidelobe fruit, we added a seventeenth aircraft to the scenario at 2.6 nm range. That aircraft produced 33 additional elicited replies, an average of 8 per scan, consistent with its short range. It also produced 273 additional fruit, mainly in the sidelobes, more than the total produced by all the other aircraft. The reply sequences shown in Figure 4-13 contain these additional replies from the close-range aircraft, and can be compared with Figure 4-12 to see them. From its range, we would expect to see about 40% of the total fruit produced by that aircraft, 254 (31.75 x 20 x 40%).

As a consistency check on the changes resulting from addition of the seventeenth aircraft, the scenario was further modified to remove all aircraft but that one. Its power output was increased by 10 dB, equivalent to moving it a factor of 3.1 closer to the victim, to a range of about 0.8 nm. At that range we would expect that about 50% of its sidelobe fruit would get through the victim antenna sidelobes. The total amount of fruit received was 349. This compares with a predicted value of (31.75 fruit per aircraft x 20 seconds x 50%) = 318.

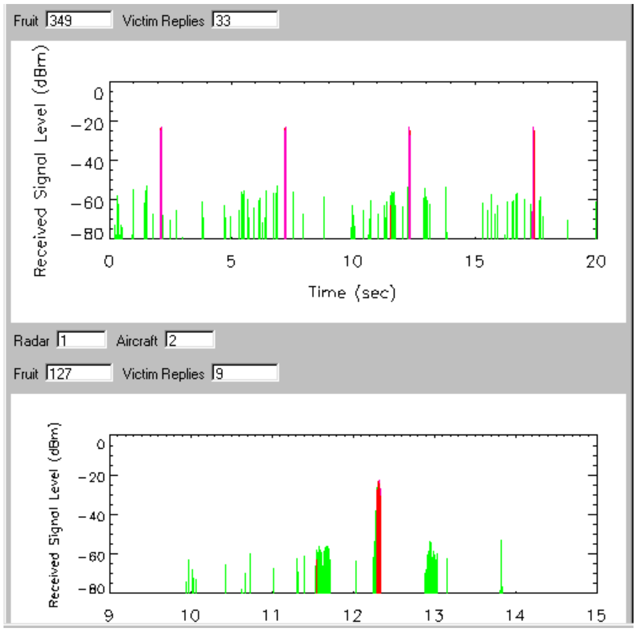

Fruit 531 Victim Replies 476

Radar 1 Aircraft 2

Fruit 106 Victim Replies 67

Figure 4-13. Addition of a 17th Aircraft at Close Range to the Previous Case
Note the Four Additional Strong Reply Sets and Occasional Sidelobe Fruit

Figure 4-14 shows the replies received from only the single close-range aircraft. The top plot shows all four scans; the bottom plot shows the scan that contained the most fruit, 127. The other three scans produced 69, 64, and 89 fruit (totaling the 349 noted above). This variability from scan to scan is due to the random initial orientations and different scan rates of the radars in the scenario (and the fact that the San Pedro ARSR scanned past the aircraft only once during the 20 seconds).


Fruit 349 Victim Replies 33

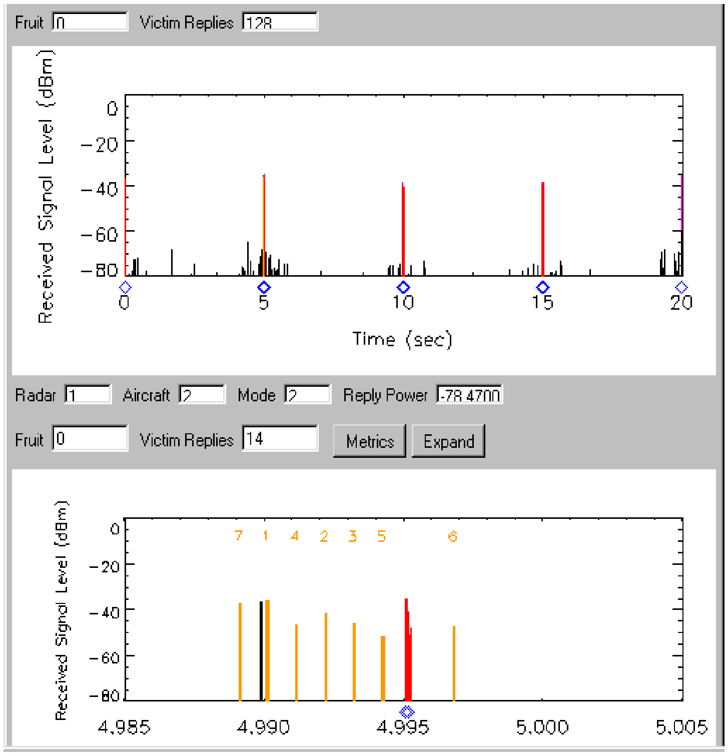
Radar 1 Aircraft 2

Fruit 127 Victim Replies 9

Figure 4-14. Replies From the Seventeenth Aircraft, Alone.
(With power output increased by 10 dB)

4.1.5 Mode S Scheduling, Garble Detection, Squitter

Proper operation of the Mode S scheduling algorithm, ADS-B squitter generation, and ATCRBS synchronous garble detection was confirmed with a scenario containing seven Mode S targets arrayed at close range in a radial line, directly north of the victim interrogator. The "Terra Fix" was activated in the victim Mode S interrogator, so all the aircraft responded to its ATCRBS interrogations as well. Figure 4-15 shows what was observed: all aircraft generated nearly simultaneous Mode S and (garbled) ATCRBS replies once per scan (at 5 sec intervals).



Fruit 0 Victim Replies 128

Radar 1 Aircraft 2 Mode 2 Reply Power -78.4700

Fruit 0 Victim Replies 14

Figure 4-15. Mode S Replies, Squitter, and Garbled ATCRBS Replies
(from seven Mode S Aircraft closely spaced along a radial line)

Squitter replies (black) were noted frequently at other times in the antenna sidelobes. The lower window expands one of these intervals: individual Mode S replies from the seven aircraft can be seen occurring in sequence (along with a squitter that occurred during the same dwell period). The interrogator was programmed to elicit a maximum of six discrete Mode S interrogations per roll-call period, so the seventh occurred during the following period. The overlapping ATCRBS Mode A replies that occurred between the periods were correctly flagged as garbled (with the blue diamonds below them).

4.2 THE 1999 LOS ANGELES EXPERIMENT

Only one opportunity has arisen recently in which sufficient data was collected to both completely define a scenario and measure a system characteristic that the Simulator could predict (from the scenario), to allow comparison between the predicted and the actual. In June, 1999 Lincoln Laboratory and other organizations tested air-to-air ADS-B operation in the area around Los Angeles [10]. As part of that effort, fruit measurements were made by an instrumented airborne facility. In addition, the traffic in the area was recorded (by the LAX ARTS 3 facility).

4.2.1 Scenario

A Simulator scenario was constructed from the recorded traffic and our listing of the ground-based interrogators in the area (Figure 4-16). The victim replicated the instrumented airborne facility (stand-alone, omni antenna, 18K ft altitude, 18 miles NW of LAX). This scenario was run to estimate resulting fruit rates, which were then compared with what the airborne facility actually measured.

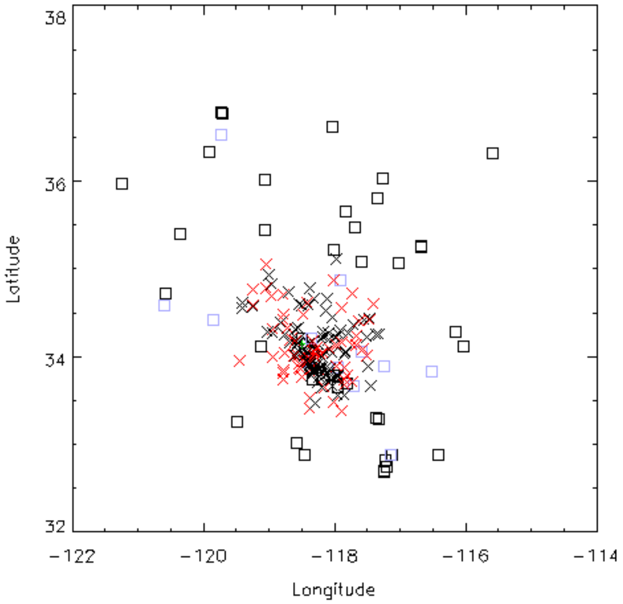


Figure 4-16. The Los Angeles Experiment Scenario

The scenario replicated the actual traffic seen by the LAX ARTS: 166 aircraft within 70 nm of LAX, of which 70 were Mode S and TCAS-equipped, and 96 had ATCRBS transponders. There were 52 interrogators, all those within 200 nm of LAX. Thirteen of these were Mode S and nine were ARSRs. (These interrogators are listed in Table 5-1.)

The instrumented facility could measure, and the Simulator could produce, several different interference parameters:

- ATCRBS cumulative fruit rate, at various received power levels
- Mode S Ground Interrogator-elicited cumulative fruit rate, various levels
- TCAS-elicited Mode S cumulative fruit per second, various levels
- Mode S Squitter (TCAS ID)
- Ground and TCAS interrogation rates (uplink).

4.2.2 Simulator Uplink Adjustment by Desensitization

Initial operation of the Simulator with the Los Angeles scenario revealed excessive interrogation rates, since initially all aircraft were being interrogated by all radars, because the Simulator did not include terrain blockage effects. The terrain around the Los Angeles basin clearly limits the view of aircraft at low altitude within the basin to those interrogators within a few miles, perhaps 30 or 40 nm, depending on direction. The Simulator was adjusted to account for this limitation by desensitizing aircraft transponders as a function of their altitudes. High-altitude aircraft above 18000 ft were modeled with full sensitivity, since at that altitude all interrogators in the scenario are above the radio horizon. Below that, sensitivity thresholds were assigned as shown in Table 4-1**.**

Note that Simulator operation was modified in August 2000 to model losses due to terrain more deterministically (as discussed in Section 3.1.3). As a result, the desensitization approach described here is no longer in use. Validation of the Simulator with terrain loss modeling is discussed in Section 4.2.3 of this report.

Altitude Range	Desensitization	Max. Range	Int. Rate
< 2500 ft	25 dB	22 nm	8 i/s
2500 – 5000 ft	20 dB	39 nm	16 i/s
5000 – 7500 ft	15 dB	70 nm	35 i/s
7500 – 10000 ft	10 dB	123 nm	85 i/s
10000 – 18000 ft	5 dB	220 nm	125 i/s
> 18000 ft	0 dB	370 nm	150 i/s

Table 4-1. Desensitization Values Used Initially in the L.A. Basin Scenario

The values in the “Max. Range” column of the table are calculated from the amounts of desensitization, assuming nominal interrogator peak power output of 300 watts, and no fading margins. They represent nominal radii of circles centered on each aircraft, within which all interrogators will be in view. The “Int. Rate” column was derived using the Simulator, by placing a single aircraft at various locations within the basin, varying its sensitivity, and noting its reply rate (in this situation equal to the interrogation rate). It is essentially the total interrogation rate from all radars within the ranges to the aircraft noted above. It was surprisingly insensitive to exact aircraft location, and agrees closely with the interrogation rate measured by the instrumented aircraft at 18000 ft, 120 interrogations per second.

4.2.3 Inclusion of Terrain Losses

One major shortcoming of the desensitization approach is that a desensitized transponder does not reply properly to TCAS interrogators at moderate range. Transponder desensitization, while properly limiting the range at which ground interrogations are received, also improperly limits TCAS coverage volumes. To correct this inaccuracy, the Simulator was augmented in August 2000 to calculate and include the additional losses due to terrain in pathloss calculations, as an alternative to desensitization. This necessitated incorporating a terrain elevation database into the model, and calculation of the additional loss caused by terrain for each interrogator-aircraft pair, at the outset of each simulation run. It also necessitated readjustment of all radar elevations, to reasonable heights above the ground elevations in the data base for their locations (and in some cases, corrections to aircraft altitudes to ensure that they were at appropriate AGL altitudes). The operation of the terrain modeling process was described in Section 3.1.3 of this report. The accuracy improvements resulting from its inclusion are discussed below. They are clearly worth the large increase in runtime that it causes. (Terrain-based calculations roughly doubled the execution times of the larger LAX scenarios.)

4.2.4 Results

Various interference rates produced by the Simulator are compared with measured values in Table 4-2. The first two columns show Simulator results for the desensitization approach and the terrain modeling approach, respectively. Values actually measured by the instrumented aircraft are shown in the right column.

Type of Fruit	Sim-(desens)	Sim-(terrain)	Measured
ATCRBS <-74 dBm	3141 per sec	4395 per sec	4-5K per sec
ATCRBS <-79 dBm	5515 per sec	8062 per sec	7-10K per sec
Mode S Ground	97 per sec	76 per sec	100 per sec
TCAS-elicited Mode S	59 per sec	181 per sec	512 per sec
TCAS ID Squitter	54 per sec	52 per sec	319 per sec

Table 4-2. Comparison of Simulated and Measured Fruit Rates

4.2.4.1 ATCRBS Fruit Rate Estimation

The ATCRBS fruit rates produced by the Simulator when using the desensitization approach were lower than measured values, for two reasons. First, the desensitization vs. altitude profile that was chosen was apparently too severe. When the 5 dB steps shown in Table 4-1 were reduced to 4 dB steps (Table 4-3), the resulting fruit rates increased to 3878 and 6692**.** These rates are about 15% below the averages of the measured rates.

Altitude Range	Desensitization	Max. Range	Fruit Rate
< 2500 ft	20 dB	39 nm	16 f/s
2500 – 5000 ft	16 dB	64 nm	30 f/s
5000 – 7500 ft	12 dB	100 nm	65 f/s
7500 – 10000 ft	8 dB	155 nm	95 f/s
10000 – 18000 ft	4 dB	247 nm	135 f/s
> 18000 ft	0 dB	370 nm	150 f/s

Table 4-3. Less Severe Desensitization Profile (4 dB Steps)

Second, although the actual measurement situation was well-instrumented, there was still missing information. While the instrumented aircraft saw all aircraft in the area, including those at low altitudes and long ranges (because of its 18000 ft altitude), the LAX ARTS saw only those long-range aircraft at high enough altitudes to be above its horizon (limited by mountains). There was no information on how many aircraft were present at long-range and low-altitude. Such aircraft would contribute to the measured fruit rates, but were not included in the simulation. Based on this, we selected the 4-dB-step desensitization profile of Table 4-3 (which understates fruit rates slightly) in the analyses discussed in Section 5.1 through 5.3, which were performed prior to incorporation of the terrain loss model.

ATCRBS fruit rates produced by the Simulator using terrain loss calculations were in substantial agreement with measured values, just slightly (2%) lower than measured mean values, presumably because of the long-range low-altitude aircraft noted above.

4.2.4.2 Mode S Fruit Rate Elicited from Ground Radars

Mode S fruit resulting from ground-based interrogators was consistent with actual measurements. Differences are attributable to uncertainties in how the thirteen Mode S interrogators in the area were actually operating when the measurements were taken. (Some interrogate twice.) It is doubtful that many of the long-range low-altitude aircraft noted above were Mode S equipped, since they were likely military and general aviation.

4.2.4.3 TCAS – Elicited Mode S Fruit Rate

The model produced only about 11% of the measured fruit resulting from discrete interrogations by TCAS when using the desensitization approach. This was primarily because desensitization reduced TCAS coverage range significantly. It was noted that many TCAS discrete interrogations did not elicit replies from aircraft that should have produced them, given their distances from the TCAS interrogators.

Several other factors also contributed to this large discrepancy. First, the Simulator implements TCAS version 7 software, which has significantly enhanced interference-reduction features. Measurement occurred before any aircraft were updated with the new software. Examination of actual data by Lincoln Laboratory [10, pp. 36-37] revealed that some aircraft were responding to TCAS interrogations at very high rates, as many as 25 replies per second from one aircraft. Examination of some individual TCAS replies produced by the Simulator showed them to be generated by the 45 Mode S aircraft closest to the victim, and produced consistently with version 7 rules. Replies elicited by various TCAS aircraft were only generated by other aircraft very close to them, and depending on threat, about half the replying aircraft replied only once every five seconds. Individual TCAS interrogators tracked various numbers of potentially threatening targets, from as few as one to as many as nine, with an average of 2.7. The simulation did not include any of the potentially high rate communications that occurs during an encounter, and because the ARTS data did not include heading, that parameter was assigned randomly in the simulation.

When the scenario was re-executed with terrain loss calculations included, transponder desensitization was not used, so numbers of aircraft responding to discrete TCAS interrogators increased significantly, by about a factor of three. A typical TCAS aircraft (Figure 4-17) elicited replies from thirteen Mode S equipped aircraft, at ranges greater than 20 nm. Total TCAS-elicited fruit increased by about a factor of three, but still is only 35% of what was measured, presumably because of the other discrepancies in the data noted above.

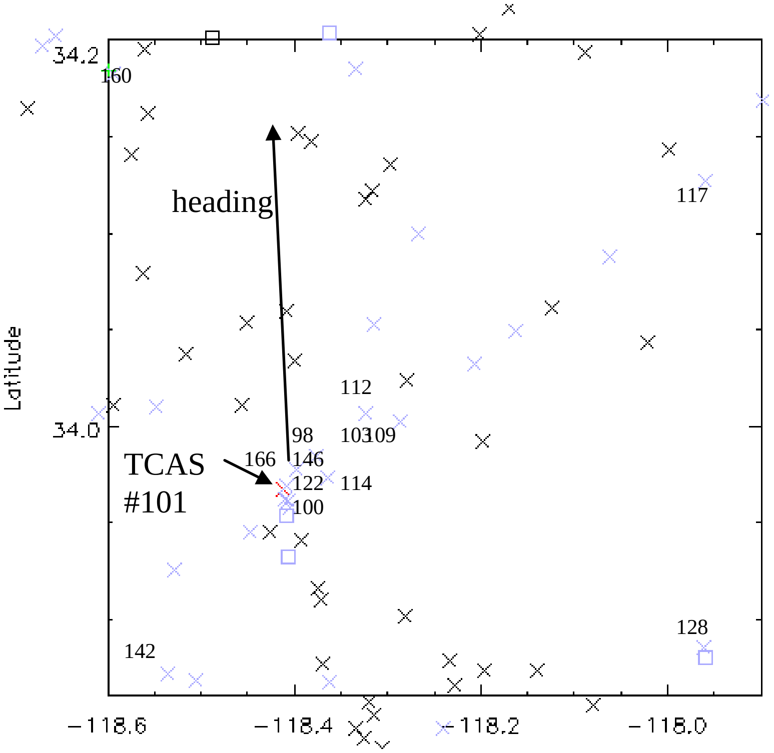


Figure 4-17. Mode S Aircraft Replying to TCAS #101
Terrain Loss Calculation in use – No Desensitization

4.2.4.4. TCAS ID Fruit Rate

TCAS standards specify that each equipped aircraft generate a TCAS ID once every second. Since there were 45 equipped aircraft (of the 70 total) that were close enough to the victim for their replies to be detected, we would expect to see TCAS ID squitters occurring at a rate of about 45 per second. The Simulator produced 54 per second with desensitization and 52 per second with terrain loss calculations. (Since squitters are not elicited and the receiver was airborne, we would not expect transponder desensitization to affect this number.) Actual measurements revealed 319 per second. Lincoln Laboratory concluded [10, p. 38] that about half of these were replies to Mode S Only All-Call interrogations (which are not modeled by the Simulator), and that the remainder was still excessive, because some Mode S transponders were producing short squitters at higher than the proper rates. (One produced as many as seven per second at some times.)

4.2.4.5 Interrogation Rate

With inclusion of terrain effects on the uplink, it became possible to model the expected interrogation rate as a function of aircraft altitude. (Desensitization also establishes different rates at different altitudes, but does so somewhat arbitrarily.) With the terrain loss feature in place, we ran multiple simulations with a single aircraft 20 nm ESE of LAX, at various altitudes. Figure 4-18 shows the resulting interrogation rate dependence on altitude. Note that it agrees closely with the one sample measured during the 1999 test program: 120 interrogations per second at 18000 ft. altitude.

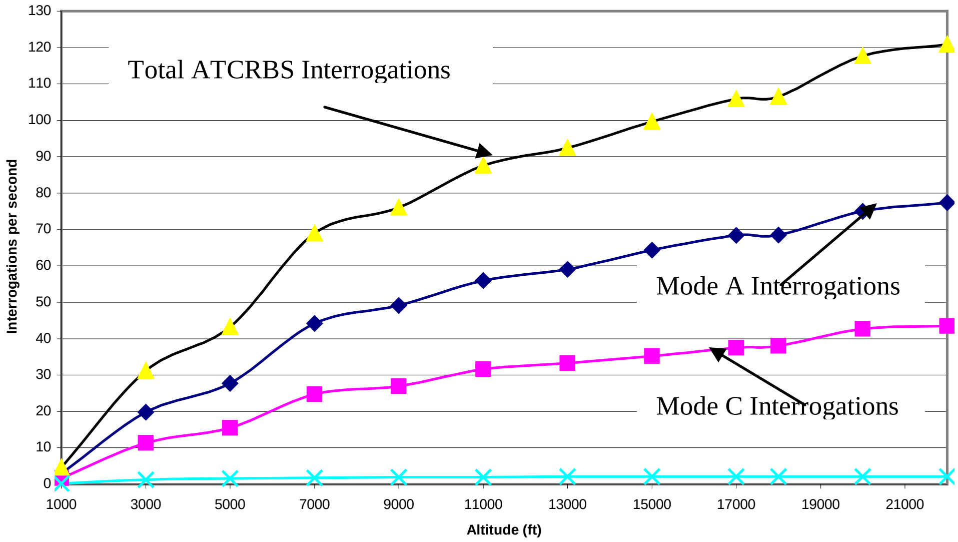


Figure 4-18. Simulated Interrogation Rate vs. Altitude
(20 nm ESE of LAX)

The initial analyses of interference in the LA area employed the 52 ground radars located within 200 nm of LAX. When we began to use the scenario generated by TLAT (Section 5.4), we augmented the ground radar database, by adding those additional 46 radars between 200 nm and 500 nm (Table 5-7). (The TLAT analyses presumed highly sensitive 1090 MHz receivers, so fruit from aircraft at long ranges - well beyond the LA region - became important to simulate. These radars had to be added to elicit it.)

The effect of these more distant radars on interrogation rate near LAX was determined by repeating the experiment described above, with these radars present. As Figure 4-19 shows, they have no effect below 18000 ft, but raise the total interrogation rate by about 3 or 4 interrogations per second above that.

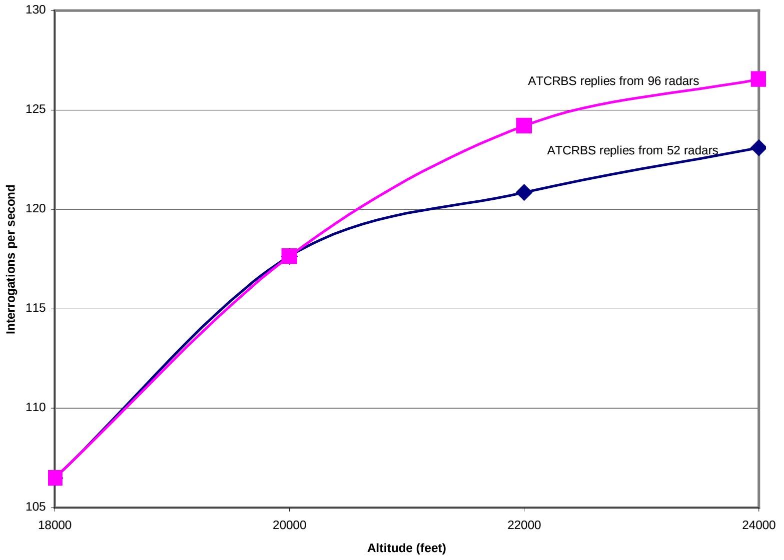
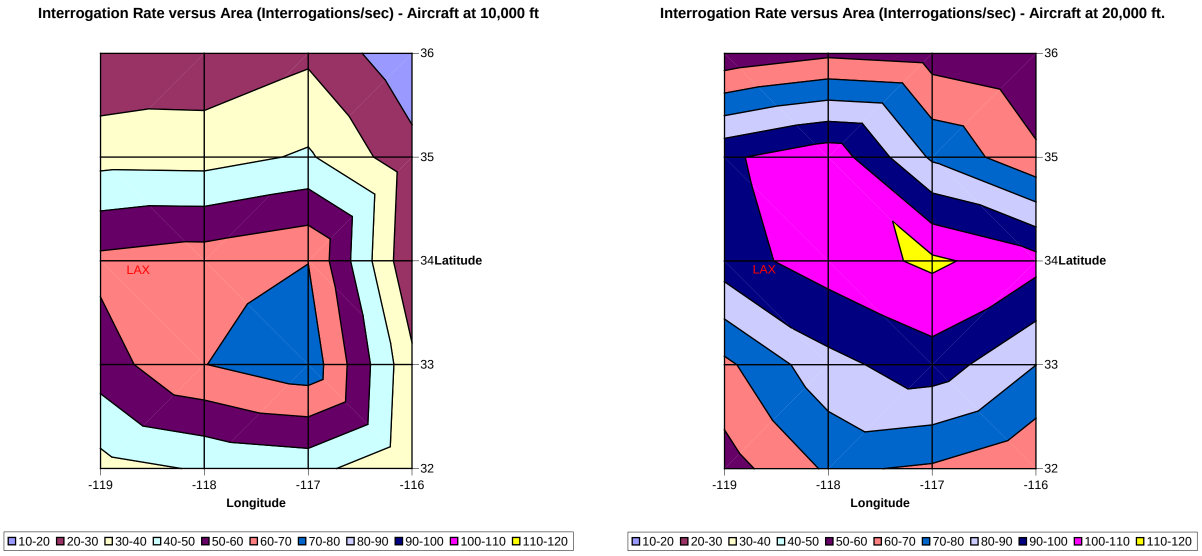


Figure 4-19. (Simulated) Effect of Distant Radars on Interrogation Rate
Rate measured 20 nm ESE of LAX
(Lower curve - 52 radars within 200 nm;
Upper curve – additional 46 radars within 500 nm)

To determine the dependence of interrogation rate on location within the LA area, several more simulations were executed, with measurements made at different locations at altitudes of ten and twenty thousand feet. Locations were at intersections of whole degree latitudes and longitudes, and the Excel contour-mapping feature was applied to the results (Figures 4-20a and b).



a. 10,000 ft Altitude

b. 20,000 ft Altitude

Figure 4-20. Interrogation Rate Contours in the LA Area
Locations of LAX and San Diego (SAN) as shown

4.2.4.6 Fruit Arrival Rate as a function of Level

Lincoln Laboratory was able to sort the ATCRBS fruit received during the 1999 measurement program according to its received signal level, and to present cumulative arrival rates for various signal level thresholds down to –90 dBm. This relationship (between fruit rate and fruit power level) is of importance in evaluating the performance of new ADS-B receivers that use knowledge of the structure of interfering signals to advantage. We modified the reply display process to allow efficient determination of this relationship, in order to compare measured and simulated fruit incidence statistics over the entire range of received fruit level (not just the –74 and –79 dBm points discussed previously). Figure 4-21 presents the comparison. It can be seen that the simulated and measured results track quite closely down to about –80 dBm. At lower received power levels than that, the measured fruit increases dramatically, while the simulated fruit does not.

This is because the bulk of such low-level fruit would be expected to come from distant aircraft, typically those beyond 70-80 nm. Many such aircraft were apparently present during the measurement, but were not included in the simulation. The simulation initially included only those aircraft detected by the LAX radar, whose maximum range is between 60 and 70 nm, depending on aircraft status.

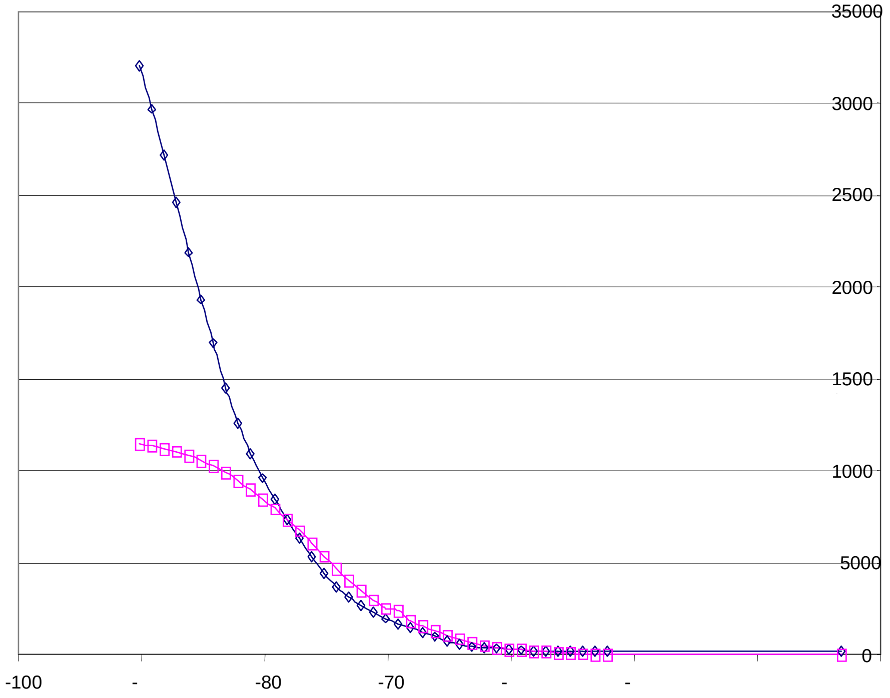


Figure 4-21. Comparison of ATCRBS Fruit Incidence Rates Measured and Simulated

To compensate for this omission, we created another scenario, a "hybrid", which contains the 166 aircraft that were detected by the LAX radar, and 498 additional aircraft beyond 60 nm (for a total count of 664 aircraft), placed to make the simulated and measured fruit curves match in the region below –80 dBm (Figure 4-22). This was done as follows:

- The measured aircraft distribution was not changed in any way. It contained all 166 aircraft visible to the LAX radar within 60 nm, and in certain cases (inbounds in track) between 60 and 72 nm.
- More hypothetical aircraft (22) were added at random locations and 20000 ft. altitude between 60 and 70 nm. This number was determined initially by dividing the actual and simulated fruit difference at –80 dBm by the interrogation rate at 20000 ft, and was then adjusted for the best curve fit.
- This process was then repeated in ten-mile segments, out to 300 nm. A total of 498 "virtual" aircraft were added.
- The altitudes of these hypothetical aircraft were all set to 20000 feet.

A further minor modification was made to account for variations in the vertical pattern of the receiving antenna. Lincoln Laboratory determined from analysis of pattern measurements made on scale model aircraft that top and bottom antennas were likely to exhibit gain variations in the vertical plane as follows:

$$G = 10 \log (2/(BW*pi/180) \exp - (1.66*(elev-peak)/BW)^2)$$

where BW is nominal beamwidth (45º), "elev" is the elevation angle (positive above the equatorial plane), and "peak" equals +26.2 for a top antenna and –26.2 for a bottom antenna. (Note that this relationship yields a maximum gain of 4 dB at the peak elevation angles, and a gain of 0 dB on the horizon.)

This adjustment was made only to the (measured) aircraft within 60 nm, by calculating their elevation angles relative to the victim receiver at 18000 ft, and adjusting their transmitted power levels accordingly. The elevation angles of the aircraft beyond 60 nm were all so close to 0º that vertical-plane gain variations were insignificant, so their transmitted power values were not adjusted. This entire process was performed in Excel on the aircraft parameter input files, so Simulator software was not modified.

This adjustment reduced the signal levels received by the victim's top antenna from most nearby aircraft, which were for the most part at significantly negative elevation angles. Its effect can be observed by comparing the portions of the Simulator output curves in Figures 4-21 and 4-22 in the region above –70 dBm.

Note that with the inclusion of the hypothetical aircraft beyond 60 nm, Figure 4-22 no longer serves fully to illustrate the fidelity of the model. The portion of the figure to the right of the –79 dBm point compares measured and simulated data, but the portion to the left of that simply demonstrates our ability to create an aircraft distribution that results in a curve with the characteristics we want. That the distribution is reasonable (nominally uniform in range with 2.1 aircraft per mile) suggests that a similar long-range aircraft distribution was likely present when the measurements were made.

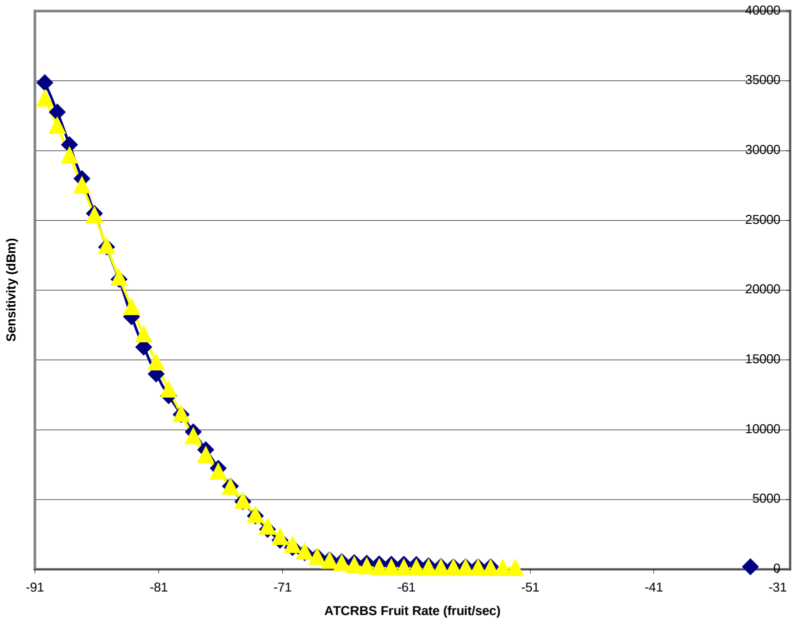


Figure 4-22. Comparison of Measured and Simulated Fruit
(top antenna, hypothetical aircraft distribution beyond 60 nm)

4.3 Discussion of Discrepancies

Simulator validation is an ongoing process, with new opportunities whenever new measurements are made of the actual environment. As the Simulator evolves and new processes are incorporated into it, there is a continuing need to re-validate the results it produces by re-running scenarios for which measured data is available. At present, there are only two: the 1999 LA Basin situation described in Section 4.2.1, and a similar situation measured in Europe in the summer of 2000. Efforts are currently underway to model the European scenario and derive additional validation information from it.

Prior to incorporation of terrain-loss modeling, we were forced to estimate uplink losses by assigning transponder desensitization values somewhat arbitrarily. Since no independent determination of these values was possible, they were established as those which put the resulting fruit levels into closest agreement with measured values. This provided a consistent picture, but was hardly an independent verification of Simulator accuracy.

Subsequent addition of terrain-based calculations allowed the removal of that process, as those calculations produced a deterministic model of uplink operation, which did not require adjustment. The Simulator now produces ATCRBS fruit results (the rightmost column of Table 4-2, and the rightmost portions of Figures 4-21 and 4-22) that agree very closely with measurements.

There is still much room for improvement. As noted, efforts are in process to perform a similar comparison with measured data taken during European testing of ADS-B. In addition, several relatively easily performed measurements and analyses could greatly enhance Simulator validity.

ATCRBS interrogation rates produced by the Simulator (Figures 4-18 through 4-20) have presently been confirmed with only a single measurement, made at one altitude (with which they are consistent). They could be validated thoroughly by conducting a single additional measurement effort, involving a single aircraft operating independently, collecting total interrogation rate data as a function of altitude in the vicinity of LAX.

Resolution of the differences between measured and simulated values of TCAS-elicited Mode S fruit would require two reconciliation efforts:

- The Simulator could be expanded to include a second TCAS model, operating consistently with previous versions of the software (in addition to the v.7 version modeled presently).
- The evidence in the 1999 experimental data that the actual system is not operating properly should be examined to determine the sources of the discrepancies and correct them if necessary. It is difficult to model TCAS accurately when there is so much uncertainty about how it actually operates.

The same point applies to TCAS ID rates: the Simulator output is consistent with standards of operation, and the actual measurements are not, for reasons that are not presently clear. Experimental evidence must be analyzed and further data collected, to determine the source of this discrepancy in the actual operation of the ATC system.

To the extent that the Simulator accurately replicates how the system should operate, it is an effective tool in pointing out anomalies in how it actually operates. It appears to be already proving itself in that regard.

5. INITIAL APPLICATIONS

The Simulator has been used to address several interference-related questions of current interest to FAA/ASR. As its calibration and refinement continue, these questions will likely be revisited, to increase the level of detail and enhance the accuracy of the answers. The questions pertain to the interference mechanisms that might arise in future high-traffic situations from several proposed new applications using Mode S squitter:

- Will proposed use of Mode S squitter for air-ground and air-air ADS-B surveillance cause undue interference to current Mode S and ATCRBS surveillance services?
- Will proposed use of Mode S squitter for airport surface traffic ADS-B surveillance cause undue interference to the adjacent ASR?
- Will current Mode S and ATCRBS cause undue interference to proposed air-ground and air-air ADS-B applications?

Several large scenarios were developed and employed to address these questions. The assumptions behind the analyses, the scenarios and processes employed, and the results are discussed in the following sections.

5.1 ADS-B SQUITTER INTERFERENCE TO MODE S AND ATCRBS

Mode S, ATCRBS, IFF and TCAS share a common downlink frequency and operate successfully in today’s dense environments because their transmissions are very short and asynchronous, so the probability of overlapping replies interfering with one another is acceptably low. As traffic density increases, that probability will obviously increase, and as new services that produce additional replies are implemented, it will increase further, to the point where the performance degradation it causes becomes unacceptable. MIT Lincoln Laboratory and others are proposing such a major new service: use of additional asynchronous Mode S long replies (known as “extended squitter”) to convey GPS-derived aircraft position and related data. FAA/ASR wishes to determine whether this new service might produce so much additional interference in future high-density situations that conventional Mode S and ATCRBS performance is degraded excessively.

5.1.1 Proposed New Service

In this Automatic Dependent Surveillance Broadcast (ADS-B) concept, each equipped aircraft would transmit several additional unelicited extended (120 μs) Mode S replies each second, containing position, velocity, identity and intent data. (Section 3.2 of this report describes the characteristics of these squitters.) They would be received by ground sites and other aircraft and used to determine position and track information, in lieu of the current surveillance functions performed by ATCRBS, Mode S and TCAS. The current concept, presented in [1], entails transmission of from 5.2 to 8.4 extended squitter replies per second per aircraft, depending on equipage. These are in addition to the one short squitter per second now used by Mode S aircraft to identify themselves, and, of course, those replies elicited by ground Mode S and ATCRBS, or airborne TCAS interrogators.

The proposed new squitter transmissions convey several types of information:

- Position information, transmitted twice per second
- Velocity Information, transmitted twice per second
- Intent information, in the form of planned Trajectory Change Points (TCPs). Five types are defined: TCP, TCP+1, TCP+2 , TCP+3, and status. Each is transmitted once every 1.7 seconds, resulting in a total transmission rate of 2.9 messages per second. (Not all aircraft will transmit all of these messages.)
- Identity, transmitted once every 2 1/2 or 5 seconds (0.4 or 0.2 per sec).

The total transmission rate of all these types of ADS-B squitter varies between 5.2 and 8.4 per second. Depending on equipage, different aircraft transmit different squitter sets. Each squitter is transmitted at a random time within the ±100 ms interval centered on the nominal delay after the previous squitter of the same type.

Slightly different versions of these transmissions are planned for use by aircraft on the airport surface. In that application, position and velocity are combined into a single message, whose transmission rate depends on whether the aircraft is moving. Section 5.2 of this report addresses interference issues associated with airport surface ADS-B.

The question posed by FAA/ASR was whether the additional squitters generated by airborne targets would unduly interfere with the basic surveillance functions in a worst-case future traffic situation. Definition of the worst-case scenario has been a major ongoing effort [2,3] for many years, and the evaluation scenarios used by the Simulator were taken directly from that effort.

5.1.2 Scenarios for Evaluating ADS-B Interference to Mode S and ATCRBS

FAA and others developed two Los Angeles Basin traffic models over the past 20 years. One of these contains 474 airborne aircraft, and the other contains 743, located within 70 nm of LAX. The 474-aircraft scenario includes 362 ATCRBS-equipped, 63 Mode S-equipped and 49 TCAS-equipped aircraft. The 743-aircraft scenario includes 557, 103, and 83 aircraft with these equipages. (Note that these scenarios are already somewhat out of date: the 474-aircraft scenario includes fewer TCAS interrogators than those actually seen in the 1999 experiment described in Section 4.2.) Figure 5-1 shows the 743-aircraft scenario as well as the layout of ground interrogators. Aircraft are placed in locations representative of L. A. Basin traffic patterns, with the major portion of the traffic to the southeast of LAX, near the large concentration of general-aviation and military airports there.

Exact locations, altitudes, and tracks of the TCAS-equipped aircraft that were modeled by JSC in previous work were available, and therefore incorporated into the Simulator scenario. The only Mode S and ATCRBS aircraft location data available from that previous effort was graphical, so positions of those aircraft were determined as follows:

- The 70 nm circular area centered on LAX was subdivided into 36 subregions, by laying out 12 radial lines at 30º intervals, and three circles (20, 40 and 70 nm).
- Percentage of total traffic in the JSC simulation graphic was estimated for each.
- TCAS aircraft were accounted for and the appropriate numbers of Mode S and ATCRBS aircraft were placed within the subregions.
- Exact aircraft locations within subregions were modified to minimize synchronous garble and make the overall distribution visually resemble that of the JSC work.

No specific altitude, heading, or velocity information was available for the non-TCAS aircraft. An overall altitude distribution was available, and altitudes were assigned consistently with that. Headings and speeds of Mode S aircraft were assigned randomly. Heading and speed data are used by the Simulator only to orient TCAS antenna patterns and establish threat potentials of Mode S aircraft. They are not used at all for ATCRBS-equipped aircraft. The 474-aircraft scenario was derived from the larger one by randomly removing the appropriate numbers of aircraft from the subpopulations. The locations of the ground radars in the Los Angeles basin were established through examination, verification, and editing of FAA files, and discussions with military representatives. Those military radars that are used for Air Traffic Control, and are consequently

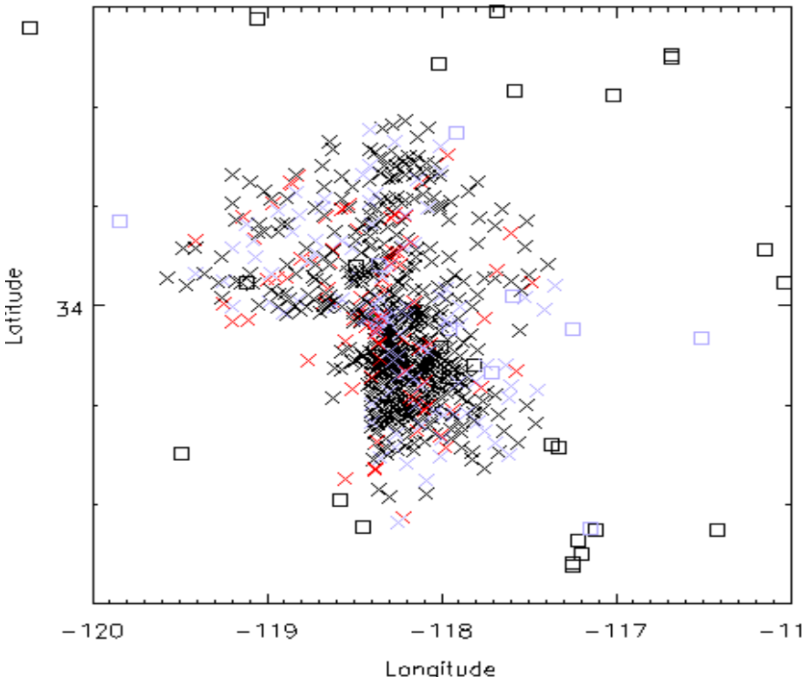


Figure 5-1. Distribution of Traffic in the L. A. 743-Aircraft Scenario
(Locations of the 52 Interrogators in the region are also shown)

operating most of the time, were included in the scenario. Those that are used only rarely in special applications were not included. Fifty-two radars within a 200-nm circle centered on LAX were identified and used (Table 5-1). The parameters of these radars were obtained from FAA files and through discussions with military personnel. Although the scenario only includes aircraft within about 70 nm, all radars within 200 nm are included. This was done (in previous scenarios as well) because the aircraft within view (70 nm) can generate fruit elicited by any radar within their view.

To account for terrain blockage of aircraft at low altitudes, ***the 4-dB desensitization profile shown in Table 4-3 and discussed in Section 4.2.2 was employed.*** This effectively limited the impact of the radars at longer ranges on the lower-altitude aircraft.

5.1.3 Results – ADS-B Interference to Mode S and ATCRBS

The 743-aircraft scenario shown in Figure 5-1 was executed for twenty seconds, resulting in the following statistics:

- The number of elicited replies averaged 834 per second. Of these, 287 were overlapped (34%). The bulk of this interference was synchronous garble.
- On average, 1552 fruit were received per second. Almost all of these were received over the mainbeam.
- On average, 6.6 elicited replies per second were overlapped by ADS-B squitter. Of these, 3.4 had relative levels and overlap durations that would likely cause failure to decode or detect the reply.
- Thus, the additional squitter due to ADS -B caused a reduction in the probability of successful reply reception by 0.4% (3.4/834).

To generate those statistics, all overlapped replies received during the 20-second period were printed out for detailed manual analysis. Each that was overlapped by an ADS-B squitter was examined to determine whether the squitter had sufficient power to disrupt decoding or detection. Failure was presumed whenever squitter power was greater than reply power minus 12 dB. Detection failure was presumed whenever the squitter completely overlapped a victim ATCRBS reply, and ATCRBS decoding failure was presumed whenever the overlap was partial. (About 30% of the overlaps were partial.) Only one Mode S reply was overlapped by squitter within 12 dB, and that overlap was almost complete.

Because of the high incidence of synchronous garble, there were many instances where an ADS-B squitter overlapped an elicited reply that was already overlapped by another elicited reply (i.e., synchronously garbled). Although garbling caused failure as well, such cases were nonetheless counted as failures due to squitter overlap. Treating them differently would have been equivalent to the erroneous assumption that squitter-produced interference diminishes when synchronous garbling increases.

Radar ID	Type	Latitude (dd.ffff)	Longitude (dd.ffff)	Power Output (dBm)	PRF	Scan Rate (sec)
SAN PEDRO - ARSR	ATCRBS	33.7458	-118.33611	33.75	289.94	15
VAN NUYS	ATCRBS	34.2017	-118.48778	34.20	305	5.4
GARDEN GROVE	ATCRBS	33.7925	-118.00194	33.79	406	5.2
HUNTINGTON	ATCRBS	33.6444	-117.95833	33.64	267	5.1
TUSTIN	ATCRBS	33.7	-117.81667	33.70	270	5.2
POINT MUGU	ATCRBS	34.1167	-119.11667	34.12	315	5.4
SAN CLEMEMT - N	ATCRBS	33.0228	-118.58472	33.02	300	5.3
SAN CLEMENT - ARSR	ATCRBS	32.8844	-118.44972	32.88	272.5	15.2
CAMP PENDLETO - N	ATCRBS	33.3	-117.36667	33.30	267	5
CAMP PENDLETO - S	ATCRBS	33.2875	-117.33083	33.29	411	4.8
SAN NICOLAS - ARSR	ATCRBS	33.2569	-119.48611	33.26	360	12
FREMONT VAL	ATCRBS	35.2169	-118.01194	35.22	342	5.2
BORON - ARSR	ATCRBS	35.0822	-117.58139	35.08	355	14.9
NORTH ISLAN	ATCRBS	32.8192	-117.21583	32.82	323	5.3
MIRAMAR - ARSR	ATCRBS	32.8764	-117.11917	32.88	260	15
SAN DIEGO	ATCRBS	32.75	-117.19722	32.75	230	5.2
PT LOMA	ATCRBS	32.7081	-117.24639	32.71	235	4.9
BAKERSFIELD	ATCRBS	35.4431	-119.05972	35.44	330	5.1
PT LOMA - ARSR	ATCRBS	32.6931	-117.25083	32.69	315	15
VELVET PEAK	ATCRBS	35.0603	-117.01444	35.06	340	5
CHINA LAKE	ATCRBS	35.4794	-117.68222	35.48	365	5.4
INDIAN WELL	ATCRBS	35.6558	-117.83528	35.66	338	5.2
TWENTYNINE - ARSR1	ATCRBS	34.2833	-116.15	34.28	270	14.9
VANDENBERG - ARSR1	ATCRBS	34.5872	-120.59361	34.59	284	15.1
FT IRWIN	ATCRBS	35.25	-116.68333	35.25	400	4.8
FT IRWIN - ARSR	ATCRBS	35.26	-116.68389	35.26	235	14.9
VANDENBERG - ARSR2	ATCRBS	34.7275	-120.58028	34.73	294	14.8
TWENTYNINE - ARSR2	ATCRBS	34.1167	-116.03333	34.12	240	14.9
MOUNT LAGUN - ARSR	ATCRBS	32.8767	-116.41528	32.88	330	15.2
SEARLES VAL	ATCRBS	35.8036	-117.345	35.80	345	4.9
PORTERVILLE - ARSR	ATCRBS	36.025	-119.06111	36.03	267	14.8
PASO ROBLES - ARSR	ATCRBS	35.395	-120.35444	35.40	280	15.1
PANAMINT VA	ATCRBS	36.0342	-117.26972	36.03	347	5.2
LEMOORE	ATCRBS	36.3333	-119.91667	36.33	327	5.3
OWENS VALLE	ATCRBS	36.6181	-118.02972	36.62	343	5
FRESNO - ARSR1	ATCRBS	36.7744	-119.71583	36.77	267	15
FRESNO - ARSR2	ATCRBS	36.78	-119.73361	36.78	259	14
FT HUNTER L	ATCRBS	35.9656	-121.23444	35.97	400	4.8
ANGELS PEAK - ARSR	ATCRBS	36.3186	-115.57583	36.32	281	14.8
LOS ANGELES - N	Mode S	33.9536	-118.40778	33.95	125	4.61
LOS ANGELES - S	Mode S	33.9325	-118.40639	33.93	125	5.3
BURBANK	Mode S	34.2042	-118.36222	34.20	125	4.9
FULLERTON	Mode S	33.88	-117.95889	33.88	125	4.8
EL TORO	Mode S	33.6628	-117.71278	33.66	125	5
ONTARIO	Mode S	34.0525	-117.59417	34.05	125	5.2
MARCH	Mode S	33.8864	-117.24389	33.89	125	4.8
EDWARDS	Mode S	34.8728	-117.91139	34.87	125	4.9
SANTA BARBA	Mode S	34.4239	-119.84222	34.42	125	5.1
MIRAMAR	Mode S	32.8833	-117.14389	32.88	125	5
PALM SPRING	Mode S	33.8347	-116.50639	33.83	125	5.2
VANDENBURG	Mode S	34.5872	-120.59361	34.59	125	5.2
FRESNO	Mode S	36.5375	-119.71778	36.54	125	5.4

Table 5-1 Radars Included in the L A Basin Scenario

Consistent results were noted in the 474-aircraft case:

- The number of elicited replies averaged 542.4 per second, of which 142 (26%) were overlapped, largely synchronously garbled.
- There were 965 fruit per second, on average.
- On average, 3.5 elicited replies per second were overlapped by ADS-B squitter. Of these, 1.5 had relative levels and overlap durations that would likely cause failure to decode or detect the reply.
- Thus, the additional squitter due to ADS-B caused a reduction in the probability of successful reply reception by 0.27% (1.5/542.4), below its already-depressed value.

We conclude from these values (0.4% and 0.27% additional degradation in the 743- and 474-aircraft cases) that the additional interference due to worst-case use of air-ground ADS-B squitter is negligible, especially when compared to all the other interference present in the worst-case environment.

5.2 INTERFERENCE TO ASRS BY AIRPORT SURFACE SURVEILLANCE

In the previous analysis, interference was almost entirely due to aircraft at relatively distant range, which happened to be in the antenna mainbeam when they produced ADS-B squitter. The same basic squitter concept has been proposed for use in identification of airport surface traffic, in which case interference sources will be much closer to the interrogator. In this situation, interfering squitter will be received through interrogator antenna sidelobes as well as the mainlobe, and we would expect a smaller number of aircraft to produce a larger amount of interference.

5.2.1 Scenarios for Evaluating Airport Surface Squitter Interference

Two different situations are envisioned in this application, one involving unelicited Mode S (TCAS ID) squitter from Mode S equipped aircraft, the other involving ATCRBS equipped aircraft on the airport surface replying in response to specially-designed low-power ATCRBS whisper-shout interrogators located around the airport periphery. To model these situations, 200 additional aircraft were deployed on the LAX surface, on taxiways and in the gate areas (Figure 5-2). In the first situation, the Mode S transponders on these aircraft only transmitted squitter; they were totally desensitized to prevent them from replying to interrogations.

To model the second situation, whisper-shout ATCRBS interrogators with fixed antennas (with beamwidths varying between 90 and 360 degrees, to provide full airport surface coverage) were placed about the airport surface (the boxes in Figure 5-2). All aircraft were equipped with ATCRBS transponders with the normal parameters. ***(It should be noted that this situation violates current rules, which require turning off ATCRBS transponders on the airport surface.)***

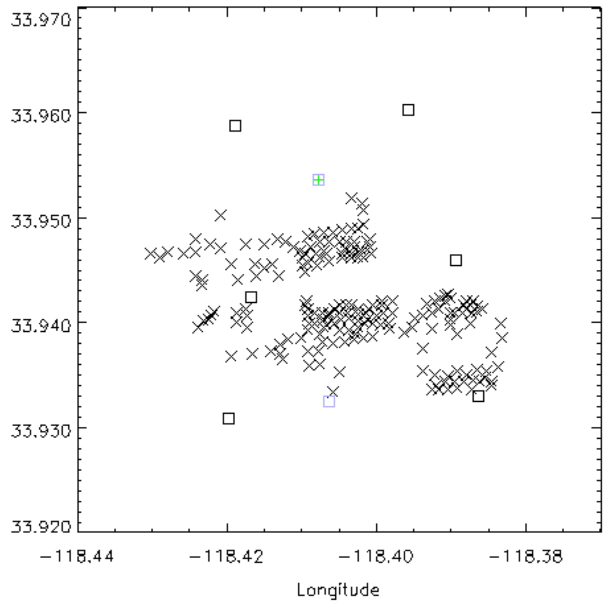


Figure 5-2. Airport Surface Traffic at LAX

5.2.2 Results – Airport Surface Mode S Squitter Interference

The 474-aircraft scenario was executed with 40, 120 and 200 additional aircraft on the airport surface, transmitting only squitters. Half of these aircraft were moving. (Squitter transmission rate on the surface varies with motion.) The victim was the LAX North Mode S interrogator. It elicited on average 539 replies per second, and there were 940 fruit per second. 25% of the elicited replies were synchronously garbled. Air-to-ground squitter was disabled. Ground squitter caused the following interference:

- In the 40-aircraft case, 4 of the replies elicited from airborne aircraft were lost (0.6%)
- In the 120-aircraft case, 11 replies (2.0%) were lost
- In the 200-aircraft case, 16 replies (3.0%) were lost.

The 743-aircraft scenario produced similar results. In that scenario on average 835 replies were elicited per second (33% of which were synchronously garbled), and there were 1560 fruit per second. Elicited reply loss rates due to the surface squitter were:

- In the 40-aircraft case, 5 replies (0.6%) were lost
- In the 120-aircraft case, 16 replies (1.9%) were lost
- In the 200-aircraft case, 24 replies (2.9%) were lost.

We would expect the results for the 474- and 743-aircraft scenarios to be comparable, since both cases involved the same numbers of interfering aircraft. The same amounts of squitter were produced in both cases, so the probability that an elicited reply is overlapped by a squitter should be the same. The slightly lower interference level in the larger scenario apparently resulted from the fact that the average range of the airborne aircraft in that case was also slightly lower. As a result the average received power level of an elicited reply was slightly greater for the larger scenario, and a slightly greater percentage of replies were therefore strong enough to be decoded successfully.

As in the previous analysis, elicited ATCRBS replies were deemed lost only if they were overlapped by a squitter whose power level was more than the level of the elicited reply less 12 dB (i.e., the S/I ratio was below 12 dB.) To make that determination, all instances of overlapping squitter were printed out and examined manually to determine those in which replies would have been lost. As before, effects of synchronous garble were ignored.

We conclude from the results presented above that 67 squittering aircraft on the airport surface will cause a 1% reduction in successful reply reception probability. Thus, each squittering surface aircraft causes roughly 7 times more interference than an airborne squittering aircraft. This is because its squitter penetrates the sidelobes of the victim radar due to the close proximity.

5.2.3 Results - Airport Surface ATCRBS Interference

FAA envisions that most large airports with ASDE-X will have surface traffic that is largely commercial and hence Mode S equipped. There are, however, several busy general-aviation airports whose future traffic will not be Mode S equipped. To address these, a variant of the previous scenario was used, in which airport surface whisper-shout interrogators are activated and the surface aircraft are ATCRBS-equipped.

This scenario required use of a new object: the ATCRBS ground whisper-shout interrogator. This was constructed by modifying the whisper-shout interrogation-scheduling portion of the TCAS interrogator object. Power output is low (10 watts maximum), enabling coverage of only the nearby airport surface. Antenna beamwidth is adjustable between 90 and 360 degrees. Each interrogator broadcasts a single six-interrogation whisper-shout sequence of Mode A interrogations once per second, with timing staggered relative to that of the other ground interrogators.

The same 200-aircraft surface traffic distribution that was used in the prior case was used here, but instead of being Mode S equipped, all aircraft had ATCRBS transponders. The 474-aircraft airborne traffic distribution was used.

The fruit level noted at the LAX North interrogator with this scenario was noted to be 7488 fruit per second. This total subdivided into four categories:

- 965 (12.9%) were from airborne aircraft, predominantly received over the interrogator mainbeam. (This quantity is comparable to the 940 airborne fruit seen in the previous case.)
- 572 (7.6%) were Mode A replies to the whisper-shout interrogators, by surface aircraft and nearby airborne aircraft (i.e., the replies used by ASDE-X to perform its function).

- 264 (3.5%) were replies to nearby radars (LAX South and San Pedro) produced by the surface targets (which now result from the fact that surface transponders remain activated).
- 5,687 (75.9%) were replies generated by the surface traffic to TCAS interrogators in the vicinity.

From this we see that the ATCRBS surface interrogation mechanism by itself contributes only a modest amount of additional fruit, 572/second (an increase of 59% compared to the low value of 965/second already present). On the other hand, the requirement that transponders remain active on the airport surface results in a far greater increase in fruit (616%) because it exposes these aircraft to other (primarily TCAS) interrogations. (It also exposes them to reflected (multipath) interrogations, with the potential for false target generation. This mechanism was not addressed in the simulation.)

It should be noted that this high fruit level is a consequence of two simultaneous worst-case assumptions in the scenario, which is perhaps somewhat unrealistic. The scenario includes both a large number of ATCRBS equipped aircraft on the ground, and a large number of approaching TCAS aircraft. The large increase in total fruit is the result of the latter interrogating the former. This would only arise in a case where an airport with much ground GA activity is located along a major approach path to another airport with traffic that is largely commercial (TCAS-equipped).

Although the increase in fruit resulting from ASDE-X deployment is quite large, it nonetheless has only minimal impact on ASR performance. It was found that the LAX ASR elicited a total of 19,585 replies from airborne aircraft within its coverage area. Of these, 882 were overlapped. Since 87% of the total fruit seen by the interrogator was due to the presence of ASDE-X, it can be assumed that 87% of the overlapping fruit (715) were due to the presence of ASDE-X. These 715 replies comprised 3.6% of the total replies. In previous studies we found that a fruit overlap resulted in loss of a synchronous reply in about 50% of the cases, so we conclude here that additional fruit resulting from the presence of ASDE-X will reduce ASR reply probability by 1.8%.

5.3 AIR-GROUND EXTENDED SQUITTER PERFORMANCE

The previous two analyses focused on the interference that ADS-B Extended Squitter adds to the 1090 MHz channel. Also of interest to FAA/ASR is the susceptibility of ADS-B Extended Squitter surveillance to interference caused by the other services on that channel (TCAS, and conventional ATCRBS and Mode S). Extended Squitter entails asynchronous transmission of replies containing air-to-ground and air-to-air data on a low-occupancy channel with no coordination, so the likelihood that an occasional reply will be overlapped grows with increasing channel utilization. Data is sufficiently redundant that loss of occasional messages due to interference can be tolerated. As channel occupancy increases, however, the quality of this data communications link clearly degrades, eventually to the point where it becomes unusable.

Unlike conventional Mode S and ATCRBS, which employ high-gain directional antennas, the proposed new services use antennas with wider beamwidths to provide wide area coverage. As a result, a greater number of aircraft are expected to contribute to the total interference. More significantly, lower antenna gains make link power budgets far more fragile, so fading due to antenna pattern variations becomes a significant limiting factor, and must be addressed in greater detail. Receivers with higher sensitivity are being proposed to counteract this, but such receivers consequently receive more fruit.

Extended Squitter ADS-B is proposed as a solution to two problems. In air-to-air applications, it can support a service akin to TCAS, which provides both range and bearing to another aircraft with high accuracy. In this application, the need for timely and proper reception of data from the other aircraft grows with proximity, as the collision threat severity increases, but so too does the quality of the link.

ADS-B is also being promoted as an alternate means of providing surveillance information to ground ATC facilities, a substitute or adjunct to current radar systems. In this application, required performance is uniform over a region, independent of the location of the aircraft relative to the ground receiver site. Link quality issues constrain maximum allowable distance from the aircraft to the nearest ground site, and hence the separation between adjacent sites, and total number of ground sites required in a region. This section focuses on air-ground Extended Squitter operation, attempting to establish that maximum allowable range. (Air-air Extended Squitter is discussed in Section 5.4.)

There is no consensus at present on what message reception characteristics and failure rates are acceptable in this application, and what patterns and rates of missing messages are allowable. Clearly, gross message reception failure rates averaged over entire aircraft populations tell only a small part of the story; patterns of sequential reception failures for specific aircraft are far more meaningful. Simulation efforts reported subsequently are focused on creating such patterns, and determining how they depend on range.

5.3.1 The ADS-B Performance Evaluation Scenario

The 474- and 743-aircraft scenarios were used in this analysis, with various TCAS-equipped aircraft in those scenarios originating the extended squitter sequences of interest. Evaluation of ADS-B performance requires redefinition of several key Simulator parameters. The victim receiver is no longer tied to an interrogator, and ADS-B squitters, rather than elicited replies, are now of interest. All other replies are counted as fruit. The Simulator was designed to allow such operation when the victim is decoupled from any associated radar (by specifying radar number 0 in the receiver parameter menu Radar ID window). Display software in this situation defines squitters as the desired signals and flags their overlaps by other squitters or fruit.

The victim receiver was modeled as one of the six that would be located within each ground-based receiving site in a high-density area, each covering a 60º sector of the surrounding airspace. It was connected to a fixed directional antenna with 12 dB gain and 60º beamwidth at the –3dB points. The ground site was located 5 nm north of LAX, and its antenna was oriented to point due east for some runs, and 60° south of east for others (the direction of maximum traffic density).

Since the sequence of squitter reception from a given aircraft is important here, the display software was also modified for this analysis to allow accentuation of all squitter from a specified aircraft, for ease of identification by the analyst.

5.3.2 Initial Results – Gross Statistics

Although gross message detection statistics are of only limited interest, the first few Simulator runs produced some:

- In the 474-aircraft scenario with the victim antenna pointing east, 24 Mode S and TCAS aircraft were within the coverage area, and produced a total of 2940 ADS-B squitters in the 20-second period. Of those, 580 (20%) failed reception: 15 overlapped by Mode S fruit, 95 by other squitters, and 470 by multiple ATCRBS fruit.
- In the 743-aircraft scenario with the victim antenna pointing east, 31 Mode S and TCAS aircraft were within the coverage area, and produced a total of 3750 ADS-B squitters in the 20-second period. Of those, 948 (22%) failed reception: 44 overlapped by Mode S fruit, 168 by other squitters, and 736 by multiple ATCRBS fruit.
- In the 474-aircraft scenario with the victim antenna pointing south-southeast, 43 Mode S and TCAS aircraft were within the coverage area. These aircraft produced a total 5281 ADS-B squitters, of which 1905 (36%) failed reception: 70 overlapped by Mode S fruit, 460 by other squitters, and 1375 by multiple ATCRBS fruit.
- In the 743-aircraft scenario with the victim antenna pointing south-southeast, 56 Mode S and TCAS aircraft were within the coverage area, producing 10,974 squitters, of which 6807 were overlapped, 5430 of which (49.5%) were lost.

As in the previous analyses, the determination that certain squitter replies failed detection was made by obtaining printout of all overlapped squitters, and examining them manually for instances of failure. The criteria for the Mode S replies of interest here were different from those for ATCRBS replies. As before, squitters were deemed lost if overlapping interference reduced the S/I ratio below 12 dB, but different overlap situations pertained because of the ability of the Mode S receiver to perform error correction. Mode S error-correction coding enables successful reception whenever errors are contained within intervals shorter than 24 μs, slightly greater than the duration of an ATCRBS reply. Overlap by a single ATCRBS reply was therefore presumed to lead to successful reception, as was overlap of up to the last 24 μs of the squitter by a Mode S reply.

5.3.3. Fruit Arrival Statistics

In analyzing the incidence of ATCRBS fruit overlap on squitter in the previous cases, we noted that overlaps involving <u>multiple</u> closely-spaced fruit were far more frequent than would be expected. Indeed, in the cases discussed in Section 5.3.2, there were more cases of multiple overlap than there were of single overlap, and in several instances truly large quantities of fruit (as many as sixty) overlapped a single squitter. To characterize these fruit arrival statistics, the Simulator was modified to produce ATCRBS fruit occurrence rate histograms. Rather than counting numbers of ATCRBS fruit overlapping individual squitters, the modified software counted the number of ATCRBS fruit arriving during each of the 200,000 100-μs intervals of the 20 second simulation run, and formed a histogram based on these data. Figures 5-3 through 5-6 present histograms for four cases that were examined (in order of increasing fruit rate):

- 474-aircraft scenario, east-pointed sector antenna (7130 fruit/sec)
- 743-aircraft scenario, east-pointed sector antenna (8870 fruit/sec)
- 474-aircraft scenario, SSE (150º) sector antenna (15300 fruit/sec)
- 743-aircraft scenario, SSE (150º) sector antenna (24900 fruit/sec)

In all cases, there were rare instances of very large numbers of fruit falling within individual cells, more than sixty in the last case. Conversely, there were many more empty cells (100 μs intervals containing no fruit) than what would be expected from total fruit rates and calculated mean quantities of fruit per cell. Fruit arrival clearly did not follow a Poisson distribution. Tables 5-2 through 5-5 compare the Simulator-generated probabilities of various quantities of fruit falling within a cell to what Poisson statistics would predict. From these data it is evident that the larger-quantity "tails" of the distributions produced by the Simulator fall off far more slowly than what Poisson would predict, and there are far more empty cells than would be predicted. The characteristic "hump" of the Poisson distribution around the mean arrival rate is totally absent.

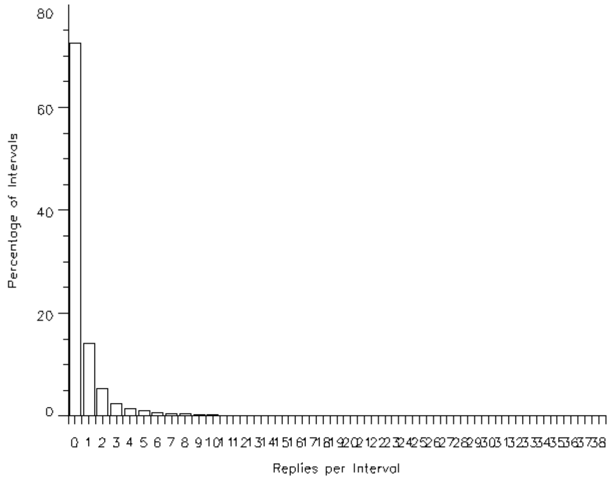


Figure 5-3. Fruit Arrival Histogram
474 Aircraft, East Antenna, 7.13K f/s

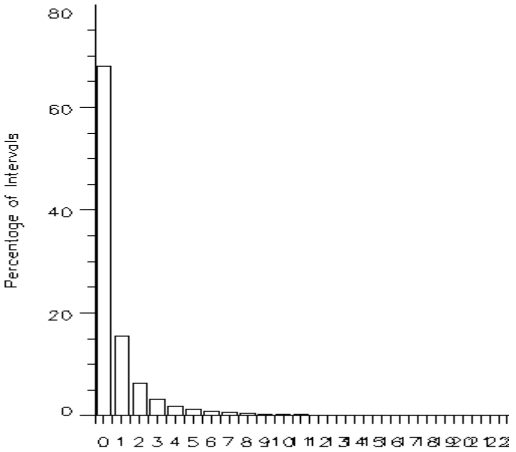


Figure 5-4. Fruit Arrival Histogram
743 Aircraft, East Antenna, 8.87K f/s

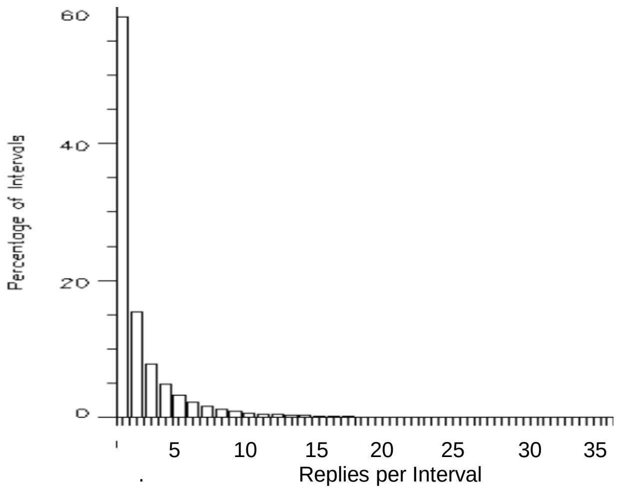


Figure 5-5. Fruit Arrival Histogram
474 Aircraft, SSE Antenna, 15.3K f/s

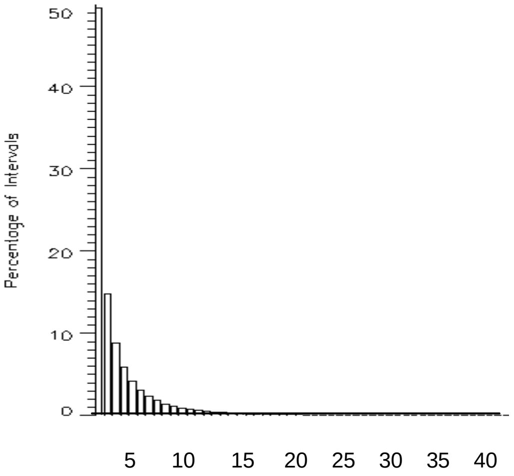


Figure 5-6. Fruit Arrival Histogram
743 Aircraft, SSE Antenna, 24.9K f/s

k	Poisson distribution (μ=.713)	Simulation distribution
0	0.4901	0.726
1	0.3495	0.141
2	0.1246	0.053
3	0.0296	0.025
4	0.0053	0.015
5	0.0007	0.01
>5	0.0004	0.03

Table 5-2. Comparison of Simulator-Produced Distribution with Poisson Distribution (474 aircraft, antenna pointed east, lowest fruit rate, 7.13K fruit/sec)

k	Poisson distribution (μ=.887)	Simulation distribution
0	0.4117	0.68
1	0.3654	0.156
2	0.1621	0.064
3	0.0479	0.031
4	0.0106	0.018
5	0.0019	0.013
>5	0.0004	0.038

Table 5-3. Comparison of Simulator-Produced Distribution with Poisson Distribution (743 aircraft, antenna pointed east, 8.87K fruit/sec)

k	Poisson distribution (μ=1.53)	Simulation distribution
0	0.2167	0.584
1	0.3314 (peak)	0.155
2	0.2534	0.078
3	0.1292	0.049
4	0.0494	0.033
5	0.0151	0.023
>5	0.005	0.078

Table 5-4. Comparison of Simulator-Produced Distribution with Poisson Distribution (474 aircraft, antenna pointed south-southeast, 15.3K fruit/sec)

k	Poisson distribution (μ=2.49)	Simulation distribution
0	0.0825	0.495
1	0.2059	0.148
2	0.2568 (peak)	0.088
3	0.2135	0.059
4	0.1332	0.043
5	0.0664	0.032
6	0.0276	0.021
>6	0.015	0.11

Table 5-5. Comparison of Simulator-Produced Distribution with Poisson Distribution (743 aircraft, antenna pointed south-southeast, 24.9K fruit/sec)

Most previous efforts to estimate Enhanced Squitter ADS-B capacity have been based on the assumption that fruit, being essentially random, obeys a Poisson distribution. The fact that it apparently does not has two major consequences:

- ADS-B performance in very high-density traffic should be better than previously predicted, due to the higher incidence of time intervals without interfering fruit.
- The ability of the Mode S receiver to correct for cases of single ATCRBS reply overlap is somewhat less important since fewer single overlap instances occur.

Table 5-6 shows predicted ADS-B performance for the four cases that were simulated, assuming Poisson-distributed fruit, ("Poisson Success") and the distribution produced by the Simulator ("Simulation Success"). The probability of correct squitter reception is in each case the sum of the probabilities that there are zero and one fruit in each cell. Note that in the highest-density case, the probability of successful reception is more than twice as great as what Poisson statistics would suggest.

Case	Fruit/sec	Poisson Success	Simulation Success
1 (Fig. 5-3)	7.1K	.84	.87
2(Fig. 5-4)	8.9K	.78	.84
3(Fig. 5-5)	15.3K	.55	.74
4(Fig. 5-6)	24.9K	.29	.64

Table 5-6. Comparison of ADS-B Performance Predictions
Based on Poisson and Simulator-Generated Statistics

Investigation of individual instances of multiple-fruit overlap presented in the printout provides insight into why the degree of fruit bunching is so great in the dense traffic geometry. Many aircraft are simultaneously in the mainbeam of each distant radar and so respond nearly simultaneously to each of its ATCRBS interrogations. What appears as synchronous garble to the distant radar appears as bunched fruit to the stand-alone receiver. The bistatic geometry further aggravates the situation: bunching is most pronounced when the many aircraft within the eliciting radar's mainbeam lie near the line between the eliciting radar and the victim receiver. In that case, the total distances from the eliciting radar to the victim by way of all the aircraft are nearly the same. As a result, the sum of the propagation times of the interrogation and reply from each aircraft is nearly the same for all aircraft, so the replies coincide at the victim. Thus, there is a high probability of large amounts of bunching. Since total fruit still depends on the number of radars, the number of aircraft, interrogation rates and antenna characteristics, fruit bunching at some instants in the timeline leads to far more empty spaces at other instants than what Poisson predicts.

5.3.4. Initial Results - Squitter Sequences from Specific Aircraft

Several of the longer-range aircraft in the 743-aircraft scenario were identified for additional investigation, and the sequences of squitter they produced were examined to determine outage patterns. As would be expected, outages due to overlaps are randomly-distributed and uncorrelated, and even in the most severe interference cases, where outage probability is high, the probability of a run of more than n outages in sequence is very small for large n. We tentatively conclude that even in this worst-case interference scenario, the probability of an outage sequence lasting over several seconds is acceptably small, as long as interference is the only outage mechanism.

This is essentially the conclusion of an analysis performed by Lincoln Laboratory in 1994 [11], which, although based on a predecessor to the current Extended Squitter ADS-B concept, still pertains here. That analysis reasoned that with two squitters per second, even with a very low individual squitter reception probability the likelihood that none will be received successfully in a five second interval is still very small. Even when the detection probability for each individual squitter is only 0.4, the probability that ten of them in a row will be missed is only $(1-0.4)^{10} = .006$.

5.3.5 ADS-B Performance Modeling Issues

The Lincoln Laboratory analysis provokes two questions:

- It applies only if outages are uncorrelated. Those caused by interference clearly are. Are there any other mechanisms contributing to outage which are not?
- It presumes that the success criterion is one or more successful reports every five seconds (the update rate of the current airport surveillance radar). Is that the proper criterion?

There is indeed another mechanism that contributes to outages, that is highly correlated: fading due to nulls in antenna patterns that drive received signal level below the threshold of detectability. Such nulls are aircraft attitude dependent, and their effects persist when aircraft attitude is not changing rapidly (as, for example, when the aircraft is flying straight at the victim).

Conventional radar downlinks employing high-gain directional antennas such as the ones discussed in Section 4.1.2 of this report are sufficiently overpowered that fading is rarely of practical significance. Antennas proposed for ADS-B ground stations and airborne receivers have lower gain, and their wider beamwidths make them more susceptible to multipath (a major fading mechanism). This suggests that future Simulator work should focus on the time-dependence of received signal level due to aircraft antenna pattern and motion, both rotational and translational. Effects of such fading are likely to be more important than interference effects in determining ADS-B air-ground performance.

Our initial effort in modeling antenna gain variation involved selection of a new random value for the antenna gain correction factor from the distribution (Figure 3-1) every T seconds (where T is adjustable between 1 and 4 seconds), and varying the gain factor linearly (in dB) between adjacent values. The effect of this approach is predictable: sustained outages whose durations are equal to the times the received signal level is below the receiver threshold. These can be readily calculated from the adjacent values and from T.

A more accurate approach would involve focusing on a single aircraft which moves in accordance with a dynamic (six degree of freedom) model, and which employs an actual antenna pattern with appropriate lobing/nulling fine structure in the forward direction. Johns Hopkins used this approach in the air-air work mentioned in Section 5.4.

The issue of what outage durations are acceptable is highly dependent on the processes that operate on the data provided by the ADS-B system, to merge data from multiple sources and form tracks on aircraft. Current software performing those functions was built to operate with radar data, and is highly-tuned to the limitations and idiosyncrasies of that data (e.g., disparities between its range and azimuth accuracy, the frequency and severity of false targets, and the long times between successive position updates). Its performance is heavily constrained by the long intervals between position updates that are the consequence of the large mechanically-scanned radar antenna, and the importance of determining quickly if changes in aircraft direction have occurred during those times.

Study is needed to determine the best approach to merging future ADS-B data with radar surveillance date, and forming tracks on the composite. That study should include a thorough parametric analysis between ability to support future higher levels of automation and acceptable outage patterns. The current criterion, that outages persist no longer than the current radar antenna scan period, fails to capitalize on a key ADS-B attribute that can materially improve its output quality, and hence the performance of the automated functions it serves.

Simulation can provide much insight and information on outage sequences, their durations and frequencies of occurrence. How those affect the bottom-line quality of the future automation processes that will employ the surveillance data depends on the merging and tracking software that the ADS-B system feeds, whose sensitivity to patterns and frequencies of outages must be determined before surveillance data quality can be meaningfully evaluated.

5.4 AIR – AIR EXTENDED SQUITTER PERFORMANCE

As part of its effort to select the data link to be used for ADS-B, FAA tasked RTCA to form a Technical Link Assessment Team (TLAT), and requested that the TLAT forecast the expected future high-density performance levels of the three candidate links: Extended Squitter, the Universal Access Transceiver (UAT), and the VHF Data Link Mode 4 (VDL4). Of these three alternatives, only Extended Squitter operates in the 1030/1090 MHz bands and interacts with the systems there.

The TLAT contracted with the Applied Physics Laboratory of Johns Hopkins University to perform detailed modeling and performance analysis of the three systems. APL in turn contracted with Volpe/TASC to provide the interference environment appropriate to testing Extended Squitter, using the Simulator with scenarios provided by TLAT. APL developed detailed computer models of the Extended Squitter receiver proposed by Lincoln Laboratory (based on measurements made on prototype equipment), and of representative air-air encounters, with appropriate aircraft motion and antenna pattern variations. (While the source and victim aircraft were modeled as moving in the APL simulation, the aircraft that produced the interference in our Simulator were stationary.)

Simulator output was provided to APL for insertion into their simulated air-air link, based on several TLAT-defined scenarios. This data was provided in the form of an ASCII file, with each record (line) representing a single reply in the time sequence. Each record contained the arrival time of the reply, the type of reply (e.g., Mode A, C, or S, or one of the several defined types of squitter), the source aircraft and the radar that elicited the reply, and the received power level.

In each scenario, TLAT defined a victim receiving aircraft. To model the situation, we placed our victim receiver very close to that aircraft, so it saw essentially the same interference the victim aircraft saw. In addition, it saw all the replies the victim aircraft's transponder produced. APL separated these out based on their very high level (and the aircraft ID), and applied them to its model of the internal suppression process used on the victim aircraft. The APL receiver model also required information on all 1030 MHz (TCAS) transmissions by the victim aircraft (which also produced internal suppressions). To generate these, we placed a hypothetical additional aircraft very close to the victim, set its threshold very high so it received only the1030 MHz transmissions of the victim, disabled its transmitter so it produced no additional interference, and provided its uplink interrogation file to APL, in addition to the reply file.

The TLAT-defined LA Basin scenario ("TLAT 2020") had an aircraft density approximately double that of the 1999 measurement, but included aircraft out to 400 nm from LAX, a total of 2694 aircraft. Distant aircraft were included for consistency with the models used to analyze the performance of the alternatives, and also to generate very weak fruit. The Extended Squitter receiver postulated by Lincoln Laboratory will have very high sensitivity (on the order of –90 dBm), and will therefore be affected by fruit at levels even lower than that. Such weak fruit would be expected to come from aircraft at great distances, so it was necessary to include distant aircraft in the model, and to record all received fruit at levels down to –100 dBm.

To properly model the fruit generation of these distant aircraft, it was necessary to add distant radars. The model up to this point included the 52 radars within 200 nm of LAX (Table 5-1). To properly execute the TLAT 2020 scenario, it was necessary to add the 46 radars that are located between 200 and 500 nm of LAX (Table 5-7). As in the case of the closer radars, the parameters of these distant radars were determined from FAA records, and through discussions with DoD personnel involved with the many military radars located in the Nevada desert.

Our TLAT support effort involved modification of the Simulator to employ the terrain loss calculation process described in paragraph 3.1.3, augmentation of many internal software parameters to handle the far larger scenarios and associated interference levels, validation of the Simulator with the data measured during the 1999 Los Angeles test program, and execution of many large TLAT-specified scenarios with various aircraft equipage mixtures and victim locations. An attempt to validate the TLAT-specified scenarios revealed a different relationship between fruit rates and levels from those shown in Figure 4-22. In addition to a scale factor that accounts for the differences in aircraft density, the TLAT-specified scenario produced a noticeably less concave curve, with proportionally higher levels of strong fruit.

This difference was traced to the uniform distribution of aircraft positions in the TLAT scenario, and the fact that the same altitude distribution was used for all aircraft regardless of location. In the 1999 measured scenario, we noted that aircraft close to LAX had lower average altitude (by more than a factor of two) than more distant aircraft. The disproportionately large number of high-altitude close-in aircraft in the TLAT

Radar ID	Type	Latitude (dd.ffff)	Longitude (dd.ffff)	Power Output (dBm)	PRF	Scan Rate (sec)
TETHERED BA 1	ATCRBS	33.0161	-114.2419	54.77	375	4.6
TETHERED BA 2	ATCRBS	31.3667	-110.29583	54.77	375	4.8
YUMA ASR	ATCRBS	32.6542	-114.5908	56.36	325	4.7
YUMA	ATCRBS	32.65	-114.6	57.01	270	4.8
CASTLE	ATCRBS	37.3761	-120.553	50	347	4.9
INDIAN SPRI	ATCRBS	36.5875	-115.67222	54.77	295	4.6
LAS VEGAS	Mode S	36.0706	-115.13278	56.02	125	4.6
NELLIS	ATCRBS	36.2294	-115.05361	54.77	414	4.6
TOLICHA PEA	ATCRBS	37.2847	-116.81167	54.77	375	4.7
TONOPAH	Mode S	38.1414	-117.20028	59.03	125	12
MARYSVILLE	ATCRBS	39.1303	-121.46111	56.99	392	5.2
PROVO	ATCRBS	40.2247	-111.72389	50	392	5.3
MOFFETT	ATCRBS	37.4247	-122.015	54.77	406	4.9
RENO	ATCRBS	39.5006	-119.78139	59.03	337	4.8
TUCSON	ATCRBS	32.16	-110.88667	53.01	414	4.7
OAKLAND	ATCRBS	37.7061	-122.225	54.77	417	4.6
SACRAMENTO	ATCRBS	38.6656	-121.40444	55.56	423	5
WILLLIAMS	ATCRBS	33.3122	-111.64833	54.77	337	5.1
MARINA	ATCRBS	36.6944	-121.7575	54.77	340	5.2
PHOENIX	Mode S	33.4272	-112.00611	53.01	125	5.3
STOCKTON	ATCRBS	37.8875	-121.24361	51.76	205	4.9
FT HUACHUCA	ATCRBS	31.5981	-110.34167	56.99	354	4.8
LUKE	ATCRBS	33.5678	-112.38306	54.77	275	4.7
PAPAGO	ATCRBS	33.4708	-111.96333	54.77	245.1	4.6
DUGWAY	ATCRBS	40.15	-113.33333	54.77	280	5
WENDOVER	ATCRBS	40.725	-114.02083	54.77	445	5.1
MCCLELLAN	ATCRBS	38.6439	-121.40222	54.77	275	5.2
TRAVIS	ATCRBS	38.2517	-121.25833	53.01	315	5.3
TROUT CREEK	ATCRBS	39.5667	-113.75944	54.77	395	4.9
FALLON	ATCRBS	39.4056	-118.7225	54.77	347	12
UTAH(UTTR)	ATCRBS	40.425	-113.30833	54.77	400	4.7
AJO-ARSR	ATCRBS	32.4311	-112.945	61.76091	242	15
HUMBOLDT-ARSR	ATCRBS	33.98	-111.7625	61.76091	355	10
SELIGMAN-ARSR	ATCRBS	35.3528	-112.9497	63.01	317	11.7
MILL VALLEY-ARSR	ATCRBS	37.9239	-122.5978	61.76091	295	14.7
RAINBOW RIDGE-ARSR	ATCRBS	40.3956	-124.1653	61.76091	271.1	14.8
RED BLUFF-ARSR	ATCRBS	40.1461	-122.3044	61.76091	360	14.9
SACRAMENTO-ARSR	ATCRBS	38.5539	-121.2692	61.76091	370	15
BATTLE MTN.-ARSR	ATCRBS	40.4033	-116.8678	61.76091	365	9.6
FALLON-ARSR	ATCRBS	39.4056	-118.7225	61.76091	355	14.7
GALLUP-ARSR	ATCRBS	36.0755	-108.86028	61.76091	352.61	14.8
SILVER CITY-ARSR	ATCRBS	32.9892	-108.96056	61.76091	358.29	14.9
CEDAR CITY-ARSR	ATCRBS	37.5933	-112.86306	61.76091	370.23	10
POINT ARENA - ARSR	ATCRBS	38.8886	-123.54861	61.76091	355	15.1

Table 5-7. Additional Radars between 200 and 500 nm of LAX

scenario produced a correspondingly excessive amount of strong fruit because of the higher interrogation rates they were exposed to, resulting in the differently-shaped curve.

The "hybrid" scenario discussed in section 4.2.4.6 of this report was also used to produce interference output files for TLAT, appropriately factored to account for increased future density. "Factoring" involved creation of additional aircraft distributions like those in the original scenario, but with slightly offset positions, and superimposing portions of these on the original scenario.

A European scenario was also studied and modeled. Measurements in that area were conducted in May 2000, allowing limited validation. There were 495 aircraft in a roughly 500 nm area centered to the east of Frankfurt during the measurements (Figure 5-7), and the future scenario (Figure 5-8) involved 2092 aircraft in a similarly-sized region centered near Brussels. The radar database for the region included 335 radars, more than half of which were military. Opportunities to validate the simulated 2000 scenario by comparison with measured data were limited:

- The simulated uplink interrogation rate variation with altitude at a point near Frankfurt was compared with very limited measured data obtained during departure and climb out of the instrumented aircraft in the same general area. The simulation produced a lower (by about 20%) rate than measured (Figure 5-9).
- The simulated fruit rate versus level relationship near Frankfurt agreed well with measured data taken during tests conducted in May 2000 (Figure 5-10).

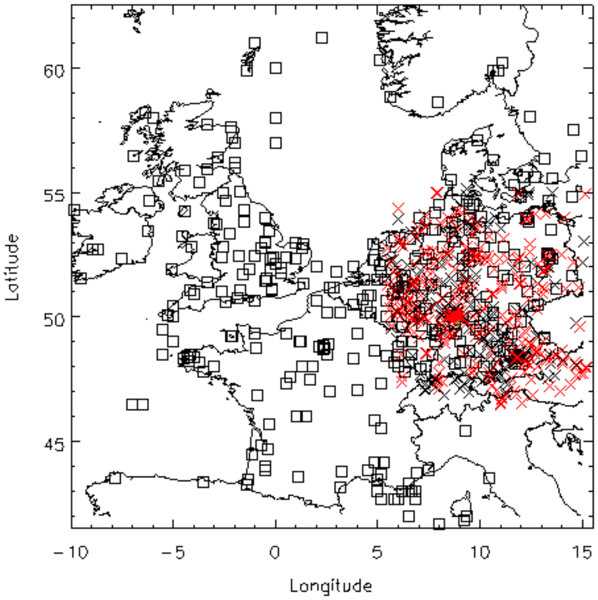


Figure 5-7. As-Measured European Scenario (May 2000)

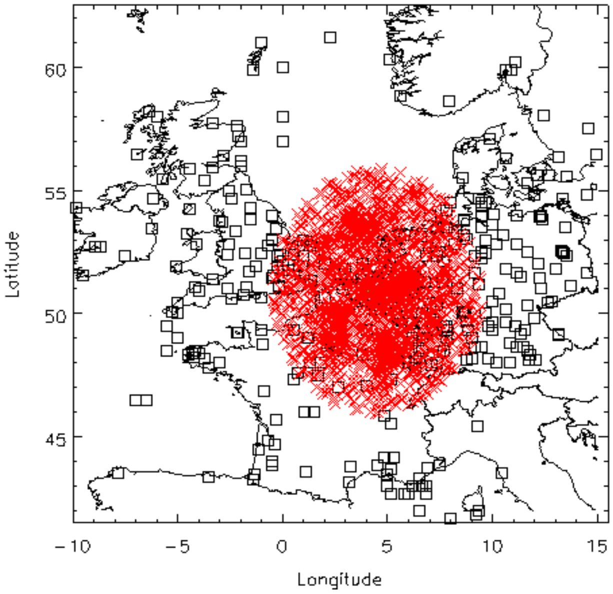
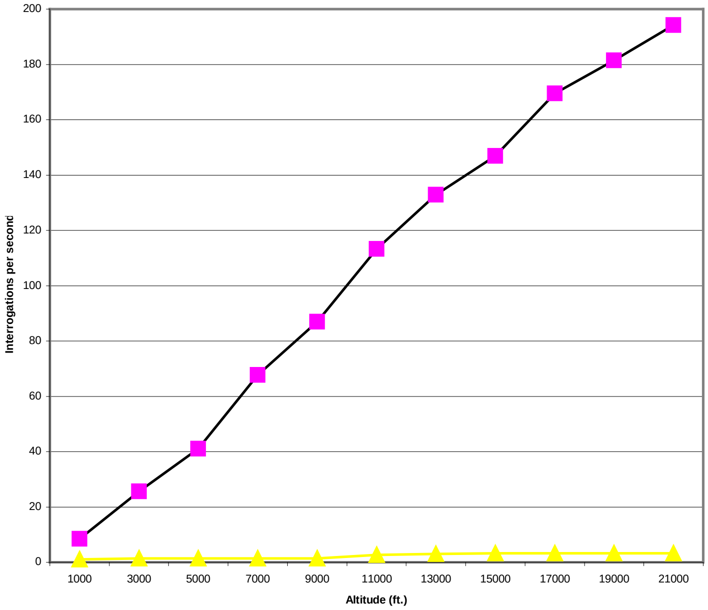


Figure 5-8. Future European Scenario (per TLAT)



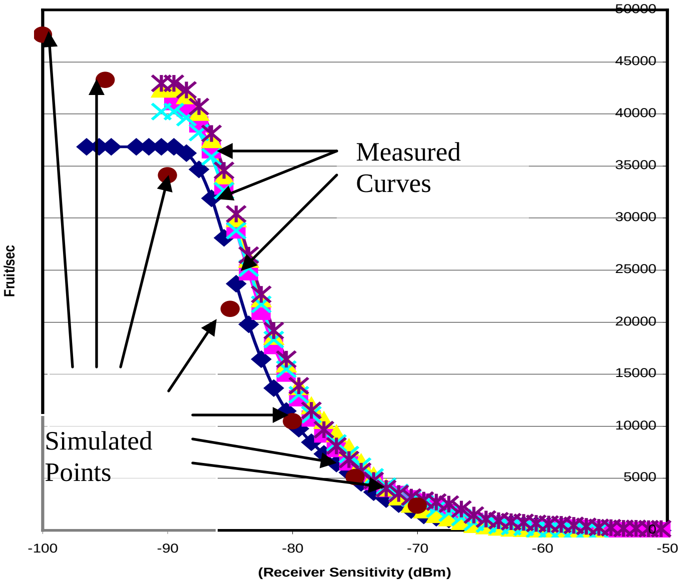


Figure 5-9. Simulated Interrogation Rate Versus Altitude – vicinity of Frankfurt

Figure 5-10. Fruit Incidence versus level – vicinity of Frankfurt

- The amounts of fruit produced by military and civil radars were determined by running the Simulator twice, with each of the two radar subpopulations. The military radars elicited 64.4% of the total 46891 fruit/second. But, when military radars were shut off for a short period during the measurement program, the fruit level dropped by only 25%.

The discrepancies in these statistics appear to be resolvable with additional investigation and analysis of the measured data. Unfortunately, the effort of the TLAT was brought to a close in March 2001, prior to the opportunity to fully validate the European data.

Over the course of our TLAT support effort, we provided over a dozen output interference files to APL for use as input to their Extended Squitter receiver model. Results of their effort to characterize Extended Squitter performance in the Los Angeles and European future scenarios will be published by the TLAT in the future.

5.5 ANTICIPATED FUTURE APPLICATIONS

Use of the Simulator to analyze beacon radar interference problems is a continuing effort. Several future applications have been proposed, including detailed modeling of the current TCAS version (which creates far more interference than the future Version 7 that was modeled), and determination of the interference effects of various proposed new Mode 4 IFF interrogation strategies. Analysis of present-day TCAS performance would involve relatively minor modifications to the Simulator (addition of another TCAS object that uses current rules). Mode 4 IFF is currently limited in use within CONUS due to the high interference it produces, and modeling could establish the interference impact of various proposed interrogation strategies intended to reduce the interference level.

Another valuable application would be to determine the system impact of proposed new waveforms, such as those planned for the new IFF Mode 5. Once laboratory testing of individual transponders has determined one-on-one effects, these could readily be incorporated into the model (for example, through modification to current transponder objects and development of new Mode 5 interrogators and transponders), and the system-level impact on overall performance could be established with a high degree of confidence. This approach would enable determination of the relative levels of interference resulting from various deployment/employment strategies.

Still another application would address the potential interference effects of the proposed new FIS-B and TIS-B services contemplated for Mode S. In these concepts, special ground transmission sites broadcast extended squitter on 1090 MHz containing flight information and traffic information. Traffic squitter would be broadcast during the transition to ADS-B, would mimic ADS-B messages but would derive position information from ground radar, and would pertain only to those aircraft not yet ADS-B equipped. Thus, at first glance, its effects would seem comparable to those of full ADS-B equipage. However, interference issues arise due to the concentration of transmissions at a single (or perhaps several) ground sites. Flight information (e.g., weather, NOTAMs) would be broadcast by FIS-B, and would add to the interference level.

Still other applications address transition issues in the process of achieving full ADS-B operation, and the interference effects of parameter settings of new interrogators. For example, the ASR-11, currently undergoing installation at over a hundred civil and military airfields, can operate satisfactorily at reduced PRF due to its monopulse azimuth measurement capability, but is presently not planned to do so. Quantification of the reduction in interference level that results from reduced PRF operation would be of value.

The Simulator is a versatile tool for the analysis of all proposed modifications and additions to the systems that operate on 1030 and 1090 MHz. As its capabilities grow and the fidelity with which it tracks current system operation and performance increases, it will undoubtedly find many new applications.

REFERENCES

[1] **Minimum Operational Performance Standards for 1090 MHz Automatic Dependent Surveillance – Broadcast (ADS-B)**, Draft RTCA Paper 145-00/SC186-152, May 12, 2000.

[2] **The Impact of a Traffic Alert and Collision Avoidance System on the Air Traffic Control Radar Beacon System and Mode S System in the Los Angeles Basin**, DOT/FAA PM-84/30 (IITRI/ECAC), May 1985.

[3] **Mode S/GPS-Squitter Simulation Overview,** FAA/ASR-200 Briefing, June 3, 1998.

[4] **PV-Wave Tutorial for Windows, Version 6.21**, Visual Numerics, Incorporated Handbook, 1998. Also see the VNI web site (www.vni.com).

[5] **Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II) Airborne Equipment,** RTCA DO-185A (16 Dec 97).

[6] **Development of Improved TCAS II Surveillance and Interference Limiting Functions,** Ronald G. Sandholm, Air Traffic Control Quarterly, v. 7(1) 19-46 (1999).

[7] **Radar Propagation at Low Altitudes,** M. L. Meeks (Artech House, 1982), p. 26.

[8] **Uplink ATCRBS Environment Measurements Along the Boston-Washington Corridor, Vol. 2: Interrogator Characteristics,** (MIT/LL Project Report ATC-83, F. Nagy, Jr., 28 Feb. 1979)

[9] **U. S. Air Force ARSR-4 System Specification** 2109e/1105e (1988).

[10] **Measurements of 1090 MHz Extended Squitter Performance in the Los Angeles Basin,** FAA Advanced Technologies IPT, Report DOT/FAA/ND-00/7, May 2000

[11] **GPS Squitter Capacity Analysis,** MIT Lincoln Laboratory Project Report ATC-214 (20 May 1994).