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ANALYSIS OF 1090 MHZ EXTENDED SQUITTER GROUND BASED TRANSCEIVER PERFORMANCE IN THE LA 2020 TERMINAL ENVIRONMENT

POWER PROJECTION SYSTEMS DEPARTMENT

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY

11100 Johns Hopkins Road, Laurel, Maryland 20723-6099

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ABSTRACT

Through the Federal Aviation Administration's Safe Flight 21 Program and the associated aviation community, new communication systems onboard aircraft and on the ground are being developed that have the potential to increase the safety and efficiency of the National Airspace System. This report analyzes the performance of the 1090 MHz Extended Squitter (1090ES) data link Ground-Based Transceiver (GBT) as it is expected to operate in future terminal environments. The 1090ES GBT is intended to support the reception of Automatic Dependent Surveillance – Broadcast (ADS-B) messages to enable radar-like air traffic functions. In addition, the 1090ES GBT will also broadcast traffic information to 1090ES equipped aircraft in a service called Traffic Information Services – Broadcast (TIS-B). To provide this performance analysis, a simulation was developed at Johns Hopkins University Applied Physics Laboratory (JHU/APL) that models the 1090 MHz RF channel and uses a validated 1090ES receiver performance model. The results of the simulation are analyzed against developed requirements for air-ground, ground-air, and air-air information transfer. The parameters that have the largest impact on performance are analyzed as well.

KEYWORDS: Traffic Information Service – Broadcast
Automatic Dependent Surveillance-Broadcast
Ground Based Transceiver
1090 MHz Extended Squitter

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EXECUTIVE SUMMARY

New technologies for use in civil aviation are being developed that have the potential, within the next several years, to change the manner in which aircraft operate in the National Airspace System (NAS). Through the Federal Aviation Administration's Safe Flight 21 Program and the associated aviation community, evolving communication systems onboard aircraft and on the ground are expected to dramatically increase the amount of available surveillance, navigation, and meteorological information that users of these systems can then act on, increasing the safety and operational efficiency of the NAS. This report quantitatively characterizes and evaluates the performance of a Ground Based Transceiver (GBT) of one of the datalinks that will enable this transfer of information, 1090MHz Extended Squitter (1090ES).

The 1090ES GBT acts as a bridge between airborne users and the ground surveillance network. It receives ADS-B messages transmitted by aircraft and issue reports based on these receptions to ground-based users via its network interface. It will also transmit traffic information it receives from the surveillance network up to aircraft. The air-ground reception performance is compared to both terminal radar performance and Precision Runway Monitor radar supporting parallel approaches at airports. The ground-air performance will be compared to developed standards that levy requirements on the airborne reception of surveillance data.

A number of important assumptions were made for the analysis, most importantly:

- The LA 2020 scenario is the basis for the air traffic model, but not all aircraft are assumed to be equipped with ADS-B, and of these aircraft, only some were equipped with 1090ES. In past analyses of LA 2020, the entire aircraft population was assumed to be equipped with 1090ES.
- The Fruit (Mode A/C) rate for all runs was 24,000 per second, for both airborne and ground receivers. The Mode S and Extended Squitter interference varied as a function of altitude. The Extended Squitter interference also varied as a function of 1090ES aircraft equipage.
- 16 GBT locations were sited (13 at airports) in an area resembling the Los Angeles ARTCC
- The GBT uplink rate at the LAX station, which has the largest throughput of the ground station network, averaged 187 and 254 broadcast messages each second in the 50% and 90% ADS-B equipage cases. The maximum numbers of uplink messages broadcast in these two cases were 252 and 358, respectively. This uplink rate serves as interference for airborne receivers and inhibits ground reception of ADS-B messages for 1090ES GBTs.
- The airborne receiver used for uplink performance evaluation was placed near the intersection of five GBT service volumes, which is expected to be a worst-case condition due to GBT self-interference.
- A radar model was used to determine detection rates for the radar locations in the LA 2020 scenario. The average detection rate for aircraft in a region around LAX was every 2.7 second, which is used as the standard radar detection rate for all aircraft. Fundamental TIS-B uplink performance must be evaluated by comparing the update intervals with this 2.7 second value. It represents the minimum update interval that is achievable, and update intervals will be approximately equal to a multiple of this value.
- UAT reception at each of the proposed GBTs is assumed to be once per second. This is the detection rate used for all UAT equipped aircraft in the scenario. ADS-B Rebroadcast uplink performance must be evaluated by comparing the update intervals with a 1.0 second value that represents the minimum ADS-R update interval. Received update intervals will tend to be integer multiples of this one second detection rate.

- The metric used in both ADS-B and TIS-B performance evaluations is the 95th percentile state vector update interval. The requirements used to compare these results were taken from standards documents where possible. In the case of air-ground reception of ADS-B messages, the results were compared to nominal radar sweep rates.

The air-ground performance of the 1090ES system in the terminal environment was very robust. The expected configuration of the GBT will update a given aircraft's state vector upon the reception of a Position or a Velocity Extended Squitter Message. The A1/A2 transmit powers, which have a lower minimum than the recommended powers for A3, will set the range of RF coverage for the GBTs. For a ground receiver with A3 receiver characteristics, 95th percentile state vector update intervals matched similar radar sweep rates in all cases. For ADS-B in the terminal domain, the accuracy and integrity of the data from airborne transmitters may be the limiting factor in providing acceptable ground-based surveillance.

For the TIS-B uplink performance, fundamental TIS-B is expected to support airborne receivers performing Enhanced Visual Acquisition in the terminal area, while ADS-B Rebroadcast is expected to support both Enhanced Visual Acquisition and Conflict Detection. Both of these conclusions depend heavily on the GBT receiving data from those surveillance sources at the rates specified above.

The ADS-B air-air performance in the dual-link scenario was also analyzed. Ranges of compliance with the DO-242A (ADS-B MASPS) update interval requirements up to and beyond 60 NM were achieved for all combinations of A2 and A3 as transmitter and receiver. In addition, the Enhanced Visual Acquisition, Conflict Detection, and Enhanced Visual Approach applications as defined in DO-289 are supported between airborne participants exchanging ADS-B data for each application's service volume in the terminal environment.

However, the FAA is expected to limit the number of uplink broadcasts allowable by a 1090ES GBT in a given time period in order to ensure that Secondary Surveillance Radar performance is not degraded in the terminal environment. The message repeat strategy described in the report may need to be revised in order to accommodate these uplink limits and subsequent analysis undertaken to determine the effect on the TIS-B performance.

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Section 1

Introduction

New technologies for use in civil aviation are being developed that have the potential, within the next several years, to radically change the manner in which aircraft operate in the National Airspace System (NAS). Through the Federal Aviation Administration's Safe Flight 21 Program and the associated aviation community, evolving communication systems onboard aircraft and on the ground are expected to dramatically increase the amount of available surveillance, navigation, and meteorological information that users of these systems can then act on, increasing the safety and operational efficiency of the NAS. This report quantitatively characterizes and evaluates the performance of one of the datalinks that will enable this transfer of information, 1090MHz Extended Squitter (1090ES).

The first section of this report gives an overview of the architecture in which 1090ES will operate. In Section 2, the assumptions used in the analysis to follow are stated and developed. Section 3 presents the results and the supporting analysis. Finally, section 4 summarizes the findings in this report.

The appendices have a good deal of supplemental information. Appendix A and B are lists of the references and the acronyms/abbreviations used in this report. Appendix C is a list of the airport and GBT codes used in the LA 2020 scenario. Appendix D describes the validation of the 1090ES receiver performance model used in the simulation and analysis.

1.1 OBJECTIVE

This report seeks to quantitatively characterize the information transfer on the 1090ES datalink between the aircraft and ground in a terminal environment. For the transfer of Automatic Dependent Surveillance – Broadcast (ADS-B) data from aircraft to the ground, the performance of a 1090ES Ground Broadcast Transceiver (GBT) receiving messages from aircraft in a high-density, terminal airspace will be simulated. The results will be compiled as a function of range between the transmitting aircraft and the GBT, and compared to nominal radar surveillance performance in these settings. For the transfer of information from the ground surveillance network to the aircraft, the reception of Traffic Information Service – Broadcast (TIS-B) messages will be modeled in the same high-density scenario. The results will be compared to the requirements specified for airborne applications to be performed by a receiving aircraft.

1.2 OVERVIEW OF THE SYSTEMS

A depiction of the major systems involved in the Safe Flight 21 technologies* is shown in Figure 1. In the sections that follow, each system and how they interact is explained in more detail.

* There is no single term that encapsulates all of these systems and how they are related in future surveillance for aviation. "Safe Flight 21 technologies" is the term used here.

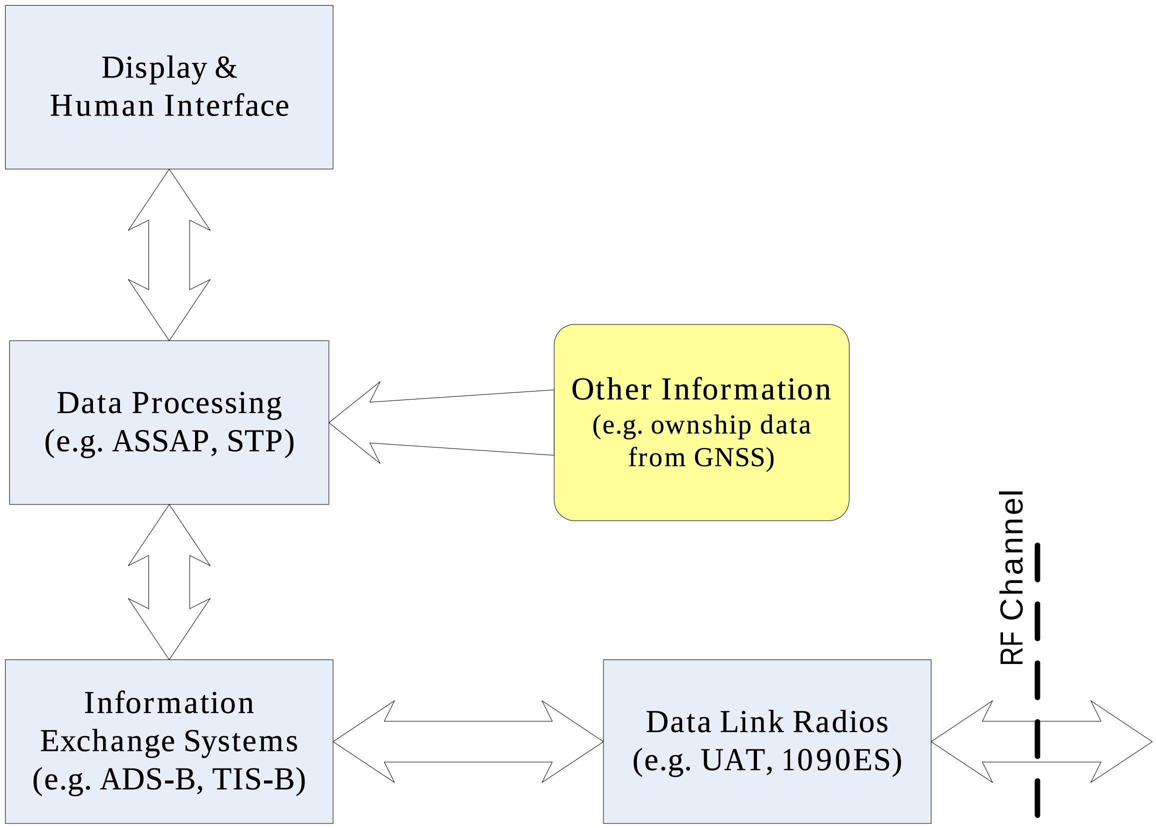

Figure 1: Block Diagram of Safe Flight 21 Technologies

1.2.1 Applications and Application Processing

The human interface to these systems is located at the top of the figure. On aircraft, the display is termed the Cockpit Display of Traffic Information (CDTI). The CDTI will be the primary interface between flight crew and these systems. Some examples of the interaction between user and system include entering information about the capability of the flight crew, requesting more information about aircraft in the vicinity, and reacting to alerts or warnings. There are currently five applications that are standardized for future use in aircraft, called Aircraft Surveillance Applications (ASA), as shown in Table 1.[1] The applications that will be used for ground-based users have not been fully defined at this point.

Application	Description
Enhanced Visual Acquisition	CDTI provides relative range, altitude and bearing data of target aircraft, assisting flight crew in visual searches
Conflict Detection	Enhance awareness of proximate traffic by providing alerts when aircraft separation is predicted to become compromised
Airport Surface Situational Awareness	Provide flight crew with own-ship positional and traffic situational awareness relative to an airport map
Final Approach & Runway Occupancy Avoidance	Provide flight crew with supplemental traffic situational awareness to support determination of whether a runway is, or soon will be, occupied. The application will also provide the flight crew with additional information to enhance landing, takeoff, and runway crossing decisions.
Enhanced Visual Approach	Extension of current visual approach procedure that uses the CDTI to detect and track the preceding aircraft more effectively

Table 1: Currently Defined Aircraft Surveillance Applications

The display/interface (which may be ground-based) has a two-way communication path with data and application processing systems. Onboard the aircraft, the Aircraft Surveillance and Separation Assurance Processor (ASSAP) and the Surveillance Transmit Processor (STP) are two such processing systems.† ASSAP systems will take received surveillance data, combine that with own-ship data from navigation systems (such as GNSS - Global Navigation Satellite System), process the data to perform aircraft applications, and forward the required information to the display. The STP is a processor for the converse data flow; own-ship data is processed according to the requirements for broadcast and forwarded to the lower level distribution systems. On the ground, comparable systems have not been defined.

1.2.2 Data Exchange Systems

The two main information exchange systems, ADS-B and TIS-B, are shown near the bottom of Figure 1.[2,3] Figure 2 shows the set of systems in a slightly different way, with more focus on the data exchange and the types of users. Both of these systems have been standardized and define a set of requirements on the data to be transferred; ADS-B defines data exchange to/from aircraft, whereas TIS-B defines data exchange for ground broadcasts of surveillance data up to aircraft.

† These two processors, along with the CDTI, are defined as the Aircraft Separation Assistance System (ASAS).

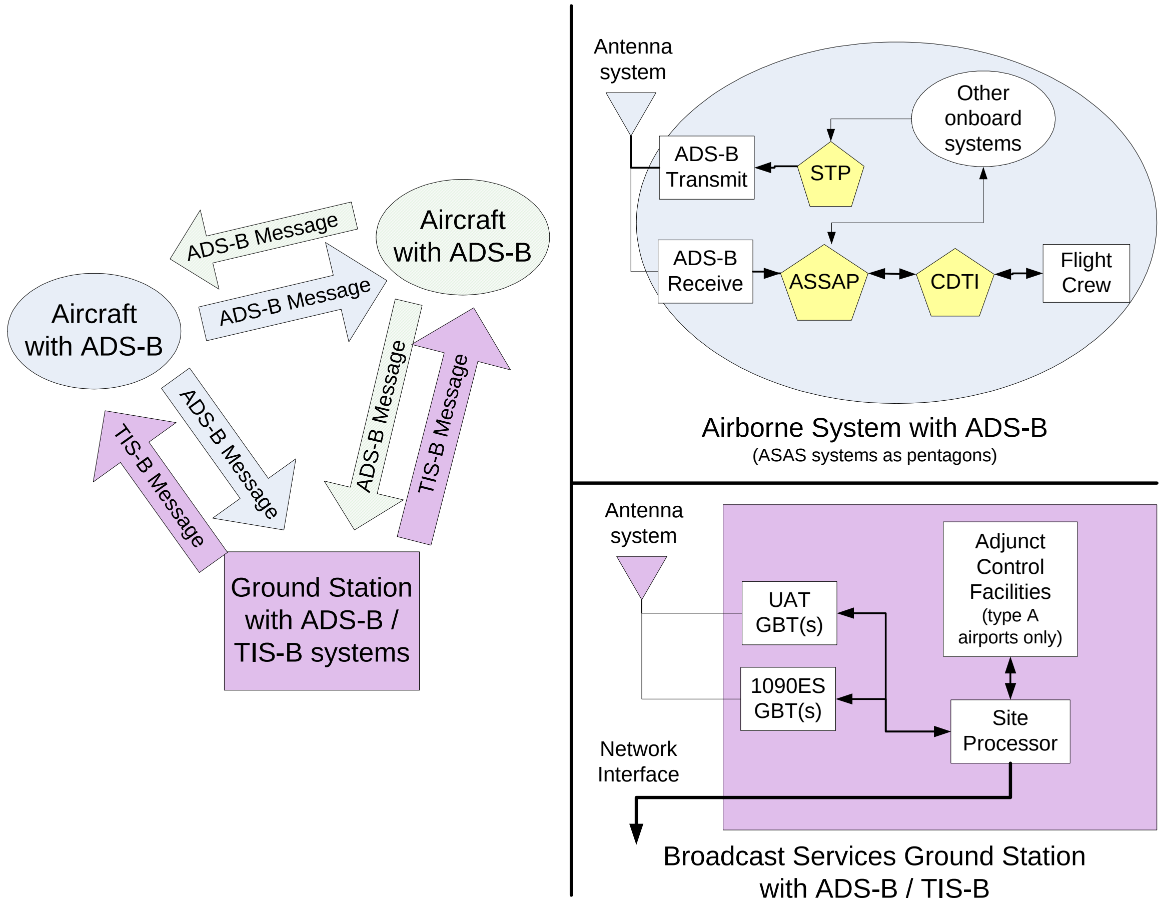

Figure 2: Depiction of ADS-B and TIS-B Information Exchange Systems

1.2.2.1 ADS-B

ADS-B is a distributed network of datalink transceivers. An aircraft with an ADS-B transceiver installed will periodically broadcast information about itself for other transceivers to receive. All ADS-B transceivers can receive data about other users. The most frequently sent information is the state vector, which includes the current position and velocity of the aircraft in both horizontal and vertical components. When this information is received frequently with high assurance, ADS-B users can achieve a rapidly updated awareness of the locations and headings of other ADS-B equipped aircraft. ADS-B is intended to be one of the principal means of enabling ASA. It is depicted in Figure 2 as the means of air-air and air-ground transfer of surveillance data.

Standard ADS-B equipment onboard aircraft will consist of two parts alluded to above: a transmitting subsystem that is capable of message generation and transmission, and a receiving subsystem capable of message reception and report assembly from received data. ADS-B equipage is a term used to indicate the level of the functional capability of the transmitting and receiving subsystems. The equipage levels run from A0, the minimum set of equipment for interactive users, to A3, which includes all of the capabilities of the airborne ADS-B system.

Although not the focus of this study, some aircraft will only be equipped with a transmission capability and, lacking a reception capability, will have a more limited role in their interaction with other airborne users and ground systems. However such aircraft equipped with only an "ADS-B OUT" capability will support ADS-B applications onboard other more fully equipped aircraft as well as ground ATC surveillance applications.

In July 2002, the FAA announced that two datalink systems would be deployed to support ADS-B connectivity.[4] The 1090 Extended Squitter (1090 ES) system will be used onboard transport class and other large aircraft that fly at high altitudes, while UAT will be deployed on smaller aircraft, such as General Aviation. A consequence of this link decision is that aircraft with different datalink systems cannot communicate directly with one another. To provide traffic awareness between aircraft equipped with different datalinks, the FAA plans to provide the ADS-B Rebroadcast service. This service will use ground stations to broadcast 'translated' ADS-B information from one datalink to the other. ADS-B Rebroadcast is part of the TIS-B service.[3]

1.2.2.2 TIS-B

TIS-B is a system that derives traffic information from ground-based surveillance sources and broadcasts the information from ground stations so that ADS-B equipped aircraft can receive the data to supplement airborne situational awareness. This allows ADS-B users to have surveillance data pertaining to most or all targets in the airspace, not just similarly equipped ADS-B transmitters. TIS-B is shown at left in Figure 2 as uplinks from ground stations, and includes TIS-B processing of radar or other surveillance system detections and the ADS-B Rebroadcast service.

Physically, the TIS-B system is expected to consist of Control Facilities and Broadcast Services Ground Stations (BSGS). The control facilities will house the surveillance processing systems that ingest surveillance data, process the system track information, and output TIS-B reports to a network interface. The BSGS can be a remote facility and will have at minimum an ADS-B transmitter for broadcasting the TIS-B messages, shown in the lower right of Figure 2.

The TIS-B and ADS-B systems will be operational at the same time, so it is important that the systems perform their functions harmoniously. As currently envisioned, TIS-B will assume a large part of the burden in the near-term for supplying traffic information, but as ADS-B technology is adopted and aircraft equip with the ADS-B datalinks, the traffic load will move from the TIS-B to the ADS-B system. However, some level of ground-based assistance may be necessary to translate the data between ADS-B data links.

Each BSGS will have several corresponding volumes of airspace defined for it. These are described in Table 2.

Table 2: Volumes of Airspace Required for Each BSGS

Airspace Volume	Description
ADS-B RF Service Volume	Airspace in which BSGS are expected to receive ADS-B messages from airborne users.
TIS-B RF Service Volume	Airspace for which a BSGS is required to support the requirements for TIS-B delivery to support ASA.
Traffic Information Volume	Airspace about which surveillance data is provided to the TIS-B system from non-ADS-B sources (to support information transfer about traffic without ADS-B)
Surveillance Coverage Volume	Airspace in which there is adequate information from one or more ground sensors.

Finally, it should be noted that this report attempts to be consistent with the language used in RTCA DO-286A, TIS-B MASPS, regarding the broadcasts of surveillance data from radar reports or other surveillance sources, which is called *fundamental TIS-B*, and the broadcast of ADS-B information derived from the reception of UAT messages at a local GBT, which is called *ADS-B rebroadcast*. Both of these functions are considered here to be part of the TIS-B system.

1.2.2.3 1090ES Data Link

At the data link and physical layers, radios will serve as a link between the ADS-B users to other airborne users and also to ground-based TIS-B transmitters. The two types of data links selected for deployment in the United States for ADS-B/TIS-B information transfer are 1090 MHz Extended Squitter (1090ES) and Universal Access Transceiver (UAT).[5,6] It is expected that aircraft that want to host ADS-B will equip with one of these data links, although equipping with both types is not precluded, and that BSGS installations will have both types of radios.

1090ES is an extension of transponder technologies that support secondary surveillance radars (SSRs) in civil and military aviation. Existing transponder technology is intended to be modified to support a longer "squitter" message that is periodic in nature (as opposed to being triggered by an interrogation via SSR or a whisper-shout interrogation from airborne TCAS). 1090ES is the selected technology for air-carrier and high-flying commercial aircraft, including international carriers operating in the U.S. and Europe. Australia has already begun implementation of a ground surveillance system using 1090ES transmitters onboard aircraft.[7]

The 1090ES message consists of 112 bits and is 120 usec in duration. 56 of these bits are for use by ADS-B data and 56 of the bits are for the data link layer protocol and include provision for error-checking and to convey the aircraft identification.[5] In order to transfer all the information required by the ADS-B standards, data is partitioned across multiple types of 1090ES messages as shown in Table 3 for airborne participants. Aircraft on the ground transmit 2.4 squitters per second, if in motion, and 0.6 squitters per second if stationary, regardless of equipage. For airborne aircraft, the A0 and A1 equipages transmit at the rate of 4.6 squitters per second, while A2 and A3 equipped aircraft transmit at 5.4 squitters per second

Table 3: 1090ES ADS-B Aircraft Message Types and Transmission Frequency

Message Type	Contents Include	Nominal Transmission Frequency (sec^{-1})
Airborne Position	Latitude, Longitude, Barometric altitude	2
Airborne Velocity	East/West, North/South, and Vertical Velocity, difference between Geo. and Baro. altitudes	2
Surface Position	Latitude, Longitude, Heading, Ground Track and Movement (velocity range)	2 when moving 0.2 when stationary
Aircraft ID and Type	Emitter Category, Flight Plan ID or Tail Number	0.2
Aircraft Operational Status	Capability Codes, Operational Mode, Accuracy & Integrity of Position information	0.4
Target State and Status	Intent/Status Information	0.8

1.2.3 Ground Systems Architecture

The initial Broadcast Services System is currently being deployed in Alaska (the Capstone Program) and on the East coast of the coterminous 48 states.[8,9] Additional "pockets" of like capability are expected to be deployed elsewhere in the NAS during 2004-2008. This program will provide aircraft and surface users of ADS-B equipment (primarily UAT equipment) with an initial TIS-B capability to augment their air-to-air data link equipment, as well as provide limited Flight Information Service – Broadcast (FIS-B) services.

The next development stage is expected to augment the equipment infrastructure initially deployed with expanded capability and coverage, as well as provide service for 1090ES equipped aircraft. These expanded capabilities include additional FIS and Aeronautical Information Service broadcast products over the UAT datalink, ADS-B Rebroadcast service, and an interface over which Air Traffic Services automation systems can ingest ADS-B Reports for use by controllers.

1.2.3.1 Airport and BSGS types

For the purposes of defining appropriate ground equipment configurations, four (4) different types of airports are defined below.

- Type A airports are towered, high-density airports that have or will have a surface radar/multi-lateration system. Additionally all current and candidate locations for installation of a Precision Runway Monitor (PRM) system are type A airports. A type A airport contains terminal radar(s) located at the airport and includes all airports equipped with an ASDE-X surveillance system, enabling TIS-B to support FAROA and ASSA applications. Currently, 59 airports fit into this category.

- Type B airports are medium-density airports that have a Mode S terminal radar system located at the airport but no ASDE-3X surveillance system. There are 60 candidate Type B airports.
- Type C airports are the remainder of the towered airports in the NAS: C1 types have an ATCRBS terminal radar system, while C2 airports have no radar systems. There are approximately 395 airports of this type.
- Type D airports comprise all non-towered airports in the NAS. There are approximately 4900 airports that fit into this category.

Broadcast Services Ground Stations (BSGS) will be configured to support services at each of the four different airport types. At a minimum, the equipment located at a BSGS control site features both 1090ES and UAT Ground Based Transceivers (GBTs), a Site Processor, and an Antenna Subsystem. Additional equipment that may be needed at some airport types consists primarily of additional transceivers to increase coverage or to provide validation functions.

An important assumption for this analysis is that a single GBT will be used to determine air-ground performance. The contributions in air-ground performance due to satellite or auxiliary GBT receptions are ignored. This will provide a worst-case performance baseline. The differences in performance between the primary and secondary GBTs are likely to be site-specific and beyond the scope of this type of general analysis.

Another important assumption is that datalink performance between the GBT and surface aircraft will not be analyzed. The reason for this is that, once again, the performance is likely to be strongly influenced by site-specific issues, e.g. the location of secondary GBTs, the location of the gates /runways, and multipath reflections off of structures, and is beyond the scope of the approach taken here.

1.3 1090ES SIMULATION DEVELOPED BY JHU/APL

JHU/APL has developed a simulation to analyze the performance of the 1090ES data link. A depiction of the 1090ES simulation is shown in Figure 3. Figure 3 shows inputs to the simulation as (green) parallelograms, JHU/APL developed tools as (blue) rectangles, and the output of these tools as (pink) ellipses. Additionally, a tool developed at the Volpe National Transportation Center that models interference at 1090 MHz due to transponder equipment onboard aircraft is shown in the figure as well.[10]

The simulation itself resides in the center of the figure. The nucleus of the simulation is a validated 1090ES receiver performance model that can simulate every type of receiver equipage at the pulse level (the receiver performance model is described more fully in Appendix D). This granularity allows for analysis of many different facets of 1090ES performance, although the simulation is used primarily to analyze large-scale performance for designed scenarios. Inputs include the air traffic and ground network scenarios, and interference seen by the receiver due to transponders, 1090ES equipped aircraft, and co-site systems onboard the aircraft that trigger a suppression bus, such as DME and TCAS systems. The major assumptions for all of the configurable parameters are described in Section 2.

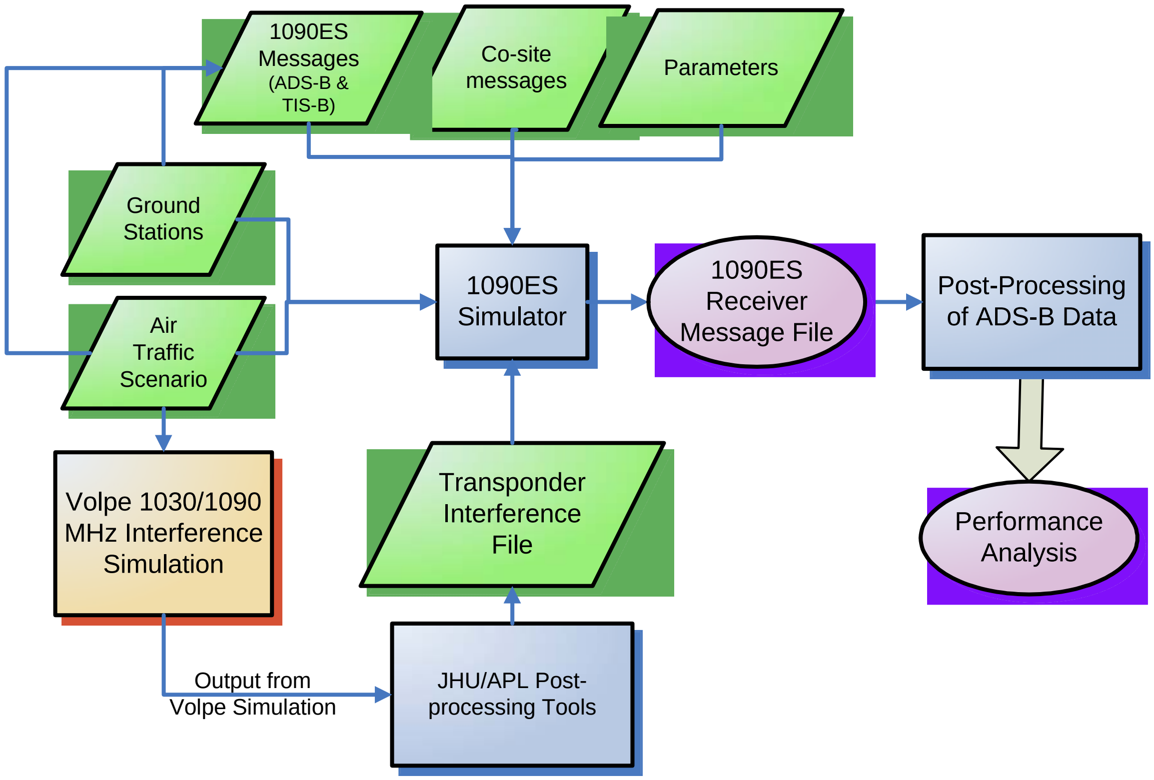

Figure 3: Diagram of JHU/APL 1090ES Simulation

Section 2

Assumptions for Analysis

2.1 TERMINAL AREA SCENARIO

The terminal area model analyzed in this report has two main components, the air traffic scenario and the ground surveillance network. The Los Angeles region in the year 2020 is taken as the area under investigation, and has been studied in previous analyses.[5,14]

2.1.1 Air traffic Scenario

The LA 2020 scenario, described in several standards [1,2], will be used for the air traffic model, with some adaptations to account for the future dual-link airspace and the TIS-B ground stations. As mentioned earlier in this document, not all aircraft in the scenario will be assumed to be equipped with ADS-B, and those that are equipped will be split between the UAT and 1090ES datalinks. Two cases of overall ADS-B equipage, where 50% and 90% of the aircraft are equipped with ADS-B (either UAT or 1090ES), will be examined. Of the aircraft that have ADS-B, approximately 60% of these aircraft are assumed to be equipped with 1090ES*, and the remainder with UAT. Table 4 shows the breakdown of the scenario for each equipage case. Figure 4 shows the plan view of the LA 2020 scenario. Approximately 2700 aircraft are located within 400 NM of LAX.

Table 4: LA 2020 Air Traffic Scenario Characteristics

	50% ADS-B Equipage Case	90% ADS-B Equipage Case
Number of Aircraft	2694	2694
Number of 1090ES equipped Aircraft	841 (31%)	1496 (56%)
Number of UAT equipped Aircraft	518 (19%)	937 (35%)
Number of Aircraft without ADS-B	1335 (50%)	261 (10%)

* Of those aircraft that are assumed to be equipped with 1090ES, about half use A3 transceivers, about 1/6th are A2 transceivers, and the remaining third are A1 transceivers.

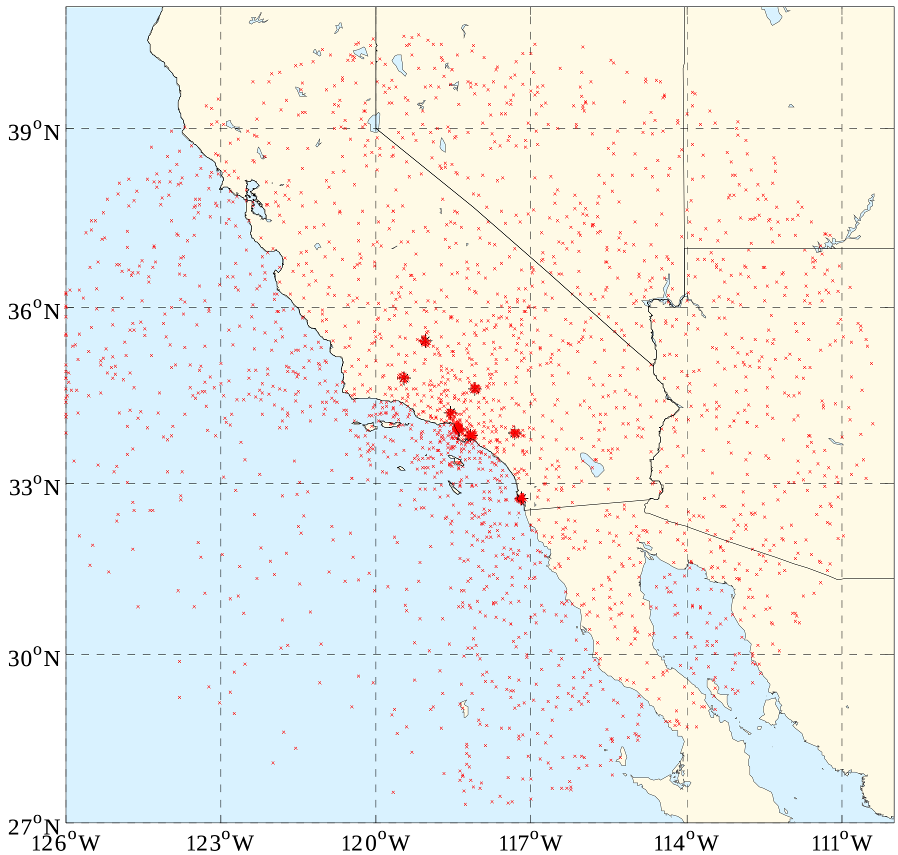

Figure 4: Plan View of LA 2020 Scenario

2.1.2 Ground Surveillance Network

For the LA basin region, the network of ground station locations is based on a simple assumption that BSGS sites will be deployed at all airports with terminal radar by 2020. There are 13 airports that meet this criterion that are within an area resembling the LA ARTCC. These airports and the three character airport codes are shown in Figure 5 (a key to these codes is provided in Appendix C). Also shown in the Figure are the approximate Traffic Information Volumes for each GBT. The stations are marked with several symbols to indicate the Airport type/BSGS type:

- Blue Circle : Type A (LAX, BUR, SAN, LAS, ONT, SNA)
- Red Square: Type B (LGB, PSP, SBA)
- Green Triangle : Type C1 (SMX, FAT, BFL, YUM)
- Pink Plus Sign : Type C2 (no terminal radar – added for coverage AAA, BBB, CCC)

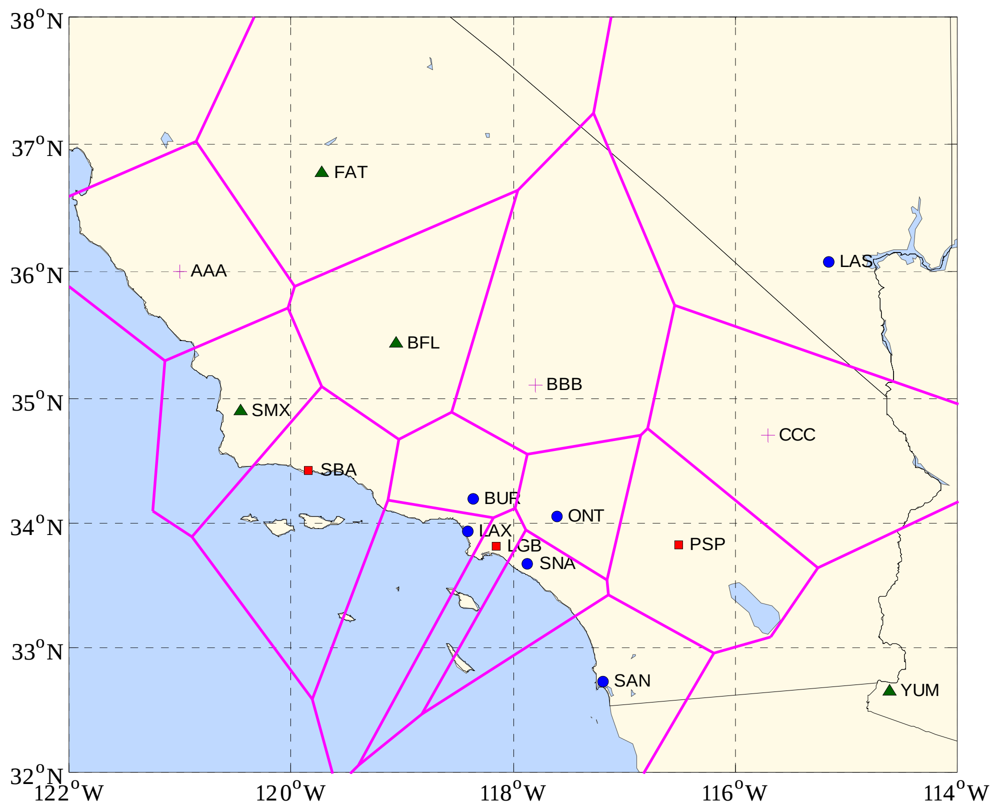

Figure 5: Plan View of BSGS Sites with Corresponding Traffic Information Volumes

The three type C2 stations (AAA, BBB, and CCC) were added in the scenario without respect to siting criteria or airport location. These locations were placed to approximate full air-ground coverage for this future scenario.

Some of the most important assumptions for the TIS-B uplink analysis are the frequency and types of surveillance detections that furnish the TIS-B system with traffic information. Because the LA region has many radars providing surveillance, any given target can be detected by multiple radars. However, the performance metrics used in evaluating TIS-B are dependent on the surveillance data being provided from the ground network, i.e. the detection rate. This report is concerned with the aspects of TIS-B performance that are governed by the 1090ES GBT. To attempt to remove the dependence on the surveillance system, a fixed rate of radar detection will be chosen to provide input data for the Fundamental TIS-B service and another fixed rate of UAT reception will be chosen to provide data for ADS-B Rebroadcast service. Details about this assumption used for the TIS-B analysis include:

- For fundamental TIS-B service, only terminal or enroute radars will provide surveillance data to be broadcast. No surface radars or multi-lateration systems will be assumed to detect aircraft.
- Within 100 NM of LAX, the average detection rate was once every 2.7 seconds, which is approximately equivalent to two radars detecting each target in the core region of this scenario. This 2.7 second rate for radar detection will be assumed as the standard detection rate for each

aircraft that is not equipped with ADS-B in the LA scenario. TIS-B messages with the most recent traffic data about these targets will be broadcast every 2.7 seconds.

- It will be assumed that each aircraft in the scenario that is equipped with UAT data link will be received each second by the BSGS. The 1090ES GBT will broadcast traffic information about UAT equipped aircraft every second.

2.1.3 Interference environment

The interference environment at 1090 MHz includes replies to Secondary Surveillance Radar (SSR) in the form of Mode A, Mode C, or Mode S.[11] The Mode A/C interference, called ATCRBS Fruit, was set to 24,000 (24k) ATCRBS messages per second above -84 dBm at the receiving aircraft. A 1030/1090 MHz interference simulation developed at the Volpe Transportation Center was used to obtain an initial approximation to the expected interference environment. This resulted in approximately 55,000 ATCRBS messages per second above -84 dBm, which was then normalized to 24,000 ATCRBS messages at the bottom antenna on the receiving aircraft, seen in Figure 6. This was also the assumption used for the aircraft at 4,000 ft. and the ground receiver at LAX. Although the expected Fruit rate would most likely drop for a receiver at 4,000 ft., the assumption was kept for this case in order to make direct comparisons with the performance of the 40,000 ft. receiver. The ground receiver would have fewer Fruit incident on it due to line-of-sight (LOS) issues, but this decrease may be offset by the increased gain for a ground antenna compared to airborne antennae.

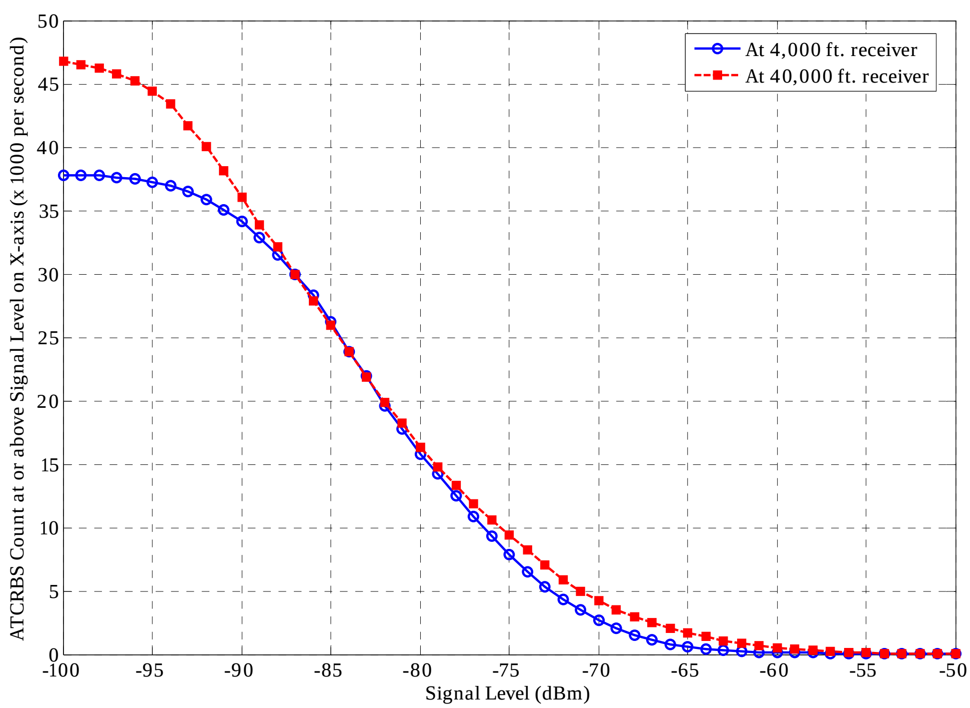

Figure 6: CDF of Average Number of ATCRBS Messages per Second on the Bottom Receiver Antenna in 24k Fruit LA2020 Scenario

Mode S interference was not scaled as ATCRBS interference was. The Mode S rate was calculated based on the output of the Volpe simulation. Figure 7 shows a CDF of Mode S replies received at the bottom antenna of each of the four airborne receiver cases. The dependence is entirely based on the altitude, not on ADS-B equipage levels, as one would expect.

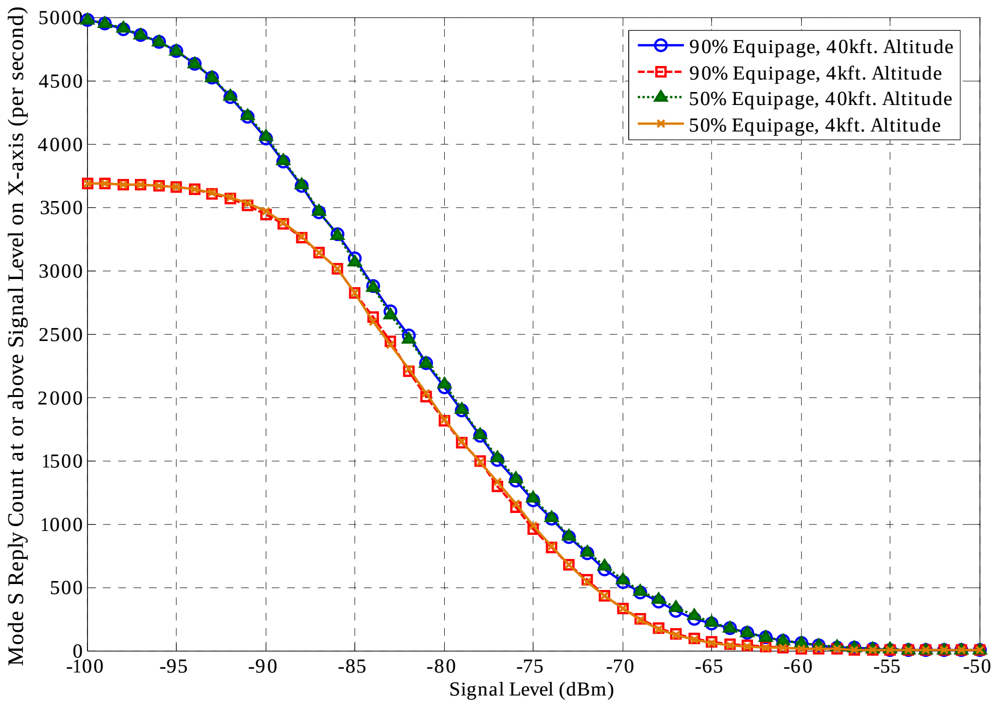

Figure 7: Average Number of Mode S Messages per Second at the Bottom Receiver Antenna in the LA 2020 Scenario

Co-site interference is any transmission near enough to the receiver to warrant inhibiting reception in order to protect receiver components. Sources of co-site interference onboard aircraft include replies to ATCRBS, Mode S, and TCAS interrogations, ADS-B transmissions, TCAS interrogations, and Distance Measuring Equipment (DME) transmissions. At the GBT, the assumed co-site interference is TIS-B uplinks and blanking when two assumed co-located terminal radars are pointing at the GBT receiver. The duration of blockage per transmission and the average number of transmissions per second are shown in Table 5.

Table 5: Co-site Interference Summary

	Co-site Interference Type	Duration (us)	Average Per Second	Blanking (%)
AIRCRAFT ONLY	ATCRBS Reply	58	53	0.3%
	Mode S / TCAS Reply	100	23	0.2%
	ADS-B Transmission	165	5.4	0.1%
	TCAS Interrogation	105	66	0.7 %
	DME Transmission	44	70	0.3 %
Percentage of Time Receiver is Blanked on Aircraft				1.6%
GBT ONLY	TIS-B Transmission	165	254 in 50% ADS-B equipage case 187 in 90% ADS-B equipage case	4.2% 3.1%
	Radar Boresight Sweep-by	25,000	0.4 (2 radars with 5 second sweeps)	1%
Percentage of Time Receiver is Blanked at GBT				5.2% (max. at LAX)

Aircraft equipped with 1090ES in the scenario are assumed to be transmitting ADS-B messages as described in Section 1.2.2.3. A CDF of the Extended Squitter incidence rate for the four airborne receiver cases is shown in Figure 8. The 1090ES self-interference is seen to be a function of altitude and the ADS-B equipage.

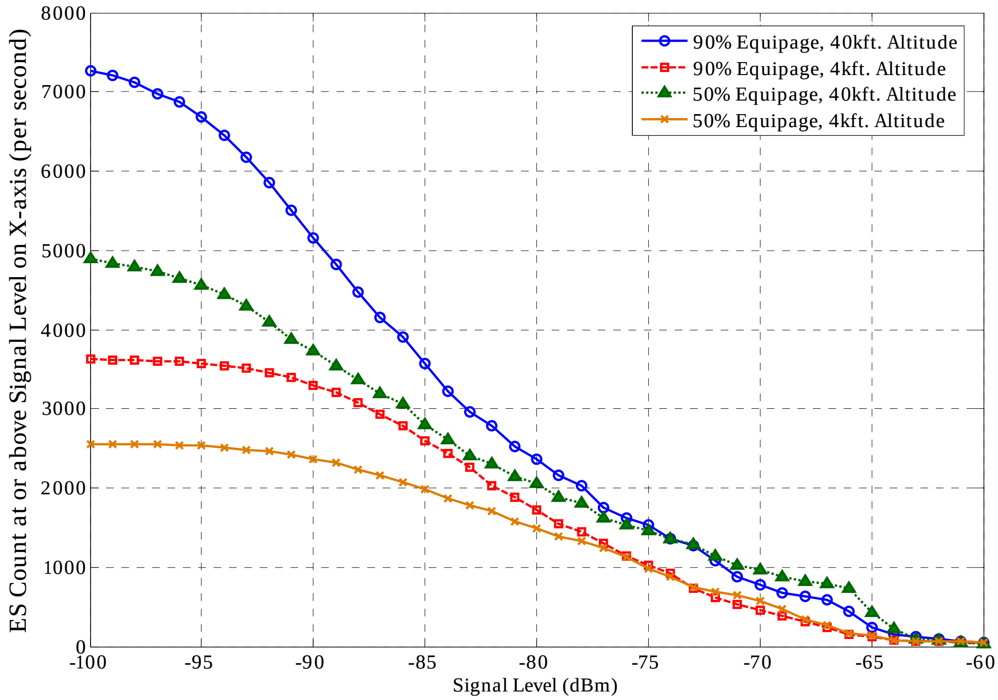

Figure 8: CDF of the Average Extended Squitter Messages per Second for a Bottom Receiving Antenna in LA 2020

2.2 1090ES RECEIVER ASSUMPTIONS

The 1090ES simulation models, processes, and stores data about all 1090ES messages that are incident on an aircraft, i.e. all messages that are not blocked due to line-of-sight limitations. This section describes the assumptions made about the behavior of the 1090ES receivers in modeling and processing these messages.

2.2.1 Characteristics of the Decoders

Minimum Triggering Level (MTL) is defined as the signal level at which 90% of messages are successfully decoded in the absence of interference. MTL levels are specified for each aircraft equipage in 1090ES standards.[5] It is expected that the most sensitive enhanced decoder 1090ES receiver (A3 equipage) will be used for the ground stations.* The MTL and the decoder properties of each equipage are described below, and Figure 9 shows a curve of the MTL performance for each equipage.

The A3 equipage uses a 10 MHz sampling rate with the baseline decoding algorithm described in Appendix I of the 1090 MOPS. The A3 equipage has an MTL of –85.5 dBm, which was derived from the 1090 MOPS requirement that the A3 equipage achieve 90% reception at –84 dBm and 15% reception at –87 dBm in the absence of interference.

* Note that because of the requirement specified by 2.2.4.3.1.1.c in DO-260A, the effective MTL for an A3 receiver is -85.5 dBm.

The A2 receiver uses an 8 MHz sampling rate along with an even-odd lookup table decoding method (as described in DO-260A Appendix I), which was developed by MIT Lincoln Laboratory, and has a MTL of –79 dBm.

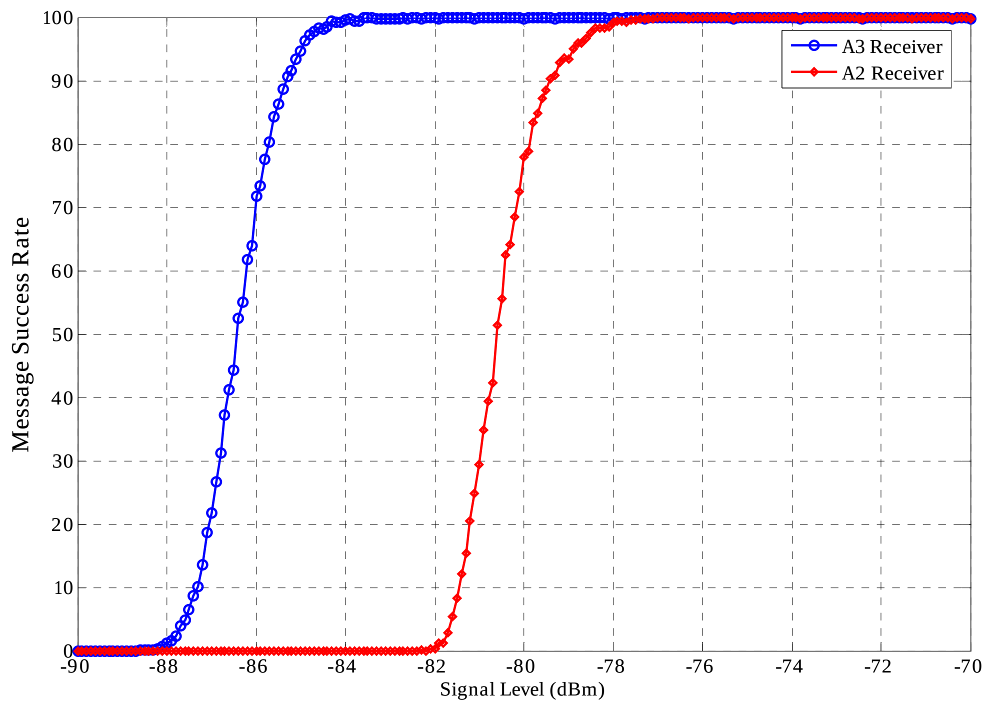

Figure 9: Receiver Performance in the Absence of Interference (MTL Curve)

2.2.2 Antenna characteristics

2.2.2.1 Gain Patterns for Aircraft and GBT Antennae

Antenna gain patterns for both aircraft and GBT antennae are modeled as two independent components of elevation and azimuth, which are added to calculate total gain. Aircraft antennae are modeled using the antenna gain pattern distribution developed in support of the TLAT analysis, which is documented in Appendix J of the TLAT report.[12] The elevation component is based on the angle between transmitter and receiver, while the azimuthal component is drawn from a representative distribution to model the complex nature of antennae installation, blockage due to aircraft structure, etc… The peak gain in the elevation component for aircraft antennae is approximately 4 dB, while the minimum can be below -30 dB for extreme angular differences such as directly above or below.

The elevation component of the GBT antenna is assumed to be represented by the elevation gain from measured TACAN/DME antenna patterns. The model features a boresight approximately 4 degrees above the horizon, an 8 dBi peak gain, and a "cone of silence" effect at high elevation angles where the gain drops off significantly. Figure 10 shows the average signal calculation from a GBT to a receiver at the altitudes examined in Section 4 for the uplink performance. The azimuthal gain is assumed to be 0 dBi for both transmit and receive antenna; only elevation gains are shown in this figure. The GBT power is at the midpoint of the allowable range (54 dBm / 250 W) as described in Section 2.3.1.

The azimuthal component of the GBT antenna is dependent on whether or not the antenna is sectorized. In an omni-directional configuration (one sector), 0 dB gain is modeled at all azimuthal angles. Three-sector and six-sector antennae will also be simulated. Figure 11 shows a polar plot of the angular dependence of the gain for one of the sectors from the three- and six-sector versions of the ground station antenna. The six-sector model is based on measured data.[13] The three-sector model uses the six-sector model as a basis and extrapolates the data into the relatively larger angular coverage. Note that an additional 8 dB peak gain to the TACAN/DME pattern is not reflected in the azimuthal gain plot; total gain would add in the elevation component and this extra 8 dB (peak) gain. For example, using a six sector antenna with an aircraft 4 degrees above the horizon, the effective gain would be approximately 16 dBi at the center of the antenna beam (in the horizontal plane) and approximately 13 dBi at 30 degrees off of the center of the beam.

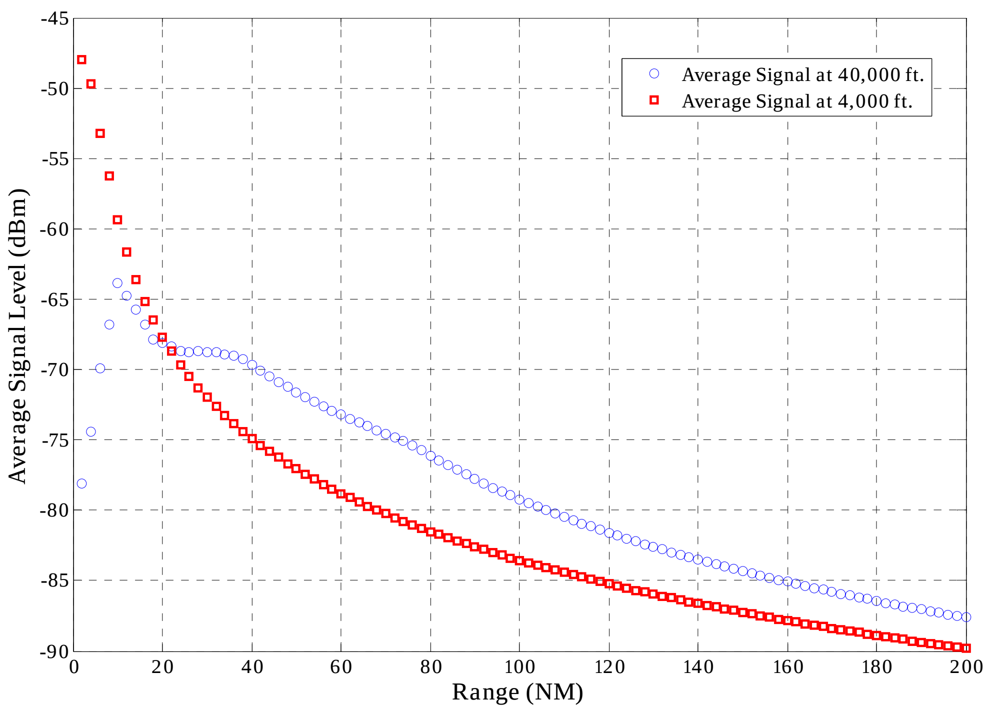

Figure 10: Average Received Signal at the Bottom Antenna of an Aircraft at 4,000 and 40,000 feet from 1090ES GBT Using a TACAN Antenna Pattern

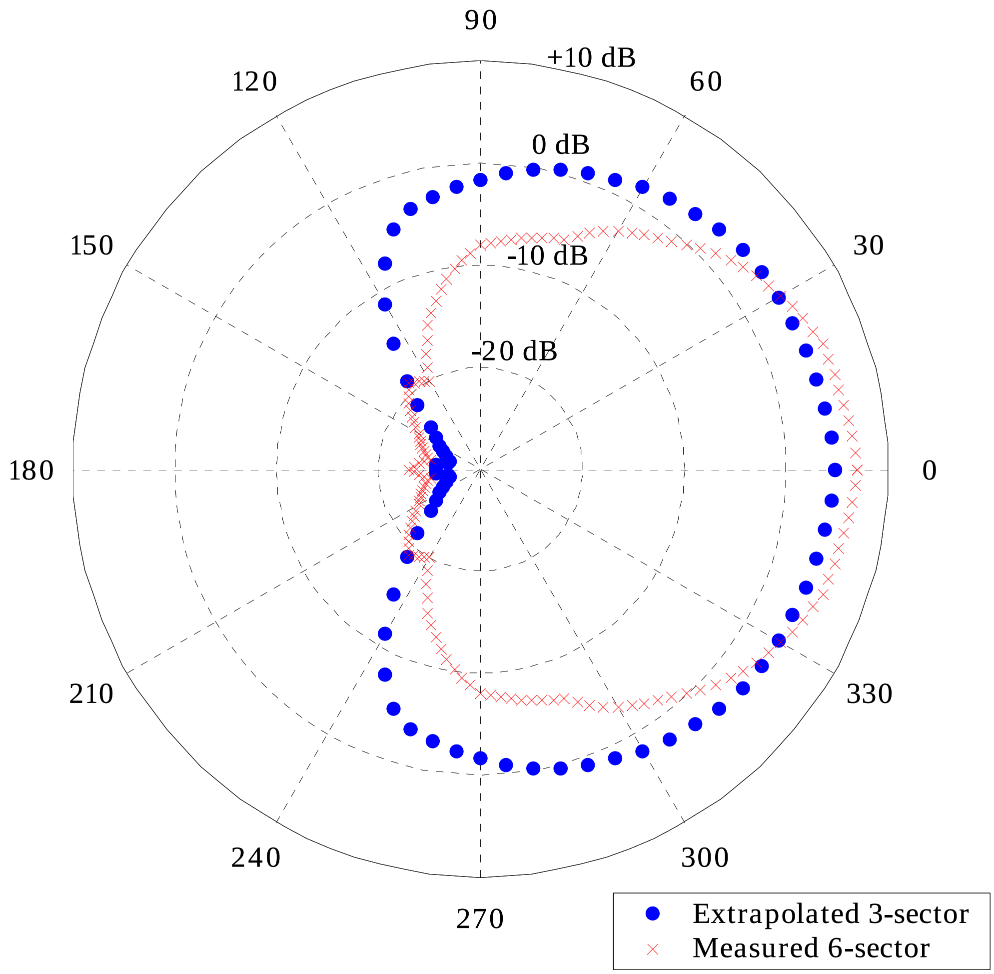

Figure 11: Azimuthal Dependence for One Sector of Three- and Six-Sector Models (8 dB Peak TACAN Gain not included)

2.2.2.2 Sharing and Blanking

1090ES GBTs configured for type A airports will have separate antennae for the transmit and receive functions, which may be shared with the UAT system. Sharing antennae with the UAT system is assumed to have no effect on the performance of either datalink and will be handled through a diplexer component connected to the antenna (see Appendix E in DO-282A[6]). Depending on how the antennae are installed, the transmit antenna may interfere with the receive antenna. 1090ES GBTs located at type B/C/D airports will have one antenna which is shared between transmit and receive functions. Receptions on this common antenna will be suppressed when broadcasting TIS-B messages to prevent overload damage to the receiver circuitry. The interval during which the reception is blanked is between 10 microseconds before transmission through 10 microseconds after the message broadcast (see 2.2.2.2.11 in [5]).

2.2.3 Receiver locations evaluated

The antenna patterns assumed in the previous section will modulate signal levels for both TIS-B uplinks and interferers when the receiver is located in certain positions. If the receiver position chosen tends to decrease performance (both ground-air and air-air) because the 'desired' signals are relatively low compared to interferers, the position is called a 'hotspot'. For any TIS-B system, there will be receiver locations that will have lower performance than others (hotspots), although the degree to which the performance is degraded may be slight. An exhaustive simulation of locations in LA 2020 was not practical, so based on lessons learned in a similar analysis for the UAT datalink[14], the position with the greatest number of proximate GBT service volumes was chosen.

In the LA 2020 scenario, this position corresponds to an airborne receiver 22.5 NM East and 6.4 NM North of Los Angeles. This position is in close proximity to 5 Traffic Information Volumes, shown in Figure 12. The receiver will be evaluated at 40,000 ft. and 4,000 ft. at this position.

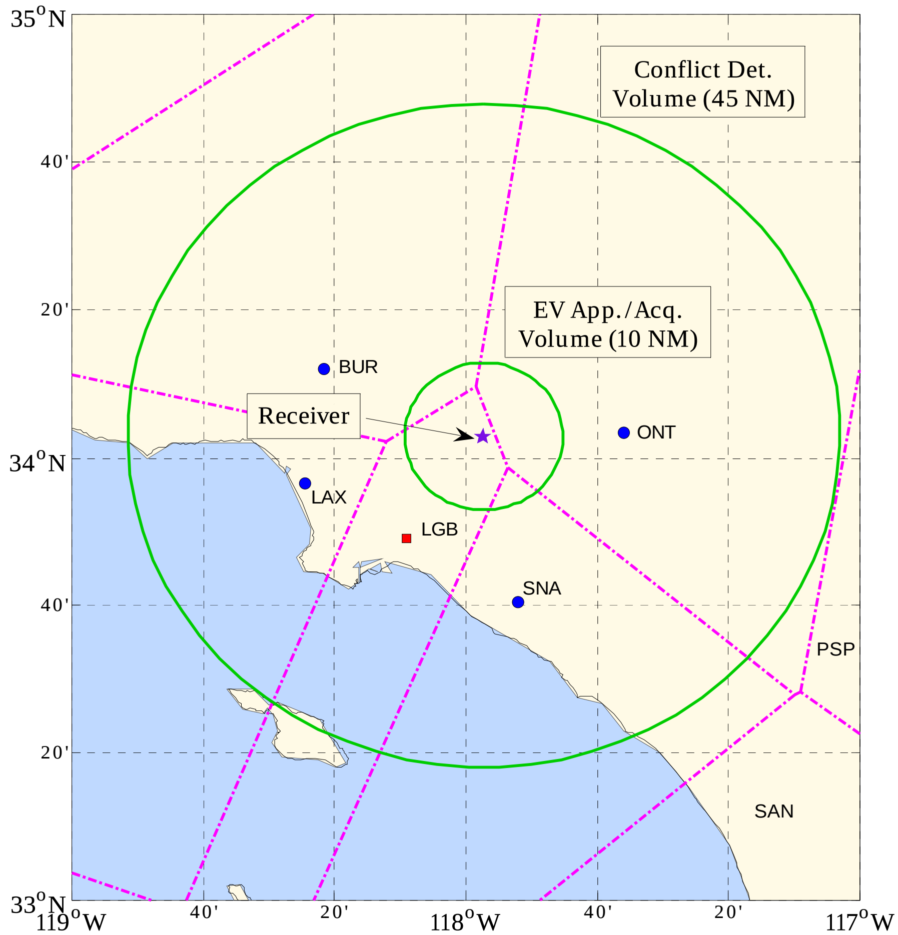

Figure 12: Zoomed View of LA 2020 with ASA Application Coverage Volumes

2.2.4 Definition of State Vector Update

Once the track state is initiated for a 1090ES receiver, the 1090ES MOPS requirements state that the correct reception of either a position (P) or a velocity (V) Extended Squitter is sufficient to update the state vector data. This requirement may not be sufficient for ground systems, especially for controlling and separating aircraft, and is currently being evaluated. In certain cases analyzed here, the requirement for a state vector update for ground receptions will be parameterized to show its effect. Whatever the requirement eventually becomes, the analysis can provide an estimate on expected performance. The possible definitions analyzed for state vector update, from most readily achieved to most difficult are: reception of either position or velocity Extended Squitters (P OR V), reception of position Extended Squitter (P ONLY), reception of both position and velocity Extended Squitters (P AND V), and reception of both position and velocity Extended Squitters within 1.0 second of each other (SYNC-1.0).

2.3 OTHER ASSUMPTIONS

2.3.1 1090ES Transmitter Powers (GBT and Aircraft)

GBT transmit power will be selected from a uniform distribution from 23 to 25 dBW at the antenna output (200 to 316 W). Per 1090ES standards, airborne transmitters are required to have output powers, referenced to the antenna output, of 51 to 57 dBm for the classes analyzed in this report (A1 through A3). The A1 and A2 transmitters made a uniform random determination of their power in that range. The A3 transmitter class, based on a recommendation from the 1090ES MOPS working group, made a similar selection at a slightly more restricted range, from 53 to 56 dBm.

2.3.2 TIS-B Message Scheduling

The 1090ES datalink uses a random access channel. In principle, when data to be broadcast arrives at the GBT from a network interface, the TIS-B messages can be formatted and broadcast immediately. To limit the transmitter duty cycle, it will be assumed that only one broadcast can be made each millisecond.

The TIS-B message load (both ADS-B rebroadcast and fundamental TIS-B broadcast) at each GBT is determined by a combination of simulations developed at JHU/APL. A model of terminal and enroute radars detecting aircraft and another model that simulates UAT GBT receptions feed data into a model of the future surveillance network. The combined set of TIS-B reports that are to be broadcast from 1090ES GBTs are shown as an input to the 1090ES simulation in the upper left of Figure 3.

When the TIS-B report arrives at the 1090ES GBT, an uplink burst consisting of multiple 1090ES messages are broadcast. For fundamental TIS-B service, six Extended Squitter uplink messages are sent in a burst. For ADS-B rebroadcast service, the burst will consist of 4.2 messages. Each message in a burst is broadcast at the next available opportunity when the transmitter is not active and when at least 1 ms has elapsed since the last transmission.

For fundamental TIS-B service, the six messages in the burst are either coarse format position extended squitters or alternating fine TIS-B position and velocity messages (defined in DO-260A §2.2.17), depending on the availability of accuracy and integrity parameters. In the case where more than 3 radars are detecting a given target, it is assumed that the system will limit the number of TIS-B reports that flow to the GBT(s) responsible for uplinks on that target. This is implemented as follows: when four or more radars are detecting the same target, an algorithm will select the three 'best' radar sources and send data from those three radars. The algorithm is to sort radars in terms of ascending distance between the target and the radar, and then put all terminal radars above enroute radars. The top three after this sorting are the 'best'.

Table 6: Number of Uplinks Messages as a Function of the Number of Radars Detecting Target

Number of Radars Detecting Target	# of Uplink Messages per 5 sec. (approx.)
1	5
2	10
3	15
4+	15

When the 1090ES GBT receives TIS-B reports based on data derived from received UAT messages, two fine airborne position and two airborne velocity extended squitters are assumed to be broadcast, along with one ID/type extended squitter every five seconds. In the analysis, it is assumed that the UAT GBT is receiving a message from each UAT-equipped target each second, which yields the 4.2 per second rate for ADS-R mentioned above.

2.4 METRICS

2.4.1 Update Intervals

Both ADS-B and TIS-B are traditional broadcast systems, where the receiver does not acknowledge the successful reception of messages back to the transmitter. To maximize safety benefits, the system must be engineered to insure that reliable reception of messages occurs from these broadcasts. The metric typically used is the 95th percentile update interval of state vector information. This is the interval of time that elapses between the successful receptions of state data, 95% of the time.

The 95th percentile update interval is actually taken over all messages from each aircraft and over all aircraft within sets of ranges. By cascading two successive 95th percentiles, degraded or outlying performance is captured and retained in the metric. However, interpretation of this metric has slightly different meanings for the air-ground and ground-air data transfers, mainly in terms of which parameters the intervals depend on.

Update intervals for the ground reception of ADS-B messages are calculated as a function by the transmitter/power of the aircraft and the range from the aircraft to the ground station. Update intervals for the TIS-B uplink are calculated as a function of the detection rate of the sensor that feeds the TIS-B data (typically radar or the other ADS-B data link) for each GBT whose service volume is within a given range of the receiving aircraft.

Note that the update intervals for TIS-B are not calculated as a function of range. ASA requirements are specified for a given range between the receiving aircraft and the aircraft about which the data is transmitted, which in the case of TIS-B, could be anywhere within the service volume of the transmitting GBT. Evaluating performance becomes a complex interaction of the GBT-receiver and target aircraft-receiver ranges.

2.4.2 Requirements for State Vector Update Intervals

The applications which will use ADS-B receptions at ground stations have not yet been fully developed, and so no formal requirements have been written for air-ground performance. In this report, the results will be compared to radar performance in the airspace and scenario at the typical ranges of the radar. Table 7 summarizes the requirements for air-ground performance. Note that this only addresses the air-ground update intervals necessary to support ground ATC surveillance applications. However the air-ground update interval requirements may be more demanding to support the ADS-B rebroadcast function of the BSGS.

Table 7: Air-ground Update Interval Requirements

Airspace	GBT Type	Update Interval Req.	Ranges (NM)	Comment
Terminal	A	2 sec	30 NM	Comparable to PRM for parallel approach
Terminal	A/B/C1	5 sec	0-60	Comparable to terminal radar

The TIS-B uplink requirements are assumed to be based on the defined aircraft surveillance applications.[1] These requirements will be evaluated for each application against all GBT transmissions to receivers when the service volume of that GBT is within the horizontal coverage volume specified for the application. As an example, imagine a receiver is 50 NM from a particular GBT, but slightly outside of its service volume. There may be an aircraft without ADS-B inside that GBT's service volume that is less than 10 NM from the receiver. In order to perform Enhanced Visual Acquisition with that target, the receiver must receive state vector updates about that target aircraft more frequently than every 12.1 seconds (at the 95th percentile level) from that remote GBT. Table 8 summarizes the requirements. Figure 12 shows range rings centered on the receiver position that was used in determining which GBTs need to be received to perform each application.

Table 8: ASA Requirements for Update Intervals (Ground-Air performance)

Application	Update Interval (sec)		Coverage Volume	GBTs Included in Volume
	Maximum	Desired		
EV Acq.	12.1	6	10 NM, ±3,500 ft.	BUR, LGB, ONT, SNA
CD	10	3	45 NM, ±15,600 ft.	BUR, LGB, ONT, SNA, LAX, PSP
EV App.	5	3	10 NM, ±3,500 ft.	BUR, LGB, ONT, SNA

2.4.3 Uncertainties in the Results

Any simulation or model is judged solely on its ability to recreate the actual performance in the real world. A great deal of effort was made to validate the 1090ES simulation with the actual performance of receivers measured at the FAA Technical Center. Appendix D describes this validation. The JHU/APL receiver performance model agrees with the measured data in this Appendix to within measurement uncertainties. The JHU/APL simulation is more conservative with the most recent FAATC measured values, which should produce a conservative analysis in the results that follow.

In past analyses conducted by JHU/APL [5,6], the 95th percentile update interval metric was found to have a moderate amount of uncertainty if computed for fewer than 100 targets in each bin. Here the word 'targets' means airborne transmitters for ADS-B performance and uplinks about aircraft for TIS-B performance. However, the LA 2020 scenario doesn't have 100 airborne transmitters in every 10 NM range bin to properly evaluate ADS-B performance. In most cases, there aren't 100 unique aircraft about which TIS-B uplinks are being made from each GBT in the scenario as well. To overcome these limitations and provide more robust values for the results, the analysis uses 'probe' transmissions. These probe transmissions are not used as interference in the scenario, but are used as the 'signal' that the receiver is attempting to decode. Using probe transmissions, 500 aircraft are present in each 10 NM range bin for the ADS-B results, each transmitting 4 Extended Squitters each second that can update a State Vector upon reception. For TIS-B performance analysis, probe GBTs were created at the same location as the assumed 'real' GBTs. These probe GBTs transmit uplinks for 500 non-existent aircraft at the rates described for Fundamental TIS-B (every 2.7 seconds) and ADS-R (every second).

Based on these numbers, an estimate of the statistical uncertainty of the MSR presented in this report is approximately 0.12% for ADS-B transmitters, 0.17% for fundamental TIS-B uplinks, and 0.13% for ADS-B Rebroadcast uplinks. Still inherent in the simulation is the systematic uncertainty, which may have many forms such as the difference between the JHU/APL model and the measured FAATC data or antenna nulls in antennae not taken into account or the effect of multipath fading. Unfortunately, it is not as easy to put an upper bound on this uncertainty. As more operational and measured data becomes available, the iterative process of validation and model refinement will allow for an estimate for this uncertainty.

Section 3

Simulation Results and Analysis

This section presents and analyzes the results of the simulation of the RF performance of the 1090ES GBT for the cases described in the previous section. Section 3.1 is dedicated to the air-ground results for the terminal scenario. Section 3.2 describes the results for an aircraft receiving uplink broadcasts from a GBT in the terminal setting. Note that the 1090 MOPS (section 2.2.10.4.1.3) specifies that if no position or velocity messages are received within 25 ± 5 seconds the track is lost and must be re-established. This process is not accounted for in our simulation, and so any update intervals greater than 25 seconds are not valid in the results that follow.

Section 3.1 describes the air-ground results for the terminal scenario. Section 3.2 provides the results and analysis for the 1090ES TIS-B uplink performance, including the impact to the ADS-B air-air transfer. For brevity in captioning, the term T95 will refer to the 95th percentile state vector update interval, as defined in Section 2.4.1.

3.1 ANALYSIS OF ADS-B AIR-GROUND DATA TRANSFER

To quickly review, for the 50% ADS-B equipage case, approximately 70% of all aircraft in the LA2020 scenario do not have 1090ES transmitters. In the 90% ADS-B equipage case, about 46% of aircraft do not have 1090ES. The transponder interference scenarios in both cases are the same, so the interference environment is more severe to a ground receiver in the 90% case. The solid black lines on the plots show the nominal terminal and enroute radar sweep period. As noted before, lower update interval criteria on air-ground performance may be necessary in the future to enable ASA applications with ADS-B Rebroadcast uplinks.

3.1.1 Effect of State Vector Update Requirement

Figure 13 and Figure 14 show the 95th percentile state vector update interval broadcast from A3 transmitters as a function of range for omni-directional antenna when the state vector updates are defined as described in Section 2.4.2.

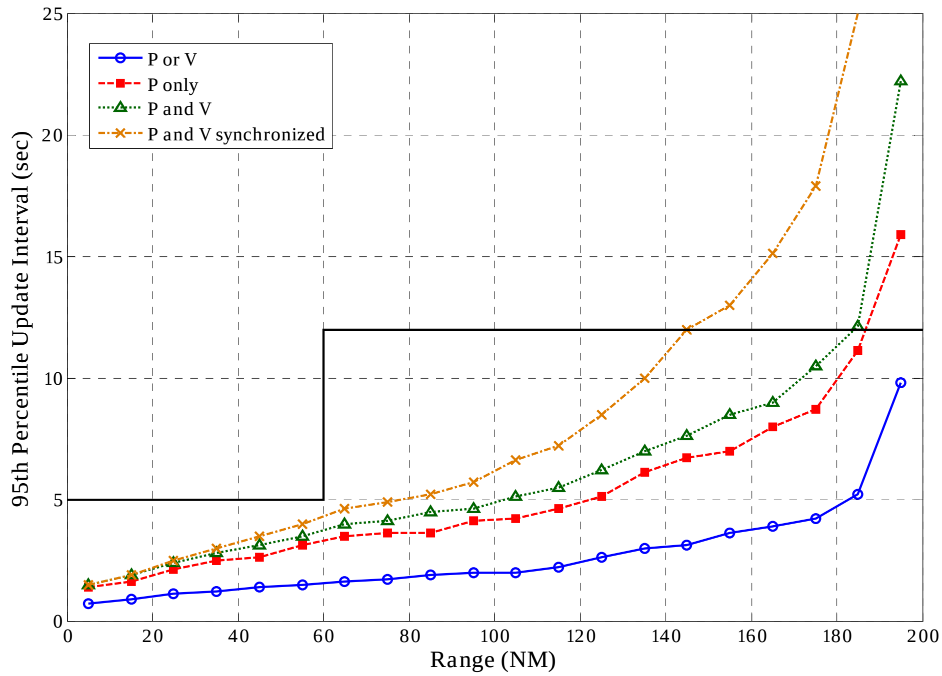

Figure 13: T95 for an Omni Ground Receiver Receiving A3 Transmitters in the 90% ADS-B Equipage Case of LA 2020 for Different SV Update Requirements

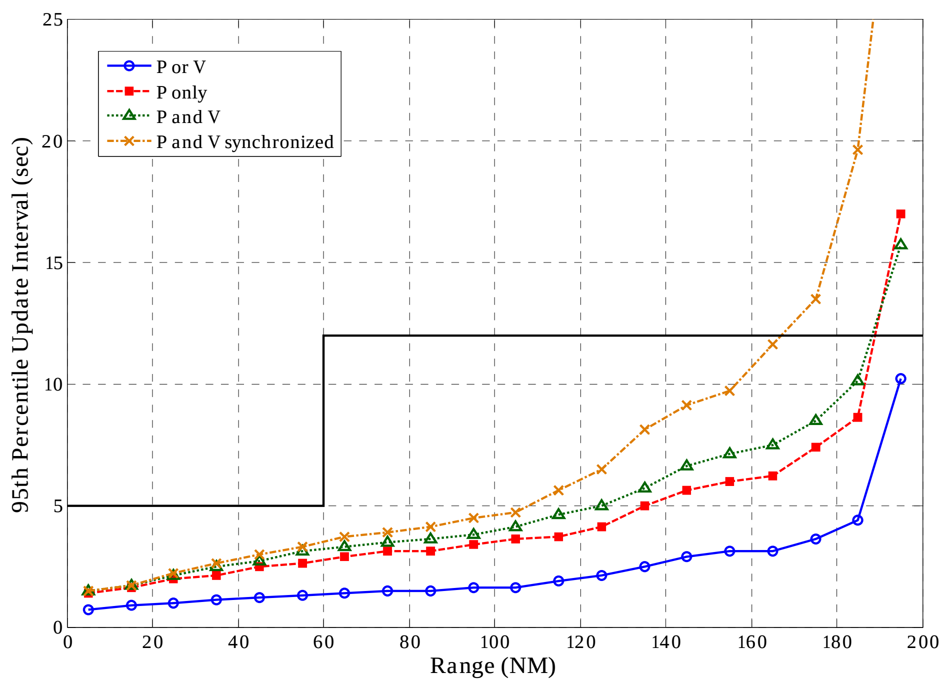

Figure 14: T95 for an Omni Ground Receiver Receiving A3 Transmitters in the 50% ADS-B Equipage Case of LA 2020 for Different SV Update Requirements

The manner in which a state vector update is defined is seen to have a significant effect on the performance of the air-ground transfer. Table 9 compares the values for the data plotted in Figure 13 and Figure 14 in two ways: the value of the update intervals at 60 NM, and the range at which the intervals exceed 5 seconds (the nominal terminal radar range and sweep period, respectively).

Table 9: Effect of State Vector Update Requirement on Air-Ground Performance in LA 2020 at GBT with Omni Antenna

SV Update Requirement	Transmitter – Equipage %	T95 at 60 NM	Approx. Range where T95 Exceeds 5 sec.
OR	A3 – 50%	1.3 sec	190 NM
OR	A3 – 90%	1.5 sec	180 NM
P-only	A3 – 50%	2.6 sec	140 NM
P-only	A3 – 90%	3.1 sec	120 NM
AND	A3 – 50%	3.1 sec	130 NM
AND	A3 – 90%	3.5 sec	100 NM
SYNC-1.0	A3 – 50%	3.3 sec	110 NM
SYNC-1.0	A3 – 90%	4.0 sec	80 NM

This strong effect is repeated when observing the performance of A2 and A1 transmitters in the terminal scenario in Figure 15 and Figure 16.

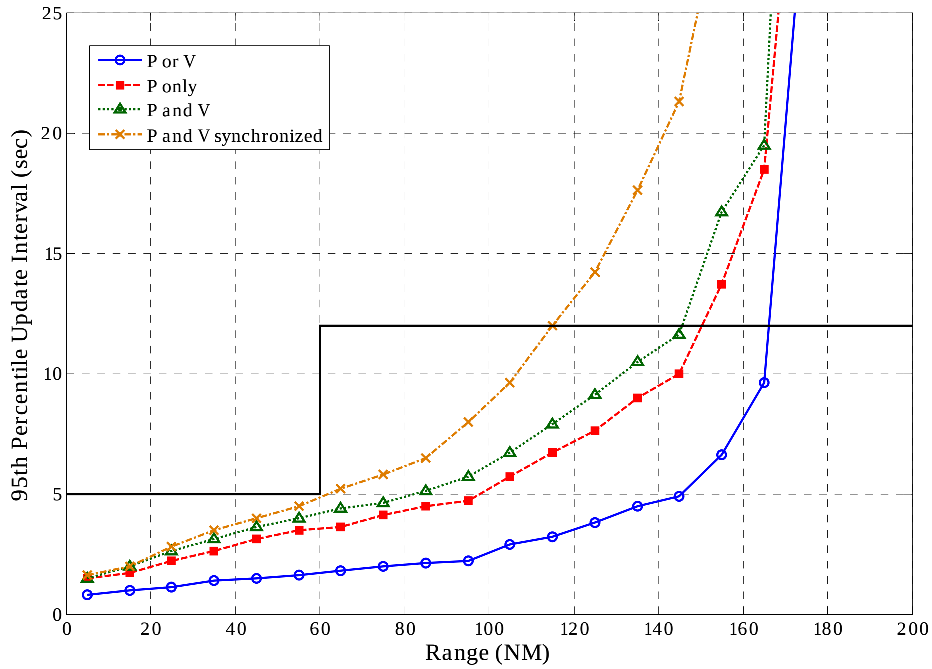

Figure 15: T95 for an Omni Ground Receiver Receiving A2/A1 Transmitters in the 90% ADS-B Equipage Case of LA 2020 for Different SV Update Requirements

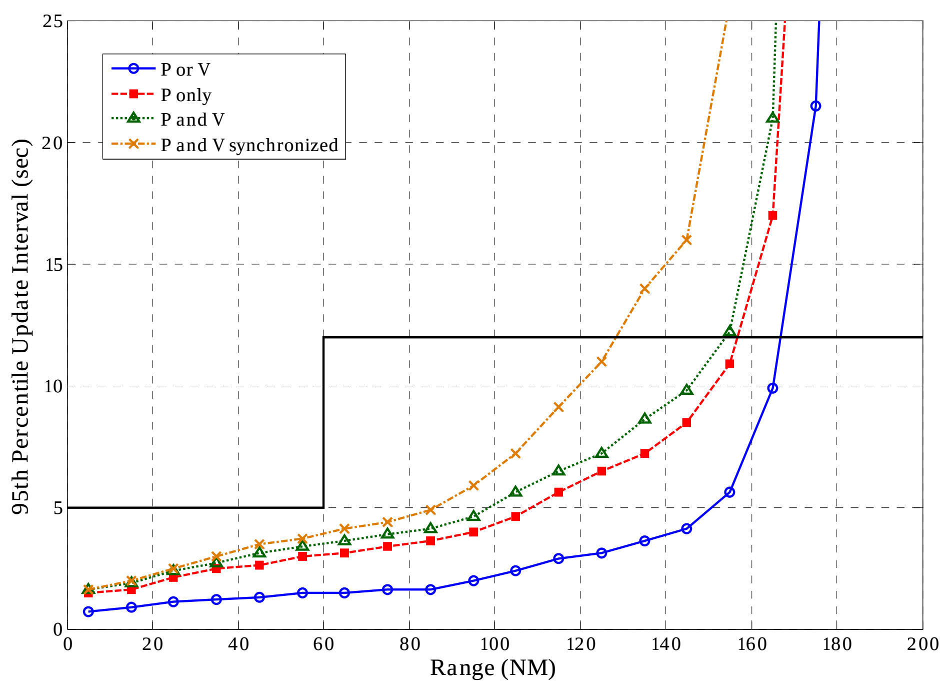

Figure 16: T95 for an Omni Ground Receiver Receiving A2/A1 Transmitters in the 50% ADS-B Equipage Case of LA 2020 for Different SV Update Requirements

At the time of this report, there is no final decision on what ground systems will require to declare an update to the state vector data. However, it is expected that, similar to the avionics, the successful reception of a position or velocity extended squitter will suffice, provided the data is processed in a Kalman filter to provide estimates of both position and velocity and also to provide the accuracy of the two elements.

In the remainder of the air-ground results, the standard assumption will be that a position OR velocity will trigger a state vector update. Excursions with other state vector update definitions will occasionally be shown to explore the sensitivity of this requirement.

3.1.2 Effect of ADS-B Equipage Assumption

Figure 17 and Figure 18 reconfigure some of the data from the last section to highlight the difference between the two different cases of ADS-B equipage for A3 and A2/A1 transmitters, respectively.

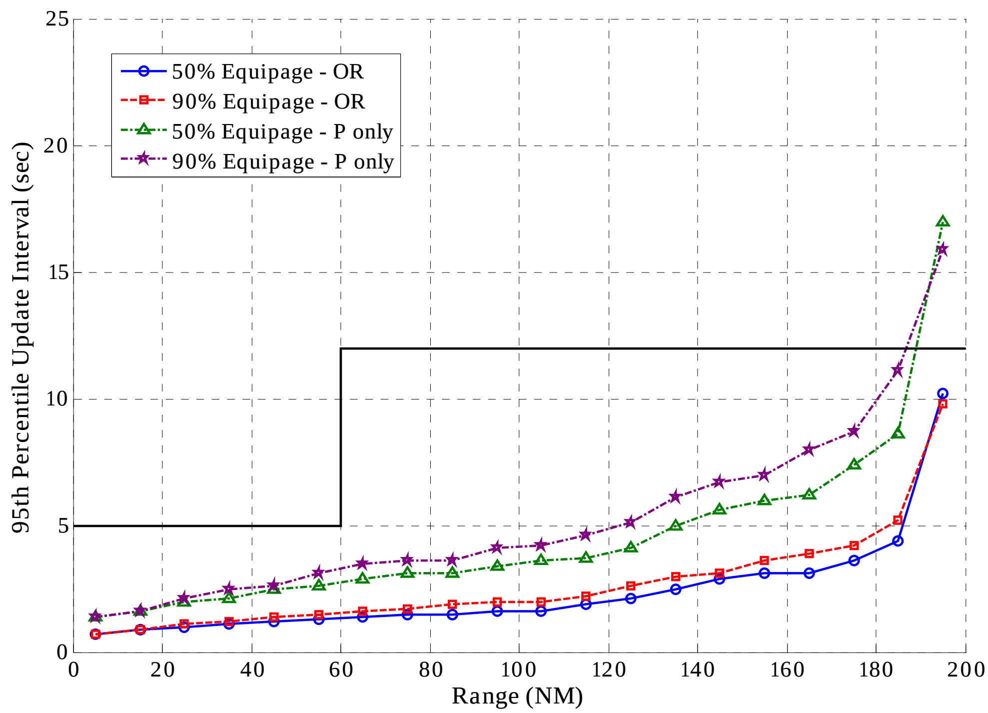

Figure 17: T95 for an Omni Ground Receiver Receiving A3 Transmitters in LA 2020 for Different Equipage and State Vector Update Requirement Cases

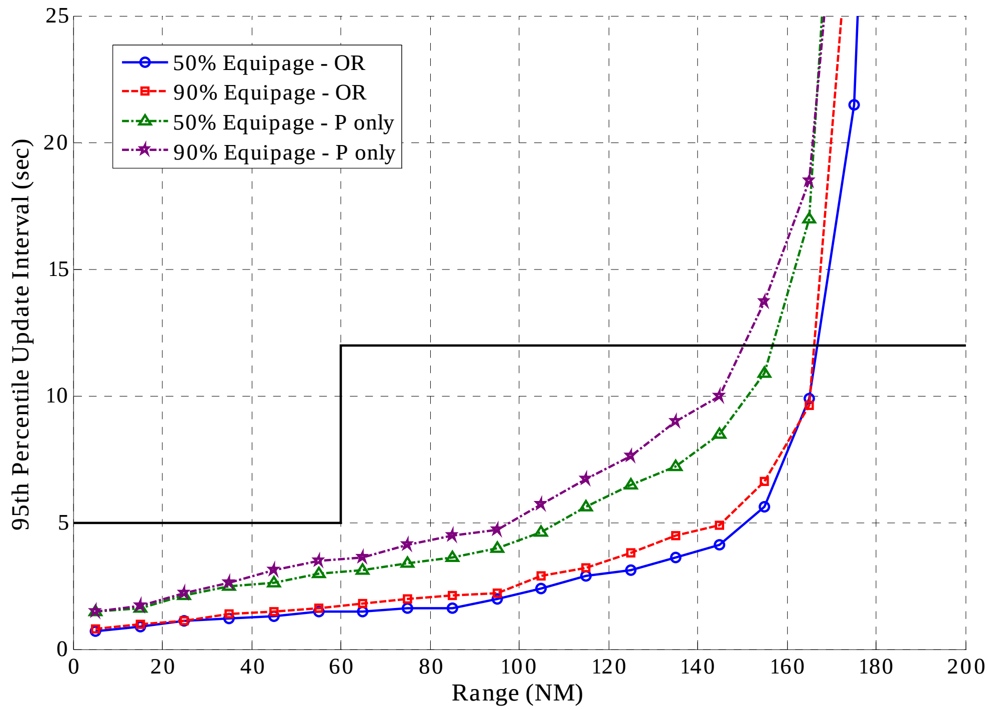

Figure 18: T95 for an Omni Ground Receiver Receiving A2/A1 Transmitters in LA 2020 for Different Equipage and State Vector Update Requirement Cases

The major difference between the 50% and 90% ADS-B equipage cases from the perspective of a receiving GBT is the number and origin of ADS-B and TIS-B broadcasts made on the 1090 MHz channel. In the 90% case, the self-interference from Extended Squitter messages is much higher. However, offsetting this slightly is the blanking due to uplink broadcasts, of which more made in the 50% ADS-B equipage case.

A ground-based receiver will not receive uplinks from remote GBTs because of LOS blockage. So, the interference observed by a ground-based receiver is slightly less for the 50% case than the 90% case, confirmed in Figure 17 and Figure 18, and in the interference plots from Section 2.1.3. The effect is small for the baseline (P OR V) case for state vector update requirement, less than 1 second difference at all ranges for reasonably performing update intervals (less than 12 seconds). The effect is much greater for the case where Position Squitters are used to update the state vector.

3.1.3 Effect of Antenna Configuration

Figure 19 shows the 95th percentile update interval for air-ground data reception as a function of range from A3 transmitters in the LA 2020 scenario for three cases of antenna configuration of the 1090ES GBT: an omni-directional, a three-sector, and a six-sector antenna. Figure 20 shows a similar plot for the case of A2/A1 transmitters. The 90% ADS-B equipage case is shown because it is a more stressing case for performance evaluation.

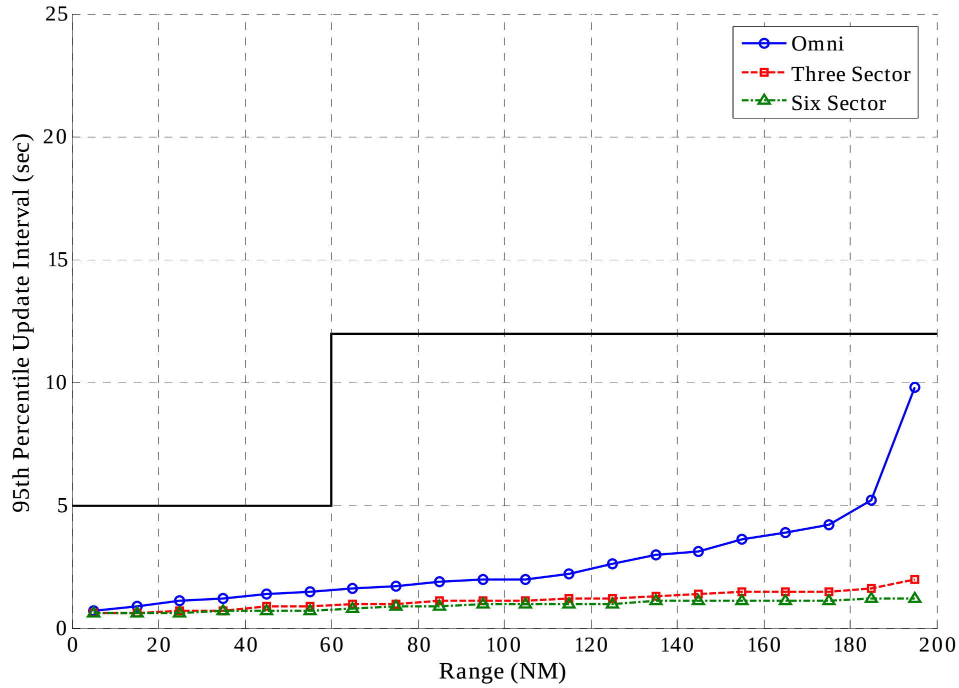

Figure 19: T95 for Several Antenna Configurations Receiving ADS-B Broadcasts from A3 Transmitters in the 90% ADS-B Equipage LA 2020 Scenario

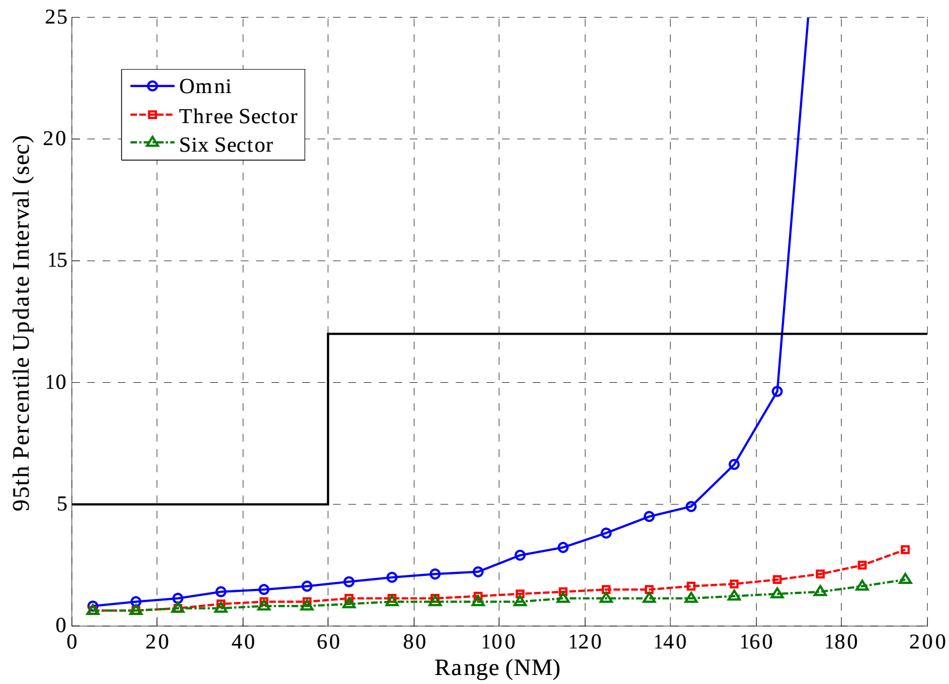

Figure 20: T95 for Several Antenna Configurations for ADS-B Broadcasts from A2/A1 Transmitters in the 90% ADS-B Equipage LA 2020 Scenario

The effect of the antenna configurations is pronounced. In the most stressing case, a sectorized antenna limits the 95th percentile update interval to below four seconds out to 200 NM range.

The benefit from using a sectorized 1090ES ground receiver antenna holds up even when the state vector update requirement is changed to an update only when a position AND a velocity extended squitter are received, as shown in Figure 21, for the case of a three-sector antenna.

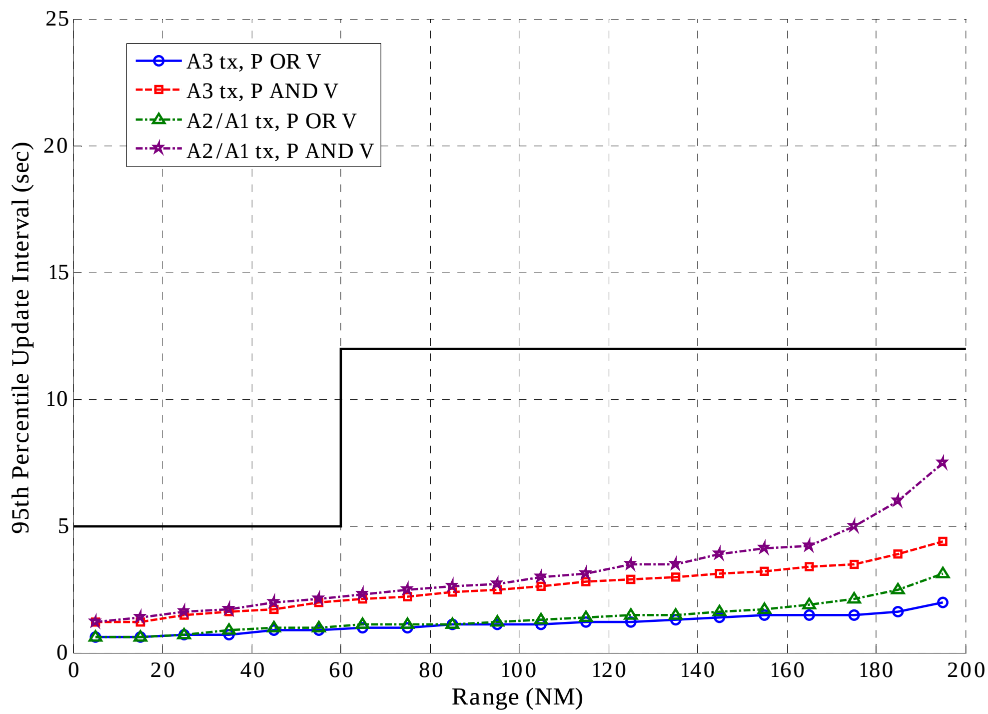

Figure 21: T95 for a Three-Sector Antenna on a Ground Receiver in the 90% ADS-B Equipage LA 2020 Scenario - Different Transmitters and SV Update Reqs.

3.1.4 Summary of Terminal Area Air-Ground Performance

The air-ground analysis has examined the transfer of ADS-B data from 1090ES equipped aircraft to ground systems in the LA 2020 terminal environment in a variety of ways. In general, the reception as measured by 95th percentile state vector update intervals met the requirements laid out in Section 2.4.2. Three- and Six-sector antenna configurations meet all of the PRM-like and terminal radar requirements in all cases examined for transmitter types, overall ADS-B equipage assumptions, and state vector update requirements. Table 10 summarizes the performance of the 1090ES GBT receptions of ADS-B messages when using an omni-directional antenna, and allows for some comparison of the trade-offs of some of the parameters. The requirement of update intervals less than 5.0 seconds at 60 NM is met for all cases examined. The PRM-like requirement, however, of less than 2.0 second update interval at 30 NM is not met for most cases of the P-only and all cases for the AND and SYNC-1 state vector update requirements with an omni-directional antenna. If these requirements are to be used in the terminal environment, it is recommended that a sectorized antenna is used to support PRM-like service.

Table 10: Summary Chart of the Performance of 1090ES GBTs with Omni-directional Antenna in the LA 2020 Air-Ground Simulations

Antenna config.	Tx Type	SV Upd. Req.	ADS-B Equip.	PRM/ ASSA req. T95 @ 30 NM	Term. Radar req. T95 @ 60 NM
Omni	A3	OR	50%	1.0 (✓)	1.3 (✓)
Omni	A2/A1	OR	50%	1.1 (✓)	1.5 (✓)
Omni	A3	OR	90%	1.1 (✓)	1.5 (✓)
Omni	A2/A1	OR	90%	1.1 (✓)	1.6 (✓)
Omni	A3	P-only	50%	2.0 (✓)	2.6 (✓)
Omni	A2/A1	P-only	50%	2.1 (✗)	3.0 (✓)
Omni	A3	P-only	90%	2.1 (✗)	3.1 (✓)
Omni	A2/A1	P-only	90%	2.2 (✗)	3.5 (✓)
Omni	A3	AND	50%	2.1 (✗)	3.1 (✓)
Omni	A2/A1	AND	50%	2.4 (✗)	3.4 (✓)
Omni	A3	AND	90%	2.4 (✗)	3.5 (✓)
Omni	A2/A1	AND	90%	2.6 (✗)	4.0 (✓)
Omni	A3	Sync-1	50%	2.2 (✗)	3.3 (✓)
Omni	A2/A1	Sync-1	50%	2.5 (✗)	3.7 (✓)
Omni	A3	Sync-1	90%	2.5 (✗)	4.0 (✓)
Omni	A2/A1	Sync-1	90%	2.8 (✗)	4.5 (✓)

3.2 ANALYSIS OF TIS-B GROUND-AIR DATA TRANSFER

This section will present the analysis of airborne reception of TIS-B uplinks and how these uplinks impact ADS-B performance. Section 3.2.1 will give a typical result for the uplink performance, in order to give a general sense of the performance of the uplinks in LA 2020. Section 3.2.2 examines the effect of the receiver altitude on TIS-B performance. Section 3.2.3 analyzes the effect of the overall ADS-B equipage assumption on TIS-B performance. Section 3.2.4 examines the impact of TIS-B on air-air performance of 1090ES ADS-B. Finally Section 3.2.5 summarizes the analyses of the terminal area uplink performance. It should be noted that the selected 1090GBT transmit power (Section 2.3.1) used for this simulation was believed to be appropriate to provide sufficient RF link margin over the TIS-B service volume for terminal airspace (i.e., approximately a range of 60 NM). However, higher transmit power levels may be required to support enroute BSGS sites, where the TIS-B service volume may be substantially greater.

To briefly review some assumptions, in the 50% ADS-B equipage case, approximately 50% of all aircraft in the LA2020 scenario do not have ADS-B installed. These aircraft will have data broadcast about them on the fundamental TIS-B service every 2.7 seconds in a six-message uplink burst (see Section 2.1.2 for more detail about surveillance detection rates). Approximately 20% of aircraft have UAT installed, and their state vector will be broadcast on ADS-B Rebroadcast every second in a 4 message (approximately) uplink burst. In the 90% ADS-B equipage case, about 10% of aircraft are broadcast via fundamental TIS-B, and approximately 36% are broadcast on ADS-R. A receiving aircraft in either of these cases should encounter a similar quantity of Extended Squitter messages, although the mix of transmissions originating from ground or airborne transmitters will be different.

3.2.1 Baseline Results

Table 11 shows the results for an A3 receiver at 40,000 feet in the 90% ADS-B equipage case. Table 12 follows and shows the results for a similar case with the receiver at 4,000 ft. Six stations are shown, 4 of which have service volumes within 10 NM of the receiver (ONT, BUR, LGB, SNA), and all of which are close enough to the 45 NM coverage volume for the conflict detection application to be evaluated against those requirements shown in Section 2.4.2.

Note that in Table 11, the Long Beach (LGB) station has a slightly larger MSR than the others, while the lower altitude data in Table 12 shows an MSR that is a monotonically decreasing with range. The structure of the MSR data for these two tables is similar to the structure of the curves in Figure 10, which indicates that this is related to the antenna gain pattern from the GBT for each altitude and range.

Table 11: TIS-B Update Intervals and Message Success Rate for TIS-B Uplinks to an A3 Receiver at 40,000 feet in the 90% ADS-B Equipage LA 2020 Scenario

GBT Code	Range to Receiver (NM)	Fundamental TIS-B		ADS-B Rebroadcast	
		T95 (sec)	MSR	T95 (sec)	MSR
ONT	19.5	2.8	0.827	2.0	0.829
BUR	21.8	2.8	0.767	2.0	0.769
LAX	23.4	2.8	0.724	2.0	0.727
LGB	32.3	2.8	0.873	1.1	0.876
SNA	38.9	5.4	0.705	2.0	0.708
PSP	73.5	5.4	0.616	2.1	0.619

Table 12: TIS-B Update Intervals and Message Success Rate for TIS-B Uplinks to an A3 Receiver at 4,000 feet in the 90% ADS-B Equipage LA 2020 Scenario

GBT Code	Range to Receiver (NM)	Fundamental TIS-B		ADS-B Rebroadcast	
		T95 (sec)	MSR	T95 (sec)	MSR
ONT	19.5	2.8	0.936	1.1	0.937
BUR	21.8	2.8	0.840	1.1	0.841
LAX	23.4	2.8	0.759	2.0	0.760
LGB	32.3	2.8	0.723	2.0	0.725
SNA	38.9	5.5	0.573	2.1	0.573
PSP	73.5	5.5	0.429	3.0	0.430

The update intervals in the table are all approximately equal to an integer multiple of the 2.7/1.0 second surveillance detection rates for Fundamental TIS-B/ADS-R. This is an artifact of the assumption used to simplify this analysis; a single surveillance detection rate for each service was used to isolate 1090ES uplink performance. For several GBTs shown, the TIS-B target is updated in every uplink burst (at the 95th percentile). For the worst case GBT shown in the Table, the Palm Springs (PSP) station over ADS-R, the 95th percentile target's update intervals were received at 3.0 seconds. Some of the times are slightly larger than the quantized detection rates, for example, the Fundamental TIS-B update interval from the Ontario station (ONT) is 2.8 seconds. Slight time delays were introduced in the system owing only to the 1090ES TIS-B function. The source of these delays includes transmitter queuing, propagation delay, and not receiving the messages at the beginning of the burst (realistic MSR calculations), but towards the end of the burst, where more time has elapsed.

The two short-range applications, Enhanced Visual Acquisition (EVAcq) and Enhanced Visual Approach (EVApp), are evaluated against the first 5 GBTs listed in the tables. For the detection rates assumed, these five GBTs would be expected to provide updates to an A3 receiver that meet the EVAcq application requirements described in Section 2.4.2. The requirements for the EVApp application are also expected to be met for these stations broadcasting to an A3 receiver, except when using Fundamental TIS-B uplinks from several GBTs (Orange County Airport GBT in the 4,000 ft. and 40,000 ft. receiver cases).

The Conflict Detection (CD) application extends to 45 NM, and so the PSP station is also considered in evaluating this application in the terminal airspace. All stations are seen to enable the CD application with the detection/broadcast rates that were assumed.

The message success rates for uplink broadcasts from these stations are relatively high. Figure 22 shows the MSR as a function of range to each station from an A3 receiver in LA 2020 for the 90% equipage case. The data in Table 11 and Table 12 show that the MSR for fundamental TIS-B and ADS-B rebroadcast service are nearly identical from any given GBT. This is to be expected since the large-scale signal and interference environments are the same from the perspective of a receiver attempting to decode any given message. The most important parameter is the transmitter to receiver range. Because of this, the MSR data shown in Figure 22 is combined between the two services.

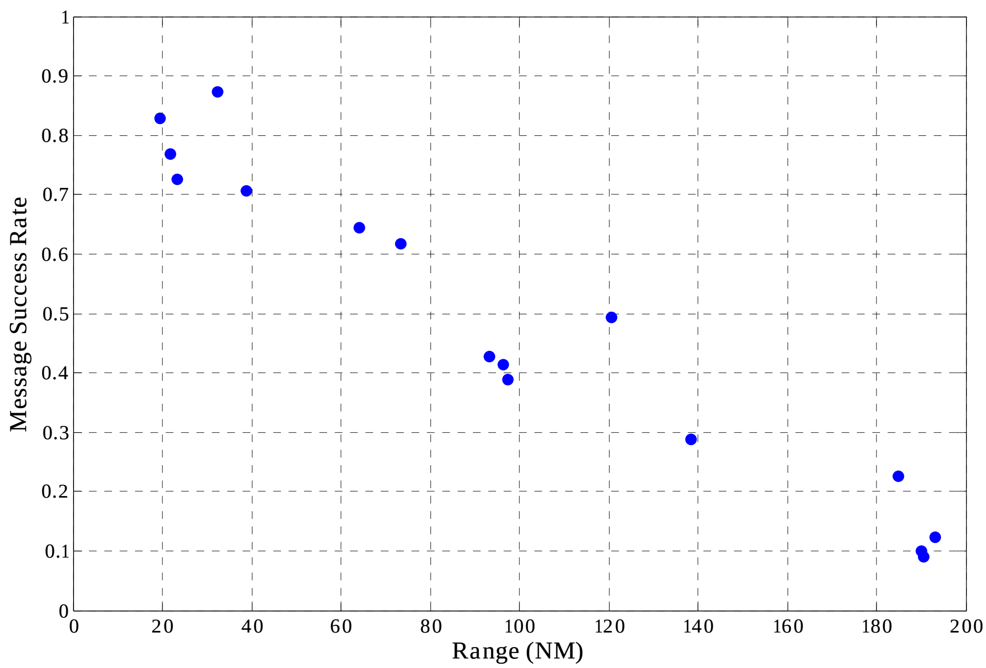

Figure 22: Message Success Rate as a Function of Range from Each GBT in 90% ADS-B Equipage LA 2020 Scenario for A3 Receiver at 40,000 ft.

3.2.2 Effect of Receiver Altitude

The altitude of the receiver will affect its ability to receive uplinks for two main reasons: the antenna patterns assumed and the interference present due to line-of-sight blockage. The antenna patterns assumed in Section 2 will modulate signal levels depending on the geometries involved for transmitter and receiver. For example, note that in Figure 10, the average received signal for an aircraft at 40,000 ft. does not follow a smooth pattern, but is relatively level between 20-40 NM.

Figure 23 and Table 13 show, respectively, the MSR and T95 results for A3 receivers in the 90% ADS-B equipage cases at the different altitudes. At ranges out to approximately 25 NM, the low altitude receiver has a higher MSR and a lower T95 time for the same type of uplink service. Past 25 NM, the high altitude receiver has an MSR up to almost 20% higher (near 73 NM) and an equivalent or lower T95.

The minimum and maximum altitudes for a GBT service volume, the GBT antenna, and the number and range of nearby GBTs will all affect uplink performance. With the assumptions made in this report, no significant difference was seen between the TIS-B message reception of high and low altitude receivers. A more realistic assumption here would exhibit greater variability in the surveillance detections for both Fundamental TIS-B and ADS-B Rebroadcast. This variability may impact performance, especially when compounded with the other attributes that can affect system performance (like min/max altitudes etc… mentioned above). Therefore a more comprehensive study might be needed to properly estimate end-to-end TIS-B service.

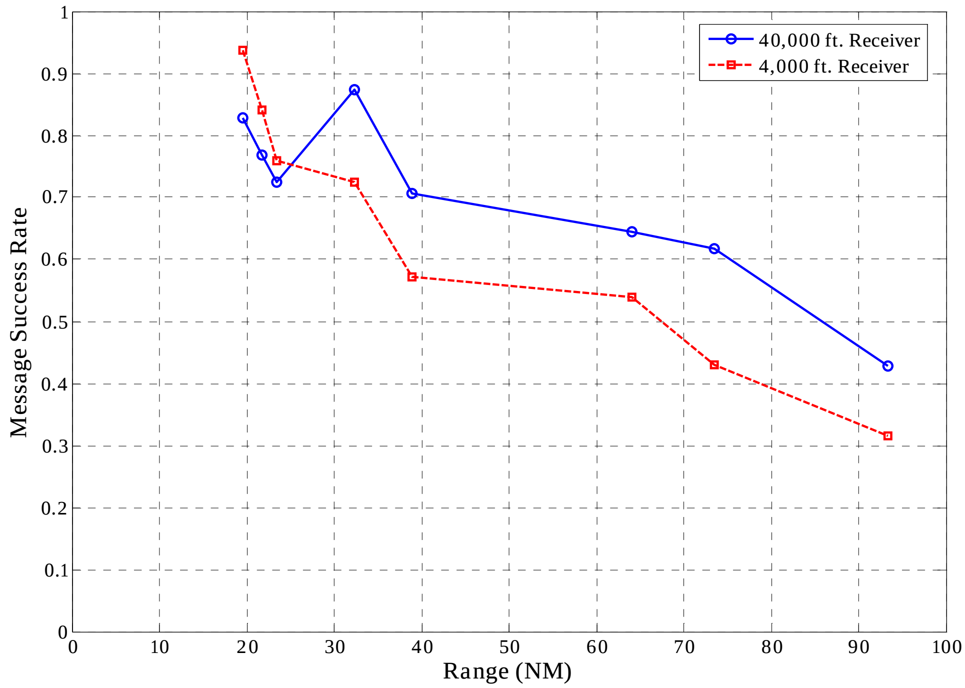

Figure 23: Comparison of MSR for Uplinks to A3 Receivers in the 90% ADS-B Equipage LA 2020 Scenario

Table 13: TIS-B Update Intervals for Uplinks to A3 Receivers in the 90% ADS-B Equipage LA 2020 Scenario

GBT Code	Range to Receiver (NM)	Fundamental TIS-B T95 (sec)		ADS-B Rebroadcast T95 (sec)	
		4,000 ft. Receiver Alt.	40,000 ft. Receiver Alt.	4,000 ft. Receiver Alt.	40,000 ft. Receiver Alt.
ONT	19.5	2.8	2.8	1.1	2.0
BUR	21.8	2.8	2.8	1.1	2.0
LAX	23.4	2.8	2.8	2.0	2.0
LGB	32.3	2.8	2.8	2.0	1.1
SNA	38.9	5.5	5.4	2.1	2.0
BBB	64.0	5.5	5.4	2.1	2.0
PSP	73.5	5.5	5.4	3.0	2.1
BFL	93.4	8.1	5.5	4.0	3.0

3.2.3 Effect of ADS-B Equipage in Scenario

For the air-ground performance, the GBT did not receive transmissions from other GBTs in the scenario due to LOS considerations. This assumption means that the interference was greater in the 90% ADS-B equipage case, since the bulk of 1090ES transmissions were made from aircraft. However, the TIS-B performance is analyzed for airborne receivers and the effects from LOS screening are much smaller than for GBT receptions. To first approximation, there are similar total number of squitters incident on an airborne receiver in both 50% and 90% equipage cases. In the 50% case, fewer aircraft are equipped with 1090ES. But if an aircraft is not equipped with 1090ES, a GBT in the scenario is broadcasting TIS-B messages on 1090 MHz at a roughly similar rate. To first order, one might expect that the uplink performance in both ADS-B equipage cases would be similar, since the other sources of interference (the main limit to receiver performance) are the same.

Table 14 shows the difference in Message Success Rate for the two ADS-B equipage cases for both A3 and A2 receivers at 40,000 ft. altitude. Looking at the mean and standard deviation for the differences at the bottom of the Table supports the hypothesis that overall, the two equipage cases are roughly equivalent for receiving GBT uplinks. Looking at the individual GBTs, however, the difference between some of the GBT message success rates in each equipage case does not seem to be roughly equivalent. For example, the uplink MSR from the Bakersfield (BFL) station to an A3 receiver is 7% lower in the 90% equipage case. The mechanism for this difference is not well-understood, although there seems to be a strong trend that at larger distances, the 50% equipage case has a higher uplink MSR. This difference in the equipage cases will also be explored in Section 3.2.4, which examines how the uplinks impact the air-air ADS-B data transfer.

Table 14: TIS-B Message Success Rates for Uplinks to Receivers at 40,000 ft. in the LA 2020 Scenario

GBT Code	Range (NM)	A3 Receiver MSR			A2 Receiver MSR		
		50% ADS-B	90% ADS-B	Diff.	50% ADS-B	90% ADS-B	Diff.
ONT	19.5	0.850	0.828	2.2%	0.844	0.821	2.3%
BUR	21.8	0.755	0.768	-1.3%	0.748	0.764	-1.6%
LAX	23.4	0.744	0.725	1.9%	0.738	0.719	1.9%
LGB	32.3	0.857	0.874	-1.8%	0.854	0.872	-1.8%
SNA	38.9	0.714	0.707	0.8%	0.707	0.702	0.5%
BBB	64.0	0.678	0.645	3.3%	0.668	0.631	3.6%
PSP	73.5	0.611	0.618	-0.6%	0.604	0.613	-0.9%
BFL	93.4	0.499	0.428	7.1%	0.480	0.407	7.4%
SAN	96.3	0.442	0.414	2.8%	0.414	0.389	2.5%
SBA	97.4	0.460	0.389	7.1%	0.438	0.359	7.8%
CCC	120.6	0.525	0.494	3.1%	0.514	0.485	2.9%
SMX	138.4	0.338	0.288	4.9%	0.238	0.202	3.6%
LAS	184.8	0.279	0.226	5.3%	0.068	0.050	1.8%
FAT	190.0	0.138	0.099	3.9%	0.000	0.000	0.0%
YUM	190.7	0.131	0.090	4.2%	0.000	0.000	0.0%
AAA	193.2	0.166	0.123	4.3%	0.000	0.000	0.0%
Mean				2.9%			1.9%
St. Deviation				2.7%			2.8%

Table 15: TIS-B Update Intervals for Uplinks to an A3 Receiver at 40,000 feet in Both ADS-B Equipage Cases of the LA 2020 Scenario

GBT Code	Range to Receiver (NM)	Fund. TIS-B T95 (sec)		ADS-R T95 (sec)	
		50%	90%	50%	90%
ONT	19.5	2.8	2.8	1.1	2.0
BUR	21.8	5.4	2.8	2.0	2.0
LAX	23.4	5.4	2.8	2.0	2.0
LGB	32.3	2.8	2.8	1.1	1.1
SNA	38.9	5.4	5.4	2.0	2.0
PSP	73.5	5.5	5.4	2.1	2.1

3.2.4 Effect of Uplinks on ADS-B Air-Air Performance

This section quantifies the ADS-B air-air performance of 1090ES in order to assess the impact of the TIS-B uplinks. Figure 24 through Figure 27 show the results of ADS-B performance for the four different combinations of A3 and A2 as transmitter and receiver. Four curves are plotted in each Figure, two for each overall ADS-B equipage case. The two curves for each particular ADS-B equipage case (50% or 90%) can provide insight into whether it matters if the Extended Squitter messages that act as self-interference all come from aircraft or if the ES transmissions are divided between GBTs and aircraft as assumed in the other sections. Looking at these to cases may show if the local geometry of TIS-B and ADS-B transmitters is a significant limit to performance (a "hotspot"). The curves that are marked with "0% UAT" have assumed that all ADS-B aircraft are equipped with 1090ES and are transmitting at the rates expected for airborne transmitters. The cases where the UAT percentage noted is non-zero, that percentage of ADS-B aircraft are equipped with UAT, and the data about those targets is rebroadcast from a GBT every second, consistent with the scenarios as described in Section 2.1. If the difference is significant between these curves, the source of the 1090ES messages is important to ADS-B performance.

In all four figures, the difference between the performance curves for the same overall equipage case is small. There is no evidence in the cases that were simulated to suggest that there is a hotspot effect due to TIS-B uplinks.

The two parameters that do make the largest difference are overall ADS-B equipage (50% or 90%) and the airborne receiver class, i.e. A3 or A2 receiver. The ADS-B equipage has an effect because there are more 1090ES aircraft transmitters in the 90% equipage case within LOS of the receiver, which adds to the self-interference environment. The difference between the A3 and A2 receivers was described in Section 2.2.1. In these figures, note that if the ASA update interval requirements from Section 2.4.2 were applied to these results, that all three airborne applications could be supported by A2 and A3 equipage.

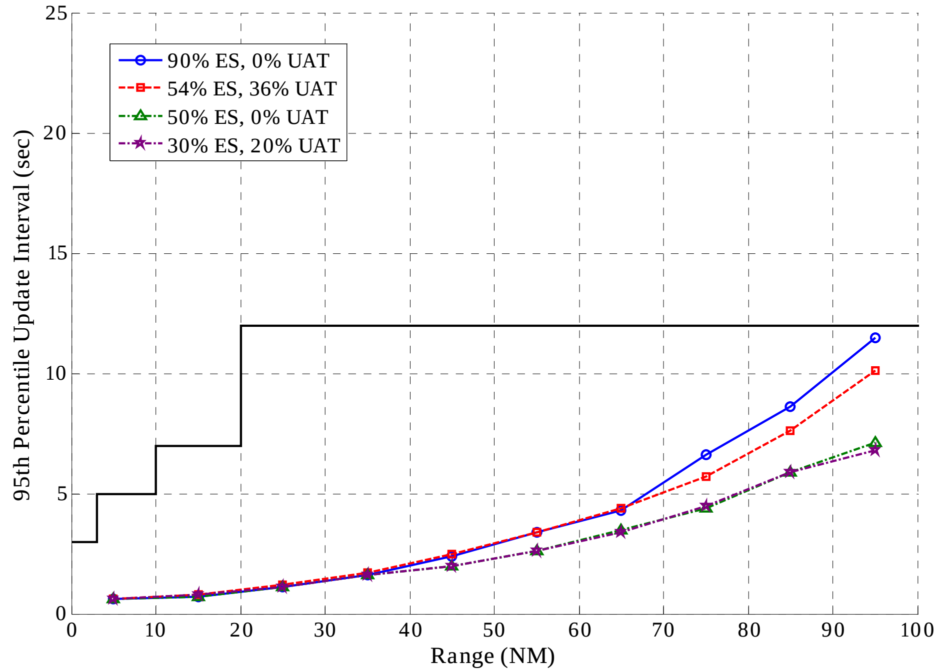

Figure 24: T95 vs. Range for A3 Transmitter to A3 Receiver in the LA 2020 Scenario for Different Equipage Cases

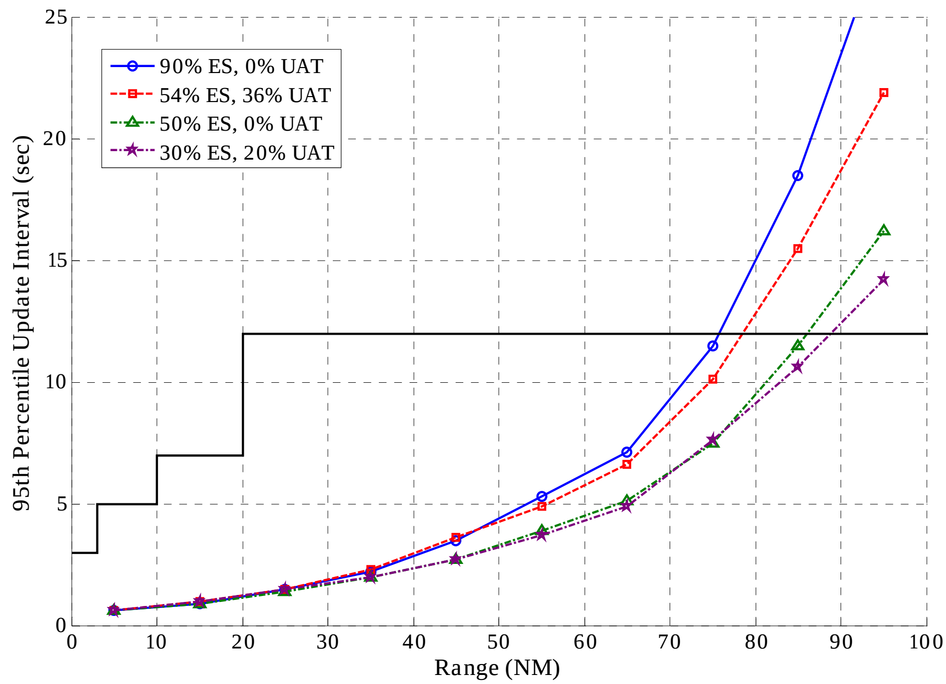

Figure 25: T95 vs. Range for A2 Transmitter to A3 Receiver in the LA 2020 Scenario for Different Equipage Cases

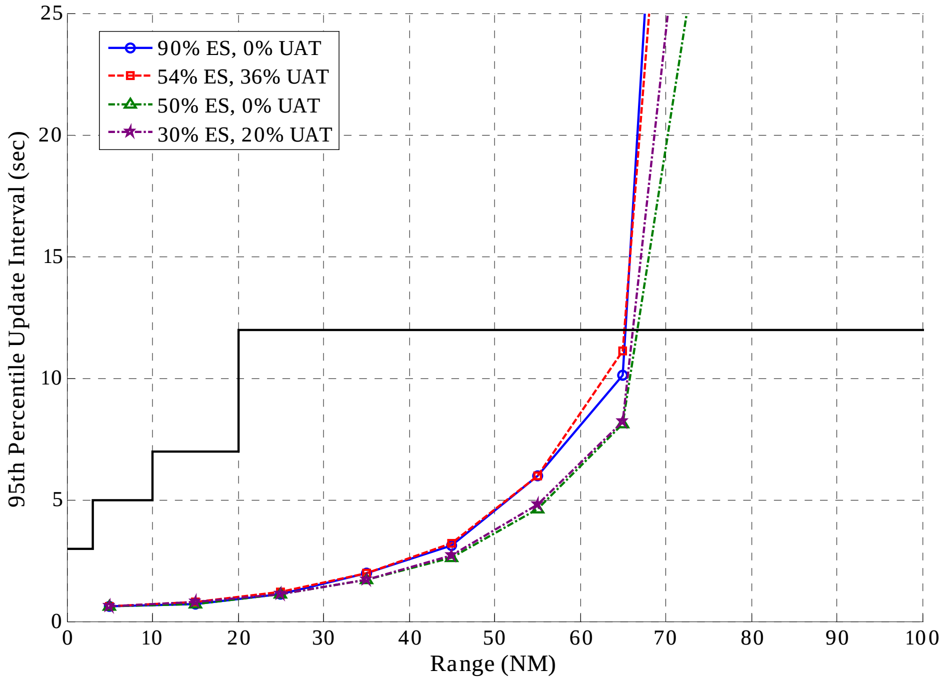

Figure 26: T95 vs. Range for A3 Transmitter to A2 Receiver in the LA 2020 Scenario for Different Equipage Cases

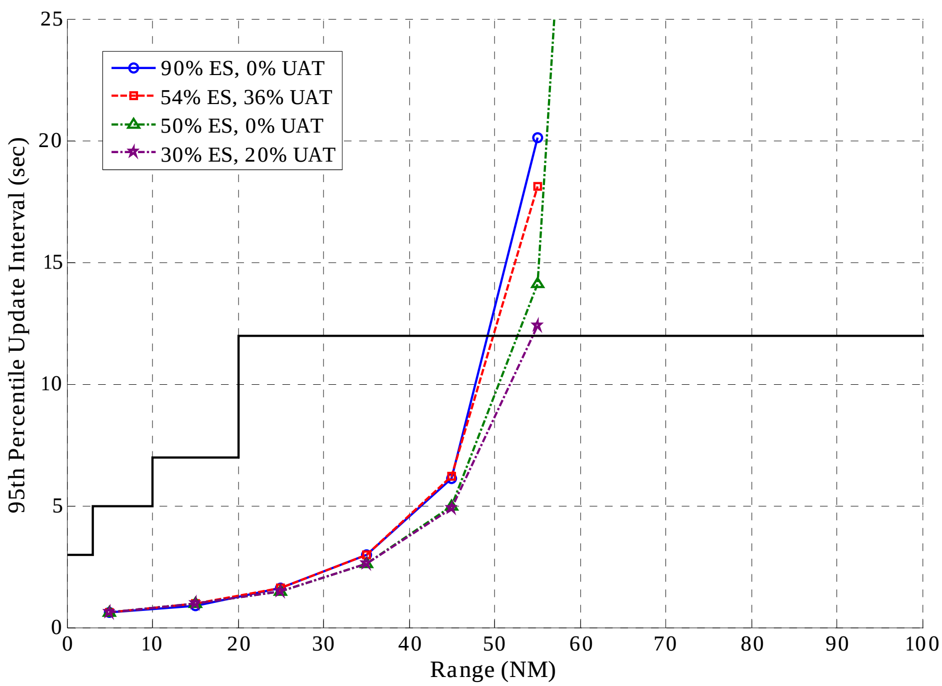

Figure 27: T95 vs. Range for A2 Transmitter to A2 Receiver in the LA 2020 Scenario for Different Equipage Cases

3.2.5 Summary of Terminal Area GBT Uplink Performance

The previous sections have analyzed the performance of information transfer over 1090ES to an airborne receiver in the LA 2020 scenario from both ground-based and airborne transmitters in a dual-link environment. Keeping in mind the important assumption that uplink bursts about each aircraft in the scenario not equipped with 1090ES will have 6 messages broadcast based on a detection from radar every 2.7 seconds and 4 messages broadcast about a UAT equipped aircraft every second, the following bullets summarize the findings from these sections:

- Both Enhanced Visual Acquisition and Conflict Detection applications are supported in the terminal LA 2020 environment in the expected worst-case position for both fundamental TIS-B and ADS-B rebroadcast uplink services. Enhanced Visual Approach is not supported for the fundamental TIS-B service from all GBTs in the worst-case position of this scenario. This may not be operationally important, since the Enhanced Visual Approach application will focus on one aircraft to be followed, not all targets over multiple GBT sites.
- Message Success Rate is proportional to range, in general. MSR does have some dependence on the ADS-B equipage scenario along with the altitude of the receiver.
- MSR rates for individual messages for fundamental TIS-B and ADS-B rebroadcast service are nearly identical. Because the message burst for fundamental TIS-B uplinks broadcasts more messages, airborne reception per burst (triggered by radar detection) is higher than ADS-B rebroadcast. But because the detection rate is higher for ADS-B rebroadcast, this service's 95th percentile update intervals are lower than for the fundamental TIS-B service. Formulation of message repeat strategies on these services is very important to their performance.
- For the two cases of altitude examined here, 4,000 ft. and 40,000 ft., each case had better performance than the other at certain ranges due to the interplay of receiver altitude and assumed GBT antenna pattern. At ranges less than 25 NM, the 4,000 ft. receiver had better reception performance than the 40,000 ft. receiver. Beyond this, however, the low altitude receiver typically had higher update intervals and lower MSRs. Altitude will be an important consideration when allocating uplink service volumes to GBTs.
- In general, the overall ADS-B equipage in the scenario was not a significant factor when receiving uplinks from GBTs. The 50% ADS-B equipage case had slightly higher update intervals from uplink broadcasts, but the MSR values were relatively close. Assumptions about ADS-B equipage primarily change the proportion of the 1090ES message load coming from airborne or ground-based transmitters.
- Air-air performance was not significantly affected when the GBT message load was shifted to the airborne transmitters. Air-air performance will support the evaluated ASA applications, and will support ADS-B MASPS requirements out to ranges between 50-100 NM depending on the 1090ES equipage in this dual-link environment.

Section 4

Conclusions

This section summarizes the approach and results for the performance analysis of the 1090ES GBT in a dual-link LA 2020 scenario.

4.1 KEY ASSUMPTIONS

The assumptions used in this report were described in detail in Section 2. The assumptions to keep in mind when making any conclusions are reviewed here:

- The LA 2020 scenario is the basis for the air traffic model, but not all aircraft were equipped with ADS-B, and of these aircraft, only some were equipped with 1090ES. In past analyses of LA 2020, the entire aircraft population was assumed to be equipped with 1090ES.
- The Fruit rate (Mode A/C replies with signal power > -84 dBm at the receiver) for all runs was 24,000 per second, for both airborne and ground receivers. The Mode S and Extended Squitter interference varied as a function of altitude. The Extended Squitter rate also varied as a function of the overall ADS-B equipage.
- The LAX GBT, which had the highest TIS-B message throughput of any of the stations in the scenario, had uplink rates ranging from 70-360 uplinks per second for the two equipage cases analyzed, with an average of 187 and 254, respectively. For the air-ground results which used the LAX GBT, the uplinks blanked the receiver approximately 5% of the time.
- 13 airports in an area resembling the Los Angeles ARTCC were assumed to have GBTs co-located at the airport. 3 additional stations were assumed to provide gap-filling service for air-ground downlink.
- The airborne receiver used for uplink performance evaluation was placed near the intersection of five GBT service volumes. This location is expected to approximate a worst-case condition due to GBT self-interference.
- A radar model was used to determine detection rates for the LA 2020 scenario at each airport. The average detection rate for aircraft in a region around LAX was every 2.7 second, which is used as the standard radar detection rate for all aircraft. Fundamental TIS-B uplink performance must be evaluated by comparing the update intervals with this 2.7 second value. It represents the minimum update interval that is achievable using the detection assumption, and update intervals will be approximately equal to a multiple of this value.
- UAT reception at each of the proposed GBTs is assumed to be once per second. This is the detection rate used for all UAT equipped aircraft in the scenario. ADS-B Rebroadcast uplink performance must be evaluated by comparing the update intervals with a 1.0 second value that represents the minimum ADS-R update interval using the detection assumption. Again, the update intervals will tend to be approximately equal to a multiple of this value.
- The metric used in both ADS-B and TIS-B performance evaluations is the 95th percentile state vector update interval. The requirements used to compare these results were taken from

standards documents where possible. In the case of air-ground reception of ADS-B messages, the results were compared to nominal radar sweep rates. The systematic uncertainties in the simulation are estimated to be much larger than the statistical error using the approach described in Section 2.4.3.

4.2 REVIEW OF PERFORMANCE RESULTS

4.2.1 Air-Ground Performance

The air-ground performance of the 1090ES system in the terminal environment was very robust. The GBT was assumed to update a given aircraft's state vector upon the reception of a Position or a Velocity Extended Squitter Message. The A1/A2 transmit powers, which have a lower minimum than the recommended powers for A3, will set the range of RF coverage for the GBTs. Table 16 summarizes the performance results when receiving A1/A2 transmitters and using the OR configuration for state vector updates and comparing the results to the nominal radar sweep rates in Table 7 (from Section 2.4.2). For a ground receiver with A3 receiver characteristics, the 95th percentile state vector update intervals are less than nominal radar sweep rates in all cases. Based on these results, the accuracy and integrity of the data from airborne transmitters may be the limiting factor in providing ground surveillance in the terminal domain. However, the required air-ground reception performance needed to support ASA applications with the ADS-B Rebroadcast was not considered, which may place more stringent requirements on the air-ground update intervals than ATC ground surveillance applications.

Table 16: Summary Chart of the Performance of 1090ES GBTs in the LA 2020 Air-Ground Simulations

Antenna config.	Tx Type	SV Upd. Req.	ADS-B Equip.	PRM/ ASSA req. T95 @ 30 NM	Term. Radar req. T95 @ 60 NM
Omni	A3	OR	50%	1.0 (✓)	1.3 (✓)
Omni	A2/A1	OR	50%	1.1 (✓)	1.5 (✓)
Omni	A3	OR	90%	1.1 (✓)	1.5 (✓)
Omni	A2/A1	OR	90%	1.1 (✓)	1.6 (✓)
3-sector	A3	OR	50%	0.7 (✓)	0.9 (✓)
3-sector	A2/A1	OR	50%	0.7 (✓)	1.0 (✓)
3-sector	A3	OR	90%	0.7 (✓)	0.9 (✓)
3-sector	A2/A1	OR	90%	0.7 (✓)	1.0 (✓)
6-sector	A3	OR	50	0.6 (✓)	0.7 (✓)
6-sector	A2/A1	OR	50	0.7 (✓)	0.8 (✓)
6-sector	A3	OR	90	0.6 (✓)	0.7 (✓)
6-sector	A2/A1	OR	90	0.7 (✓)	0.8 (✓)

4.2.2 TIS-B Uplink Performance

Table 17 shows the applications that are supported in the terminal environment at the worst-case position evaluated for all GBT's with service volumes that intersect the ASA application volume (see Table 8 in Section 2.4.2 for more detail). In all cases, fundamental TIS-B is expected to support airborne receivers performing Enhanced Visual Acquisition and Conflict Detection. ADS-B Rebroadcast is expected to support both these two and also Enhanced Visual Approach in all cases run. Both of these conclusions are dependent on the GBT receiving data from those surveillance sources at the rates specified above.

Table 17: Applications that Meet ASA Update Intervals Requirements for 1090ES Uplinks in a Worst-Case Position in the LA 2020 Scenario

ADS-B Equipage	Receiver Altitude (ft.)	Fundamental TIS-B		ADS-B Rebroadcast	
		A3 Receiver	A2 Receiver	A3 Receiver	A2 Receiver
90%	40,000	EVAcq & CD	EVAcq & CD	EVAcq, CD, & EVApp	EVAcq, CD, & EVApp
90%	4,000	EVAcq & CD	EVAcq & CD	EVAcq, CD, & EVApp	EVAcq, CD, & EVApp
50%	40,000	EVAcq & CD	EVAcq & CD	EVAcq, CD, & EVApp	EVAcq, CD, & EVApp
50%	4,000	EVAcq & CD	EVAcq & CD	EVAcq, CD, & EVApp	EVAcq, CD, & EVApp

4.2.3 Air-Air Performance in the Presence of TIS-B Uplinks

The ADS-B air-air performance in the dual-link scenario was also analyzed. Table 18 shows the range of compliance with the DO-242A (ADS-B MASPS) update interval requirements for A2 and A3 equipages in various combinations of transmitter-receiver pairs. In addition, the Enhanced Visual Acquisition, Conflict Detection, and Enhanced Visual Approach applications as defined in DO-289 are supported between airborne participants exchanging ADS-B data for each application's service volume.

Table 18: Range of Compliance with DO-242A Update Interval Requirements for 1090ES Air-Air Transfer in the Dual-link LA 2020 Scenario

Transmitter Equipage	Receiver Equipage	50% ADS-B Equipage	90% ADS-B Equipage Case
A3	A3	100+ NM	100 NM
A2	A3	90 NM	80 NM
A3	A2	70 NM	70 NM
A2	A2	50 NM	50 NM

Note: In the 50% and 90% ADS-B equipage cases, 60% of the ADS-B equipped aircraft use 1090ES, so the overall 1090ES equipage in these two cases are 30% and 54%, respectively.

4.2.4 Analytic Excursions

In addition to the findings summarized in the last three sections, a number of analytic excursions were run to determine the importance of several important parameters. Table 19 summarizes the results of these excursions.

Table 19: Summary of Analytical Excursions in Report

Analytical Excursion	Comment
Effect of the Definition of a State Vector Update to Air-Ground Performance	The definition had an important effect. For example, the range at which 5 second update intervals are achieved between the OR case and the SYNC-1.0 case was different by approximately a factor of two.
Effect on Overall ADS-B Equipage Assumption on Air-Ground Performance	There was a noticeable effect on performance, but it did not significantly limit performance out to 60 NM in the terminal environment.
Effect of Antenna Configuration on Air-Ground Performance	This was a significant performance difference, but a smaller effect, since the Omni-directional antenna was observed to support the terminal area requirements with the OR definition of State Vector update. The Three- and Six-Sector antenna configurations were able to support both PRM and terminal radar sweep rates in all cases examined.
Effect of Receiver Altitude on TIS-B Uplinks	Had a noticeable effect on MSR (up to 19% difference in MSR from a particular GBT broadcasting to receivers at 4,000 ft. and 40,000 ft.) but a relatively small effect on T95. The receiver at 4,000 ft. had poorer performance for GBT-receiver ranges beyond 25 NM.
Effect of Overall ADS-B Equipage Assumption on TIS-B Uplink Performance	No significant effect was observed. The maximum difference in uplink MSR between the ADS-B equipage cases was approximately 8%.
Effect of 1090ES Messages Being Broadcast from Ground or Airborne Transmitters	No significant difference was observed. If a difference had been observed at that location, this would indicate this location was a 'hotspot' of degraded performance.

4.3 ISSUES AND OPEN QUESTIONS

The results of the analyses in this report depend on many assumptions. As the ADS-B and TIS-B systems mature and are deployed across the NAS, these systems can, and are likely to, change. Therefore, some assumptions made for this report may no longer be valid possibilities in the future, and the analyses may not continue to reflect the characteristics of the systems.

One of the more difficult problems in evaluating the TIS-B uplink performance of 1090ES is finding a worst-case position. A more thorough investigation of various locations within a given scenario could help, to determine if hotspots are present and to find worst-case locations for ADS-B and TIS-B performance (not necessarily the same location for both systems). But these worst-case locations will change as GBTs are deployed, influenced by factors that include specifics of the air traffic scenario (including ADS-B and transponder equipages, altitude, etc...), ground station locations, antenna gain patterns, and ground station transmit powers.

The 1090ES GBT is expected to have limits imposed on its transmissions by the FAA in order to ensure that SSR performance is not degraded in the terminal environment. The repeat strategy described in Section 2.3.2 may need to be revised in order to accommodate these uplink limits. This could change some of the estimates of TIS-B system performance presented here.

Finally, this report used the LA basin scenario as the setting for the simulations in order to represent high-density, terminal air traffic and a near-capacity load for the TIS-B/ADS-B systems. In this scenario, the assumption was made that 16 ground stations would be deployed in this region to handle the air traffic. If fewer ground stations are assumed, then the TIS-B uplink load might be greater at each GBT, so 1090ES reception performance on the ground and in the air would be reduced, due to blanking and an increased self-interference, respectively.

The ADS-B Rebroadcast service is intended to enable ASA applications between aircraft with different data links. A more complete study of the data flow from aircraft to ground and back up to another aircraft, involving both types of data links, accounting for reception performance and network and processing delays is recommended. The results of this sort of analysis might produce the most critical requirements for air-ground performance from ADS-B data links.

Appendix A

REFERENCES

[1] "Minimum Aviation System Performance Standards (MASPS) for Aircraft Surveillance Applications", RTCA Inc., 9 December 2003

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[11] "Minimum Operational Performance Standards For Air Traffic Control Radar Beacon System/Mode Select (ATCRBS/Mode S) Airborne Equipment", DO-181C, RTCA Inc., 12 June 2001

[12] "ADS-B Technical Link Assessment Team (TLAT) Technical Link Assessment Report", RTCA Free Flight Select Committee, Safe Flight 21 Steering Committee, and Eurocontrol ADS Programme, March 2001

[13] "Technical Handbook for Six-Sector Squitter-Ground-Station Antenna, dB Systems Model Number 530", dB Systems Inc., 24 April 1995, Book Part No. TM-530

[14] "Analysis of UAT Providing TIS-B Service" M. Castle, Working Paper 20-02 for RTCA SC-186 WG#5 (UAT), 9 February 2004, available at http://adsb.tc.faa.gov/WG5_Meetings/Meeting20.htm

Appendix B

LIST OF ACRONYMS AND ABBREVIATIONS

1090ES	1090 MHz Extended Squitter
ADS-B	Automatic Dependent Surveillance Broadcast
ADS-R	ADS-B Rebroadcast Service
ARTCC	Air Route Traffic Control Center
ASA	Aircraft Surveillance Applications
ASDE-X	Airport Surface Detection Equipment
ASSA	Airport Surface Situational Awareness
ASSAP	Airborne Surveillance and Separation Assurance Processor
ATCRBS	Air Traffic Control Radar Beacon System
BSGS	Broadcast Service Ground Station
CD	Conflict Detection
cdf	Cumulative Distribution Function
CDTI	Cockpit Display of Traffic Information
DME	Distance Measurement Equipment
EVAcq	Enhanced Visual Acquisition
EVApp	Enhanced Visual Approach
ES	Extended Squitter
FAA	Federal Aviation Administration
FAROA	Final Approach and Runway Occupancy Awareness
FIS-B	Flight Information Service – Broadcast
FL	Flight Level
GA	General Aviation

GBT	Ground- Based (or Broadcast) Transceiver
GNSS	Global Navigation Satellite System
ICAO	International Civil Aviation Organization
JHU/APL	Johns Hopkins University Applied Physics Laboratory
LA/ LAX	Los Angeles / Los Angeles International Airport
LOS	Line of Sight
MASPS	Minimum Aviation System Performance Standards
MAUS	Multi-Aircraft UAT Simulation
MOPS	Minimum Operational Performance Standards
mps	Messages Per Second
ms	Millisecond
MSR	Message Success Rate
MTL	Minimum Triggering Level
NAS	National Airspace System
NM	Nautical Mile
PRM	Precision Runway Monitor
RF	Radio Frequency
RTCA	Radio Technical Commission for Aeronautics
SARPS	Standard and Recommended Practices
SSR	Secondary Surveillance Radar
SV	State Vector
T95	95^{th} Percentile State Vector Update Interval
TCAS	Traffic Alert and Collision Avoidance System
TIS-B	Traffic Information Service – Broadcast
TIV	Traffic Information Volume
TLAT	Technical Link Assessment Team
UAT	Universal Access Transceiver

Appendix C

AIRPORT AND GBT CODES

Table 20: Code, Name, and Type for Airports Included in LA 2020 Scenario

Code	Name	Type	Code	Name	Type
BFL	Meadows Field (Bakersfield)	C1	BUR	Bob Hope (Burbank)	A
LAS	McCarran International (Las Vegas)	A	LAX	Los Angeles International	A
LGB	Long Beach / Daugherty Field	B	ONT	Ontario International	A
PSP	Palm Springs International	B	SAN	San Diego International	A
SBA	Santa Barbara Municipal	B	SMX	Santa Maria Public/ Capt. G. Allan Hancock Field	C1
SNA	John Wayne/Orange County	A	YUM	Yuma MCAS/Yuma International	C1

Appendix D

RECEIVER PERFORMANCE MODEL

A new 1090 MHz Extended Squitter (1090ES) receiver performance model (RPM) was developed over the last two years by JHU/APL. It was based on the decoder developed at the FAA's William J. Hughes Technical Center (FAATC). The RPM was incorporated into JHU/APL's existing 1090ES simulation, replacing an older RPM component which had originally been developed based on measurements performed on an LDPU receiver.

In addition to providing the decoder software FAATC also collaborated with JHU/APL to validate the model. This appendix details some of the results of these validation efforts. The new RPM consists of two major components: the first is an RF simulation, and the second is an implementation of the 1090ES enhanced decoder. Both will be described briefly before presenting the results of the validation of the model.

D.1 RECEIVER PERFORMANCE MODEL

The RF simulation involves both an RF mixing stage and a sampling stage. Logically, the mixing stage is done first. This is where the in-phase and quadrature components of all signals are summed with an approximately Gaussian noise background to produce the net incident received power. This is then followed by the sampling stage in which the amplitude is sampled at a specific frequency (e.g., 10 MHz for the A3 equipage enhanced decoder) and the phase information is discarded.

In the RPM, these stages are handled simultaneously. For each sample that the radio would record, noise components are obtained and contributions from all signals that could affect the sample are calculated. The components are summed and the magnitude of the two components gives the level of the sample.

The noise model uses the Box-Muller transformation for obtaining two Gaussian random variables from two uniformly distributed random variables $x_{1,2} \in (0, 1]$.

$$r = \sigma_{noise}\sqrt{-2\ln x_1}$$
$$\theta = 2\pi x_2$$

with

$$(in - phase) = r\cos\theta$$
$$(quadrature) = r\sin\theta$$

Where σ_{noise} = 0.0155 (-18 dB), which was chosen to provide a good approximation to measured noise. The algorithm is slightly modified to enforce a limit on the smallness of r. Therefore $x_1 \in (0, 0.5636]$ is used instead, and $r \geq 0.0166$ (-88 dBm), again chosen to match noise measurements.

Sample component contributions from each signal are determined by modeling the message as a series of pulses with a nominal amplitude and cubic leading and trailing edges characterized by 10% to 90% rise and fall times of 197 ns and 237 ns respectively. These values correspond to a 4 MHz receiver bandwidth and match measurements performed on the FAATC equipment. Additionally, each message has a random starting phase associated with it. This phase is advanced for each sample according to the frequency at which it was transmitted (e.g., (1090 ± 1) MHz for Mode S messages).

Once the samples have been computed from the simulated RF environment, a buffer of samples is passed on to the decoder logic. This logic was developed by the FAATC and is described in Appendix I of the current 1090ES MOPS.[5]

D.2 VALIDATION

D.2.1 Processing Comparison

Sets of samples generated by the RF simulation were sent to the FAATC for processing with their decoder. Likewise, samples recorded from test equipment at the FAATC were processed by the JHU/APL decoder. In all cases tested, there was greater than 99% agreement between the results from the two decoders.

D.2.2 Core Europe 30k Scenario

An interference environment was designed to approximate what may be expected in the future air space around Brussels. This environment mainly consists of Mode A and C transmission at the rate of 30,000 per second at or above -84 dBm. This ATCRBS fruit environment was used by the FAATC for performance measurements on the enhanced decoder which served as a useful baseline for comparison. Figure 28 shows the results of the RPM with two sets of measurements, one from 2002 and the second from 2005.

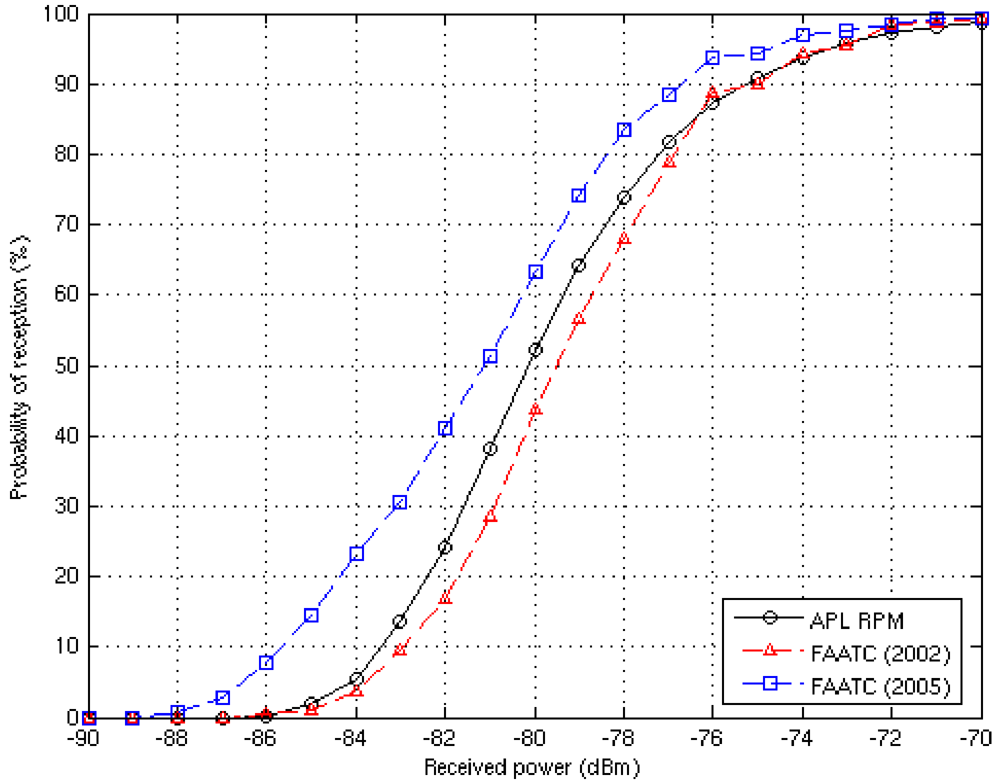

Figure 28: 1090ES Receiver Performance in the Core Europe 30k Fruit Environment

D.2.3 1090 MOPS Tests

Section 2.4.4.4 of DO-260A defines a set of compliance tests for the 1090ES enhanced decoder. These tests were performed on the JHU/APL RPM for both the A2 and A3 equipages. The results are shown in Table 21 and Table 22 along with the requirements specified in the MOPS. It should be noted that tests 2.4.4.4.2.2-05 through 2.4.4.4.2.3-10 in the following tables were found to not function as intended and will likely be changed in the next revision of the 1090ES MOPS.

Table 21: Results of Applying DO-260A MOPS Tests for an A2 Receiver on JHU/APL 1090ES Receiver Performance Model

Test	Req. (MSR %)	Result (MSR %)	Test	Req. (MSR %)	Result (MSR %)
2.4.4.4.2.2-01	90+	100.0	2.4.4.4.2.4-2-[1-7]	93+	97.7
2.4.4.4.2.2-02	90+	100	2.4.4.4.2.4-3-[1-7]	89+	93.3
2.4.4.4.2.2-03	90+	100	2.4.4.4.2.4-4-[1-7]	88+	89.7
2.4.4.4.2.2-04	90+	100	2.4.4.4.2.4-5-[1-7]	79+	81.3
2.4.4.4.2.2-05	10-	40.7	2.4.4.4.2.4-6-[1-7]	74+	77.3
2.4.4.4.2.2-06	10-	40.7	2.4.4.4.2.5-1	95+	100
2.4.4.4.2.2-07	40-	42.3	2.4.4.4.2.5-2-1	0+	9.8
2.4.4.4.2.2-08	40-	42.4	2.4.4.4.2.5-2-2	59+	85.1
2.4.4.4.2.2-09	10-	100	2.4.4.4.2.5-2-3	99+	100
2.4.4.4.2.2-10	10-	100	2.4.4.4.2.5-2-4	99+	100
2.4.4.4.2.2-11	10-	100	2.4.4.4.2.3-01	10-	0
2.4.4.4.2.2-12	10-	100	2.4.4.4.2.3-02	10-	1.2
2.4.4.4.2.2-13	10-	0	2.4.4.4.2.3-03	10-	0
2.4.4.4.2.2-14	10-	0	2.4.4.4.2.3-04	10-	1.6
2.4.4.4.2.6-1	95+	100	2.4.4.4.2.3-05	10-	50
2.4.4.4.2.6-2-1	12+	38.4	2.4.4.4.2.3-06	10-	1.2
2.4.4.4.2.6-2-2	88+	85.8	2.4.4.4.2.3-07	10-	100
2.4.4.4.2.6-2-3	94+	100	2.4.4.4.2.3-08	10-	89.1
2.4.4.4.2.6-3-1	26+	58	2.4.4.4.2.3-09	10-	100
2.4.4.4.2.6-3-2	93+	95.5	2.4.4.4.2.3-10	10-	100
2.4.4.4.2.6-3-3	94+	100	2.4.4.4.2.3-11	90+	100
2.4.4.4.2.4-1	90+	93.7	2.4.4.4.2.3-12	90+	100

Table 22: Results of Applying DO-260A MOPS Tests for an A3 Receiver on JHU/APL 1090ES Receiver Performance Model

Test	Req. (MSR %)	Result (MSR %)	Test	Req. (MSR %)	Result (MSR %)
2.4.4.4.2.2-01	90+	100	2.4.4.4.2.4-2-[1-7]	94+	99.2
2.4.4.4.2.2-02	90+	100	2.4.4.4.2.4-3-[1-7]	91+	96.3
2.4.4.4.2.2-03	90+	100	2.4.4.4.2.4-4-[1-7]	90+	92.9
2.4.4.4.2.2-04	90+	100	2.4.4.4.2.4-5-[1-7]	86+	84.5
2.4.4.4.2.2-05	10-	0	2.4.4.4.2.4-6-[1-7]	85+	79.1
2.4.4.4.2.2-06	10-	0	2.4.4.4.2.5-1	95+	100.0
2.4.4.4.2.2-07	10-	48.4	2.4.4.4.2.5-2-1	0+	7.5
2.4.4.4.2.2-08	10-	42.5	2.4.4.4.2.5-2-2	59+	68.8
2.4.4.4.2.2-09	10-	100	2.4.4.4.2.5-2-3	99+	100
2.4.4.4.2.2-10	10-	100	2.4.4.4.2.5-2-4	99+	100
2.4.4.4.2.2-11	10-	100	2.4.4.4.2.3-01	10-	0
2.4.4.4.2.2-12	10-	100	2.4.4.4.2.3-02	10-	11.3
2.4.4.4.2.2-13	10-	0	2.4.4.4.2.3-03	10-	0
2.4.4.4.2.2-14	10-	0	2.4.4.4.2.3-04	10-	11.7
2.4.4.4.2.6-1	95+	100	2.4.4.4.2.3-05	10-	0.1
2.4.4.4.2.6-2-1	12+	36.1	2.4.4.4.2.3-06	10-	11
2.4.4.4.2.6-2-2	88+	91.3	2.4.4.4.2.3-07	10-	100
2.4.4.4.2.6-2-3	94+	100	2.4.4.4.2.3-08	10-	100
2.4.4.4.2.6-3-1	26+	44	2.4.4.4.2.3-09	10-	100
2.4.4.4.2.6-3-2	93+	94.7	2.4.4.4.2.3-10	10-	100
2.4.4.4.2.6-3-3	94+	100	2.4.4.4.2.3-11	90+	100
2.4.4.4.2.4-1	90+	99.8	2.4.4.4.2.3-12	90+	100

An extension of test 2.4.4.4.2.5-2, a test with four overlapping Mode S messages, was performed for a variety of signal levels and compared with the same test performed by the FAATC. The results are shown in Figure 29.

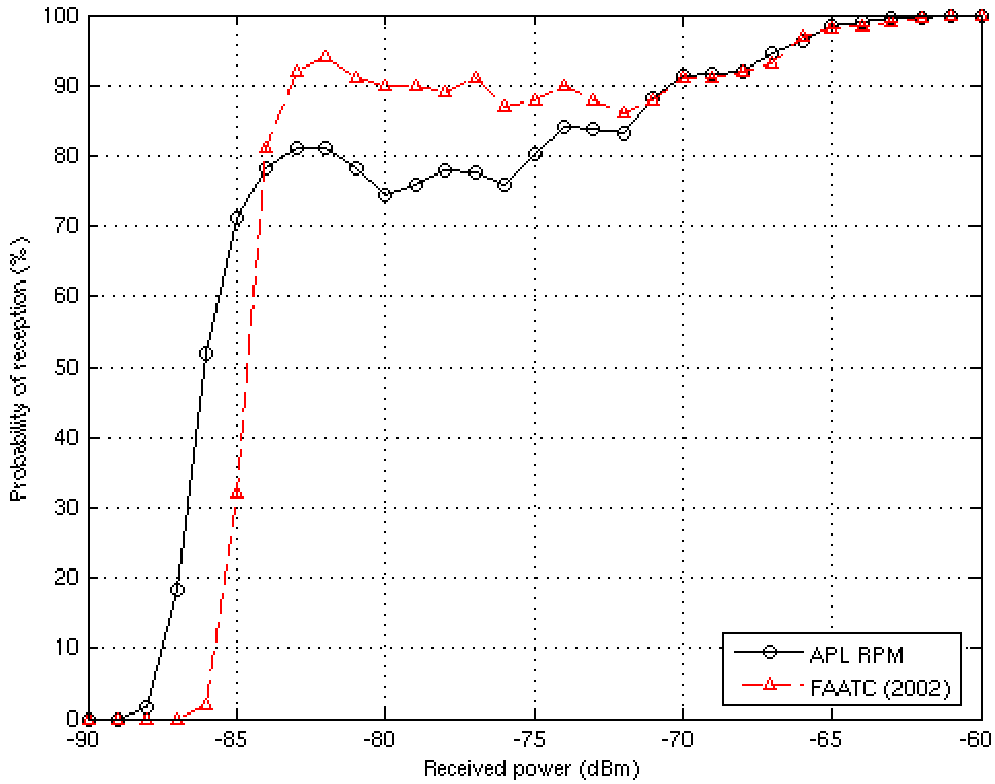

Figure 29: 1090ES Receiver Performance in the Presence of Four Overlapping Mode S Signals