MEASUREMENTS OF ADS-B EXTENDED SQUITTER PERFORMANCE IN THE LOS ANGELES BASIN REGION*

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I. Introduction

Automatic Dependent Surveillance Broadcast (ADS-B) is a system in which navigation information derived on individual aircraft is broadcast on a common data link frequency to support a variety of applications as described in the ADS-B Minimum Aviation System Performance Standards (MASPS), [1]. One proposal for implementation of ADS-B uses existing secondary surveillance radar message formats in a broadcast mode. This technique, called Mode S Extended Squitter, uses a modified version of the 1090 MHz, Mode S signal that is now spontaneously broadcast (squittered) by Mode S secondary surveillance transponders to support the Traffic Alert and Collision Avoidance System (TCAS). Because Mode S Extended Squitter operates in the secondary surveillance frequency band, shared by surveillance radars and TCAS, it is necessary to demonstrate that it can operate acceptably in the presence of signals from those systems.

The ADS-B MASPS identifies applications in which an aircraft may be required to receive and decode ADS-B messages from other aircraft up to 90 nmi away. Operation at such long range requires a more sensitive 1090 MHz receiver than is currently deployed on most airborne aviation systems today. For instance, the 1090 MHz receiver used by TCAS is designed for reliable reception of transponder replies from aircraft that are 15-20 nmi away, in the presence of interference from aircraft that may be as far as 30-40 nmi away (i.e., roughly twice the design reception range). In contrast, a long range ADS-B receiver must decode squitters from sources up to 90 nmi away, in the presence of interference that may come from aircraft as distant as 180 nmi. The interference caused by replies from transponders elicited by interrogations from secondary surveillance radars and TCAS is a function of both the density of aircraft and interrogators. Previous field measurements [2,3] have documented the reply rates seen by 1090 MHz receivers with TCAS-like sensitivity. Extrapolation of these results in the busiest parts of the U.S. National Airspace System (e.g., the Los Angeles Basin) leads to estimates that a long range ADS-B receiver may operate with up to 30,000-40,000 interference replies/second in these areas. The measurement of actual 1090 MHz reply rates as seen by a long range ADS-B receiver, and the performance of 1090 MHz Extended Squitter in a high interference environment were the subject of a series of flight tests performed in the Los Angeles Basin from June 16-19, 1999. The results of those measurements are reported in this paper.

II. LAX ADS-B Trials Configuration

The ADS-B Extended Squitter trials conducted in the Los Angeles Basin area were designed to examine several questions:

a) What are the actual 1090 MHz reply rates and underlying aircraft distributions in the L.A. Basin region?

b) What is the observed air-to-air range for reception of ADS-B Extended Squitters as a function of 1090 MHz reply rates?

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c) What is the observed air-to-ground reception range for ground equipment tracking airborne ADS-B targets (as might be required in an ADS-B-based terminal or en route surveillance application)

d) What is the observed ground-to-air reception range for airborne receivers listening to ADS-B messages broadcast from ground stations?

Airborne Platforms

Four aircraft participated in the LAX ADS-B trials. The sponsoring organization and equipage suite for each aircraft is presented in Table 1.

Table 1. Participating Aircraft

Sponsor and Aircraft Type	Environmental Measurement Sensors	ADS-B Receiver(s)	ADS-B Transmitter
FAA, Boeing B727, N40	**DATAS** (1090 MHz reply recording), **AMF** (1030/1090 MHz pulse recording) **1090TestBed** (8 Msample/sec sampled video)	**Stand-alone receiver** (UPS Aviation Technologies) **TCAS-2000** (L-3)	**L-3 Mode S transponder**
FAA, Convair C580, N49	None	**Stand-alone receiver** (UPS Aviation Technologies) **TCAS-2000 (L-3)**	**L-3 Mode S transponder**
UPS Aviation Technologies, Boeing B727, N904UPS	None	**Stand-alone receiver** (UPS Aviation Technologies)	**L-3 Mode S transponder**
L-3 (formerly Honeywell), Cessna Citation, N189H	None	**Stand-alone receiver** (UPS Aviation Technologies)	**L-3 Mode S transponder**

R.F. Environmental Measurements

The FAA Boeing B727 (N40) was equipped with three systems to measure the beacon surveillance channel occupancy, as illustrated in Figure 1. This aircraft was the only airborne platform in the LAX ADS-B trials equipped to measure the beacon surveillance channel occupancy and interference rates directly.

First, the FAA Data Link and Transponder Analysis System (DATAS) was used to record the amplitude and time of arrival of 1090 MHz beacon replies. As installed on N40, DATAS operated with a minimum sensitivity threshold of –84 dBm, and could monitor a single channel (which was connected to either a top-mounted or bottom mounted external L-band antenna).

Next, the Lincoln Laboratory Airborne Measurement Facility (AMF) recorded the amplitude, width, and time of arrival of all pulses [4]. The AMF monitored two channels simultaneously and could be set to record either 1030 MHz pulses (corresponding to beacon interrogations) or 1090 MHz pulses (corresponding to beacon reply messages. The minimum threshold at which pulses could be detected on the AMF was –80 dBm. Groups of beacon interrogations or replies could be extracted from the pulse recordings, which provided a cross check on the reply rates detected by DATAS, and also yielded information on the numbers of pulses not associated with a decodable reply.

Finally, the Lincoln Laboratory 1090 Test Bed (1090TB) was used to record sampled video directly. The 1090TB recorded 12 bit samples at an 8 Msample/second rate. A maximum of 16 seconds of continuous recording could be stored every 5 minutes. The 1090TB sample rate was high enough to allow nearly complete reconstruction of the original signals. Mode S Extended Squitters were extracted via post-processing, which allowed detailed investigation of interference sources and effects. Other transponder replies were also extracted to provide a crosscheck on the rates recorded in DATAS and AMF. The sampled video also served as a database of real world signals plus interference. By exposing a variety of Mode S Extended Squitter decoding algorithms to this reference database the relative efficiency of these algorithms could be computed.

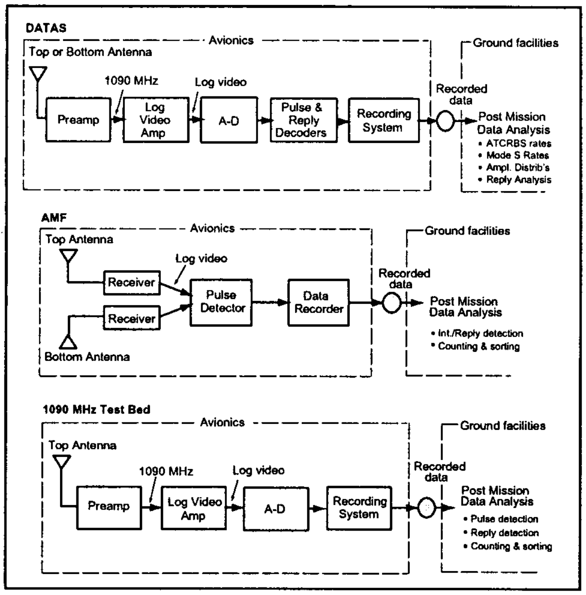

Figure 1. Block Diagrams of the Three Measurement Systems on FAA B727 Illustrating Their Major Functions.

ADS-B Transmit and Receive Avionics

All aircraft participating in these trials were equipped to transmit ADS-B messages (using a GPS navigation source and an L-3 Mode S transponder). The aircraft received and archived ADS-B messages using one of two types of receivers. Both receivers used Extended Squitter decoding algorithms developed at MIT Lincoln Laboratory [5]. The first ADS-B receiver was integrated with an L-3 TCAS unit (in which the existing 1090 MHz receiver was augmented with additional decoding software to recognize and archive ADS-B messages). This prototype TCAS-integrated receiver had a minimum sensitivity threshold of –84 dBm and devoted approximately 70% of its total time listening for ADS-B messages. The rest of the time was devoted to normal TCAS interrogation, reply, and processing tasks.

The second receiver architecture employed a dedicated logarithmic amplifier and antennas integrated with 14 dB preamplifiers to improve sensitivity. This receiver/antenna set, supplied by UPS Aviation Systems and denoted the Link and Display Processing Unit (LDPU), had a minimum sensitivity threshold of –92 +/-1 dBm (referred to the external antenna) as installed on N40, N49, and N904UPS. The LDPU decoded and recorded both the Mode S Extended Squitters received from the ADS-B trial participants and the shorter Mode S squitters that were available from all Mode S-equipped targets of opportunity. Each LDPU was configured to monitor and record data from two channels (one top antenna and one bottom antenna) independently.

Ground-based Measurement Facilities

Data from several Mode S radars (LAX North, LAX South, Long Beach, and San Diego) were recorded during the test flights to provide a basis for estimating the aircraft traffic distribution and to assist in locating the sources of the Mode S (short) squitters recorded by the LDPUs (the standard, short Mode S squitters do not encode position, although they do contain the same 24-bit address that is downlinked by the Mode S radars, allowing a positive correlation with aircraft position).

A ground station was installed just to the west of Los Angeles International Airport, located between the parallel east/west runways. This ground station included a dual channel LDPU. The LDPU was connected to two sectors of a 6-sector antenna. Each sector of the antenna had a peak gain of 14 dBi, with a 60 degree, 3 dB beamwidth.

A Mode S transponder, configured with a circulator to isolate it from beacon interrogations while allowing it to transmit Mode S Extended Squitters, was connected to an omnidirectional DME antenna with 6 dBi of gain. Mode S Extended Squitters were transmitted via this transponder/antenna combination at a 2 Hz rate during the flight tests.

Flight Paths and Times

Flights in the Los Angeles Basin were conducted on four days, 16-19 June 1999, extending for three hours on each day. FAA Air Traffic Controllers in Los Angeles assisted in determining the busiest times of day, in order for the tests to include the highest interference conditions. As a result, the flights were conducted between 11:00 PDT and 14:00 PDT on 16 June (Wednesday), 17 June (Thursday), and 18 June (Friday), and 14:00 PDT and 17:00 PDT on 19 June (Saturday). The general orientation of the flights is shown in Figure 2. Most flights were concentrated

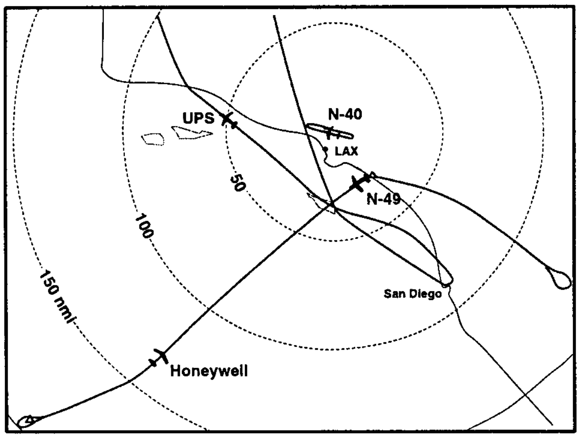

Figure 2. Flight tracks for the four participating aircraft are shown superimposed on a map of the Los Angeles Basin.

within a triangle defined by LAX to the north, the navigational fix KUMBA to the southeast, and the navigational fix FICKY to the southwest. The UPSAT B727 (N904UPS) provided a limited number of flights that paralleled the coast.

During most of the flights, one aircraft (usually N40) held at a fix 5 nmi north of LAX, flying at 17,500 feet in a racetrack holding pattern oriented roughly east-west. The other ADS-B target aircraft (usually N49 and N189H) flew back and forth along an inverted V defined by FICKY to the southwest, MIDDS (near Long Beach) at the apex and northern extent of the pattern, and KUMBA to the southeast. Additionally, the UPS B727 flew the north-south routes along the coast.

These flights were designed to provide a variety of test conditions. The aircraft holding over LAX would operate with the greatest number of interfering 1090 MHz replies, because of the high aircraft density and large number of beacon interrogators within view. The number of interfering replies would be expected to diminish substantially as aircraft flew offshore towards FICKY. The division of flights over land and water also provided an opportunity to observe any multipath degradation that might be attributed to operation over water.

III. Results

1090 MHz Reply Rates (Interference Rates)

The amplitude and rate of Mode A/C ATCRBS and Mode S transponder replies, also known as fruit, were measured using DATAS, AMF, and the 1090TB. Overall distributions are illustrated in Figures 3 and 4. Figure 4 illustrates the general repeatability of the measurements, and also exposes a modest asymmetry in the data. Recorded fruit rates on N40 were consistently about 10-20% higher when the aircraft was westbound in the hold.

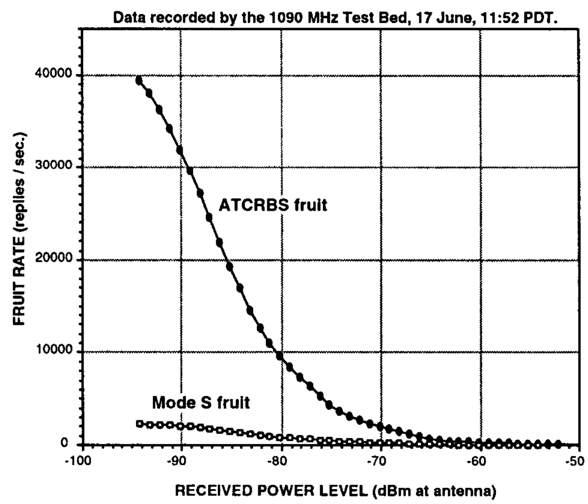

Figure 3. ATCRBS and Mode S Fruit Rates as a Cumulative Distribution vs. Received Power. Each Point on the Fruit Rate Curve Represents the Sum of All Replies Whose Amplitude is Greater Than or Equal to the Corresponding Received Power.

This is thought to be the result of the natural asymmetry in the aircraft distribution (many more aircraft are north and east of LAX, over land, than south and west of LAX, over water) and the asymmetric antenna gain pattern on N40, which was a consequence of mounting the antennas somewhat to the right of the fuselage centerline.

Variations in geographic position were noted during a flight in which N40 flew from FICKY to MIDDS to KUMBA, as illustrated in Figure 5. The top two plots show the ATCRBS fruit rates (averaged with a 1-minute sliding window filter) as a function of time while N40 is holding over LAX.

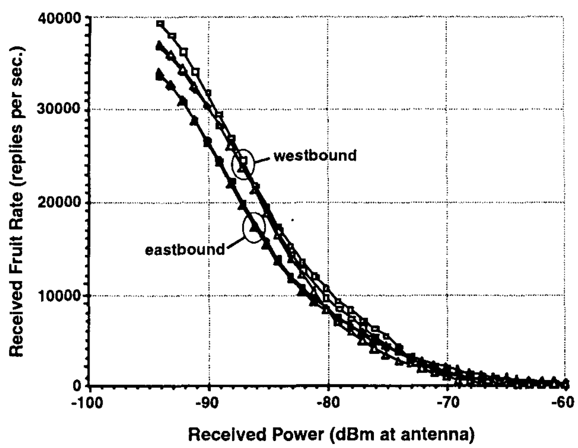

Figure 4. Repeated Fruit Measurements during Hold over LAX, Shown as Cumulative Distributions vs. Received Power.

The east/west asymmetry is clearly visible. The fruit rates offshore and well to the south drop off dramatically, and the peak fruit rate is observed near Long Beach at MIDDS.

It was also of interest to calculate the correlation between measured interrogation rates and aircraft distributions and measured 1090 MHz reply rates. The ability to correlate the underlying sources of replies (interrogation rates, aircraft distribution) with the measured 1090 MHz reply rates is important in predicting future 1090 MHz reply rates adjusted for changes in aircraft traffic density and interrogator distribution. The LAX North radar data was used to determine the aircraft distribution within 60 nmi of LAX. The aircraft distribution, shown in Figure 6, was extended to a 200 nmi radius by assuming a "linear in range" distribution, which historical measurements have validated when estimating aircraft distributions that are well separated from a major airport.

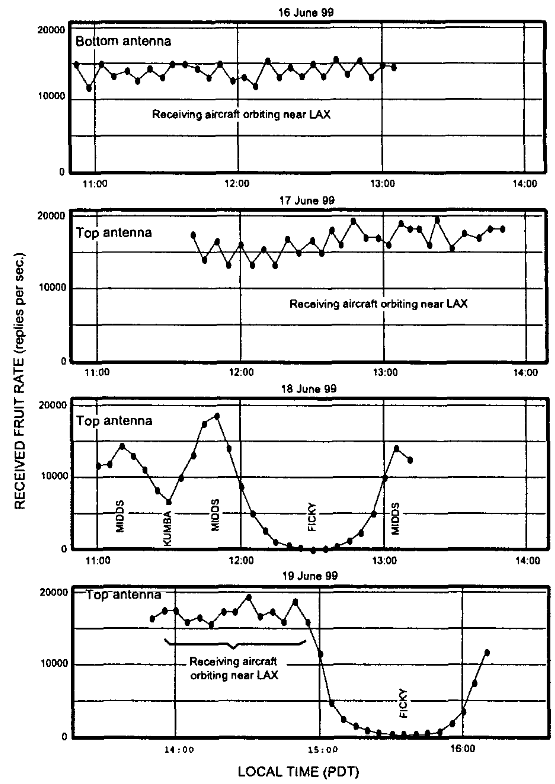

Figure 5. Summary of ATCRBS Fruit Rates, Reported as the Total Number of ATCRBS Replies Above –84 dBm (referred to the antenna) and Averaged Over a 1-Minute Interval.

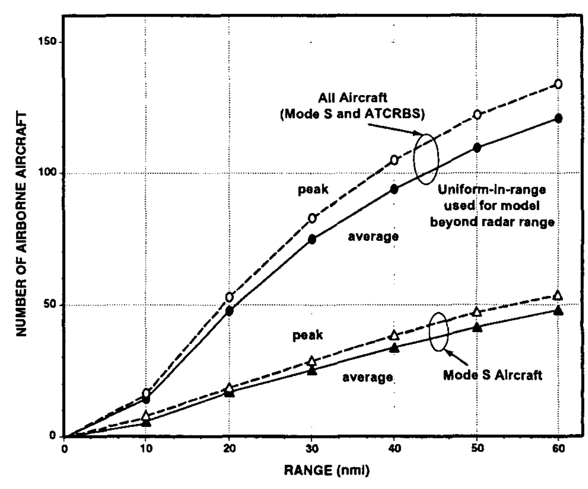

Figure 6. Aircraft Distribution with Range Near LAX (From LAX North Radar Data).

To estimate the replies that the aircraft distribution in Figure 6 would produce, an average of 75 and 90 interrogations per second per aircraft were used for Mode S and ATCRBS transponders, respectively, and a 40/60% Mode S/ATCRBS equipage distribution was assumed. The total number of replies were then calculated in a spreadsheet model, and plotted vs. received amplitude in Figure 7. This spreadsheet-based model yielded excellent correlation between the predicted and measured fruit rates, particularly at the higher rates (which correspond to the interference seen by a more sensitive receiver).

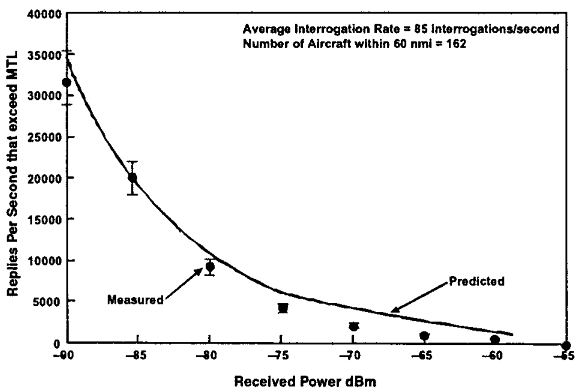

Figure 7. Comparison of Predicted, Measured Fruit Rates.

Air-to-Air ADS-B Reception Performance

The air-to-air surveillance performance of the flight test equipment is illustrated in Figure 8. The track of one of the test aircraft as derived from Extended Squitter receptions by an LDPU is plotted. The aircraft under surveillance was N40, as it flew on the long range path beginning out over the ocean and then continuing down toward the Mexican border. The receiving aircraft was N49, flying in the racetrack holding pattern near LAX. The position of every Extended Squitter from N40 is plotted, demonstrating the quality of the track.

More detailed performance results for air-to-air surveillance are plotted in Figure 9. This is a different encounter between N189H (transmitting Extended Squitters) and N-49 (receiving Extended Squitters via an LDPU), recorded on 17 June. During the time period plotted, range varied from

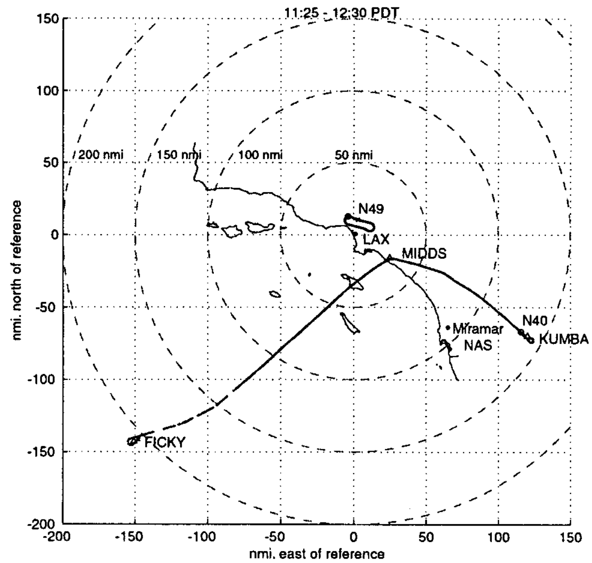

Figure 8. FAA Boeing B727 (N40) as tracked by FAA Convair C580 (N49) via ADS-B.

about 100 nmi, inbound, through nearly zero as the aircraft crossed paths, and then to about 110 nmi outbound. The Citation (N189H) was northeast-bound from the vicinity of FICKY at the start of the encounter, while the Convair (N49) was southwest-bound from MIDDS. The intercept occurred just offshore over Catalina Island.

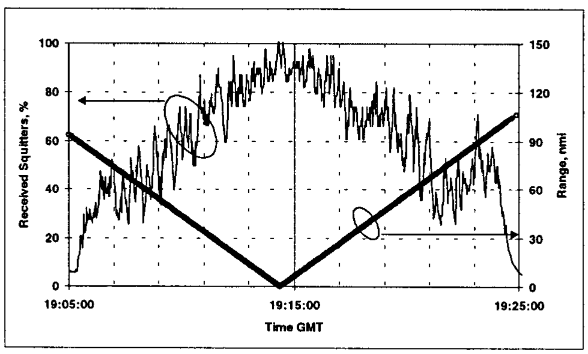

Figure 9. ADS-B Extended Squitter Probability of Reception and Range vs. Time during head-to-head pass between Citation N189H and Convair N49 on 17 June.

Performance, measured as the per-squitter reception probability averaged over a 10 second interval, varies as a function of range, and is consistently above 25% for ranges to 40 nmi and well beyond. When the per-squitter reception is 25% or above, surveillance quality meets MASPS requirements for long range applications, because the transmission rate of Extended Squitters (6.2 Extended Squitters per second) is well above the required reception rate (about 1-2 squitters per 7-10 seconds, for ranges beyond 40 nmi). Overall, the measured and required update probability for various classes of applications, as defined in the ADS-B MASPS, is illustrated in Figure 10. The long range deconfliction task requirements, which are the most challenging, were still met in the presence of the L.A. Basin interference levels.

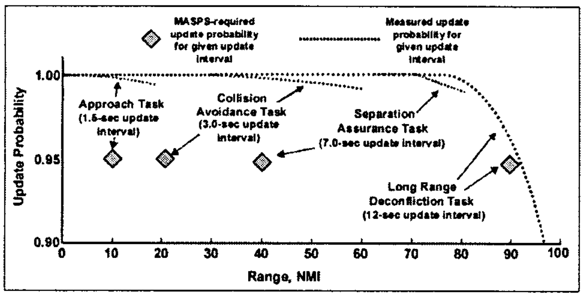

Figure 10. Comparison of Required and Measured Update Probability vs. Range.

Air-to-Ground ADS-B Reception Performance

Using the LDPU standalone receiver architecture and a multi-sector antenna with an external preamplifier to reduce the effects of cable losses, ADS-B air-to-ground tracking was achieved with excellent update rates out to well beyond 150 nmi. In the example in Figure 11, the track dropouts at long range near FICKY are a consequence of the signal loss as the aircraft flies just beyond where direct line-of-site to the ground station is available for the altitude being flown. A more detailed example is shown in Figure 12. During this profile N40 proceeds from KUMBA to MIDDS (the point of closest approach to the ground station), thence offshore to FICKY, back to MIDDS, and back to KUMBA. Examining this plot reveals the difference in reception probability that may be attributed to the changing interference environment seen by the two sectors of the ground station antenna.

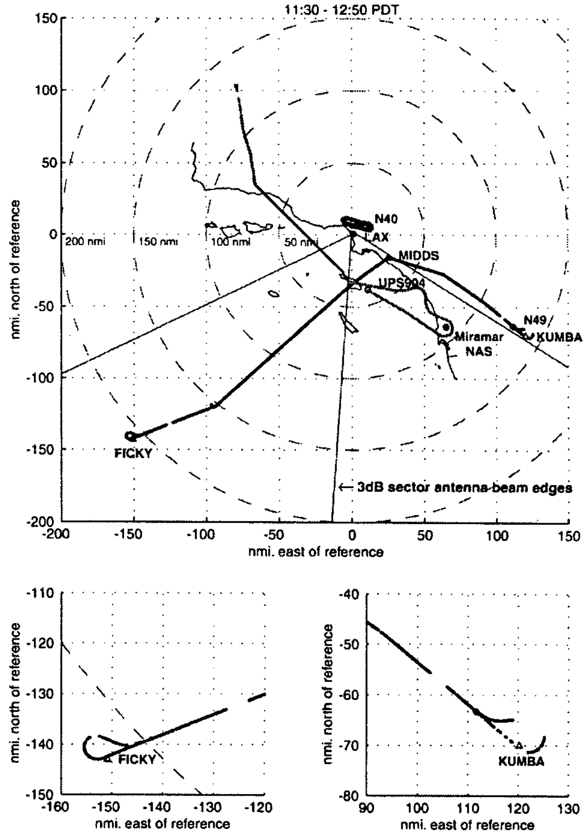

Figure 11. Air-to-Ground Tracking via ADS-B.

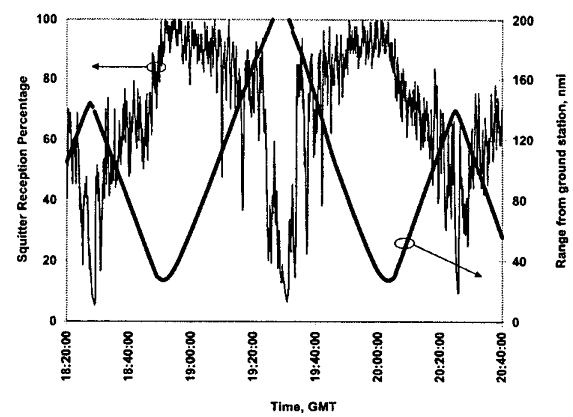

Figure 12. Range, Probability of ADS-B Reception vs. Time for Ground Station Tracking of FAA B727 (N40).

When N40 is flying between MIDDS and KUMBA, it is most visible to the sector oriented to point to the southeast, which will see the greater number of aircraft. When N40 is flying between

MIDDS and FICKY, most of the visibility is through the sector that is pointed more to the south and west, where there are fewer aircraft and thus less interfering replies. The rapid decrease in reception probability as N40 nears FICKY (at a range of greater than 200 nmi) is caused by the aircraft flying beyond line-of-sight.

Ground-to-Air Reception

As a surrogate for the transmission of uplink data for reception in an airborne ADS-B receiver, ADS-B Extended Squitters containing a test ID and the ground station position were transmitted via an omnidirectional DME antenna located near the multi-sector ground station antenna. The reception probability of these ground broadcast messages vs. range, as measured by the LDPU on the Convair (N49), is illustrated in Figure 13. Reception probability of greater than 50% is observed for ranges out to approximately 60 nmi. This is a good match for a service that must provide line of site coverage to relatively low altitude aircraft.

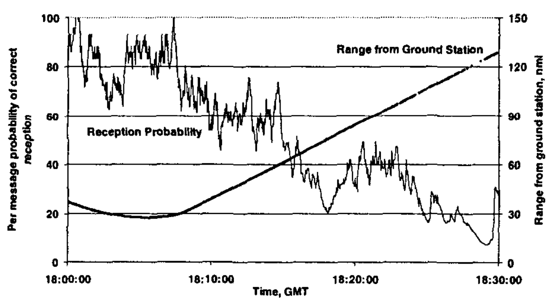

Figure 13. Ground-to-Air (Uplink) Probability of Reception vs. Range.

IV. Conclusions

The Los Angeles Basin ADS-B Measurement Trials provided a quantitative assessment of the existing interference environment at 1090 MHz and the surveillance performance of Mode S Extended Squitter in that environment. Redundancy in the measurement equipment and in the flight configurations chosen during the trials provided extensive cross checking capability, and greatly increased the integrity of the results.

ATCRBS reply rates as high as 40,000/second above –90 dBm were measured. The corresponding aircraft distribution and 1030 MHz interrogation rates correlated well with these measurements.

A wide range of scenarios were captured to measure the airborne and ground-based reception of ADS-B Extended Squitters emitted by airborne sources. Air-to-air ranges of greater than 100 nmi were routinely observed, and comparison with ADS-B MASPS requirements showed that all airborne requirements were met in the scenarios flown. Air-to-ground reception rates were routinely better than the update rates provided by either en route or terminal radars at ranges beyond 150 nmi. Ground-to-air (uplink) performance was adequate to support transmission of ADS-B or other information in broadcast formats within approximately 60 nmi of the ground station.

Finally, these measurements are a valuable source of validation and refinement data for the various models used to predict Extended Squitter performance in current and future scenarios.

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