Appendix B

UAT System Performance Simulation Results

Revision 0.1

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Do we want to include TIS-B uplink analysis (it's long), TIS-B hotspot analysis, determination of equipage type?

B UAT System Performance Simulation Results

B.1 Introduction

B.1.1 Organization

This introductory section discusses the background and assumptions for the Multi-Aircraft UAT Simulation (MAUS), which has been used as a tool for evaluating the performance of UAT as an ADS-B data link under a number of different possible system parameters and configurations.

Section B.2 describes in detail the antenna gain model, which is used by MAUS in calculating the signal levels received from the transmitting aircraft in the simulation. This antenna gain model is identical to that used in simulations employed in the past to evaluate all three ADS-B link candidates (Reference to Link Comparison Study done for ICAO).

The UAT receiver performance model used by MAUS is described in Section B.3. The model is based on measured data, and both the data and model characteristics are described in this section.

The results shown in Section B.4 are compared to RTCA/DO-242A requirements as specified in Table 3-4(a) "SV and MS Accuracy, Update Interval, and Acquisition Range Requirements" and Table 3-4(c) "Summary of TS and TC Report Acquisition Range and Uplink Interval Requirements." Section B.4 presents results for the analysis of UAT performance. Section B.4.1 describes the Los Angeles 2020 scenario and the UAT system performance in this environment. Section B.4.2 presents the Core Europe scenario, and describes the performance of UAT in this environment. Section B.4.3 describes and presents results for the Low Density scenario. Acquisition performance is presented in Section B.4.4, and aircraft-aircraft performance on the surface is discussed in Section B.4.5. Section B.4.6 presents the results for an A0 receiver on the surface receiving aircraft on approach. Section B.4.7 describes results of a study on the use of a laydown of UAT ground stations for uplinking TIS-B information in the LA 2020 environment.

Finally, validation of the MAUS results is presented in Section B.5. This section describes a comparison of MAUS predictions with measured data from specially devised test equipment. This equipment was designed to emulate a high-density UAT self-interference environment, and the MAUS was run for identical conditions.

B.1.2 Background

Analytical models and detailed simulations of data links operating in future scenarios are required to assess expected capabilities in stressed circumstances. Accurately modeling future capabilities for potential system designs in a fair way, however, is challenging. Since validation of simulation results in future environments is unrealistic, other means of verification such as the following are required. System characteristics represented in these simulations should agree with actual measurements on components of the proposed design, e.g., bench measurements on prototype equipment and calibrated flight test data

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should be used, when possible, for the receiver/decoder capabilities and as comparison with modeled link budgets. Similarly, suitable interference models help to support estimates of how these conditions may change in future scenarios. Credibility of any simulation results for future scenarios also requires that they be able to model current conditions and provide results that appropriately agree with measurements made under these conditions. Existing tools have been used as cross-checks where possible for the final detailed simulations and models.

B.1.3 General Assumptions

In an effort to capture as many real-world effects important to the assessment of the performance of UAT as possible, an attempt was made to include, to the extent possible, representations of the effects of:

- Propagation and cable losses
- Antenna gains
- Propagation delays
- Co-channel interference (specifically, DME/TACAN and JTIDS (Link 16))
- Co-site interference (in and out of band)
- Multiple self-interference sources
- Alternating transmissions between top and bottom antennas (where applicable)
- Performance as a function of receiver configuration (e.g., diversity, switched, bottom only)
- Transmit power variability and configuration
- Receiver re-triggering
- Receiver performance based on bench testing
- Message transmission sequence and information content by aircraft equipage
- Ground receiver assumptions

Section B.4.7.1 will contain additional assumptions that were required to analyze the TIS-B uplink performance of UAT.

B.1.4 UAT Detailed Simulation Description and Limitations

The UAT detailed simulation software is written in C and allows for horizontal, constant-velocity motion of the aircraft in the scenario, if the user so chooses. The simulation reads in the inputs specifying the particular case to be run, generates all of the ADS-B transmissions and interference, calculates signal levels and times of arrival for these transmissions, and determines the corresponding message error rates for each ADS-B transmission by all aircraft within line of sight of the victim receiver. MAUS is often run in a mode that regards all of the ADS-B transmissions by the air traffic scenario as interference, and inserts a number of probe aircraft as desired transmitters to provide message error rate data. This permits the augmentation of the statistical sample used. This information is then written to an output file, one entry line for each ADS-B

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transmission, which is then analyzed by post-simulation software. Each of the effects listed in Section B.1.2 will now be discussed in turn.

- Propagation and cable losses. The UAT simulation calculates the free-space propagation loss for each transmission, using the range between transmitter and receiver at the time of transmission. There is also a nominal receiver cable loss of 3 dB incorporated in the calculation. An optional transmit cable loss is also included in the simulation, but since the transmit powers have been defined at the antenna, the transmit cable loss has been set to zero.

- Antenna gains. The antenna gain model included in the UAT simulation is described in Section B.2.

- Propagation delays. Calculation of the propagation delay incurred by the signal in traversing the free space between transmitter and receiver has been included in the UAT simulation

- Co-channel interference. In certain geographic areas, UAT may have to co-exist with transmissions from DME/TACAN and Link 16 sources. Link 16 scenarios have been provided in cooperation with the USDOD and have been applied to all of the performance analysis shown in this document. Various DME/TACAN scenarios provided by Eurocontrol have been applied to Core Europe analysis. In all cases, every attempt was made to provide conservative estimates of the co-channel interference environment. (see Appendix C for more detailed explanation of the interference environment)

- Co-site interference. Co-site transmissions of UAT messages, DME interrogations, Mode S interrogations and replies, whisper-shout interrogations, and ATCRBS replies are all modeled as interference in the UAT simulation. All of these are treated as interference which completely blocks UAT reception; therefore, it is assumed that no UAT reception may occur during any of these co-site transmissions (including a 15 microsecond suppression period added to the end of each co-site transmission). (see Appendix C for more detailed explanation of the interference environment)

- Multiple self-interference sources. Although the UAT transmission protocol specifies that a transmission begin on one of a fixed number of message start opportunities, the propagation delay described above will cause the arrivals of messages at the victim receiver to be quasi-random. There may be a number of messages overlapping one another, and these overlaps will be for variable amounts of time. This interference is accounted for in the multi-aircraft simulation. Multiple UAT interferers are treated in the receiver performance model by combining their interference levels in a way consistent with bench test measurements. The simultaneous presence of UAT interference, co-channel interference, and self-interference is treated in a detailed fashion by the model. Further discussion is presented in Section B.3. Since the UAT system description specifies that the ground uplink transmissions occur in a separate, guarded time segment than the air-to-air transmissions, FIS-B should not interfere with the ADS-B transmissions of the aircraft. Therefore, the simulation does not model this data load for the ADS-B performance assessment.

- Alternating transmissions. The model simulates the alternating transmission sequence specified for A1, A2, and A3 equipage, TTBBTTBB…, where T = top and B = bottom. For A0 equipage, the model simulates transmission from a bottom antenna.

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- Receiver diversity. For A2 and A3 equipage, the model simulates receiver diversity by calculating the message error rate at both the top and bottom receive antennas and calculating the joint reception probability. For A1 equipage, the model simulates the single-receiver dual-antenna configuration by switching the receive antenna alternately between top and bottom each successive second. For A0-equipped aircraft, reception is only permitted from a bottom antenna.
- Transmit power variability. The transmit power for an aircraft is chosen from a uniform distribution given by the limits specified for the aircraft equipage. The transmit powers for different equipage levels are defined in Section 2.4.2.1.
- Receiver retriggering. The UAT simulation checks each individual ADS-B Message arriving at the victim receiver for its message error rate. This procedure amounts to allowing for retriggering in the receiver, i.e. the potential for the receiver to switch from receiving a message to a stronger message signal that arrives after the start of the reception of the first message.
- Receiver performance model. The receiver performance model used in the UAT simulation is based on experimental data collected on special UAT receivers that were provided for that purpose. These receivers were modified to be compliant with the requirements specified in this document. Both the 0.8 MHz filter specified for A3 equipage and the 1.2 MHz filter used in A0-A2 equipage were tested. The results of the bench testing and the receiver performance model are described in Section B.3. The sensitivity of the receiver is assumed to be –93 dBm. This represents the signal level at which 10% error rate is achieved in the absence of interfering signals. This parameter was validated in the simulation.
- Message transmission sequence and content. Section 3.1.1 and Table 2-2 of the UAT Technical Manual define the types of messages, their content, and the sequence of messages transmitted for each category of aircraft equipage. See the table in Section B.4.4 for a summary of all the types of information transmitted by each equipage class. The information content transmitted by each aircraft is explicitly modeled by the multi-aircraft simulation.
- Ground receiver assumptions. For Air-Ground studies that follow, several assumptions were changed for the special case of the ground receiver. There was assumed to be no co-site interference, but the same Link 16 Baseline interference used in airborne receptions was included. The receiver sensitivity used was –96 dBm. The antenna gain was slightly different, in that it used an omni-directional TACAN antenna, with elevation gain based on measured data. The ground antenna uses a 1.2 MHz filter only. In certain cases, a 3-sector antenna is used.

B.2 Antenna Model

The antenna gain model contains two components, to accommodate both the elevation pattern variation, as well as non-uniformity in the azimuth pattern. A fixed component is based on the elevation angle between the two aircraft. An additional random component is used to characterize the real-world effects of fuselage blockages in the azimuth pattern. The distributions describing these two components are based on measurement data and are intended to provide sufficient statistical variability to capture a wide variety of antenna installations on aircraft. The two components in dB units are summed to create the total antenna gain pattern for each of a given pair of aircraft.

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Figure B-1 shows the elevation gain for a top-mounted antenna. The same gain is used for a bottom-mounted antenna, with the pattern inverted vertically. The antenna has a peak gain of 4.1 dBi at an elevation angle of 26 degrees. For best resolution of display, this figure is limited to a minimum gain of –40 dB.

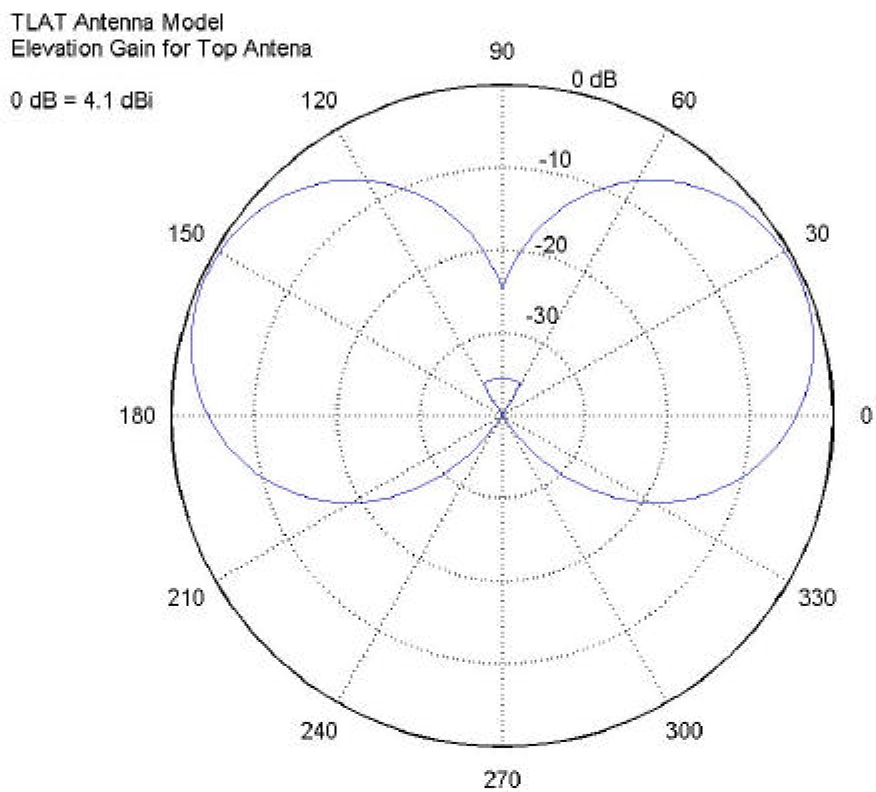

Figure B-1: **TLAT Antenna Model Elevation Gain**

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The variation in gain due to azimuth pattern effects is based on the probability distribution shown in the Figure B-2.

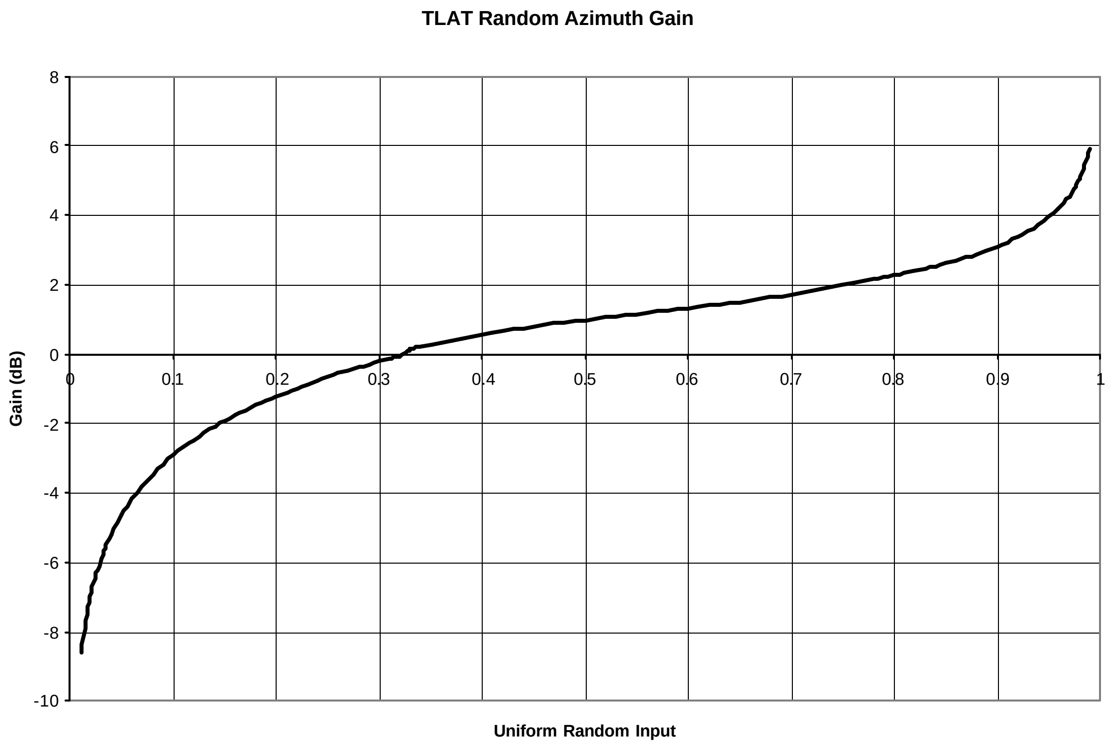

Figure B-2: TLAT Random Azimuth Gain

A uniform random variable on the x-axis is used to select a value that characterizes the azimuth variation in antenna gain. Note that approximately 1/3 of the time, the variation can be a loss of up to 8.6 dB. Approximately 2/3 of the time, the variation is an additional gain of up to 6 dB. Note that the median gain in the azimuthal direction is 1 dB.

The elevation and azimuth angles to other aircraft are constantly changing. To simulate this, the antenna model allows for a new random selection of the azimuth gain variation each time the relative azimuth between a pair of targets is altered by more than 5 degrees. This antenna gain model was used in the performance assessments of each of the three links treated in the Link Comparison Study done for ICAO.

B.3 Receiver Performance Model

B.3.1 Measured Data

Measurements of the Bit Error Rate (BER) receive performance were made on two "Pre-MOPS" UAT transceivers, one with a nominal 1.2 MHz bandwidth and one with a nominal 0.8 MHz bandwidth. Simultaneous measurements were made while the same input signal was applied to both units. The input signal consisted of a Signal of Interest (SOI), from a nominal 1.5 MHz bandwidth UAT transceiver, summed with an interference signal. The SOI was a Long ADS-B Message.

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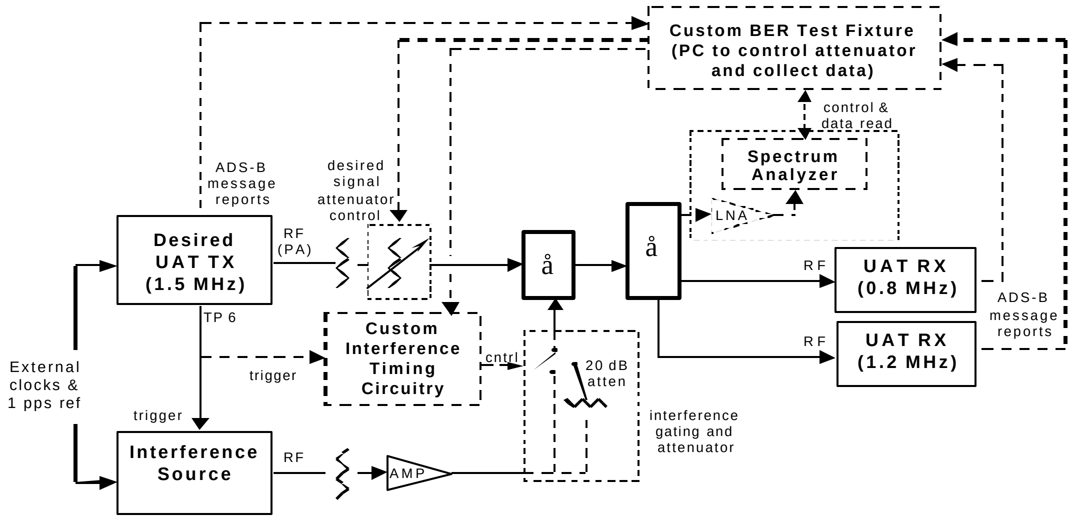
A BER test fixture was created in order to allow measuring the BER impact of pulsed interference as a function of time relative to the start of the pulse. It included circuitry for gating the test interference signal off during the UAT message synchronization header, and software for determining the position of every bit error in every received message payload or FEC. The test setup is shown in Figure B-3



Fixed attenuators and amplifiers are adjusted to provide:

- a desired-signal level at the UAT RX inputs of -20 dBm when signal attenuator is set to 0 dB, and

- a peak interference level at the UAT RX inputs of -20 dBm when interference is gated on and the 20 dB interference attenuator is bypassed.

Figure B-3: Test Setup for measuring BER

The interference signals used for the BER tests were the following:

1. No external interference (internal receiver noise only). SOI level was varied to achieve various Signal-to-Noise Ratios (SNRs). Note that SNR depends on the noise bandwidth used, which will be defined later in this section.

2. White Gaussian interference. SOI level was varied to achieve various SNRs.

3. A single UAT (1.5 MHz bandwidth) interferer. The levels of both SOI and interferer were independently varied to achieve various SNRs and various Interference-to-Noise Ratios (INRs).

4. A simulated combination of multiple UAT (1.5 MHz bandwidth) interferers. An Arbitrary Waveform Generator (AWG) produced these combination signals by playing back a variety of input data files. The input data files were generated from a set of single-UAT files recorded by a digital oscilloscope. These files were adjusted in level, offset in time and summed together to create the multi-UAT scenarios of interest, specifically:

   - Two UATs, both at the same level, and at various INRs.
   - Two UATs at high INR and at various relative levels.
   - Three, five and ten UATs, all at the same level and at high INR.

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(As a check on the fidelity of the simulation, a single UAT at high INR was also simulated and measured and the BER was compared with the corresponding BER measured using an actual UAT at high INR. The discrepancy between the two was found to be less than 0.7 dB.)

~~9.~~5. A DME interferer emitting pulse pairs with 12-usec separation. DME signals at two frequencies were used, at the SOI center frequency and one MHz above. The level of the SOI was varied to achieve a wide range of Signal-to-Interference Ratios (SIRs). The variation of BER with time during and shortly after the DME pulse pair was measured.

~~10.~~6. A Link 16 interferer, at various frequencies, at the SOI center frequency, three MHz higher, 6 MHz higher and so on up to 21 MHz higher. It was assumed that the corresponding lower frequency response would be similar. The level of the SOI was varied to achieve a wide range of Signal-to-Interference Ratios (SIRs). The variation of BER with time during and shortly after the Link 16 pulse pair was measured.

For all of the above interference conditions, bit errors were measured at every position in the message payload and FEC. Results from multiple messages were averaged together. Enough messages were measured to permit determining BER values down to about 10^{-5}. For the continuous interference conditions (no external interference or Gaussian noise), bit errors from all received payload and FEC bit were averaged together. For the UAT interferers, bit errors from all payload and FEC bits during interference transmission were averaged together.

For the pulsed interference conditions (DME and Link 16 signals), bit errors were averaged independently for each time offset after the start of the interference pulse (to a resolution of 0.5 UAT bit periods). This enabled determining BER values as a function of SIR, time and frequency offset. Sample plots of measured BER data for DME and Link 16 interferers are shown in Figure B-4 through Figure B-6.

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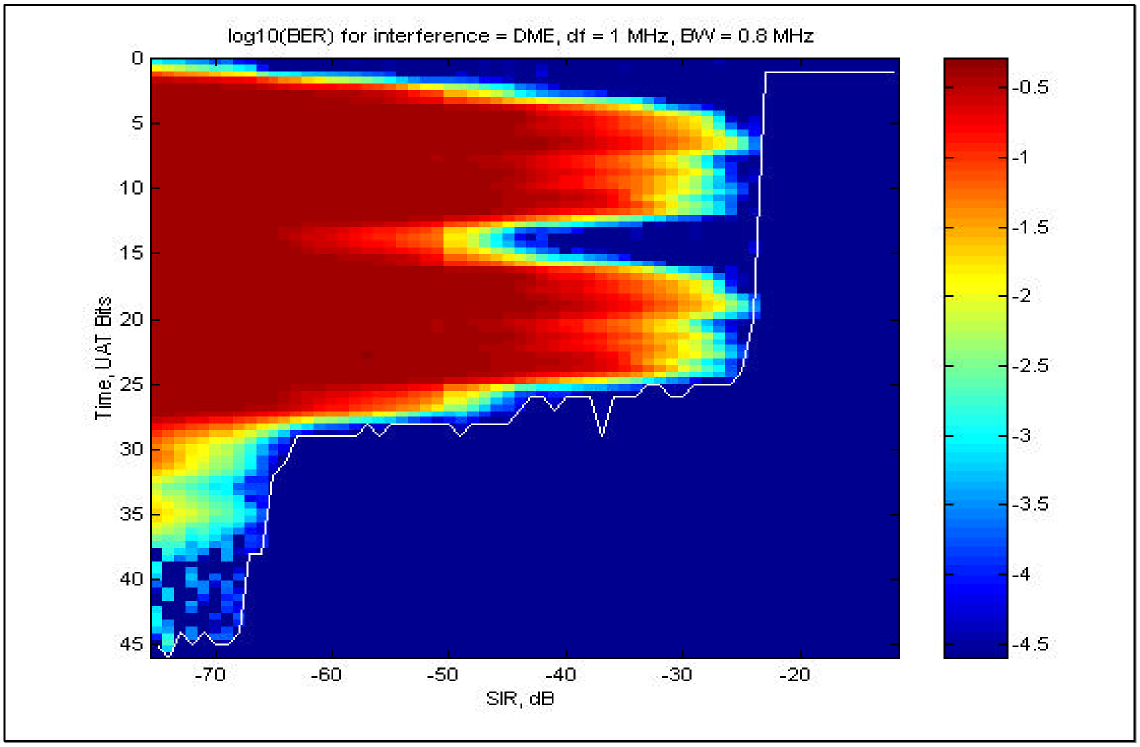


Figure B-4: **BER Due to DME interference**

(Frequency offset = 1 MHz, Receiver bandwidth = 0.8 MHz. log10 {BER} encoded as color)

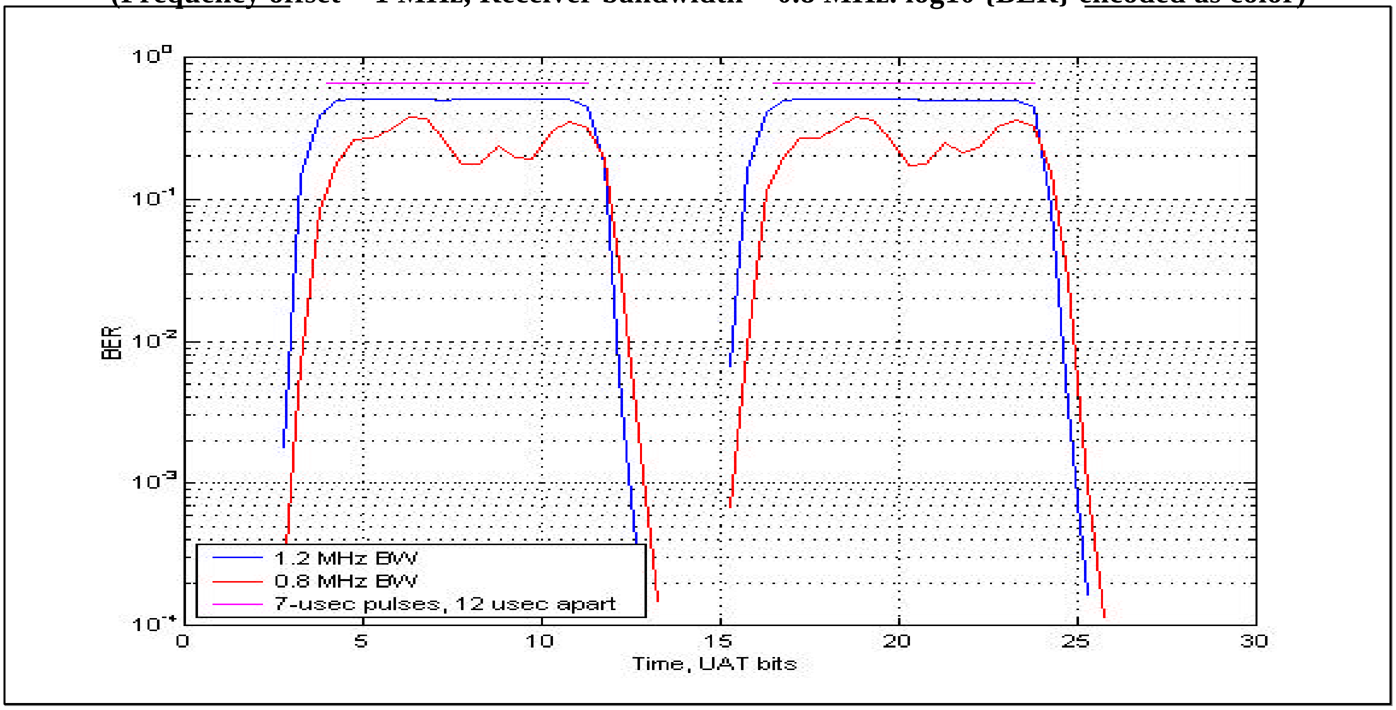


Figure B-5: **BER Due to DME Interference**

(Frequency offset = 1 MHz, Vertical Slice Through Color Plots Like Figure B-4 at SIR = -40 dB)

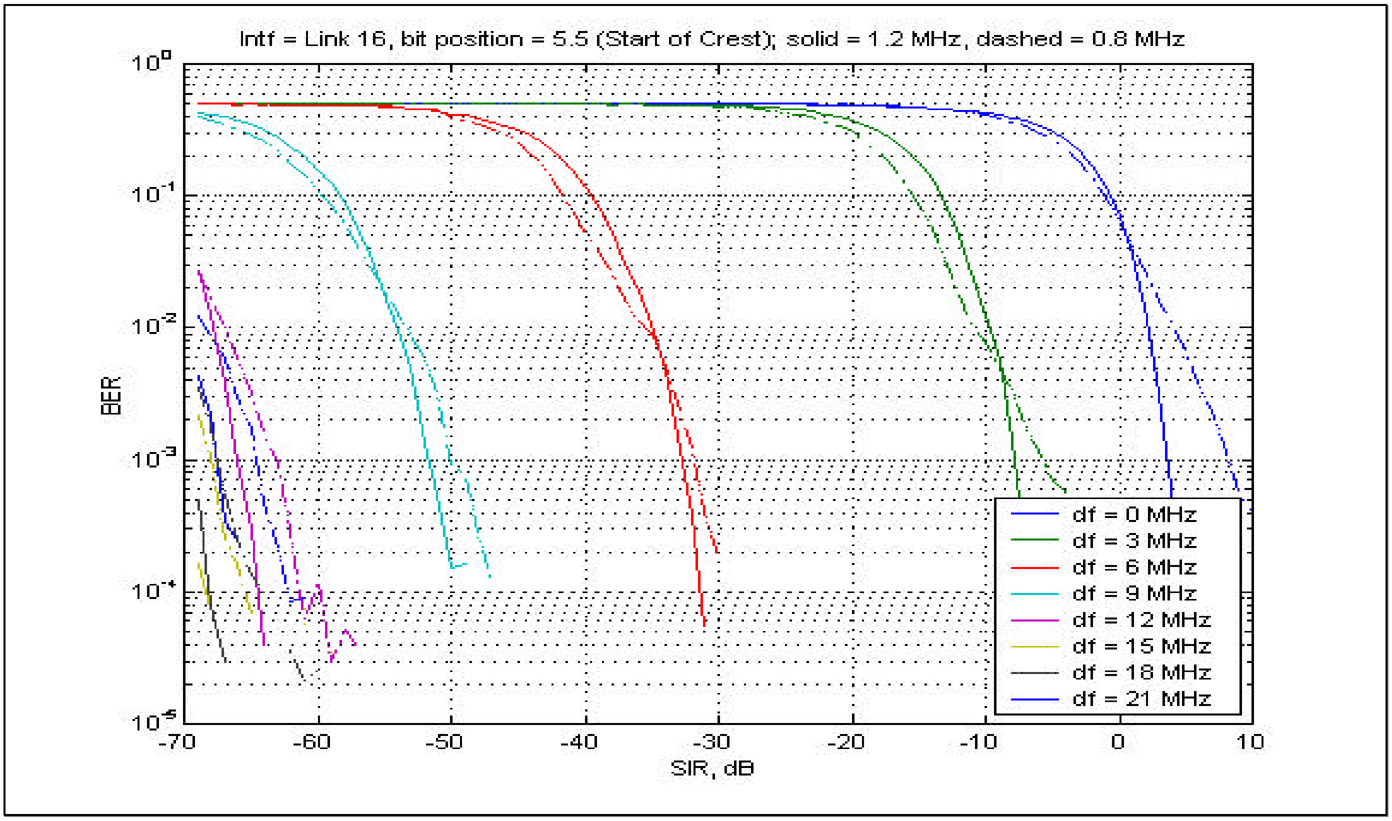


Figure B-6: Link 16 Interference

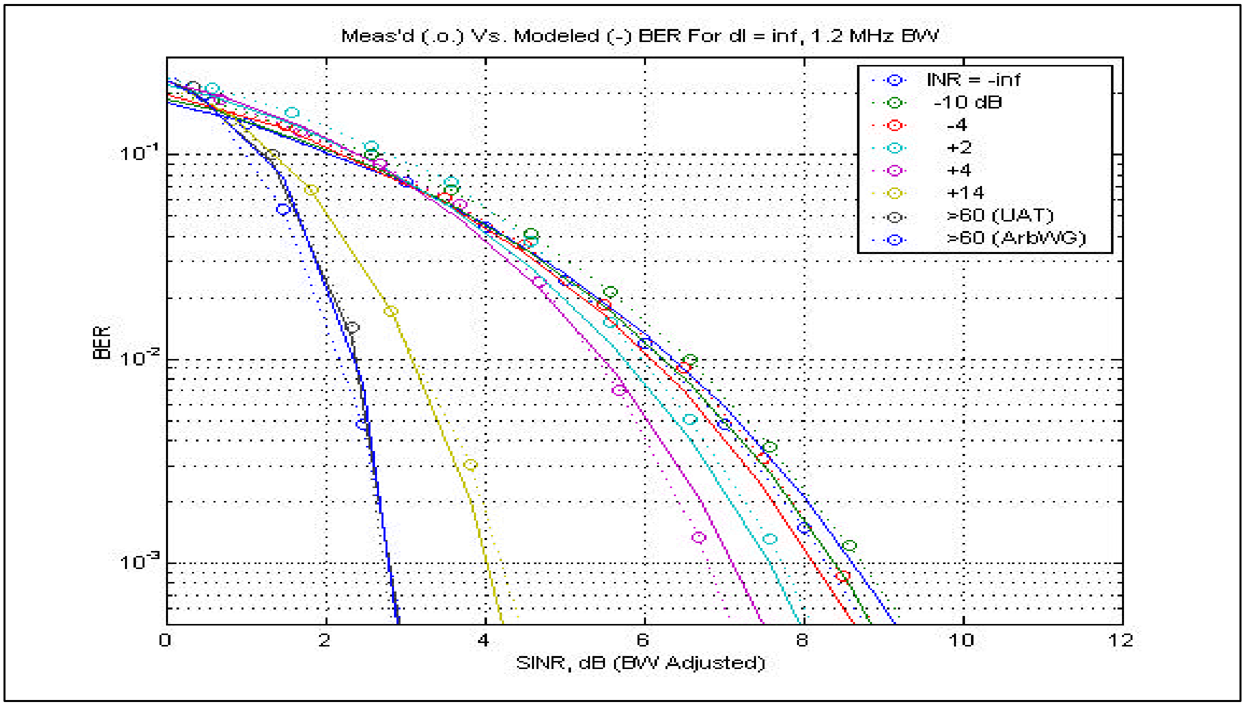
(Horizontal Slice Through Color Plots Like Figure B-4 at Bit Position 5.5)

B.3.2 Receiver Model

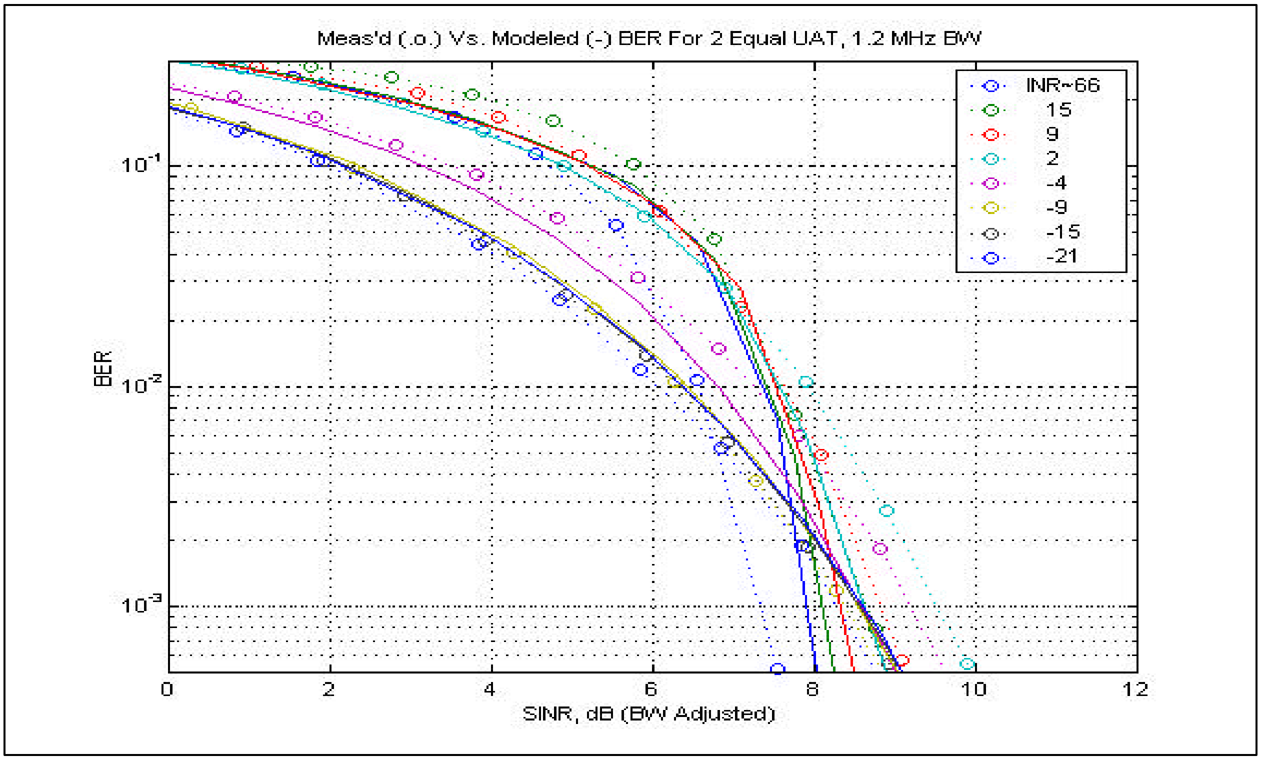
Based on the above BER measurements, a computer program (the "UAT BER Model") was designed to estimate MOPS-compliant UAT BER performance under arbitrary combinations of UAT, DME and Link 16 interference. The UAT BER Model is incorporated within the Multi-Aircraft UAT Simulation (MAUS), which uses the BER estimates to evaluate the reception success of UAT messages.

B.3.2.1 Receiver Model Accuracy

Figure B-7 through Figure B-10 show the measured and modeled BER Vs. SINR curves for four sample subsets of the measured data. Figure B-9 and Figure B-10 show the BER modeling error for all the Gaussian noise plus UAT interference data so as to indicate the equivalent power error in dB. The BER-to-power curve used for Figure B-11 and Figure B-12 is the curve appropriate for pure Gaussian noise interference. With this measure, it can be seen that most of the data is modeled to + or – 1.5 dB accuracy.



<u>Figure B-7:</u> Gaussian Noise + Single UAT, 1.2 MHz Receiver



<u>Figure B-8:</u> Gaussian Noise + Two Equal UATs, 1.2 MHz Receiver

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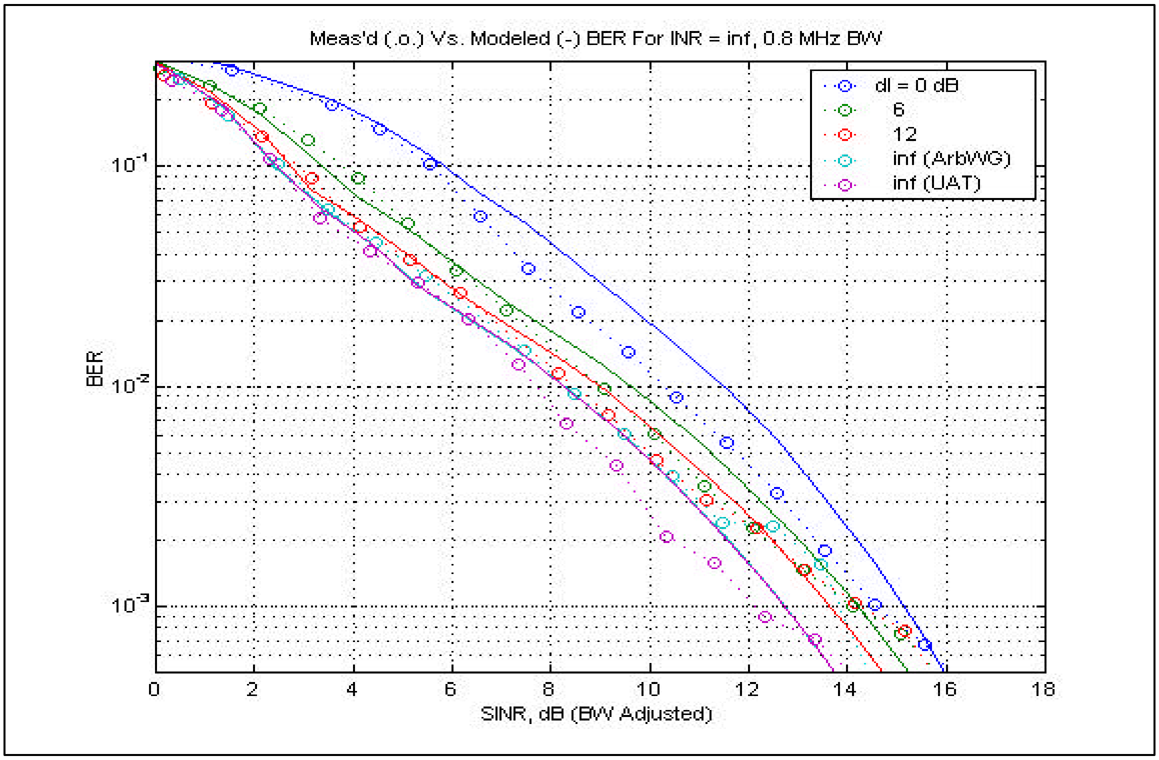

Figure B-9: **Two Unequal UATs, INR >> 0 dB, 0.8 MHz Receiver**

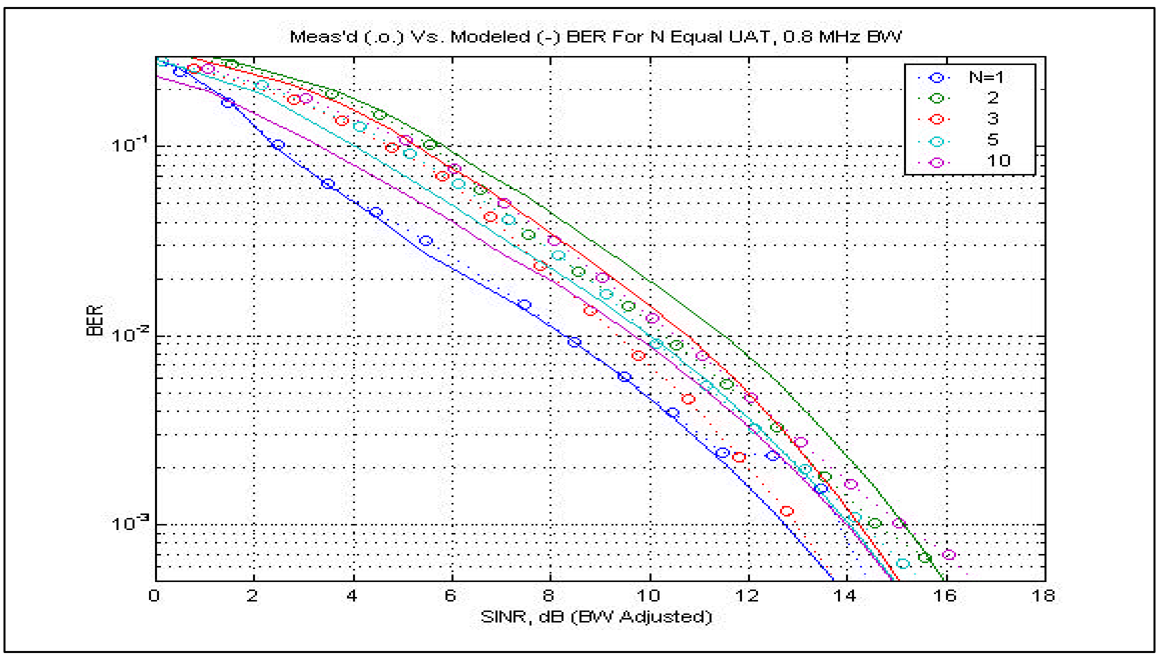

Figure B-10: **N Equal UATs, INR >> 0, 0.8 MHz Receiver**

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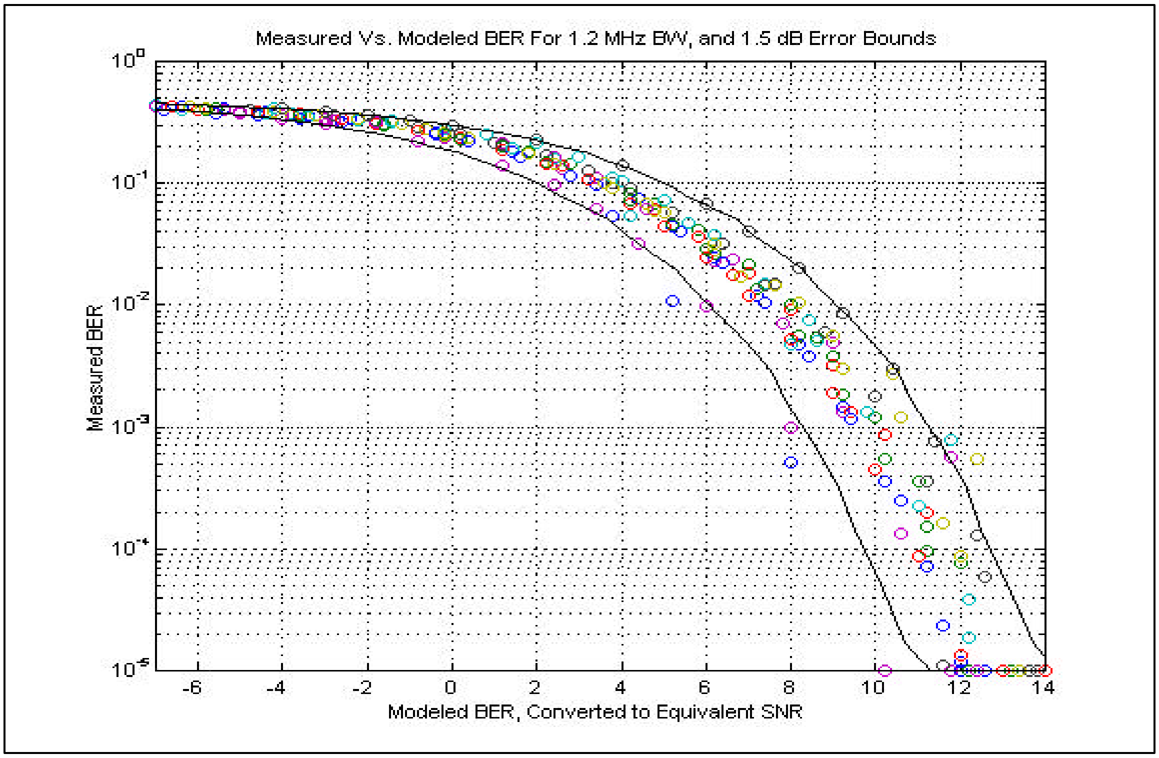

Figure B-11 Model Errors for All Data, 1.2 MHz Receiver

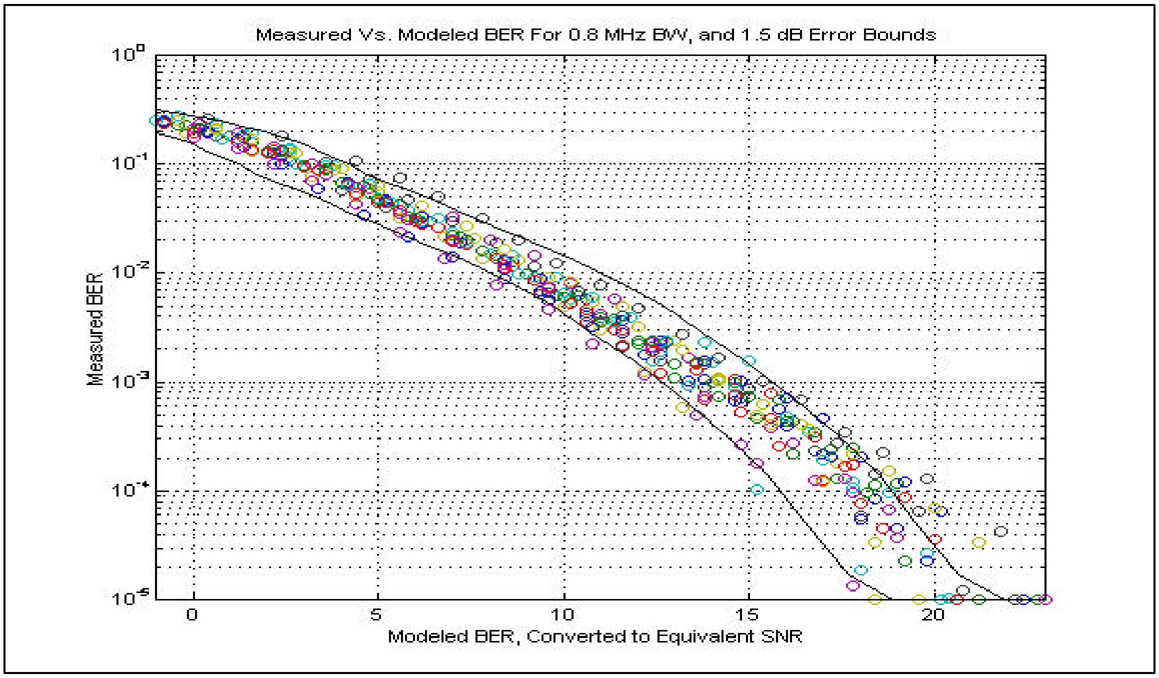

Figure B-12: Model Errors for All Data, 0.8 MHz Receiver

B.4 Multi-Aircraft Simulation (MAUS) Results

B.4.1 Los Angeles Basin 2020 (LA2020)

This scenario is based on the LA Basin 1999 maximum estimate. It is assumed that air traffic in this area would increase by a few percent each year until 2020, when it would be 50 % higher than in 1999. The distribution of aircraft in the scenario is based on approximations of measured altitude and range density distributions.

The following assumptions are made for the airborne and ground aircraft and ground vehicles for the LA Basin 2020 scenario:

- The density of airborne aircraft is taken to be:
  - Constant in range from the center of the area out to 225 nautical miles (5.25 aircraft/NM), (i.e., the inner circle of radius one NM would contain approximately five aircraft, as would the ring from 224 to 225 NM) and
  - Constant in area from 225 NM to 400 NM (.00375 aircraft/NM^2).
- There are assumed to be a fixed number of aircraft on the ground (within a circle of radius 5 NM at each airport), divided among LAX, San Diego, Long Beach, and five other small airports, totaling 225 aircraft. Half of the aircraft at each airport were assumed to be moving at 15 knots, while the other half were stationary. In addition, a total of 300 ground vehicles are distributed at these airports as well.
- The altitude distribution of the airborne aircraft is assumed to be exponential, with a mean altitude of 5500 feet. This distribution is assumed to apply over the entire area.
- The airborne aircraft are assumed to have the following average velocities, determined by their altitude. The aircraft velocities for aircraft below 25000 feet are uniformly distributed over a band of average velocity +/- 30 percent.
  - 0-3000 feet altitude 130 knots
  - 3000-10000 ft 200 knots
  - 10000-25000 ft 300 knots
  - 25000-up 450 knots
- The aircraft are all assumed to be moving in random directions.
- ADS-B MASPS equipage class A0 (and A1L as defined in §2.4.2) are restricted to fly below 18000 feet. All other aircraft are assumed to be capable of flying at any altitude. The aircraft in the LA2020 scenario are assumed to be in the following proportions:
  - A3 30%
  - A2 10%
  - A1 40%
  - A0 20%

For the LA2020 scenario, the A1 equipage was assumed to include two subclasses: A1H (high) and A1L (low). These subclasses are defined in Section 2.4.2.

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The scenario for the 2020 high density LA Basin case contains a total of 2694 aircraft: 1180 within the core area of 225 NM, 1289 between 225-400 NM, and 225 on the ground. This represents a scaling of the estimated maximum 1999 LA Basin levels upward by 50 percent. Of these aircraft, 471 lie within 60 NM of the center. (This includes aircraft on the ground.) Around ten percent of the total number of aircraft are above 10000 ft in altitude, and more than half of the aircraft are located in the outer (non-core) area of the scenario.

An attempt was made to at least partially account for the expected lower aircraft density over the ocean. In the third quadrant (between 180 degrees and 270 degrees), for distances greater than 100 NM from the center of the scenario, the density of aircraft is reduced to 25 % of the nominal value used. The other 75 % of aircraft which would have been placed in this area are distributed uniformly among the other three quadrants at the same range from the center. This results in relative densities of 1:5 between the third quadrant and the others.

As outlined in Section 3 of the UAT Requirements and Desirable Features, the ADS-B requirements for ADS-B air-to-air surveillance range and report update interval are used to assess how the candidate links perform in relation to suggested operational enhancements. These requirements specify the minimum range for acquisition of the state vector and the mode-status and TC and TS reports where applicable, as well as the maximum update periods allowed for this information.

Eurocontrol criteria augment those of the ADS-B MASPS with specific air/ground performance characteristics. These air/ground criteria specify ranges, use of intent information (TC and TS reports), and update times. Additionally, Eurocontrol criteria extend existing ADS-B MASPS air-to-air requirements for long-range deconfliction.

Results are presented as a series of plots of 95% update times as a function of range for state vector updates and intent updates, where applicable. The 95% time means that at the range specified, 95% of aircraft will achieve a 95% update rate at least equal to that shown. Each point on the plot represents the performance of Aircraft/Vehicles within a 10 NM bin centered on the point. The ADS-B requirements (Reference UAT Requirements and Desirable Features) are also included on the plots for reference. Since the transmit power and receiver configuration are defined for each aircraft equipage class, performance is shown separately for each combination of transmit-receive pair types. In addition, performance of different transmit-receive pairs is shown at several different altitudes, where appropriate. The first altitude considered is "high altitude", which is defined to be the aircraft near the center of the scenario with the largest number of other aircraft in view. This is invariably an aircraft in the range of FL 350 – FL 400, and applies to A3, A2, and A1H equipage. The other altitude used is FL150 at the center of the scenario, and applies to all equipage classes.

Results for all of these cases are shown in Figure B-13 through Figure B-21 and conclusions are presented below. The ADS-B requirements for state vector updates are shown as black lines on the plots. As specified in the UAT Requirements and Desirable Features, the maximum required ranges for air-air update rates are: for A0 to 10 NM, A1 to 20 NM, A2 to 40 NM, and A3 to 90 NM (120 NM desired), while the Eurocontrol criteria continue to 150 NM for A3. This does not include all of the potential Eurocontrol requirements. Air-ground requirements are defined to 150 NM for all aircraft equipage classes. Performance in compliance with ADS-B requirements is indicated by results that are below the black line. Note that the required range limitations for A3 transmitters are

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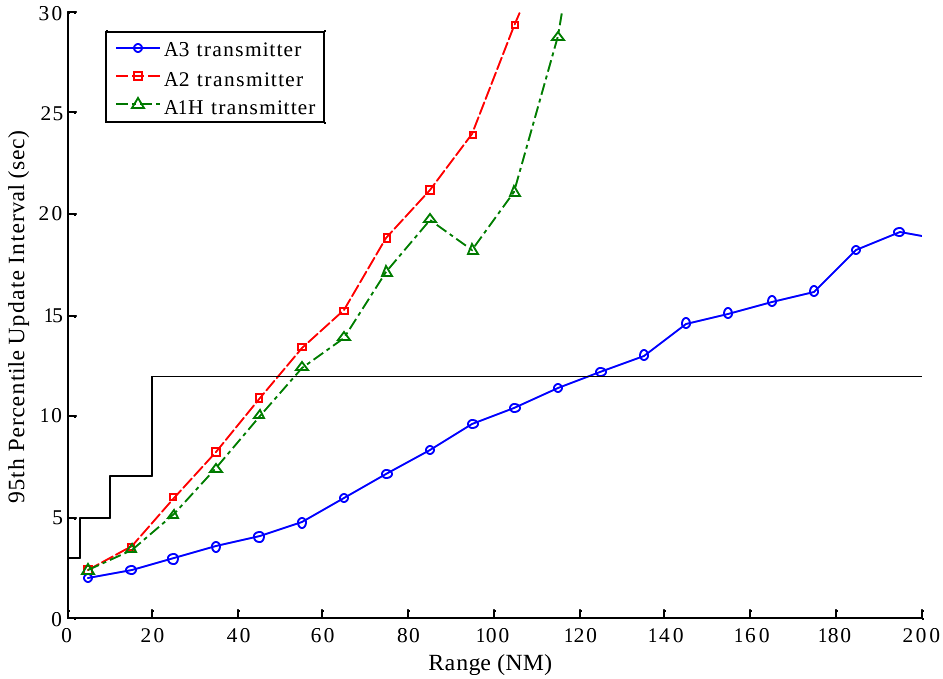
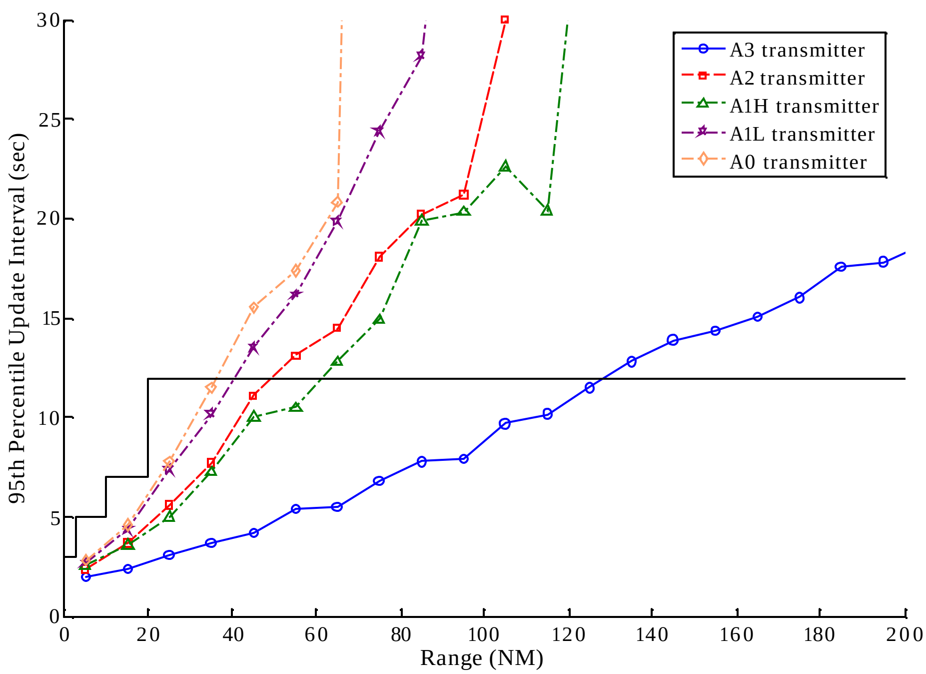
indicated on the plots by a solid vertical line, while desired range limitations are indicated by a dashed vertical line.



<u>Figure B-13:</u> Air-to-Air Reception by A3 Receiver at High Altitude over LA 2020



<u>Figure B-14:</u> Air-to-Air Reception by A3 Receiver at FL 150 over LA 2020

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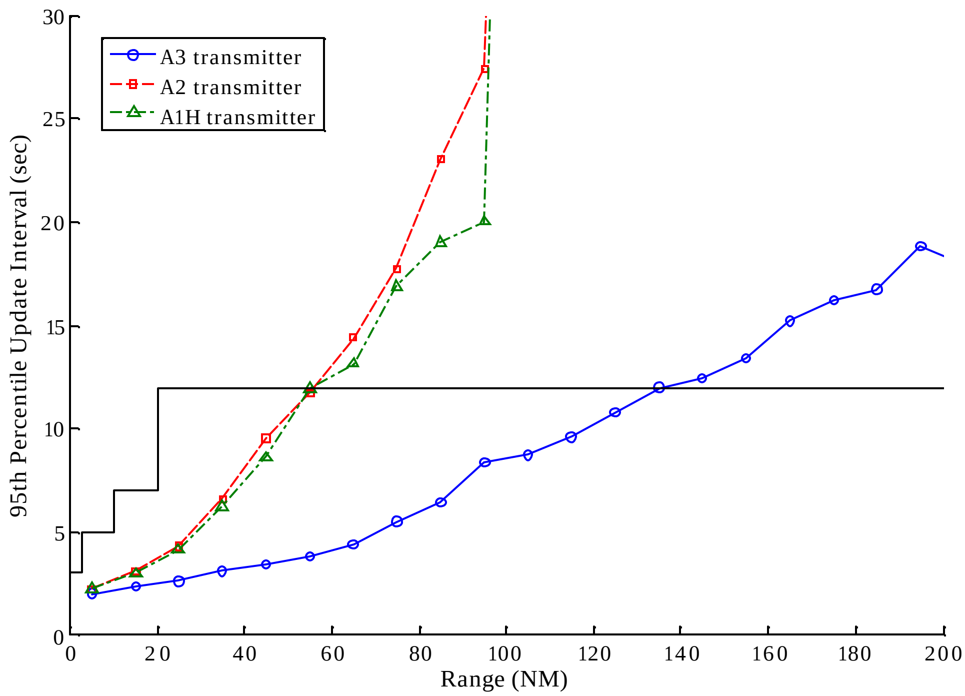

Figure B-15: **Air-to-Air Reception by A2 Receiver at High Altitude over LA 2020**

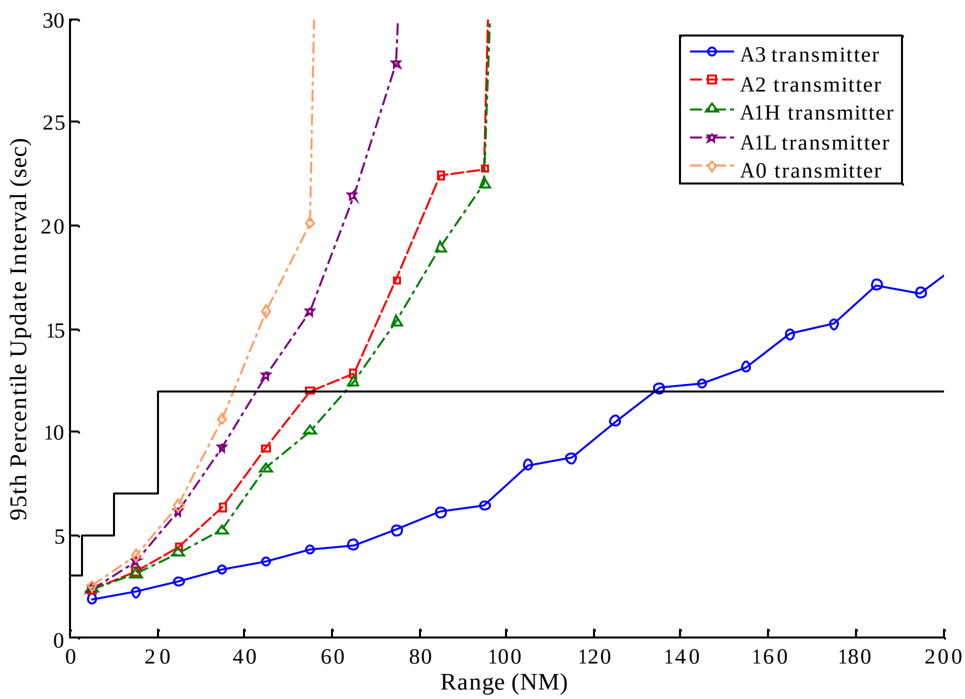

Figure B-16: **Air-to-Air Reception by A2 Receiver at FL 150 over LA 2020**

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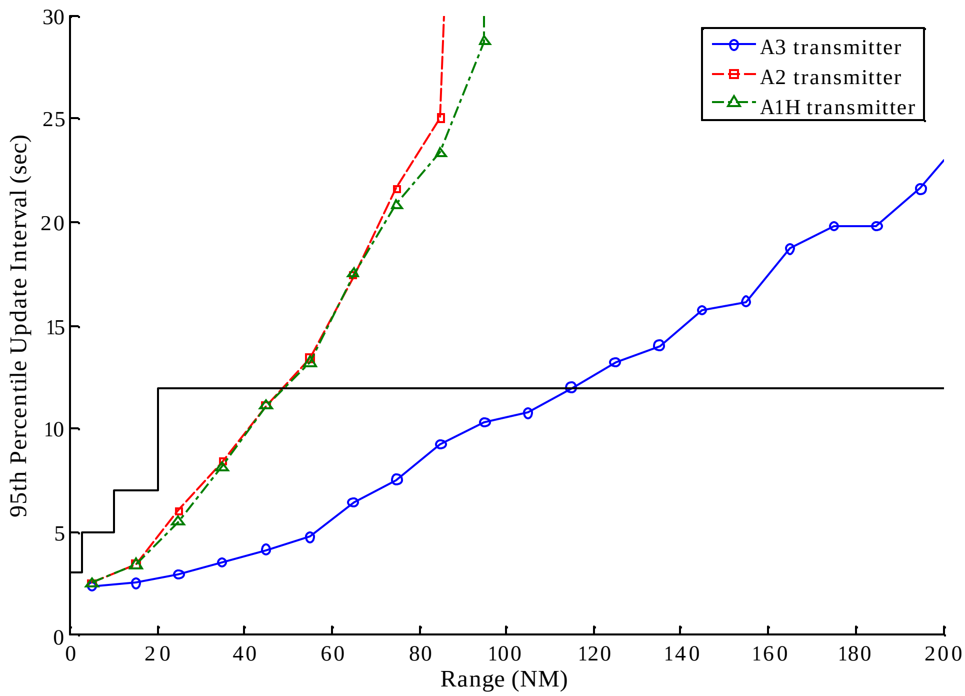
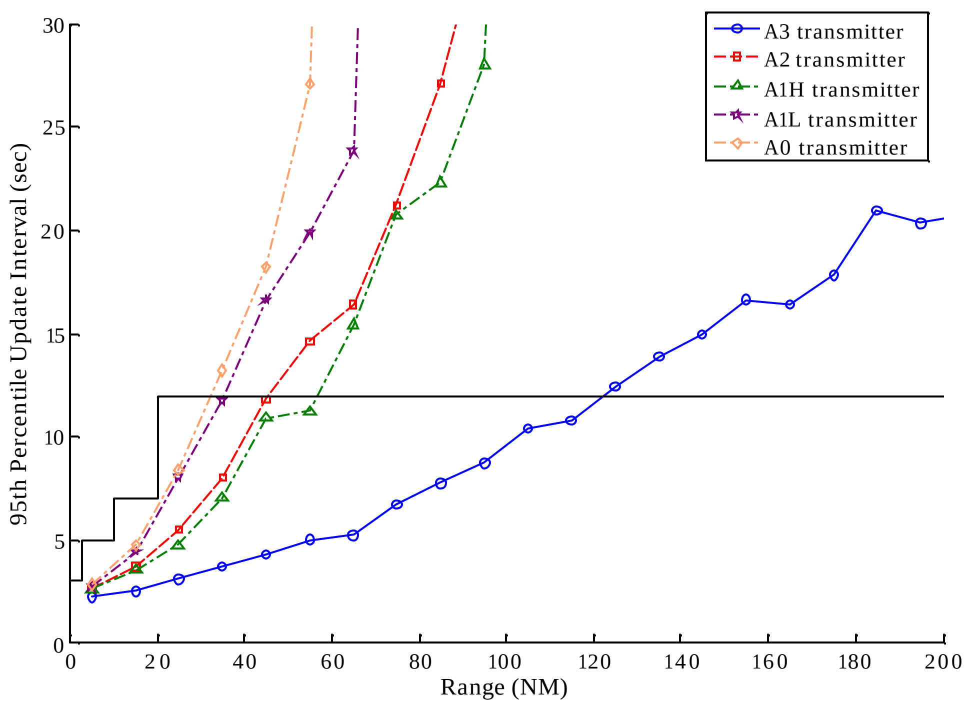


<u>Figure B-17:</u> Air-to-Air Reception by A1 Receiver at High Altitude over LA 2020



<u>Figure B-18:</u> Air-to-Air Reception by A1 Receiver at FL 150 over LA 2020

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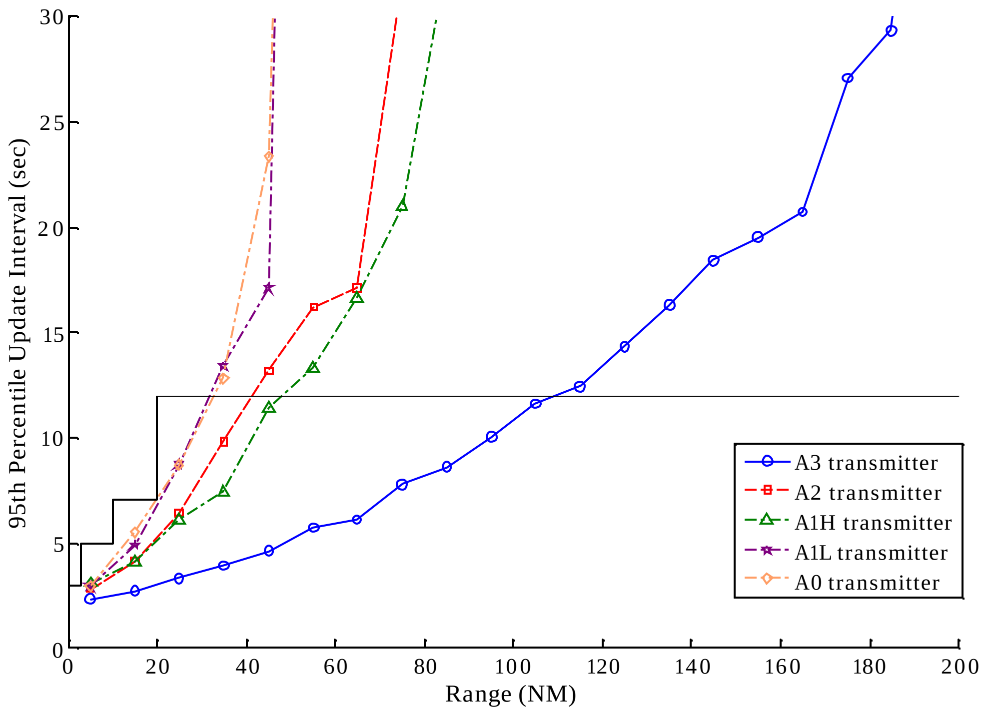

Figure B-19: **Air-to-Air Reception by A0 Receiver at FL 150 over LA 2020**

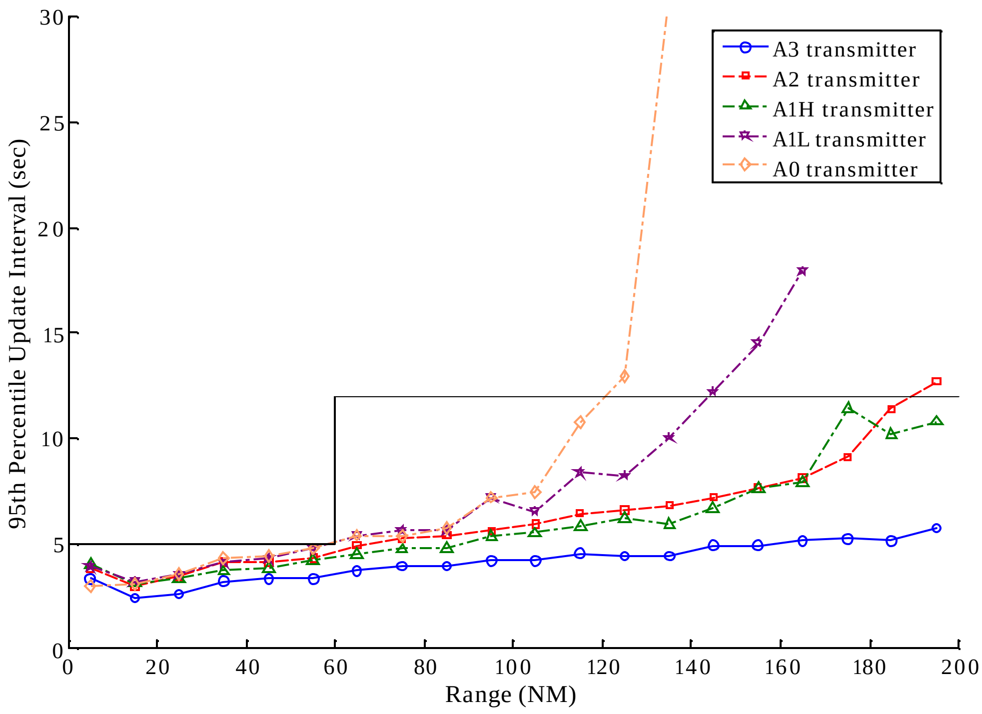

Figure B-20: **Air-to-Ground Reception by a Receiver at LAX in LA 2020**

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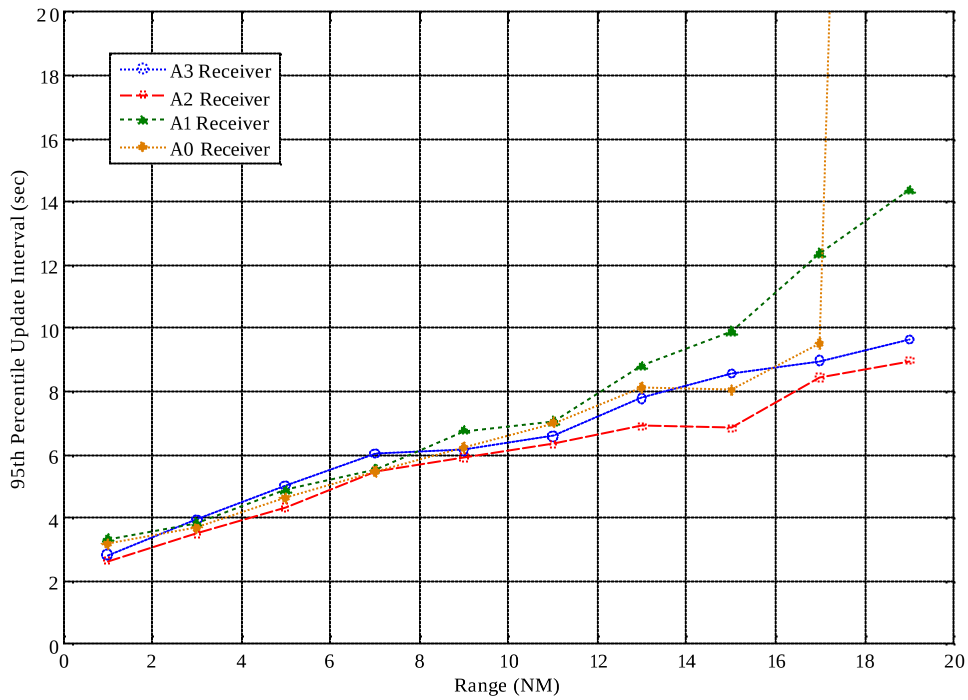

Figure B-21: Reception of Ground Vehicle Transmissions by Aircraft on Approach at 2000 feet into LAX in 2020

Recall that the LA2020 scenario includes 2694 aircraft and 300 ground vehicles transmitting on UAT. In addition, a baseline Link 16 scenario is also included as co-channel interference.

The results for LA2020 UAT air-air system performance shown in Figure B-13 to Figure B-19 are summarized in Table B-1 below. This summary indicates that the UAT System is projected to be fully compliant with the UAT Requirements and Desired Features air-to-air state vector report update requirements at both the required and desired ranges.

Table B-1: Ranges of Compliance for UAT Transmit-Receive Combinations in the LA2020 Scenario

	TRANSMITTER			
RECEIVER	**A3**	**A2**	**A1**	**A0**
A3 (High Altitude)	120	40+	40+(A1H)	NA
A3 (FL 150)	130	40+	50+(A1H)/30+(A1L)	30+
A2 (High Altitude)	130	50	50(A1H)	NA
A2 (FL 150)	130	50	60(A1H)/40(A1L)	30
A1 (High Altitude)	110	40	40+(A1H)	NA
A1 (Low Altitude)	120	40	40+(A1H)/30(A1L)	30
A0	100+	40	40+(A1H)/30(A1L)	30

The results for the LA2020 scenario shown in Figure B-13 through Figure B-21 may be summarized as follows:

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- ADS-B air-air requirements and desired criteria are met for all aircraft equipage transmit-receive pairs in the LA2020 scenario for state vector update rates at all ranges specified by the UAT Requirements and Desirable Features. Performance for receivers located at FL 150 tends to be better in general than the corresponding receivers at high altitude, due primarily to the lower levels of self-interference encountered at lower altitudes.

- The Eurocontrol extension to 150 NM for A3 class equipage air-to-air reception is only met for LA2020 at the 95% level out to 120-130 NM, but the 95th percentile update rate at 150 NM is 14-15 seconds, depending on the altitude of the receiving aircraft.

- Air-ground update requirements are met to 150 NM for a standard ground receiver located at LAX in the LA2020 scenario for equipages A3, A2, and A1H. A1L and A0 equipage met requirements out to 140 and 120 NM, respectively. A test case was run for the case of a 980 MHz DME/TACAN co-located with the ground receiver. The results of the test case show that, in the presence of a 5 kw TACAN at 980 MHz located 50 feet away from the ground receiver at LAX in the LA2020 scenario, a three-sector antenna allows the update requirements to be met for all aircraft equipages to 150 NM. Another test case was run for the case of the co-located 980 MHz TACAN with a standard ground receiver, to see what level of power at the UAT antenna could be supported without degradation in performance. The results show that –90 dBm TACAN power at the UAT antenna at 980 MHz does not significantly change the standard ground performance in LA2020: A3, A2, and A1H performance meet the MASPS requirements out to 150 NM, and A1L and A0 meet the requirements out to 120 and 110 NM, respectively. This means that, if the TACAN were located 1000 feet from the ground receive antenna, an additional 30 dB of isolation would be required in order to assure MASPS compliance. This could be achieved by increasing the separation distance, for example.

- System performance results are presented for state vector updates of ground vehicles to an aircraft on approach to LAX in the LA2020 scenario. There is no specific update rate requirement for this situation.

B.4.2 Core Europe 2015

A high density air traffic scenario was developed by Eurocontrol to represent Core Europe in 2015. The operation of UAT in Core Europe 2015 is based on the premise that the existing on-channel DME/TACANs will be moved from 978 MHz to other available frequencies. Therefore, the future scenario assumes that there will be no DME/TACANs on 978 MHz, but that all existing and planned DME/TACANs at 979 MHz will be operational and running at full allowed power levels, no matter how close they are to one another. This condition was chosen in order to provide a conservatively severe estimate of the DME/TACAN interference environment.

Two cases were analyzed: worst-case traffic density (over the center of the scenario at Brussels, selected to provide the highest UAT self-interference levels) and worst-case DME/TACAN environment (location selected to provide the highest interference from DME/TACANs). The worst-case DME/TACAN environment selection required moving a high-power mobile 979 MHz TACAN to a particular location near several other 979 MHz TACANs.

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For the Core Europe 2015 scenario, the distributions and assumptions made were taken directly from the Eurocontrol document entitled "High-Density 2015 European Traffic Distributions for Simulation," dated August 17, 1999. This scenario is well-defined and straightforward to apply. The scenario used in this analysis includes a total of 2091 aircraft (both airborne and ground) and 500 ground vehicles, and is based on the following assumptions:

- There are five major TMAs (Brussels, Amsterdam, London, Paris, and Frankfurt), each of which is characterized by:
  - The inner region (12 NM radius) contains 29 aircraft at lower altitudes,
  - The outer region (50 NM radius) contains 103 aircraft at mid to higher altitudes.
  - There are 25 aircraft on the ground within a 5 NM radius of each TMA. Additionally, there are 25 aircraft not associated with a TMA randomly distributed through the scenario.
  - There are assumed to be 100 ground vehicles equipped with transmit-only UAT equipment.
- These aircraft are assumed to be symmetrically distributed azimuthally, and the aircraft in an altitude band are assumed to be uniformly distributed throughout the band. However, all aircraft in the same band are assumed to be traveling at the same band-dependent velocity.
- Superimposed over these aircraft is a set of airborne en route aircraft, which are distributed over a circle of radius 300 NM. These aircraft are distributed over four altitude bands, ranging from low to upper altitudes. They also travel at velocities that are altitude band dependent.
- As in the LA Basin 2020 scenario, for the Core Europe 2015 scenario all aircraft are assumed to be ADS-B equipped. The equipage levels have been adjusted to be:
  - 30 % A3
  - 30% A2
  - 30% A1
  - 10% A0

Aircraft equipage is assigned according to altitude. The lower percentages of A0 and A1 aircraft than those found in the LA Basin scenarios reflect differences in operating conditions and rules in European airspace.

The two geographical areas that underlie the scenarios discussed above (LA Basin and Core Europe) correspond to very different types of situations for an aircraft to operate in, and thus should provide two diverse environments for evaluation. The LA Basin scenario contains only about 14% of all airborne aircraft at altitudes above 10000 ft, while the Core Europe scenario has around 60% above 10000 ft. Thus, there will be vastly different numbers of aircraft in view for the two scenarios. Additionally, the aircraft density distributions are also quite different, which will place different stresses on the data link systems.

The results of simulation runs which correspond to the assumptions stated above for the full complement of 2091 aircraft and 500 ground vehicles are presented below. Recall

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that DME/TACANs on 978 MHz are assumed to have been moved, and that all potential and planned DME/TACANs on 979 MHz are assumed to have been implemented and transmit at maximum allowed powers. Two locations are considered for CE2015: one in the midst of worst-case UAT self-interference, in the center of the scenario over Brussels; the other in a location that is thought to represent the worst-case DME environment, over western Germany. In addition, the Baseline B Link 16 scenario is also assumed to interfere with UAT transmissions in the CE2015 environment. Results are presented as a series of plots of 95% update times as a function of range for state vector updates. The 95% time means that at the range specified, 95% of aircraft will achieve a 95% update rate at least equal to that shown. The ADS-B requirements are also included on the plots for reference. Since the transmit power and receiver configuration are defined for each aircraft equipage class, performance is shown separately for each combination of transmit-receive pair types. In addition, performance of different transmit-receive pairs is shown at several different altitudes, where appropriate.

Results are presented in Figure B-22 to Figure B-32 for 95% update times as a function of range for state vector updates. Each point on the plot represents the performance of Aircraft/Vehicles within a 10 NM bin centered on the point. The UAT Requirements and Desired Features for state vector updates are shown as black lines on the plots. The maximum ranges specified for air-air update rates are: for A0 to 10 NM, A1 to 20 NM, A2 to 40 NM, and A3 to 90 NM (120 NM desired), while the Eurocontrol criteria continue to 150 NM for A3. This does not include all of the potential Eurocontrol requirements, since the Eurocontrol requirement for four Trajectory Change Points to be broadcast was not addressed. Air-ground requirements are defined to 150 NM for all aircraft equipage classes. Performance in compliance with requirements is indicated by results that are below the black line. Note that the ADS-B MASPS range limitations for A3 transmitters are indicated on the plots by a solid vertical line, while desired range limitations are indicated by a dashed vertical line, and Eurocontrol extension to 150 NM are indicated by a dotted vertical line.

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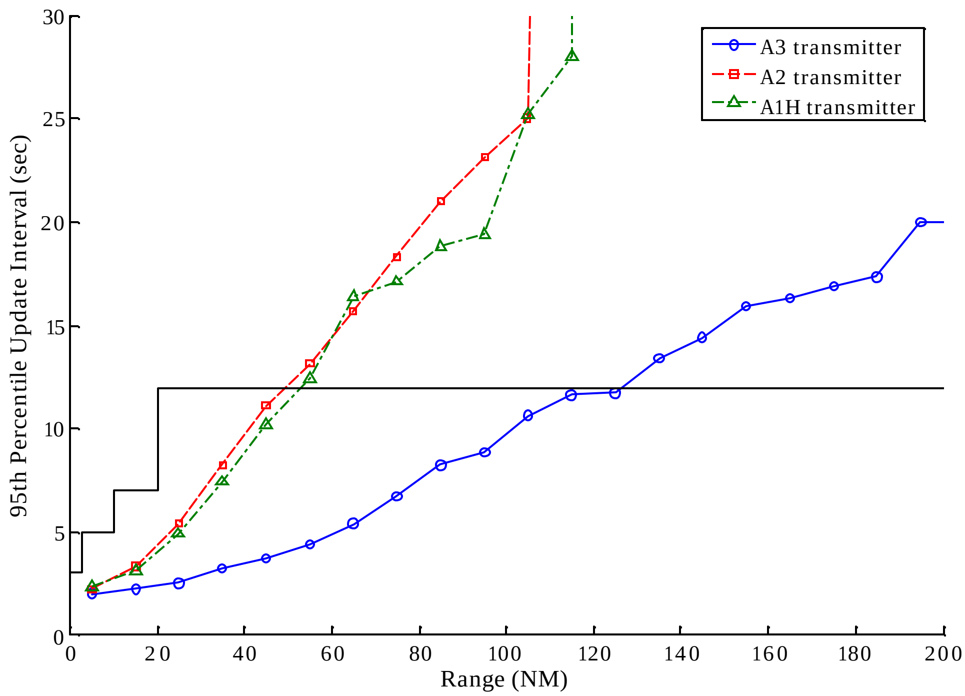

Figure B-22: **Air-to-Air Reception by A3 Receiver at High Altitude over BRU in CE 2015**

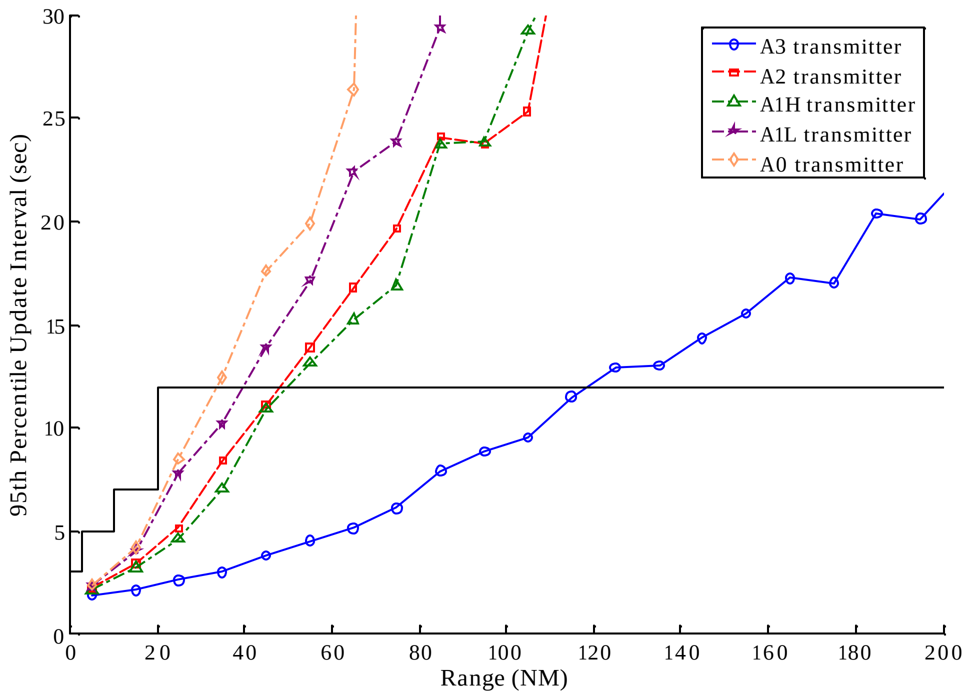

Figure B-23: **Air-to-Air Reception by A3 Receiver at FL 150 over BRU in CE 2015**

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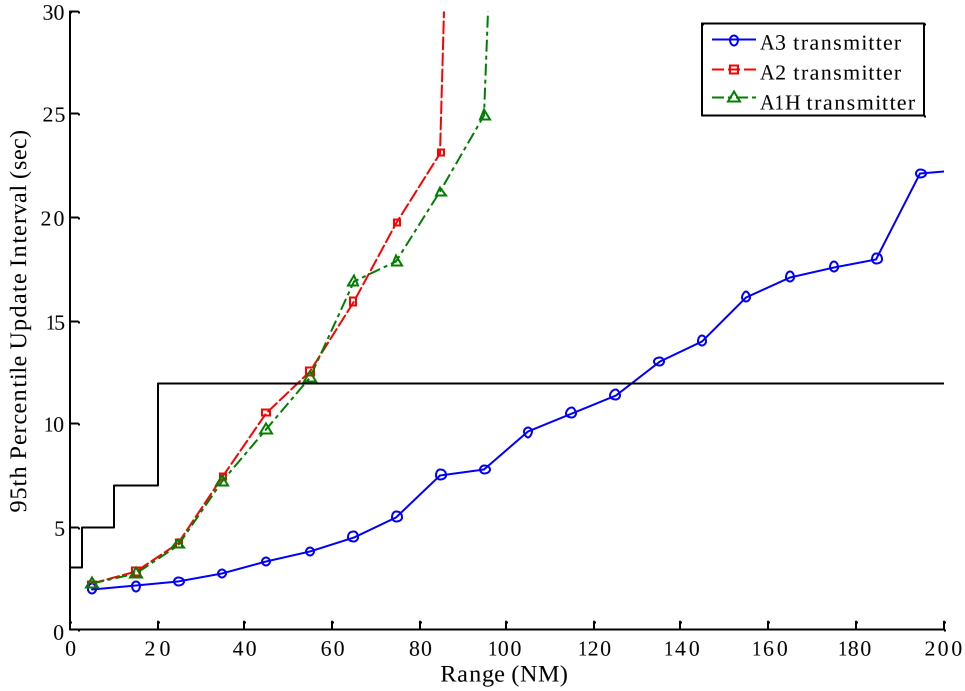
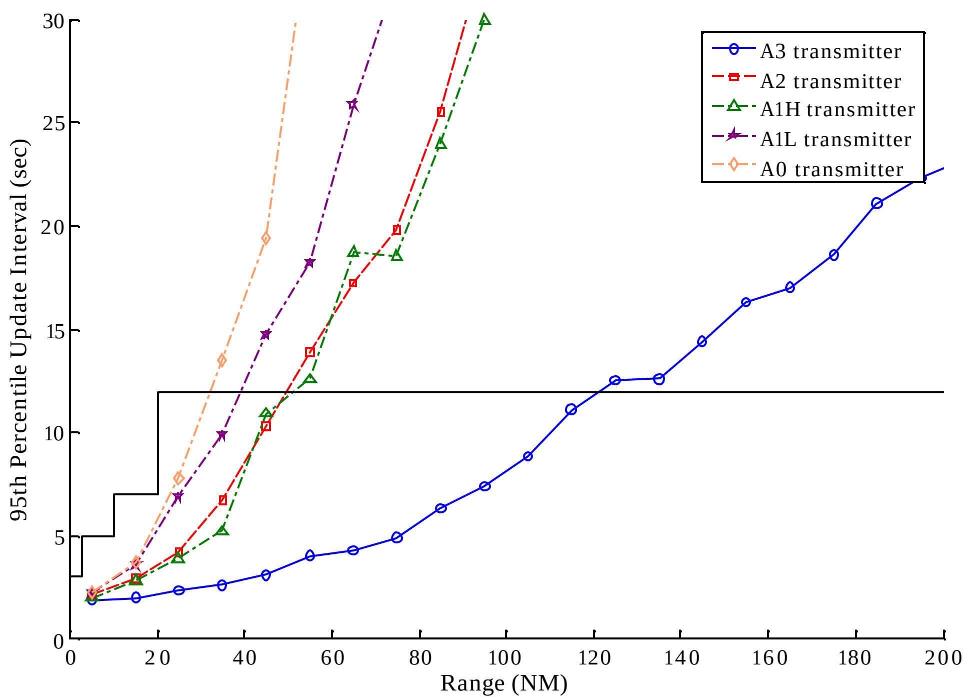


<u>Figure B-24:</u> Air-to-Air Reception by A2 Receiver at High Altitude over BRU in CE 2015



<u>Figure B-25:</u> Air-to-Air Reception by A2 Receiver at FL 150 over BRU in CE 2015

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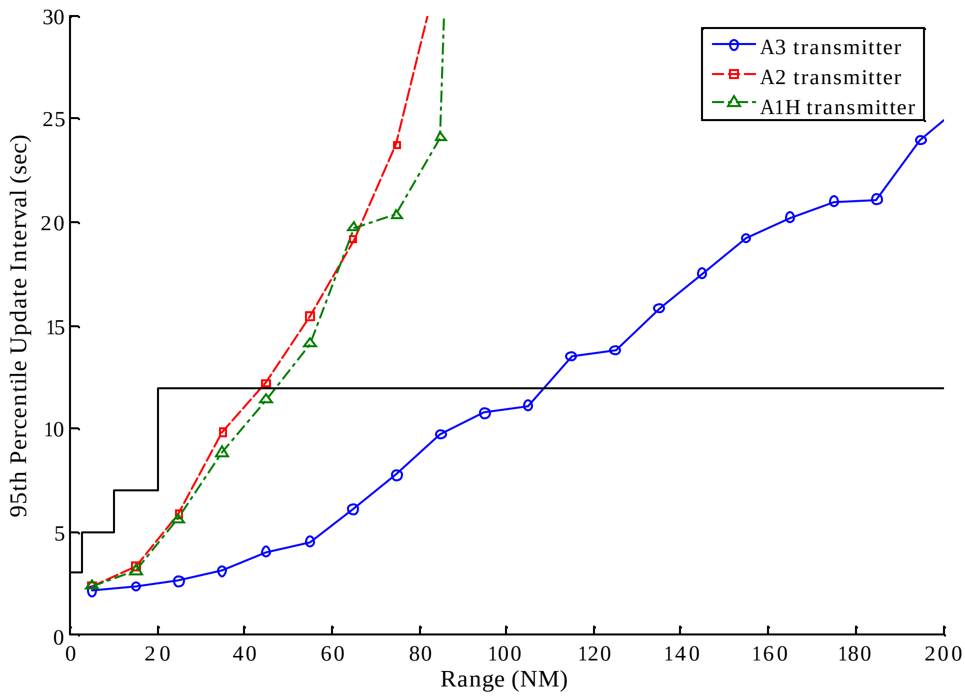

Figure B-26: **Air-to-Air Reception by A1 Receiver at High Altitude over BRU in CE 2015**

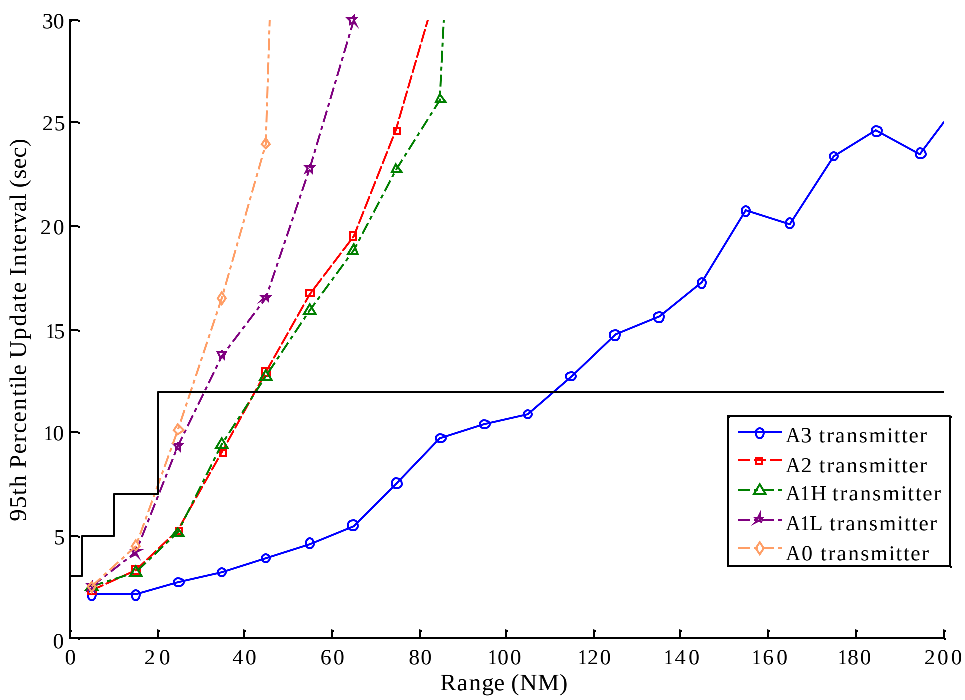

Figure B-27: **Air-to-Air Reception by A1 Receiver at FL 150 over BRU in CE 2015**

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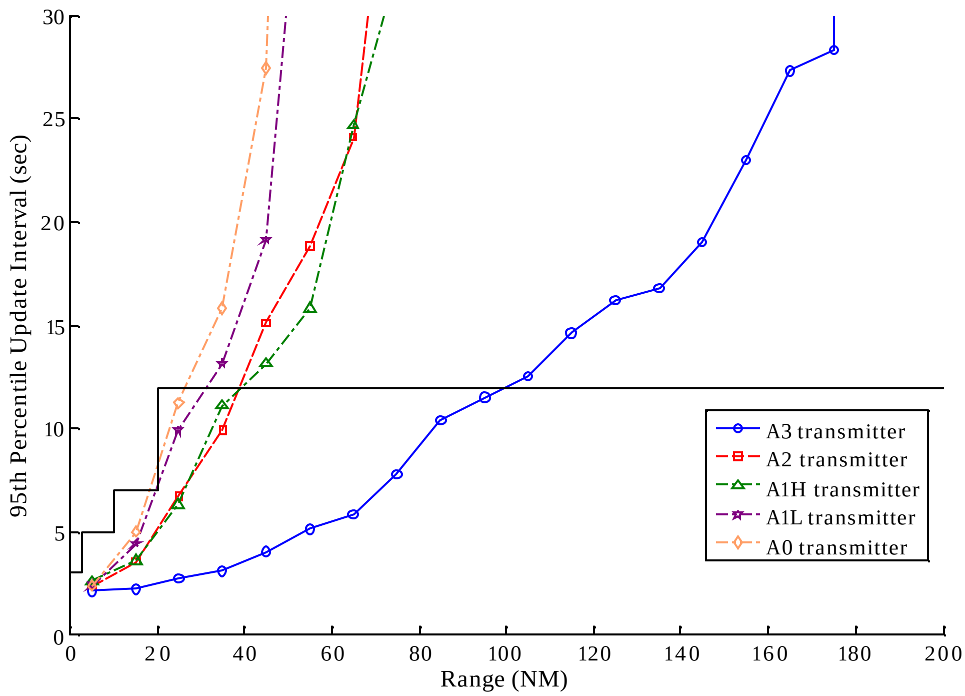
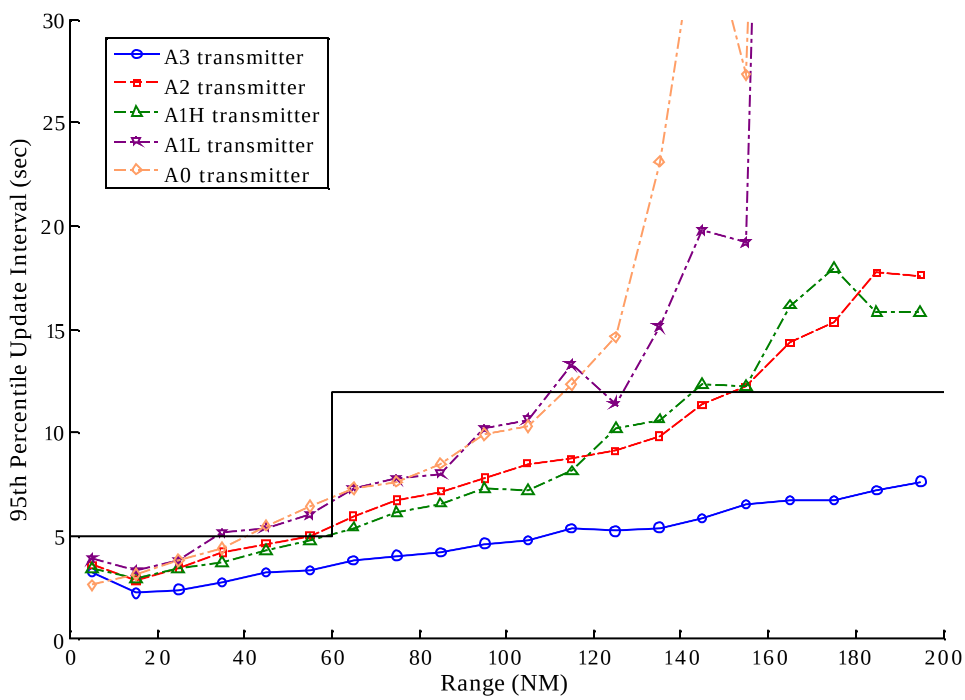


<u>Figure B-28:</u> Air-to-Air Reception by A0 Receiver at FL 150 over BRU in CE 2015



<u>Figure B-29:</u> Air-to-Ground Reception at BRU in CE 2015

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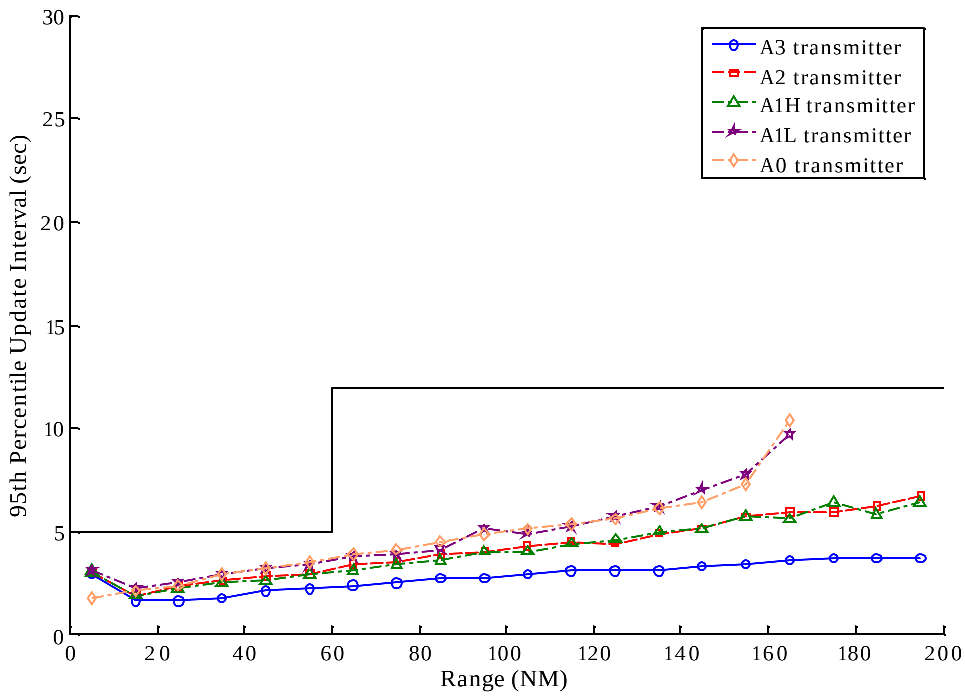

Figure B-30: **Air-to-Ground Reception Using a 3-Sector Antenna at BRU in CE 2015**

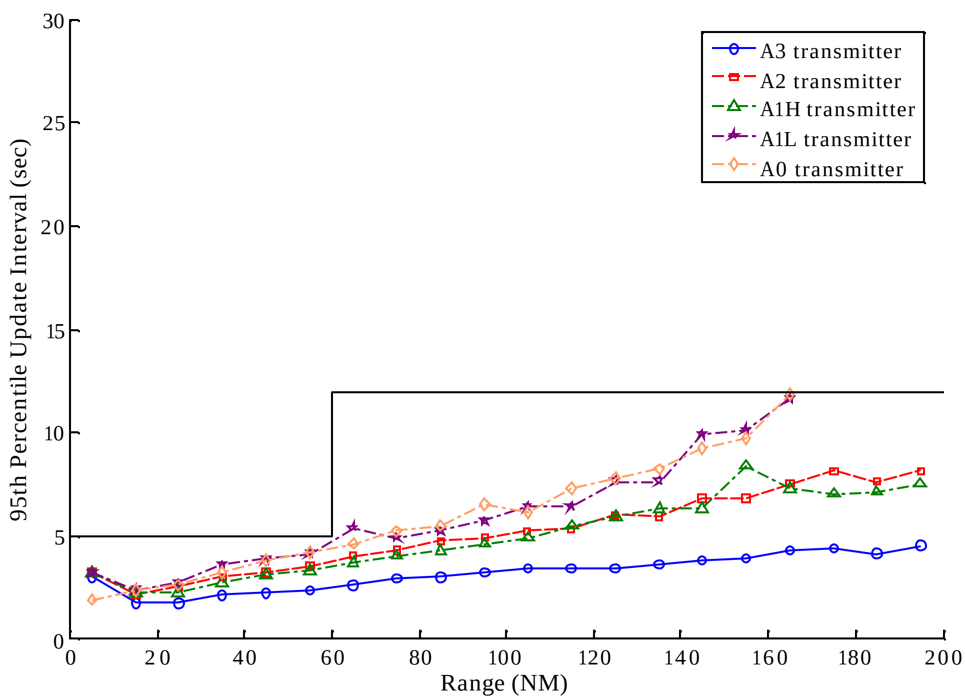

Figure B-31: **Air-to-Ground Reception 2 NM from a 10 kW TACAN Using a 3-Sector Antenna at BRU in CE 2015**

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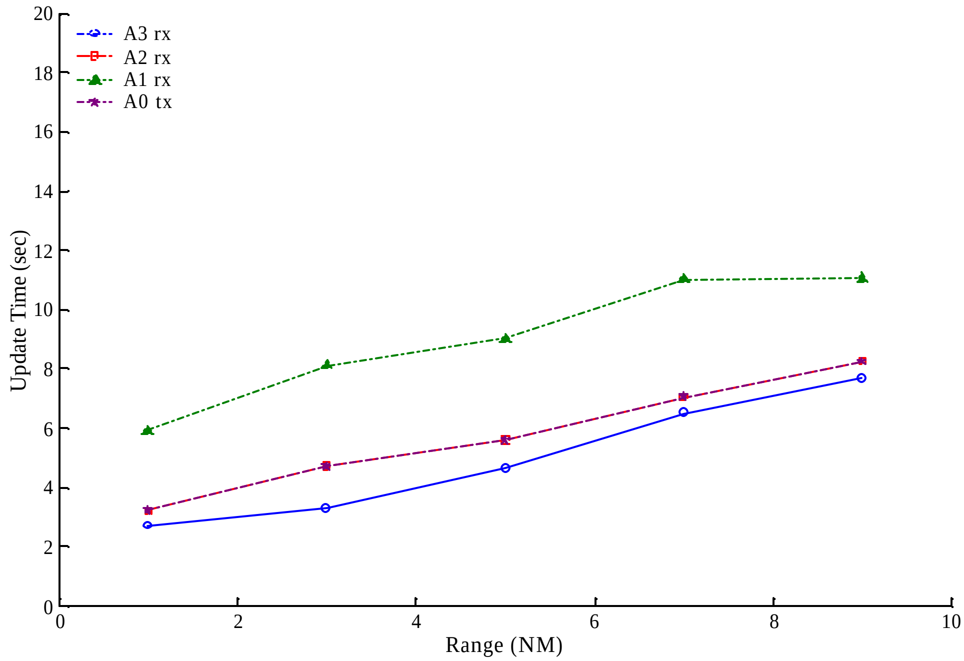

Figure B-32: Reception of Ground Vehicle Transmissions by Aircraft on Approach at 2000 feet into BRU in 2015 with 10 kW 979 MHz TACAN at Airport

Recall that the CE2015 scenario includes 2091 aircraft and 500 ground vehicles transmitting on UAT. The DME/TACAN interference environment is characterized by up to four adjacent-channel emitters, all at the maximum allowable powers. In addition, a baseline Link 16 scenario is also included as co-channel interference.

The UAT air-air performance in Core Europe shown in Figure B-22 through Figure B-28 is summarized in Table B-2. This summary indicates that the UAT System is projected to be fully compliant with the ADS-B air-to-air report update requirements at both the required and desired ranges.

Table B-2: Ranges of ADS-B Compliance for UAT Transmit-Receive Combinations in CE 2015 Scenario

	TRANSMITTER			
RECEIVER	**A3**	**A2**	**A1**	**A0**
A3 (High Altitude)	120	40+	40+(A1H)	NA
A3 (FL 150)	120	40+	40+(A1H)/30+(A1L)	20+
A2 (High Altitude)	130	50	50(A1H)	NA
A2 (FL 150)	120	40+	40+(A1H)/30(A1L)	20+
A1 (High Altitude)	100+	40	40+(A1H)	NA
A1 (FL 150)	110	40	40(A1H)/20+(A1L)	20+
A0	100	30+	30+(A1H)/20+(A1L)	20+

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The results for Core Europe 2015 shown in Figure B-22 through Figure B-32 may be summarized as follows:

- ADS-B air-air requirements and desired criteria are met for all aircraft equipage transmit-receive pairs for both state vector update rates at all ranges specified by the UAT Requirements and Desired Features.
- The Eurocontrol extension to 150 NM for A3 equipage is not met at the 95% level, but the 95% state vector update time at 150 NM is 15-16 seconds, depending on receiver altitude and location. The 95% level is achieved to around 120 NM, depending on receiver altitude and location.
- All known air-ground update rate requirements are substantially met for all classes of aircraft out to at least 150 NM, even in the presence of a co-located TACAN emitter, by using a three-sector antenna. A test case was run, which included a 10 kW co-located 979 MHz TACAN. It was determined that the TACAN signal at the receive antenna had to be received at a level that did not exceed –50 dB, in order for all equipage classes to meet air-ground requirements. This corresponds to an isolation of 40 dB from the receive antenna, in addition to that provided by a 50 foot separation distance between the TACAN transmitter and ground receiver plus isolation provided by the receive antenna null. This could be achieved by increasing the separation distance, for example.
- System performance results are presented for updates of ground vehicles to an aircraft on approach. We know of no specific ADS-B MASPS requirements for this situation.

B.4.3 Low Density Scenario

In addition to the two high-density scenarios described above, a scenario was also run to represent low-density traffic levels. This scenario was developed for 360 total aircraft. These aircraft are uniformly distributed in the horizontal plane within a circle of radius 400 nautical miles. In the vertical direction, they are distributed uniformly between 25,000 feet and 37,000 feet. The velocities are all set to 450 knots and are randomly distributed in azimuth. All of the aircraft are assumed to be A3 equipped. In order to evaluate the performance of a ground receiver in this environment, one was located at the center of the scenario, along with a co-located TACAN transmitter at 979 MHz.

Results of the MAUS runs for the low-density scenario are shown in Figure B-33 and Figure B-34, and conclusions are presented below. The ADS-B MASPS requirements for state vector and TSR updates, and preliminary requirements for TCR+0 updates are shown as black lines on the plots. Although results for TCR+1 transmissions are shown, there are currently no requirements that have been set for TCR+1 reception. The ADS-B MASPS specify that the maximum ranges for air-air update rates required for A3 to 90 NM (120 NM desired), while the Eurocontrol criteria continue to 150 NM for A3. Performance in compliance with MASPS requirements is indicated by results that are below the black line.

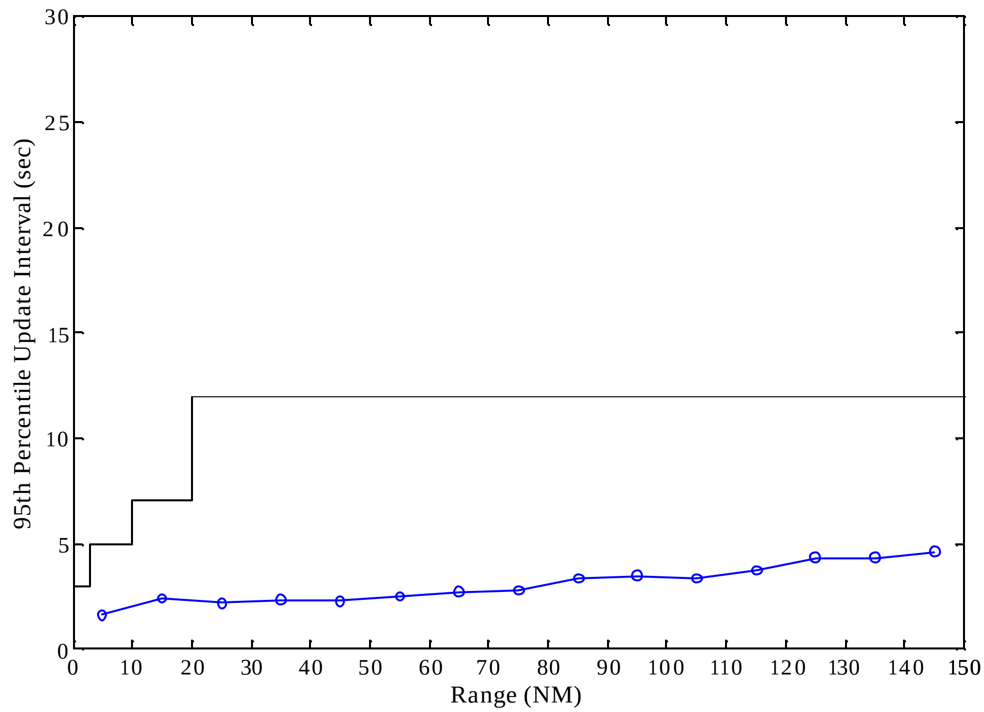

Figure B-33: A3 Receiver in Low Density Scenario Receiving A3 Transmissions

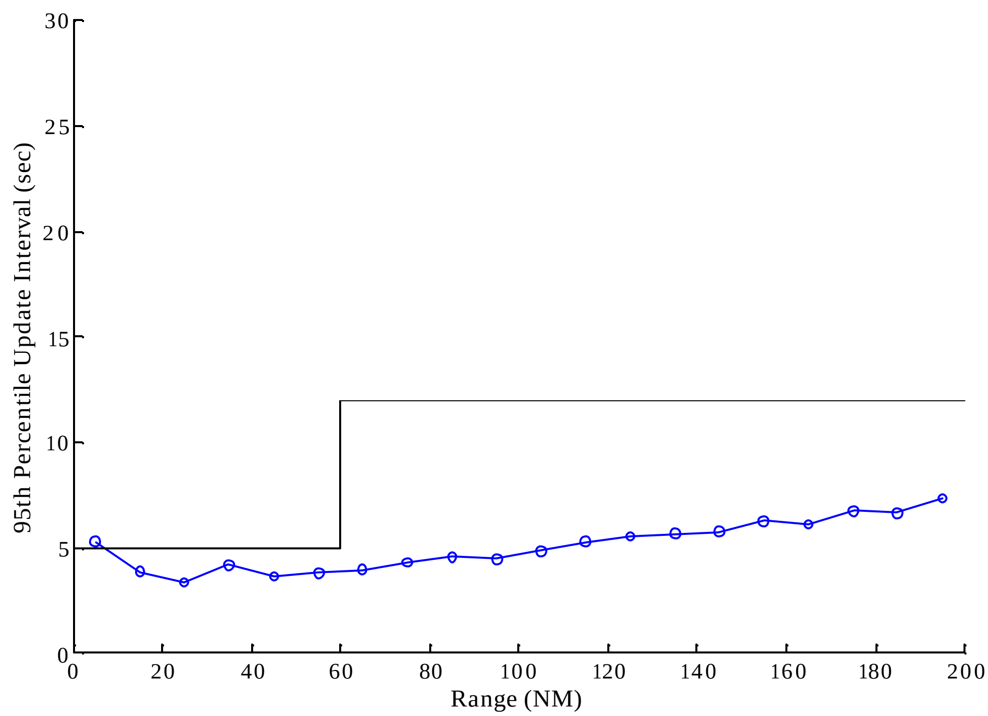

Figure B-34: Receptions of A3 Transmissions by a UAT Ground Receiver in a Low Density Scenario co-located with a TACAN at 979 MHz with –30 dBm Power at the UAT Antenna

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The results for the low-density scenario may be summarized as follows:

- ADS-B air-air requirements and desired criteria are met for all aircraft for both state vector and intent update rates at all ranges specified by the UAT Requirements and Desired Features.
- The Eurocontrol extension to 150 NM for A3 equipage is met at the 95% level, as required.
- All known air-ground update rate requirements are met out to at least 150 NM, in the absence of the co-located TACAN emitter, with the use of a single antenna on the ground. A test case was run, which included a 10 kW co-located 979 MHz TACAN. It was determined that the TACAN signal at the receive antenna had to be received at a level that did not exceed –30 dBm, in order to meet air-ground requirements. This corresponds to an isolation of 20 dB from the receive antenna, in addition to that provided by a 1000 foot separation distance. Alternatively, a three-sector ground antenna configuration should also enable satisfaction of the air-ground requirements to 150 NM.

B.4.4 Acquisition Performance

Performance of the UAT ADS-B system in the area of aircraft information acquisition was evaluated. In a head-on situation in the LA2020 scenario, the 99th percentile range for acquisition by the victim receiver of all information transmitted on ADS-B by the desired aircraft was determined for each aircraft equipage type. This was done for a large sample of cases, and the 99th percentile case was chosen. In other words, 99% of aircraft are expected to achieve a 99% probability of acquiring all information about an aircraft flying on a head-on path by the range selected.

The information necessary to acquire varies by aircraft equipage, so the evaluation was done for various transmitter-receiver combinations of equipage. For each equipage type, the message transmit sequence used was that defined in Section 2.2.6.1.3. Table B-3 shows the assumptions made in this analysis for information required to achieve acquisition for each type of transmit equipage.

Table B-3: Acquisition Requirements

Transmit Equipage	Required Information for Acquisition
A3	SV, MS, TSR, TCR0, TCR1
A2	SV, MS, TSR, TCR0
A1H	SV, MS, TSR
A1L	SV
A0	SV

The abbreviations used in Table B-3 are:

- SV: State Vector
- MS: Mode Status
- TSR: Target State Report
- TCR0: Trajectory Change Report 0
- TCR1: Trajectory Change Report 1

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The methodology used in this analysis was to run a set of probe aircraft in a head-on scenario and determine, for each, probe aircraft, the 99th percentile range at which all of the above information was received by the victim aircraft. The results are shown in Table B-4 for each transmit-receive combination.

Table B-4: 99th Percentile Range for Information Acquisition for Various Combinations of Transmit-Receive Pairs (NM)

		Transmitter				
Receiver		**A3**	**A2**	**A1H**	**A1L**	**A0**
	A3	137	53	53	49	18
	A2	145	54	53	52	17
	A1	122	50	48	37	11

These results are for somewhat more restrictive acquisition criteria than are usually applied. From the results, it appears that UAT will be able to comply with all known ADS-B track acquisition requirements. Do we want to include the results that are done for acquisition by the ground with alternating ID messages?

B.4.5 Surface Performance

An evaluation was performed of the performance of the UAT system on the surface, i.e., aircraft-to-aircraft state vector update rates were determined for transmit-receive pairs on the ground at LAX in the LA2020 scenario. The aircraft separation was varied between one and five nautical miles, and cases were run with and without severe horizontal surface multipath included. The multipath model used is described in Appendix M.6 of the ADS-B Technical Link Assessment Team (TLAT) Technical Link Assessment Report, March, 2001. It was thought that these two cases would provide conservative bounds on expected performance, since it was assumed that the severe multipath effects would always interfere destructively with the received signal.

Recall that the LA2020 scenario, in addition to a total of 2694 aircraft (75 on the ground at LAX) transmitting UAT, includes 100 transmitting ground vehicles at LAX as well. The results for the analysis of aircraft-to-aircraft surface-to-surface performance may be summarized as follows:

- For the bounding cases with no multipath and with worst-case elevation plane multipath, the 95th percentile surface update requirement for the ADS-B MASPS (1.5 seconds out to 5 NM) are met for A3 transmitters up to 1-2 NM away.
- The 95th percentile surface update requirement for the ADS-B MASPS (1.5 seconds out to 5 NM) are not met for all other cases on the surface.
- The 95th percentile update time on the surface for all aircraft classes to 5 NM for the bounding case of no multipath is approximately 2 seconds. A3 transmitters can be

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seen by A2 and A3 receivers out to 5 NM with, approximately, a 3 second 95th percentile update time. A2 transmitters can be seen by A2 and A3 receivers out to 5 NM with, approximately, a 5 second 95th percentile update time.

- The 95th percentile update time on the surface for all aircraft classes for the bounding case of worst-case multipath is approximately 3 seconds at a range of 1 NM. The limiting factor at ranges greater than 1 NM is the transmit power and antenna placement for A0 and A1L class equipment, combined with the effect of 175 interferers at close range.

B.4.6 An A0 on the Surface Receiving an Aircraft that is on Approach

An evaluation was performed of the performance of the UAT system for an aircraft on the surface receiving state vector transmissions from aircraft on landing approach in both the LA2020 and Core Europe 2015 scenarios. The aircraft on approach were modeled at an altitude of 2000 feet. The receiving aircraft on the ground is equipped as an A0 receiver. It was thought this would provide a worst case performance for aircraft on the surface receiving airborne transmitters due to the A0 receiver potentially only having a single antenna on the bottom of the aircraft. No multipath was included.

The evaluation was performed using the same co-site interference environment as for the airborne scenarios. In practice, the actual interference environment would be more benign, because of much lower instances of interrogations from TCAS/ACAS and radar ground systems when operating on the surface, and potentially from a lack of DME equipment on some portion of the A0 and A1L fleet. In addition, the Core Europe scenario had a 10 kW 979 MHz TACAN located 1000 feet away from the UAT receiving antenna.

Results of the MAUS runs for an A0 aircraft on the ground receiving UAT transmissions from aircraft on approach are shown in Figure B-35 and Figure B-36 for the LA2020 and CE 2015 scenarios, and conclusions are presented below. We know of no specific ADS-B requirements for this situation.

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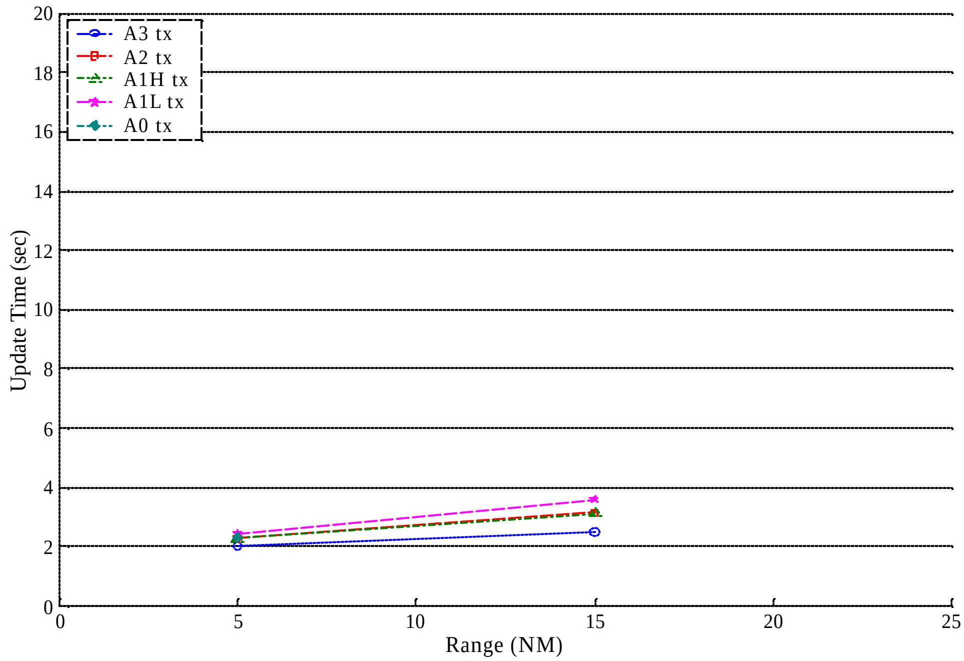

Figure B-35: A0 Receivers on the Ground in LA2020 Receiving All Aircraft on Approach at an Altitude of 2000 feet

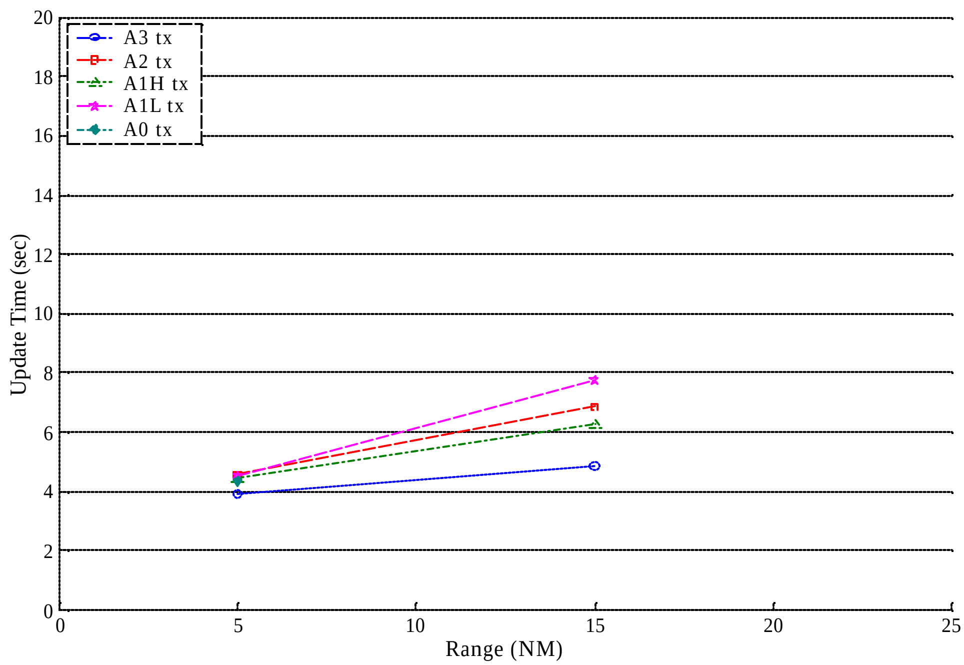

Figure B-36: A0 Receivers on the Ground in CE2015 Receiving All Aircraft on Approach at an Altitude of 2000 ft to Brussels co-located with a 10 kW 979 MHz TACAN

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Recall that the LA2020 scenario, in addition to a total of 2694 aircraft (75 on the ground at LAX) transmitting UAT, also includes 100 transmitting ground vehicles at LAX as well. Furthermore, the CE2015 scenario has 2091 aircraft transmitting UAT, including 25 aircraft and 100 ground vehicles on the surface in Brussels.

B.5 Model Validation

The validation effort for MAUS focused on reproducing a complete interference environment. The FAA's William J. Hughes Technical Center (FAATC) developed a UAT interference simulator, which was capable of reproducing both the LA2020 and CE2015 UAT self-interference environments. The additional capability of simultaneously inserting DME and Link 16 interference along with the UAT self interference was also implemented, resulting in emulation of high density, stressful environments containing a combination of all three types of interference. This simulator, along with "desired" UAT messages were combined and fed into UAT MOPS compliant UAT receivers. The Message Success Rate (MSR) was then measured as a function of desired signal level for various combinations of interference, and compared with predictions of the MAUS for identical circumstances and assumptions. In all cases, the predictions of the MAUS were in agreement with the measured results, within the experimental uncertainties. An example of this comparison is shown in Figure B-128 for the LA2020 UAT self interference environment. The results comparing measurements taken at the FAATC and the Joint Spectrum Center of the Defense Information Systems Agency (JSC) on UAT MOPS compliant equipment with MAUS simulation results are shown in Figure B-37.

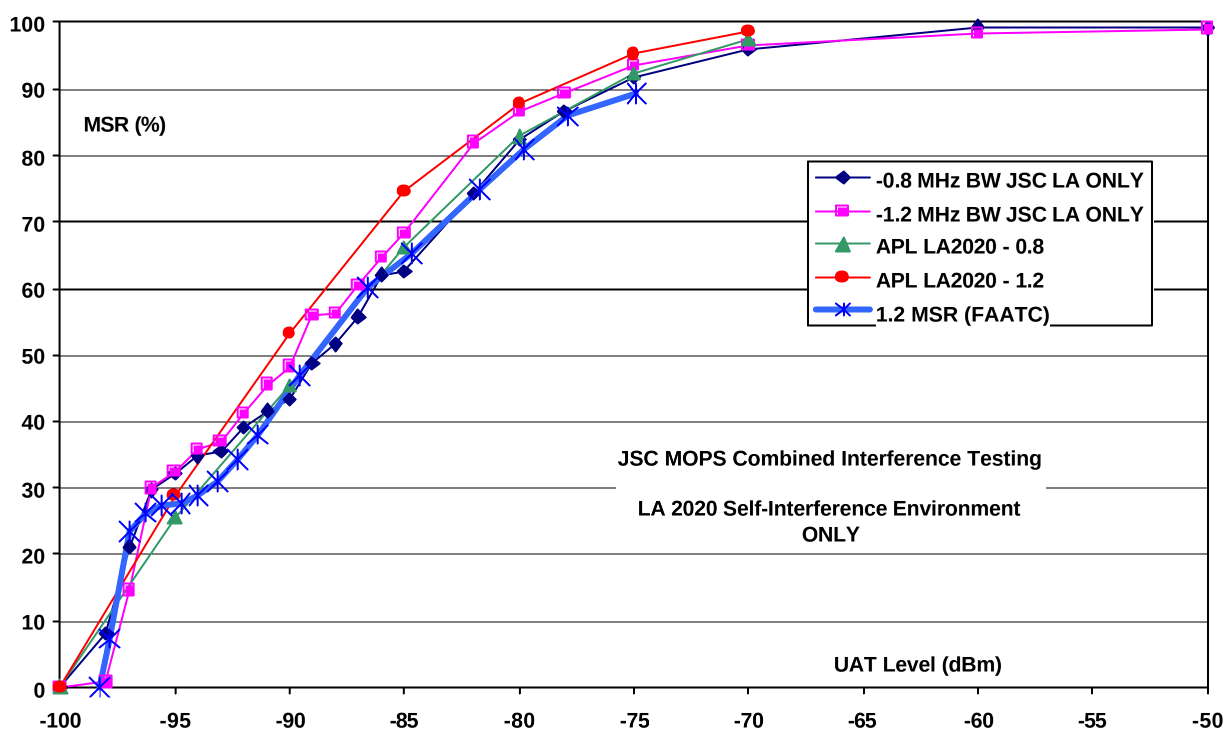

Figure B-37: Comparison of Bench Test Measurements of MOPS-Compliant UAT Reception in LA2020 Self-Interference with Predictions by MAUS

As is evident from Figure B-37, there is very little difference between the bench test data and the predictions of the MAUS. The two sets of data are quite consistent with each

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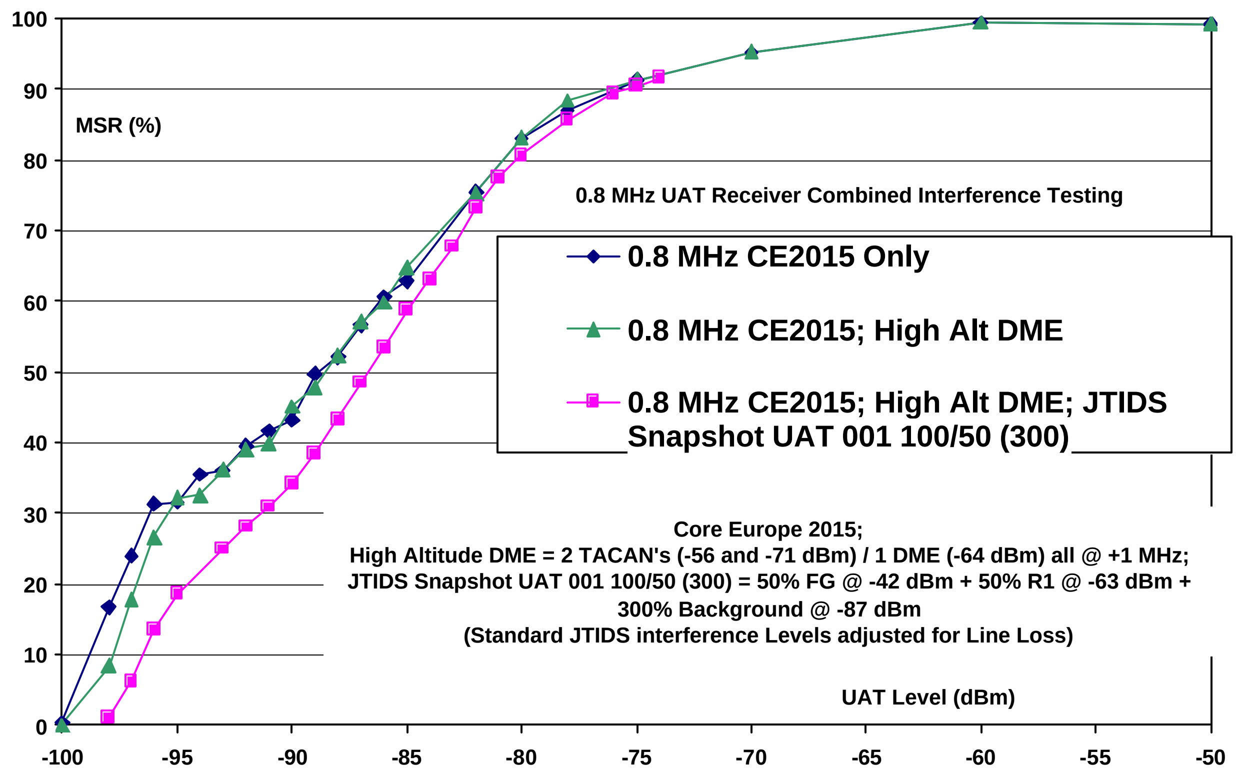
other within the limits of measurement. It is important to note that there were no free parameters that needed to be adjusted to achieve this agreement. This type of validation provides an increased measure of confidence in the simulation predictions.

Bench test measurements were also made of the Core Europe environment, which included UAT self-interference, DME/TACAN interference, and Link 16 interference. Results of these measurements are shown in Figure B-38 and Figure B-39. Figure B-38 shows the measurement results for the 0.8 MHz filter receiver, which is to be used for A3 class equipment. The addition of Link 16 interference to the DME/TACAN and UAT interference results in a reduction in MSR of up to around 10% for a given desired signal level, although the curves are much closer than that over much of the signal range. Simulation results have not been run for comparison in this scenario; however, there is a slight reduction in performance when Link 16 interference is added to the identical Core Europe scenario.



<u>Figure B-38:</u> Bench Test Measurements of UAT Performance in Core Europe UAT Self-Interference, Combined with DME/TACAN and Link 16 Interference

Figure B-39 shows the results for measurements taken with the 1.2 MHz receiver filter, which corresponds to the receiver used for all equipage classes other than A3. These results are similar in nature to those for the Core Europe scenario shown in Figure B-38, in that the addition of Link 16 interference results in a small reduction of the MSR at a given desired signal level.

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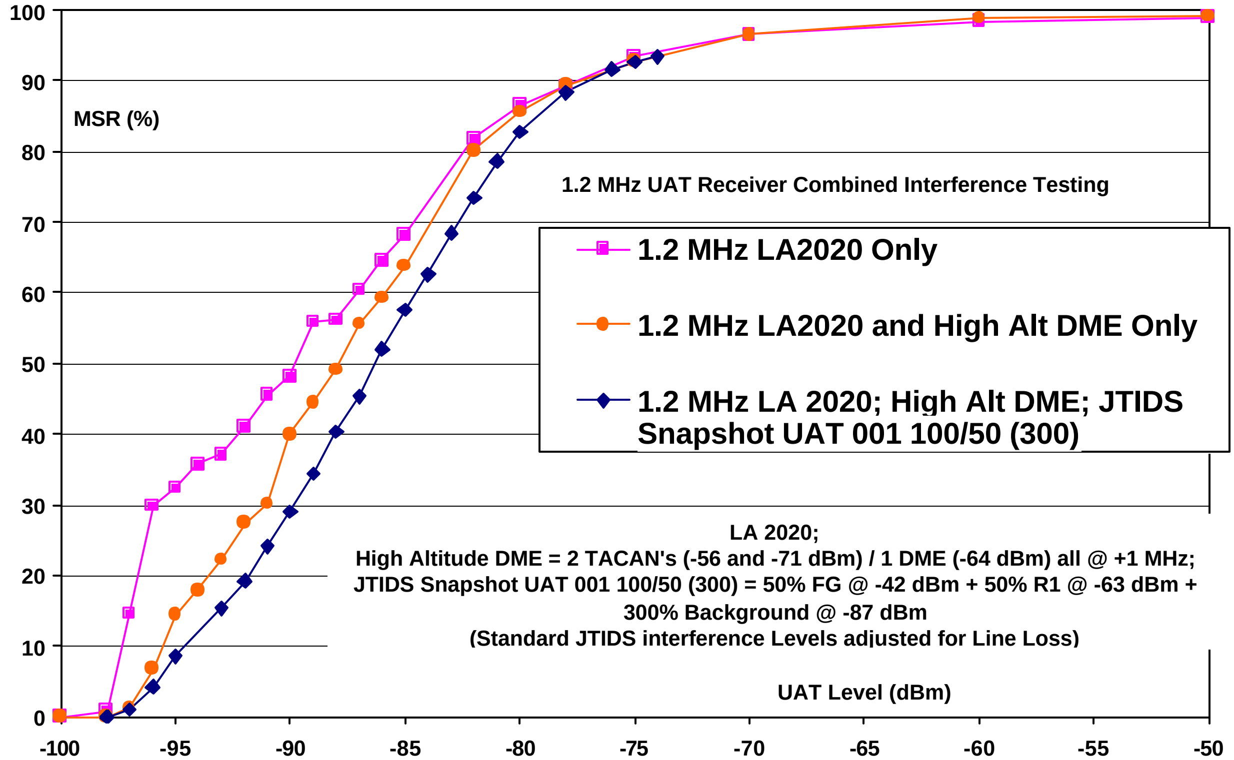

Figure B-39: Bench Test Measurements of UAT Performance in the LA2020 UAT Self-Interference, Combined with DME/TACAN and Link 16 Interference

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