MTR130464

MITRE TECHNICAL REPORT

Potential 1090 Extended Squitter Support of Wake Vortex/Meteorology Applications

Sponsor: The Federal Aviation Administration
Dept. No.: F084
Project No.: 0212RC13-06
Outcome No.: 2
PBWP Reference: 2-4.E.1
"Potential 1090 Extended Squitter Support of Wake Vortex/Meteorology Applications"

Approved for Public Release
13-3633 Distribution Unlimited.

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October 2013

Abstract

The Automatic Dependent Surveillance-Broadcast (ADS-B) 1090 Megahertz (MHz) Extended Squitter (1090ES) message broadcast requirements supporting Wake Vortex and Meteorology (WV/MET) data updates are derived from the "Aircraft Derived Meteorological Data via Data Link for Wake Vortex, Air Traffic Management and Weather Applications - Operational Services and Environmental Definition (OSED)" (DO-338). Evaluation of the OSED proposed alternatives is based on these requirements as well as an examination of the potential impact of these alternatives on ADS-B users. Criteria for this impact assessment are the "ADS-B Traffic Surveillance Systems and Applications (ATSSA) ADS-B Minimum Aviation System Performance Standards (MASPS)" (DO-338) requirements for state vector updates. Expected performance estimates in specified interference environments use The MITRE Corporation 1090 MHz Co-channel Interference Model. Model validation and expected performance in several interference scenarios proposed by the FAA's 1090 MHz Spectrum Mitigation Alternatives Working Group are described.

Executive Summary

Meteorology (MET) data update support requirements were derived from the Wake Vortex (WV)/MET Operational Services and Environmental Document (OSED) and are summarized in Figure 3. To meet adequate performance, an increase in the MET 1 broadcast rate from the OSED proposed 0.1 messages/second to 0.33 messages/second is recommended as this results in the more uniform message decode requirements for MET 1 and 2 as well as Air Reference Velocity (ARV) support shown in Figure 5.

The potential range reduction in Automatic Dependent Surveillance-Broadcast (ADS-B) Surveillance Systems and Applications (ATSSA) Minimum Aviation System Performance Standards (MASPS) compliant State Vector (SV) update rates when the WV associated ARV message is interleaved with the Global Positioning System (GPS) derived ground velocity at a rate of one message per three seconds is indicated by a comparison of Figure 11 (ARV interleave operation) with Figure 10 (current normal ADS-B Extended Squitter (ES) operation). This comparison shows that the ARV interleave has no measureable effect on ADS-B SV coverage.

Capability of 1090ES to support these WV/MET requirements is determined by comparison of these minimum support decode probabilities with expected ES message decode probabilities in future scenarios.

Expected fruit rates in several future scenarios determined by the 1090 Megahertz (MHz) Spectrum Mitigation Working Group are estimated by The MITRE Corporation (MITRE) 1090 MHz co-channel interference model described in Section 3.2.[1] ES message decode probabilities in these interference environments depend upon the message decoder capability. Although only limited data are available, the MITRE decoder model used in this evaluation is shown to be in good agreement with these data (see Section 3.3) and this is used to estimate future ES capability in the assumed interference levels.

Section 4.1 shows ES can support the WV/MET Alternative requirements for MET formats 1 and 2 and for the ARV in the 2020 Baseline scenario without penalty to normal 1090ES user capability. Section 4.2 shows only a marginal capability for this support with a traffic growth factor of two, and essentially no support capability for a growth factor of three.

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[1] A brief description of the model is given in the “1090 MHz Spectrum Congestion Mitigation Analysis Baseline and Future Growth Scenarios Model Summary.”

Acknowledgments

The newer features of The MITRE Corporation (MITRE) 1090 Megahertz (MHz) Co-channel Interference Model, and its validation with flight test measurements were accomplished with the close cooperation of Tom Pagano and Leo Wapelhorst of the William J. Hughes Technical Center (WJHTC). In addition, thanks to Janet Harvey, MITRE, for her assistance with the document preparation.

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1 Introduction

1.1 Alternatives and Objectives

Since Automatic Dependent Surveillance-Broadcast (ADS-B) broadcasts aircraft derived information, these links are attractive candidates to provide Wake Vortex/Meteorology (WV/MET) data exchange. Due to capacity limitations on 1090 Extended Squitter (1090ES) (including international restrictions on message rates), analysis is required to verify that the link specifications can be modified to accommodate the WV/MET data exchange without an unacceptable operational impact on other users of the data link channel. Two alternatives have been proposed in the WV/MET Operational Services and Environmental Document (OSED) (RTCA DO-339):

- Add two additional message types at a low rate for WV/MET data to the currently agreed 1090ES broadcast schedule.
- Interleave an Air Reference Velocity (ARV) message at a low rate with the normally transmitted Global Positioning System (GPS) derived velocity message.

The suitability of 1090ES for WV/MET support with either of these alternatives requires analysis of two aspects of these proposals:

- Assurance that the resulting 1090ES message broadcast rate meets the desired WV/MET information update requirements at the desired air-air separation range in the current and expected future co-channel interference environment.
- Assessment of the impact the WV/MET data broadcast has on other 1090ES ADS-B users:
    - The potentially reduced message reception probability due to increased co-channel interference (fruit) if additional messages are transmitted.
    - The impact of the reduced reception probability of GPS ground reference velocity messages if they are interleaved with (ARV) messages.

Since the diversity of the currently implemented Surveillance Broadcast Service ground network provides reliable air-ground reception even in high interference environments, the operational capability of either alternative is determined in this evaluation by the expected air-air range for the supported WV/MET application. Similarly, the impact of WV/MET modifications on normal ADS-B users of the 1090ES link is measured by any resulting reduction in the expected air-air range as determined by State Vector (SV) report update requirements defined in RTCA DO-338, the Minimum Aviation System Performance Standards (MASPS) for ADS-B Traffic Surveillance System and Applications (ATSSA), and the definition of a SV described as the time referenced position and velocity updates in RTCA DO-260B, the 1090ES Minimum Operational Performance Standards (1090ES MOPS).[2]

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[2] This requires extrapolation of the reported position to be time synchronized with the associated velocity to be compliant with the usual definition of a state vector.

1.2 Alternatives Analysis Approach

1.2.1 Wake Vortex/Meteorology Alternatives and Requirements

One proposed alternative is the broadcast of two new message formats: MET Format 1 is broadcast at a rate of one message/10 seconds; MET Format 2 is broadcast at a rate of one message/20 seconds. The other proposed alternative is to interleave the ARV once every three seconds with the normally broadcast two GPS derived ground reference velocity messages per second. Table 1 summarizes these proposed message broadcast rates and the minimum coverage air-air ranges at the required 95 percent confidence level update intervals.

Table 1. WV/MET Broadcast Rates and Required Coverage

WV/MET Alternative	Broadcast Rate, sm	Update Interval @ 10 Nautical Miles (NM)	Update Interval @ 20 NM
MET Format 1	0.1 mess/sec	15 sec	30 sec
MET Format 2	0.05 mess/sec	-	120 sec
WV ARV	0.33 mess/sec	15 sec	30 sec

1.2.2 Broadcast of Additional Wake Vortex/Meteorology Messages

Evaluation of this alternative requires:

- Determination of the WV/MET message reception probability required to meet the desired information update requirement with the proposed message broadcast rate given in Table 1.
- Relating the required message reception probability to the expected 1090ES air-air range for the expected future interference level.
    - The assumed broadcast rate is acceptable if the intended WV/MET coverage is met.
    - If coverage is not met, increase the broadcast rate until the WV/MET coverage is met.
- Estimate the effect of the resulting additional WV/MET broadcasts on the 1090 MHz co-channel interference (fruit) level in the current and agreed future scenarios.
- Estimate the impact of the additional interference level on coverage for 1090ES ADS-B (including WV/MET) users of the channel.
    - Continue with other 1090ES coordination issues related to link and message format modification if the resulting coverage is acceptable.
    - Reject the addition WV/MET broadcast alternative if the coverage is not acceptable.

1.2.3 Interleaved Air Reference Velocity

Evaluation of this alternative requires:

- Estimate the impact of the lower broadcast rate of GPS velocity on the reception probability required for ADS-B SV report updates with the interleaved ARV messages.
    - Determine the minimum probability of decode and associated air-air range required for a SV report at the normal GPS velocity broadcast rate.
    - Determine the minimum probability of decode required for SV report at the ARV interleaved velocity broadcast rate and resulting coverage.
- Determine the expected WV/MET air-air coverage and update capability loss with the interleaved ARV message.

1.3 Document Overview

Analytical models of the two WV/MET alternatives, and reception requirements for the position and velocity components of the SV are described in Section 2. Section 3 reviews the co-channel interference environment and relates the message decode probability to the air-air coverage range limits in that environment. Section 4 describes the evaluation process.

Performance extrapolations used in this evaluation are verified with currently available validation data. A final assessment will be determined by the 1090 MHz Spectrum Mitigation Alternatives Analysis Working Group charged with assessment of the future use of this channel.

2 Alternatives Descriptions and Functional Requirements

2.1 Wake Vortex/Meteorology Evaluation Criteria

The update intervals given in Table 1 are graphed as a function of air-air separation in Figure 1. Notice that there is no WV/MET coverage specified for ranges greater than 20 NM. This does not mean the service may not be available at longer ranges, only that this performance is not considered in evaluation of the alternative.

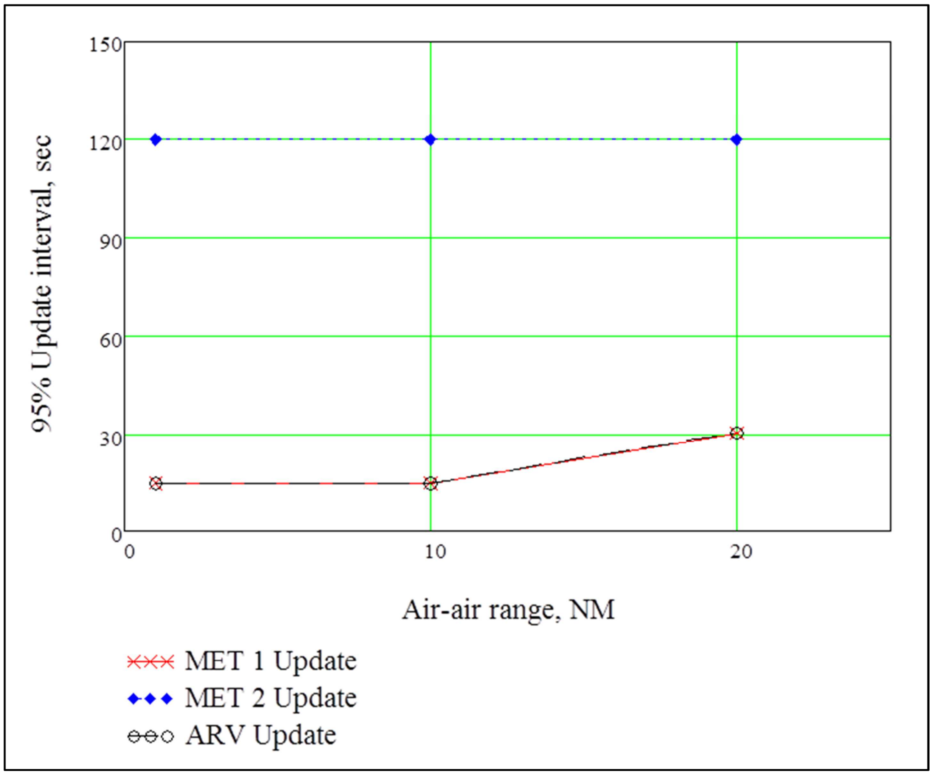

Figure 1. WV/MET Update Interval Requirements vs. Air-Air Separation

The proposed WV/MET broadcast rates given in Table 1 are:

- **MET Format 1:** 0.1 messages/sec resulting in an average $m_B = 1.5$ messages per 15 second update within 10 NM, and $m_B = 3$ messages per 30 second interval within 20 NM.[3]
- **MET Format 2:** 0.05 messages/sec resulting in $m_B = 6$ messages per 120 second update interval within 20 NM.
- **Interleaved ARV:** 0.33 messages/sec resulting in $m_B = 5$ messages per 15 second update interval within 10 NM, and $m_B = 10$ messages per 30 second update interval within 20 NM.

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[3] Higher rates may be employed on certain conditions for short intervals. This behavior should not have a significant effect on the evaluation in this report.

The required minimum probability of decode, *p*, for a desired probability of update, P_s, (or confidence level, $CL = P_s$) with m_B independent broadcasts or tries per interval is given in Figure 2.

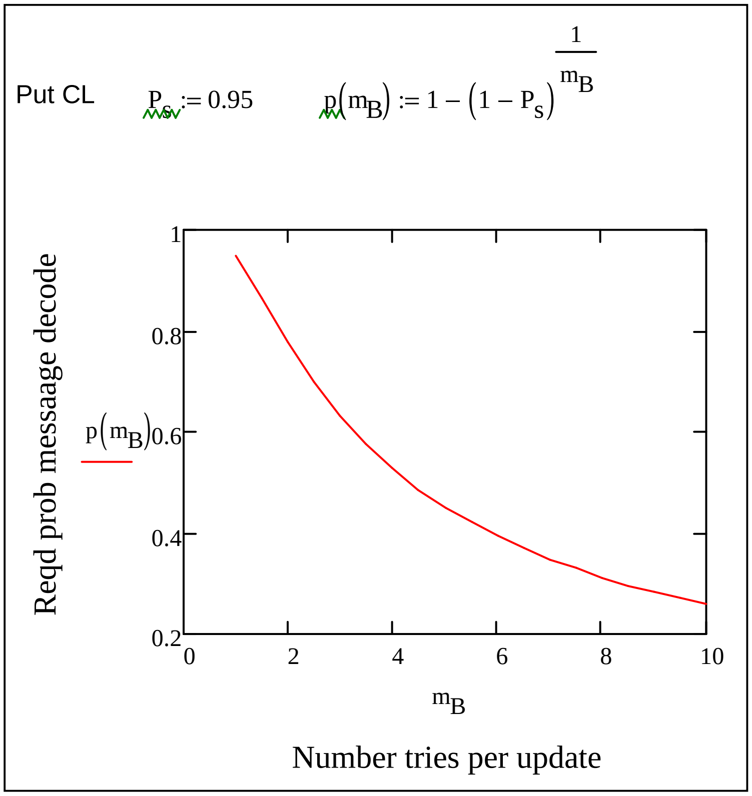

Figure 2. Required Probability of Message Decode for an Interval Update at CL = 95% vs. Number of Tries per Interval

Specific cases of required probability of single message, *p*(m_B), given in Figure 2 for MET Format 1 are *p*(1.5) = 0.86 and *p*(3) = 0.63; for MET Format 2, *p*(6) = 0.39; and for the ARV message, *p*(5) = 0.45 and *p*(10) = 0.26. These minimum required probabilities of message decode are plotted as a function of the required WV/MET coverage range in Figure 3. When the 1090ES receiver has a probability of message decode as high as that shown in Figure 3, the WV/MET service is available; when the probability of decode is below the required value, the broadcast rate is not high enough to meet the desired update rate.

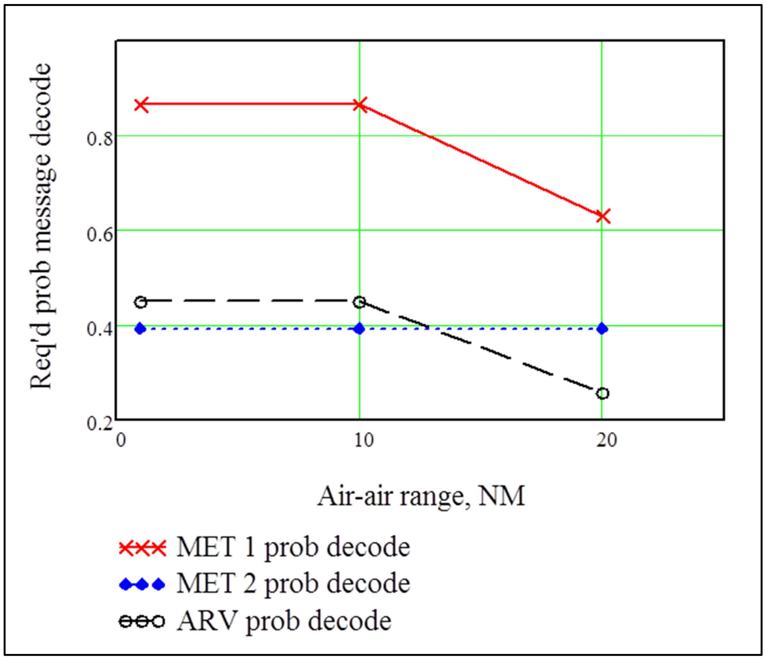

Figure 3. Required Message Decode Probabilities for Proposed WV/MET Broadcast Rates and 95% CL Update Intervals vs. Separation Range

From this point of view, notice the MET Format 1 decode requirements in Figure 3 are somewhat higher than those required for MET Format 2 and ARV updates. This implies support for this service would be more limited than that available for message Format 2 and ARV data. The improvement associated with twice the OSED proposed MET Format 1 broadcast rate, or 0.2 mess/sec is shown in Figure 4 where the minimum required value has dropped to 0.63.

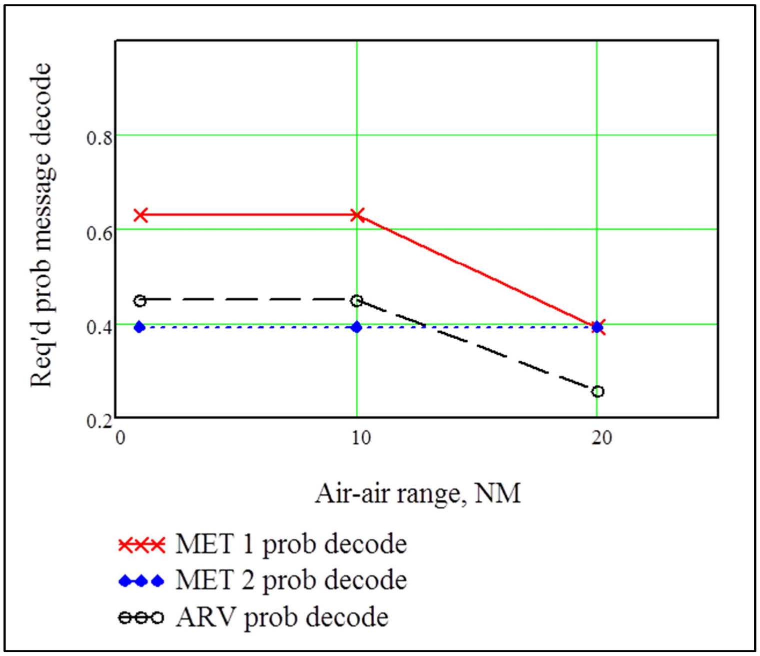

Figure 4. Required Message Decode Probabilities for Twice the MET Format 1 Broadcast Rate (or 0.2 mess/sec) and 95% CL Update Intervals vs. Separation Range

A further increase in the Format 1 broadcast rate to once per three seconds yield the results in Figure 5 where all service level requirements are essentially equal.

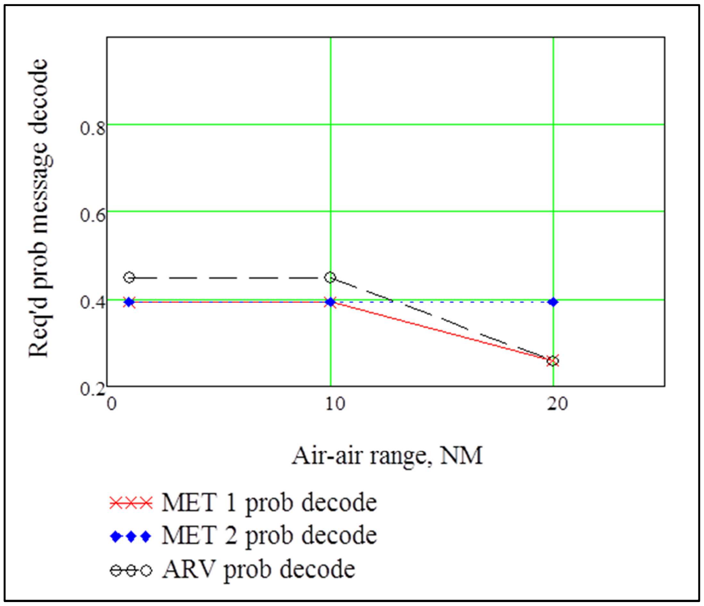

Figure 5. Required Message Decode Probabilities for a MET Format 1 Broadcast Rate of 0.33 mess/sec and 95% CL Update Intervals vs. Separation Range

The service quality improvements for MET Format 1 shown in Figures 4 and 5 do come at a cost, however. The additional fruit attributed to Format 1 and 2 broadcasts has increased from *sm* = 0.15 mess/sec for the OSED proposed rate to *sm* = 0.25 mess/sec when the Format 1 rate is increased to once per five seconds. With the Figure 5 increase to once per three seconds, *sm* = 0.38 mess/sec.

The next section discusses the evaluation approach for these performance-cost trade-offs and treatment of the ARV alternative.

2.2 Wake Vortex/Meteorology Impact on ADS-B Evaluation Criteria

2.2.1 Meteorology Formats Increase in Fruit Rate

The currently specified maximum broadcast rate for 1090ES equipped aircraft is *sr* = 6.2 ADS-B mess/sec/equipped aircraft. These broadcasts, plus the normal replies to Mode A/C and Mode S interrogations from secondary radars and Traffic Alert and Collision Avoidance System (TCAS), determine the 1090 MHz co-channel interference, or fruit rate. The increase in 1090ES broadcast rates discussed above for participating MET Formats 1 and 2 aircraft define the performance penalty for MET support on 1090ES. Using the MITRE 1090 MHz Co-channel Interference Model, if a fraction of the total traffic in view, *fes*, is ES equipped, and a fraction of these, *fm*, participate in the MET application, then the average ES rate per aircraft in view is

$$\mathrm{srm}(\mathrm{sm},\mathrm{fm}) := \mathrm{fm}\cdot(\mathrm{sr} + \mathrm{sm})\cdot\mathrm{fes} + (1 - \mathrm{fm})\cdot\mathrm{sr}\cdot\mathrm{fes}$$

In the evaluation baseline, *fm* = 0, and *srm = sr x fes* as normally used in the fruit distribution estimation. If all ES aircraft participated in the MET application, *srm = (sr + sm) x fes*, and any differential loss of coverage due to the higher interference or fruit rate is the MET impact evaluation measure.

2.2.2 Interleaved Air Reference Velocity Increase in Required Message Decode Probability

Normal 1090ES broadcast rates and reception probabilities for various components of SV reports and status updates are given in Table 2. Note that although the GPS source for ADS-B provides SV updates (i.e., a position and time registered instantaneous velocity), 1090ES must broadcast components of this update in separate interleaved odd/even position and velocity messages.

Reception of both position and velocity components of the SV within the same second defines the usual definition of a SV update (*pE* in the table), but this requires a relatively high probability of reception of each component with the associated limitation on air-air range. Thus, following DO-260B, the model also considers the probability of single message reception, *p*, required for reception of both a position and velocity component within *m* seconds as an acceptable SV update (pSV_m in the table).[4] Assuming an unambiguous global position decode has previously been achieved, this requires reception of either an odd/even position (pP_m in the table), and a velocity within *m* seconds (pV_m in the table).

Surveillance supported applications generally employ periodic surveillance updates: thus, the following treatment considers the minimum probability of single message decode required to receive a SV update within *h* tries with a window *m* seconds long for required reception of the position and velocity messages. The time between periodic SV updates is then *h x m* seconds. Parametric values of *m* = 1, 2, and 3 seconds are used to examine the sensitivity of the results. As a general observation regarding this concept, SV report assembly on reception of a position message with a previously received velocity *m* = 3 seconds ago means the velocity track angle lags by nine degrees in a standard turn rate of three degrees/sec; the lag is reduced to six degrees with *m* = 2 sec.

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[4] This is an *m* second long snapshot model of the receiver.

Table 2. 1090ES Message Broadcast Rates and Report Assemble Requirements

Broadcasts of 1090ES messages alternate on top and bottom antennas at following rates:

Even position 1 / sec,
Odd position 1 / sec
Velocity 2 / sec
Aircraft ID 1 / 5 sec
Operational status 1 / 2.5 sec
Target state and status 1 / 1.25 sec

MOPS requires acquisition of an odd and even position within 10 sec for a CPR global decode

With reception from the top and bottom antennas, there are the following number of transmissions per one sec interval

Even pos	$ne := 1$	Odd pos	$no := 1$	Vel	$nv := 2$
ID	$nd := 0.2$	Op status	$ns := 0.4$	Trgt status	$nt := 0.8$

For WV ARV interleave rate 1/3 sec, the GPS vel rate is nv = 1.67 rather than nv = 2

Global decode acq in a 10 sec interval $pGD(p) := \left[1 - (1-p)^{10ne}\right] \cdot \left[1 - (1-p)^{10 \cdot no}\right]$

At least 1 pos w/in 1 sec, pP $pP(p) := 1 - (1-p)^{ne+no}$

At least 1 vel w/in 1 sec, pV $pV(p) := 1 - (1-p)^{nv}$

SV Pos and Vel w/in same sec, pE $pE(p) := pP(p) \cdot pV(p)$

At least 1 pos w/in m sec, pPm $pP_m(p, m) := 1 - (1-p)^{m \cdot (ne+no)}$

At least 1 vel w/in m sec, pVm $pV_m(p, m) := 1 - (1-p)^{m \cdot nv}$

SV pos and vel w/in m sec snapshot, pSVm $pSV_m(p, m) := pP_m(p, m) \cdot pV_m(p, m)$

The 95 percent probability of a SV output report with position and velocity receptions within *m* seconds as a function of single message reception probability for the normal *nv* = 2 mess/sec velocity broadcast rate is shown in Figure 6 for values of *m* = 1, 2, and 3 seconds. This figure shows for example, a single message minimum probability of reception of p = 0.6 is required to assure the reception times of position and velocity components of the SV differ by no more than *m* = 2 sec at 95 percent Confidence Level (CL). The *m* = 2 second SV update time interval increases to seven seconds if the single message probability of decode is reduced to *p* = 0.3. Figure 6 also shows the SV update interval increases dramatically with unstable behavior with even small changes in decode probability for all three m values as the message reception probabilities decrease below about *p* = 0.3.

An additional lower limit on practical use of low message decode values is the requirement that a message decode probability of at least 0.2 is necessary for an ES Compact Position Report (CPR) Global Decode (GD) within 20 seconds. Since a GD might be required before track reacquisition begins, intervals longer than 20 seconds would significantly delay dropped track reacquisition.

Assume state vector decode attempt every m sec snap shot window. Prob of SV decode w/in h windows m sec long, or time, ThS = h x m sec is

Prob SV update w/in h tries $p_S(p,m,h) := 1 - \left(1 - pSV_m(p,m)\right)^h$ $p_S(0.6,2,1) = 0.95$

Updates reqd for update prob, Pu $h_S(Pu,p,m) := \dfrac{\ln(1-Pu)}{\ln\left(1 - pSV_m(p,m)\right)}$ $h_S(0.95,0.6,2) = 1$

SV update w/in h x m sec at prob, Pu $T_S(Pu,p,m) := m \cdot h_S(Pu,p,m)$ $T_S(0.95,0.6,2) = 2$

For $Pu := 0.95$ $ne = 1$ $no = 1$ $nv = 2$

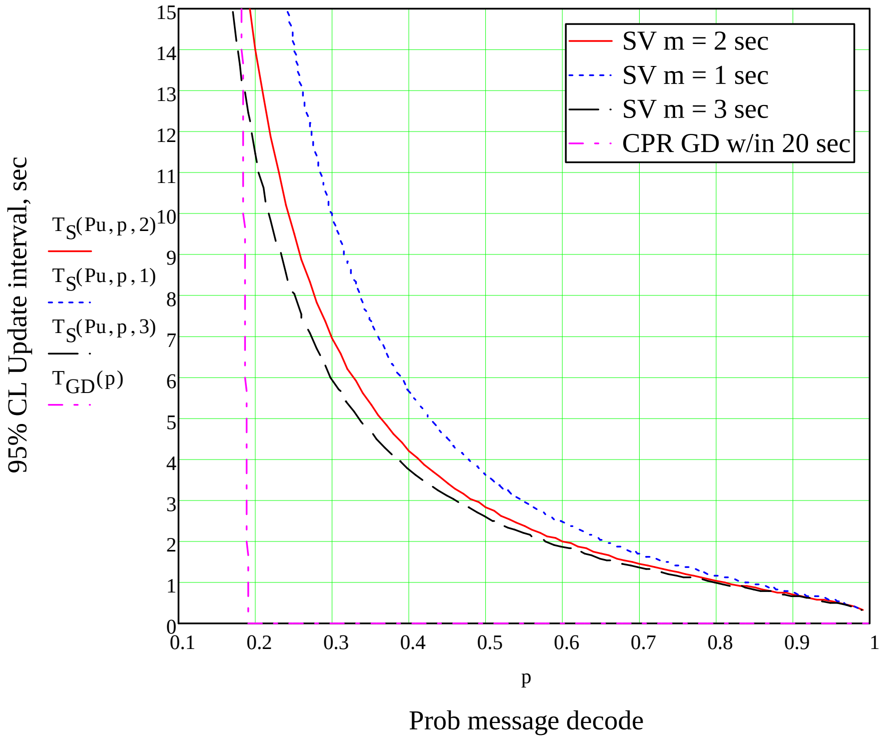

Figure 6. 95% Probability of SV Update Within m Seconds vs. Single Message Decode Probability for nv = 2 mess/sec and m = 1, 2, and 3 sec

Note in Table 2 that the GPS velocity normally used by ADS-B applications is broadcast at a rate of *nv* = 2 mess/sec. If GPS velocities are replaced by ARV messages once per three seconds, then *nv* = 1.67 mess/sec for ADS-B applications. This reduces the number of opportunities for a GPS velocity reception for ADS-B users of 1090ES and requires a slightly higher probability of reception for output of the same SV report as shown in Figure 7. The previously required *p* = 0.6 for *m* = 2 seconds is now *p* = 0.64 when *nv* = 1.67, and the initial seven second interval for *p* = 0.3 is now eight seconds. The relative reduction in SV reception air-air range associated with these required increases in reception probability is the measure of operational acceptability of this alternative.

With ARV interleave at 1/3 sec, nv = 1.67 mess/sec

$pV_a(p,m) := 1 - (1-p)^{m \cdot 1.67}$ $\quad$ $pSV_a(p,m) := pP_m(p,m) \cdot pV_a(p,m)$

$p_a(p,m,h) := 1 - \left(1 - pSV_a(p,m)\right)^h$ $\quad$ $p_a(0.64, 2, 1) = 0.95$

$$T_a(Pu,p,m) := \frac{\ln(1-Pu) \cdot m}{\ln\left(1 - pSV_a(p,m)\right)} \qquad T_a(0.95, 0.64, 2) = 2$$

$Pu := 0.95$

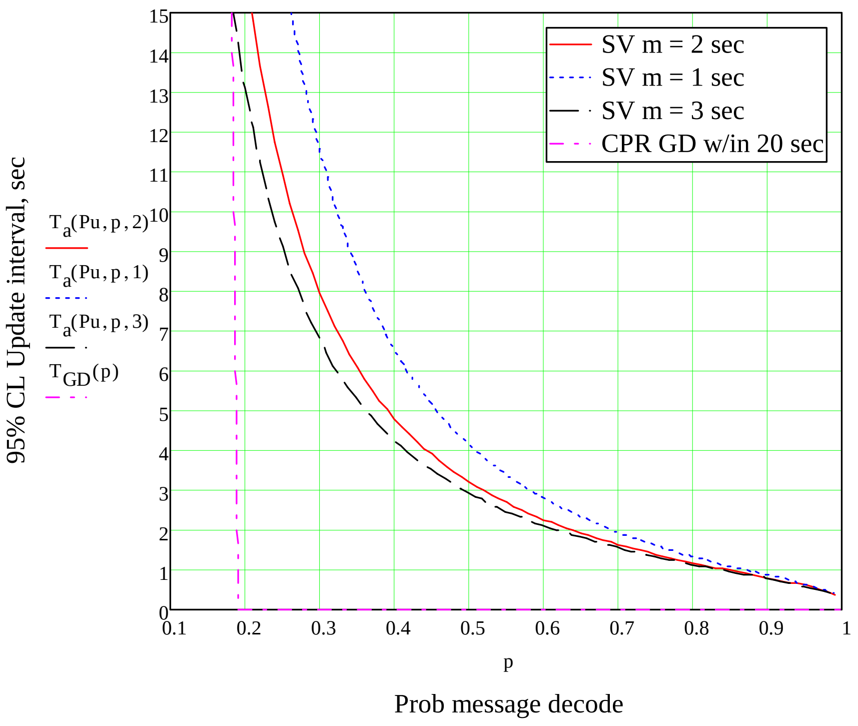

Figure 7. 95% Probability of SV Update Within m Seconds vs. Single Message Decode Probability for nv = 1.67 mess/sec and m = 1, 2, and 3 sec

All the discussion so far has been in terms of a suitable way to reassemble the very accurate GPS derived SV that was the source of the received ADS-B 1090ES message components of this update. No previous Air Traffic Control (ATC) surveillance system has offered this source derived instantaneous SV as a surveillance system update. Radar (or Secondary Surveillance Radar [SSR] and TCAS) sensors are limited to position estimates with velocity then derived from tracker smoothing of successive position estimates. This previous experience may be the reason many initial users of 1090ES have ignored the available SV update and instead focused on position only, or position or velocity updates to a suitable tracker for application support. It is expected that future ADS-B application designers will appreciate the advantages of the ATSSA MASPS required updated SV so this capability determines the evaluation criterion for examination of the impact of the interleaved ARV message on ADS-B users of 1090ES.

2.3 ADS-B State Vector Update Requirements

Required SV update intervals (95 percent) for ADS-B users of 1090ES are stated as a function of the air-air separation range in Table 3-35 of the recently updated ATSSA MASPS (DO-338). These requirements are summarized in Figure 8 along with the linear model used in the following update compliance assessment.

DO-338 Table 3-35 95% SV update reqmts, Tu sec vs range, and model:

$$R_{rqd} := \begin{pmatrix} 3 \\ 10 \\ 20 \\ 40 \\ 90 \end{pmatrix} \qquad Tu_{SV} := \begin{pmatrix} 3 \\ 5 \\ 7 \\ 12 \\ 12 \end{pmatrix}$$

$$w := \frac{12-3}{40-3} \qquad w = 0.243 \qquad Tr(R) := w \cdot R + 2.27$$

$$R := 3, 4 .. 80 \qquad Tr(R) := \mathrm{if}(R < 40, Tr(R), 12)$$

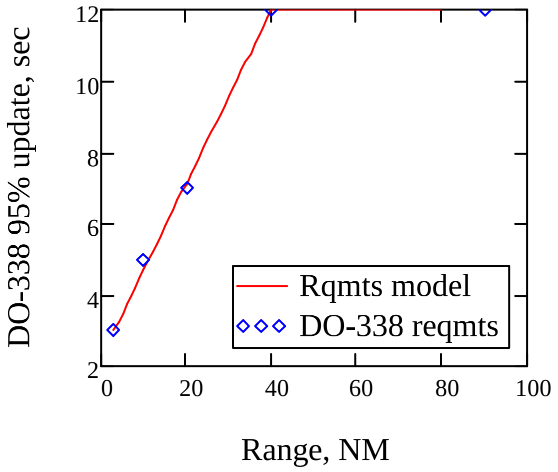

Figure 8. State Vector Update Intervals Required by DO-338

The minimum probability of single message decode required for ES to meet the above ATSSA MASPS required SV updates versus range is now determined. This can be derived in a two-step closed form solution when the position message broadcast rate is equal to the velocity message broadcast rate. First, the required probability as a function of update interval is determined as shown in Figure 9.

Mess decode prob for SV update at CL = Pu
within h intervals of m sec each

$$ps(h,m) := 1 - \left[1 - \left[1 - (1 - Pu)^{\frac{1}{h}}\right]^{\frac{1}{2}}\right]^{\frac{1}{2\cdot m}}$$

For h tries with m sec SV, update interval is Ts = h x m sec

$$T_S(h,m) := h\cdot m$$

$Pu = 0.95$ $no = 1$ $ne = 1$ $nv = 2$

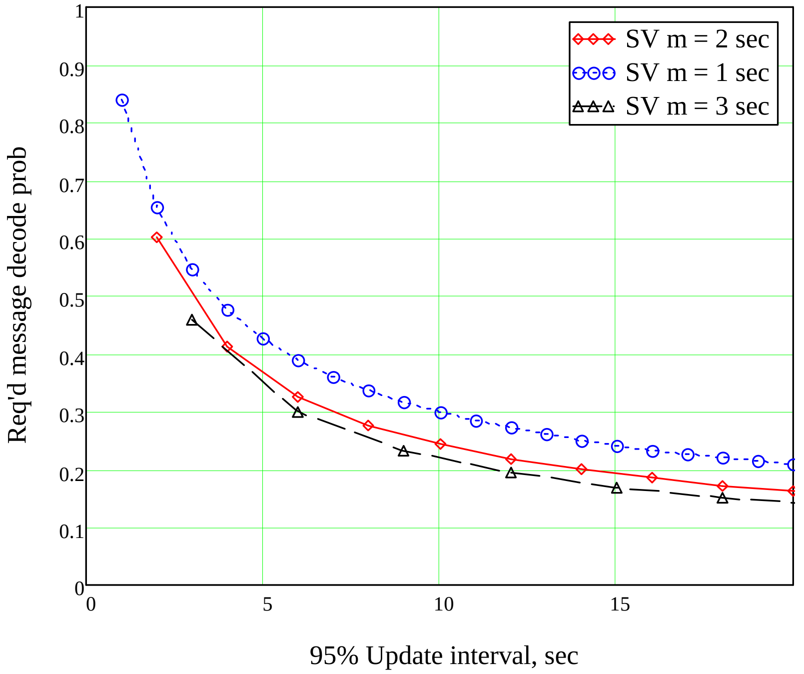

Figure 9. Probability of Message Decode for m = 1, 2, and 3 seconds Required to Meet the SV Update Interval at 95% Probability

The above Figure 9 required probability of message decode versus update interval for *m* = 1, 2, and 3 seconds is related to range through the ATSSA MASPS required update model as shown in Figure 10. This determines the required performance for 1090ES to meet the ATSSA MASPS SV update requirements.

Relationship betwn MASP reqd SV updates and range $Rs(h,m) := \frac{T_s(h,m) - 2.27}{w}$

To limit reqd min prob beyond 40 NM $ps(h,m) := \mathrm{if}\left(T_s(h,m) < 12, ps(h,m), ps\left(\frac{12}{m}, m\right)\right)$

$Pu = 0.95$ $no = 1$ $ne = 1$ $nv = 2$

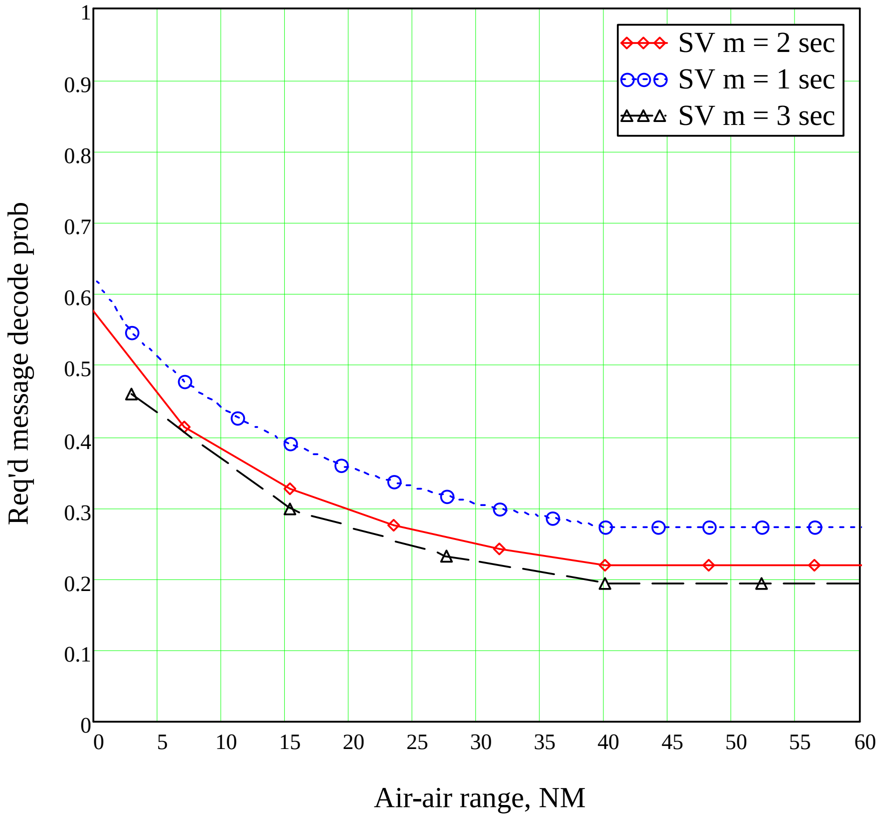

Figure 10. Probability of Message Decode vs. Range for the DO-338 Compliant State Vector Updates for the Normal 1090ES Case with nv = 2 mess/sec

Similar relationships between required probability of decode and separation range are shown in Figure 11 for the interleaved ARV (*nv* = 1.67) alternative supporting WV.[5] A closed form solution is not convenient in this case when the broadcast rates for position (*ne* + *no* =2 mess/sec) do not equal the rate for velocity, *nv* = 1.67 mess/sec, so points of interest are read off the curve of Figure 7 and converted to range as shown in Figure 11.

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[5] Note that this is the long term average rate. Periodic gaps up to 1.2 seconds occur in the short term.

$$R_{rqd} := \begin{pmatrix} 3 \\ 10 \\ 20 \\ 40 \\ 90 \end{pmatrix} \qquad pS_{a2} := \begin{pmatrix} 0.52 \\ 0.39 \\ 0.322 \\ 0.237 \\ 0.237 \end{pmatrix} \qquad pS_{a1} := \begin{pmatrix} 0.58 \\ 0.455 \\ 0.387 \\ 0.294 \\ 0.294 \end{pmatrix} \qquad pS_{a3} := \begin{pmatrix} 0.49 \\ 0.36 \\ 0.294 \\ 0.211 \\ 0.211 \end{pmatrix}$$

$Pu = 0.95$

Interleaved ARV with nv = 1.67 mess/sec

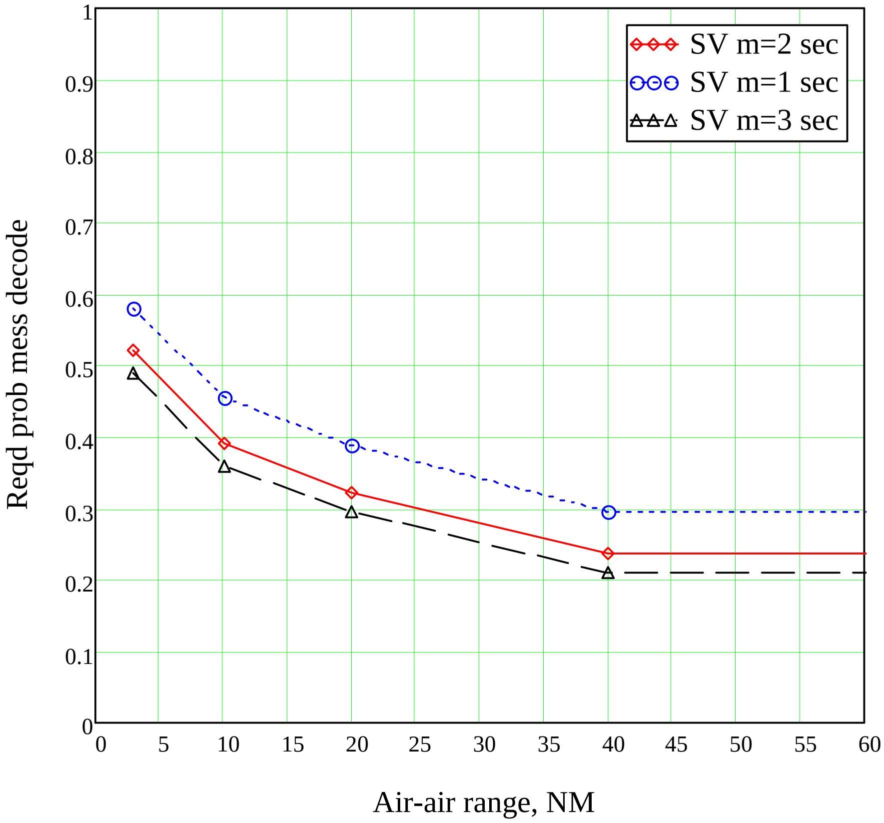

Figure 11. Probability of Message Decode vs. Range for the DO-338 Compliant State Vector Updates for the ARV Interleaved Case with *nv* = 1.67 mess/sec

At this point note that the expected air-air range for reliable SV coverage is determined by the intersection of the ATSSA MASPS (DO-338) SV update determined probability of decode as a function of range shown in Figure 10 with the monotonically decreasing probability of decode versus range curve to be determined for a 1090ES receiver in the interference environment of interest. Depending upon the slope of the message decode versus range curve of the receiver, the slightly higher curves in Figure 11 for the interleaved ARV message will reduce the air-air range by some amount. This reduction determines the acceptability or unacceptability of this alternative.

2.5 Summary of Alternatives Evaluation Criteria

Criteria for the operational evaluation of the proposed modifications to 1090ES for support of WV/MET applications are:

- Broadcast of additional MET format messages requires an increase in the 1090ES broadcast rate of either 0.15 mess/sec for the OSED proposed rate or 0.38 mess/sec if all supported services have approximately equal performance. Evaluation of the impact of additional fruit on ADS-B users with this option will therefore assume a broadcast rate from 6.35 or 6.58 mess/sec per 1090ES MET user instead of the normal limit of 6.2 mess/sec per 1090ES aircraft.
- The WV/MET supported air-air range in the future environment is determined by the probability of message decode given in Figures 3 to 5, depending upon the choice of broadcast rates.
- The operational impact of the additional fruit rate on ADS-B users is evaluated with the increased fruit rates at the air-air range corresponding to the DO-338 required single message probability of decode for nv = 2 mess/sec given in Figure 10.
- Operational impact of the interleaved ARV message on ADS-B users is determined by the relative range reduction in the future environment when the probability of message decode for a DO-338 ATSSA MASPS required SV update with nv = 2 mess/sec increases to the DO-338 required value when the velocity broadcast rate is nv = 1.67 mess/sec for the ARV interleave (Figure 10 compared with Figure 11).
- Capability of the interleaved ARV message to support WV is determined by the ARV air-air range decode probabilities given in Figures 3 to 5.

3 Co-channel Interference Environment and MITRE Interference Model Performance Validation

3.1 General Considerations

Evaluation criteria developed in the previous section were expressed as required probability of decode as a function of air-air separation range. Determination of the ability of 1090ES to support the desired operation requires estimating the expected probability of 1090ES message decode versus the air-air range in the co-channel interference environment of interest and comparing this decode probability with the application required probability. If the 1090ES estimated decode probability is higher than the application required probability at the desired range, the application is supported. Assessment of expected 1090ES capability in future environments requires a three-step process:

1. Verify that the model can parametrically represent a given interference environment and 1090ES performance in that environment by comparisons with test flight data in the current environment.
2. Verify that expected capability in future environments can be quantified by comparing the model to parametric bench measurements of future interference conditions.
3. After this validation, the expected future performance is estimated by adjusting the model parameters to represent expected future conditions as described in Section 4.

This process is achieved with the MITRE 1090 MHz Co-channel Interference Model described in the next section.

3.2 MITRE Model and Fruit Distribution Validation

Actual received signal levels reflect the usual free space path loss as well as differences in aircraft transmitted power levels and variations in air-to-air aircraft antenna gains associated with relative aircraft orientation. The desired 1090ES message competes with co-channel interference (fruit) determined by the air traffic distribution surrounding the receiver of interest, and the co-channel transmission rates of these aircraft. Specified traffic and interference source scenarios combined with the received signal level model yield amplitude distributions of this received interference. Finally, fruit rates as a function of this amplitude distribution are used in Poisson time of arrival overlap assessments of the reception capability of 1090ES receiver/decoders in this interference. The MITRE Model capabilities in these various areas are illustrated by the following comparisons with test flight and bench measurements.

Figure 12 illustrates the William J. Hughes Technical Center (WJHTC) measured radial traffic distribution relative to the victim receiver compared with the MITRE Model traffic distribution (no azimuth distribution is required since omnidirectional aircraft antennas are used).[6] This distribution, along with free space loss and modeled transmit power-antenna gain variations, determines the all in view fruit amplitude distribution.

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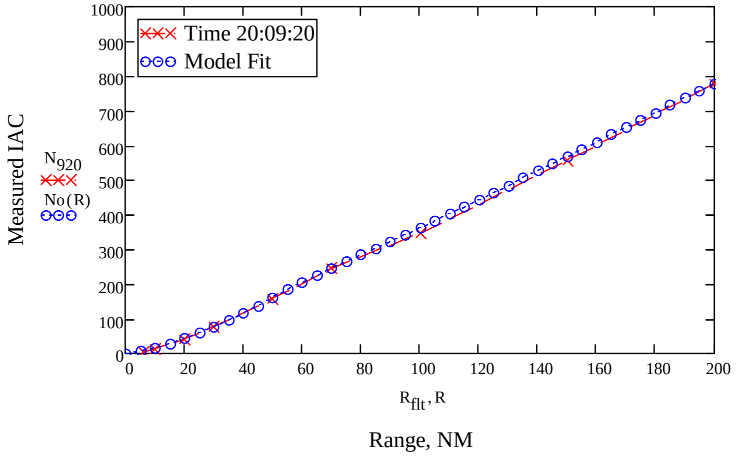
[6] All WJHTC data were provided by Tom Pagano and Leo Wapelhorst. They also contributed to development of some new features in the model.

No(6) = 8   No(10) = 17   No(20) = 45   No(30) = 79   No(50) = 161   Ro = 94   No(Ro) = 339

No(70) = 246   No(100) = 364   No(150) = 568   No(200) = 780   No(300) = 1218   No(400) = 1672



Measured traffic distribution relative to time reference point for April 7, 2011 test flight and model fit to measured distribution

Figure 12. Measured and Modeled Radial Traffic Distribution

The modeled altitude traffic distribution shown in Figure 13 was originally developed from extensive data collected by MITRE, and as shown, is independently corroborated by WJHTC measurements. For a given victim receiver altitude, this distribution determines the fraction of the all in view radial traffic that is above the Line-Of-Sight (LOS) limit and thus within view of the receiver.

Altitude Model $Ca := 0.09$ $p(h) := Ca \cdot e^{-Ca \cdot h}$

$F(H) := \int_0^H p(h)\,dh$ $m := \int_0^\infty p(h) \cdot h\,dh$ $m = 11.1$

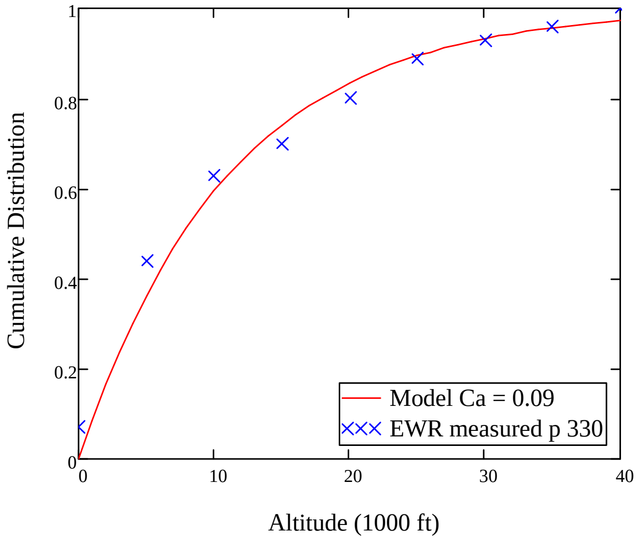
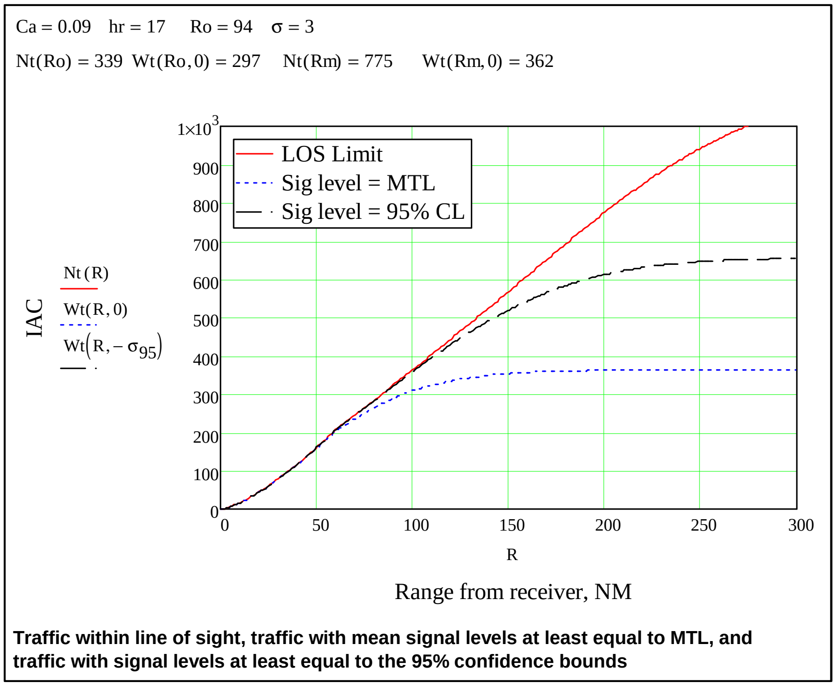


Figure 13. Altitude Distribution Model Fit Compared with WJHTC July 2007 Test Flight Measured Distribution

The link budget and signal level variations determine the detectability of transmissions from targets within view as illustrated in Figure 14 for an assumed receiver altitude of *hr* = 17 kft and a Minimum Triggering Level (MTL) = -84 dBm[7] or an MTL range of 94 NM. Figure 14 shows Instantaneous Air Count aircraft (IAC) with mean signal levels at least equal to the MTL are those within a range of about 150 NM (or approximately 375 aircraft); those with signal levels at least equal to the 95 percent confidence bound (and still potential interferers) are about 650 aircraft. Aircraft beyond about 200 NM contribute little to the interference level.



Traffic within line of sight, traffic with mean signal levels at least equal to MTL, and traffic with signal levels at least equal to the 95% confidence bounds

Figure 14. Traffic Limitations Due to LOS and Link Signal Levels and Variations

In addition to self-interference from other ADS-B 1090ES users, 1090ES operation shares the 1090 MHz channel with Air Traffic Control Radar Beacon System (ATCRBS) and Mode-Select transponder (Mode-S) fruit replies to ATC SSR, TCAS replies, and military Identification Friend or Foe (IFF) interrogation replies. Based on the effective number and characteristics of these basic interrogation sources, and the distribution and type of responding aircraft, the model develops the expected distribution of co-channel fruit interference competing with reception of the desired 1090ES message. A detailed representation of this process would require simulation of each interrogation and each reply over the whole distribution of potential interrogators and responding aircraft. In addition to a lack of details regarding these locations and aircraft velocities as well as details on actual ground and aircraft antenna patterns, practical limits on the utility of this micro level simulation approach include uncertainty in knowing how many active SSR interrogators are in view (even though an interrogator data base may be available), and how to realistically represent TCAS operations. Fortunately, experience has shown that an operationally useful representation of this process can be parametrically defined at the macro level. Modeled characteristics are closely coupled with measured test flight parameters to facilitate validation of the approach and enable sensitivity examinations of results.

In the strict sense, aircraft at different altitudes and locations over the scenario of interest will see a different field of SSRs within LOS and be exposed to different TCAS interrogation

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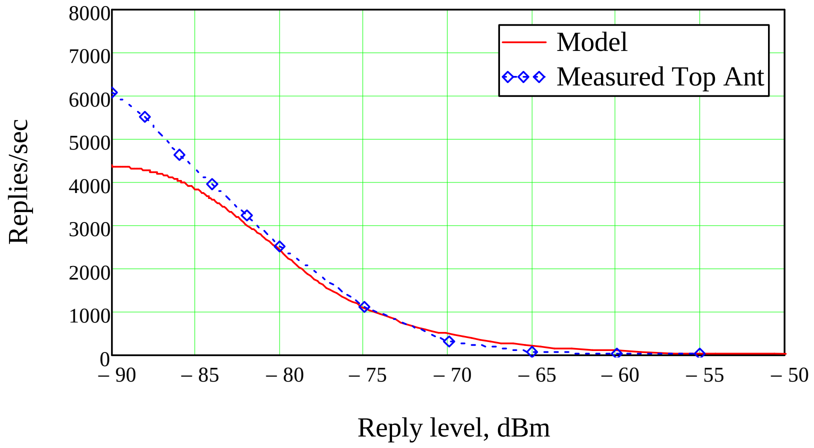
[7] The MTL is the signal level required for a 90% probability of detection.

environments. In general, those aircraft closer to the center of interrogation sources and at higher altitudes see the most intense level of interrogations. The approach described here uses an average example to typify all aircraft. The model assumes that this aircraft is exposed to *M* ground SSRs and, due to typical up-link power budget margins, that any SSR in view is an effective interrogator. These interrogations (times the probability of reply to interrogations) determine the reply rate component of the fruit. A similar average density representation of TCAS interactive behavior estimates this contribution to the total interference level. The fraction of the traffic equipped with 1090ES and the 1090ES broadcast rate (plus a ground based service broadcasting ES messages) determine the 1090ES component of the fruit rate.

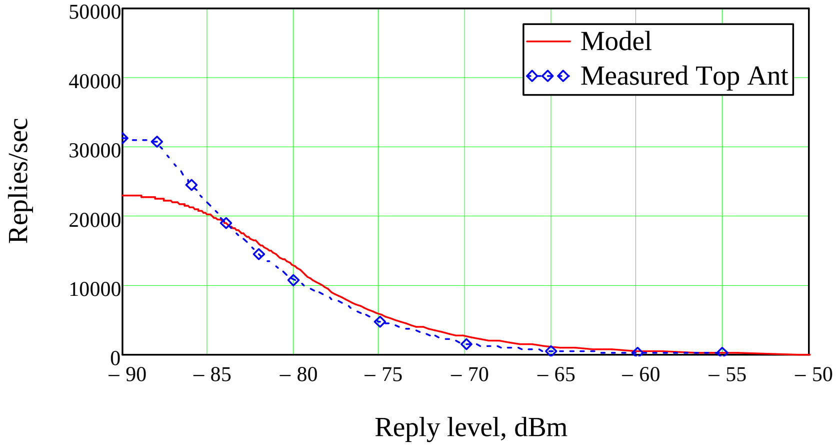
Details are not provided, but Figure 15 compares the modeled Mode-S fruit distribution (top of figure) and ATCRBS rates (bottom of figure) with recent WJHTC flight test measurements.

average reply rate/aircraft: $za = 64$ $zs = 10.2$ $zsl = 0.6$ $zsT = 12.1$ $p_r = 0.9$

$fS(Ro,0) = 0.29$ $fSt(Ro,0) = 0.6$ $fSl(Ro,0) = 0.05$ $fza(Ro,0) = 18999$ $fzsT(Ro,0) = 3604$



Modeled and top antenna measured Mode S fruit distribution



Modeled and top antenna measured Mode A/C fruit distribution

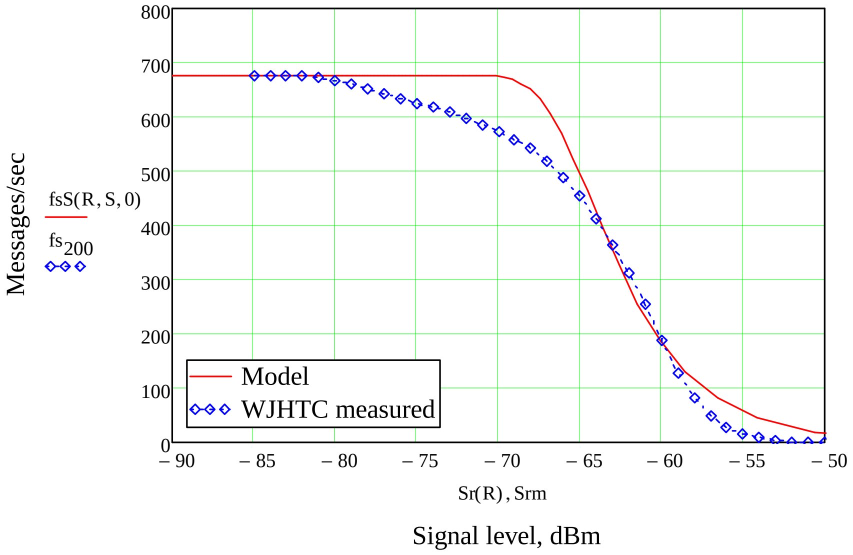
Figure 15. Comparisons of Modeled and Flight Test Measured Fruit Distributions

The higher measured rates at signal levels below the -84 dBm MTL level are due to false decode detections at these low signal levels. Modeled and measured rates are otherwise in very close agreement.

WJHTC data analysis also revealed that the current practice of supporting TCAS operation on the airport surface produced a new source of fruit when in proximity to the three large airports in the New York area. The measured and modeled distributions of this fruit component are shown in Figure 16.

$M_g = 112$ $R_g = 10$ $S = 7$ $hr = 17$ Kft $H_g \cdot 1000 = 30$ ft $zsS = 6$ $\sigma = 3$

$Nt_g(300, 0) = 112$ $Ro = 94$ $Wt_g(Ro, 0, 0) = 112$ $Wt_g(300, 0, 0) = 112$ $R := 1, 2 .. 300$

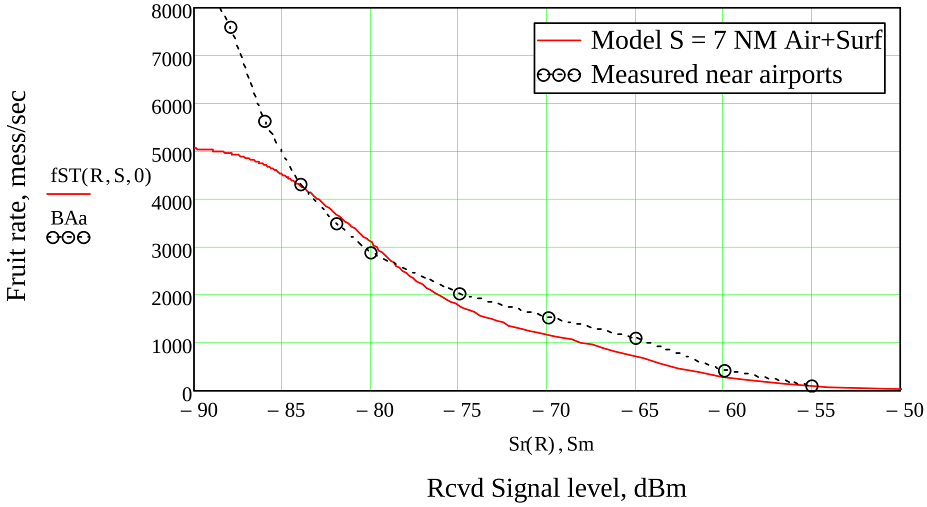


Measured and modeled fruit distribution from airport surface aircraft under above assumptions

Figure 16. Mode-S Fruit from Airport Surface Aircraft in NY Area

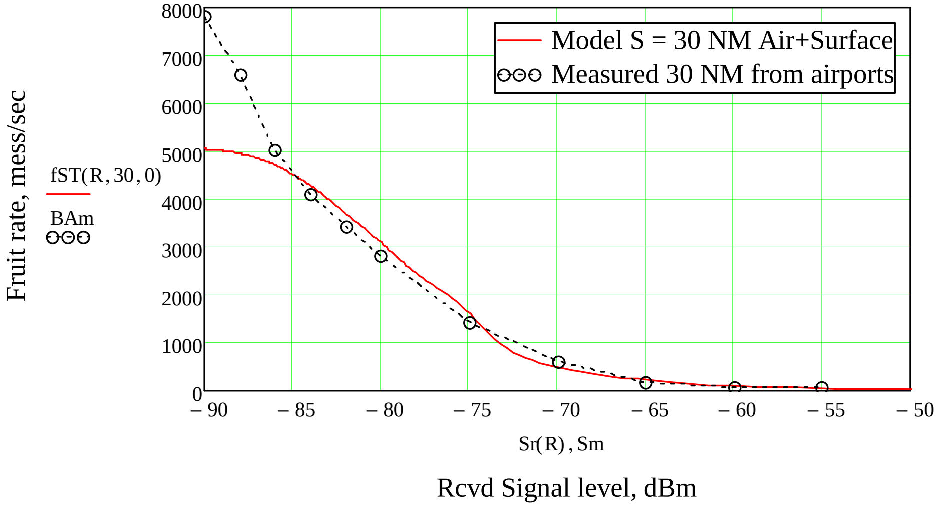
The surface traffic Mode-S fruit distributions for two distances from the NY area airport (*S* = 7 NM and *S* = 30 NM) are combined with the top antenna fruit shown in Figure 15 to yield the bottom antenna distributions given in Figure 17. Again, very close agreement between the measurements and the model distributions is shown.

$M_g = 112$ $R_g = 10$ $S = 7$ $H_g \cdot 1000 = 30$ $zsS = 6$ $hr = 17$ $zsT = 12.1$



Measured Bottom antenna and model air plus surface Mode-S fruit distributions when S = 7 NM from airports center

$M_g = 112$ $R_g = 10$ $H_g \cdot 1000 = 30$ $zsS = 6$ $hr = 17$ $zsT = 12.1$ $fST(Ro, 30, 0) = 4280$



Measured Bottom antenna and model air plus surface Mode-S fruit distributions when S = 30 NM from airports center

Figure 17. Comparisons of Measured and Modeled Bottom Antenna Mode-S Fruit Distributions at Two Distances from the NY Area Airports

The close agreement of these model results compared with test flight measurements illustrate the ability of the MITRE Model to parametrically represent a specified current or future interference scenario as described in the first part of step one in the validation process. Estimates of expected 1090ES reception capability in this specified interference environment (second part of step one and step two) requires a model of receiver/decoder capability to reliably decode a 1090 ES message in given interference conditions. This is described in Section 3.3.

3.3 Receiver Decoder Validation

Reception capability in a clear channel is limited by the receiver signal-to-noise message decode error rate. As mentioned above, this is characterized by the MTL for 1090 MHz applications. A much more significant restriction on capability is imposed, however, by co-channel interference. In this case, the ability of the receiver to properly decode the desired message when overlapped by Mode-A/C and Mode-S fruit replies as well as other ES messages limits operational use of the link.

Despite the fact that 1090ES has been of interest for ADS-B applications for over twenty years and many decoder claims have been made, only limited quantitative measurements on actual ES decoder capabilities in expected co-channel interference are available. The DO-260B MOPS requirements for decoder performance are test criteria in basic interference overlap situations that do not readily relate to actual interference scenarios. Realistic representation of the co-channel interference is challenging and bench measurements at WJHTC on a DO-260B compliant decoder are generally accepted as the industry standard for DO-260B MOPS compliant performance. These results for two interference levels (scenarios labeled High fruit rates, and Very High fruit rates) are used to tune and verify the MITRE parametric decoder model as discussed in the following.

WJHTC measured Percent ES Reception (probability of correct message decode) as a function of signal level for the assumed High levels of Mode-S and ATCRBS fruit are shown in Figure 18.

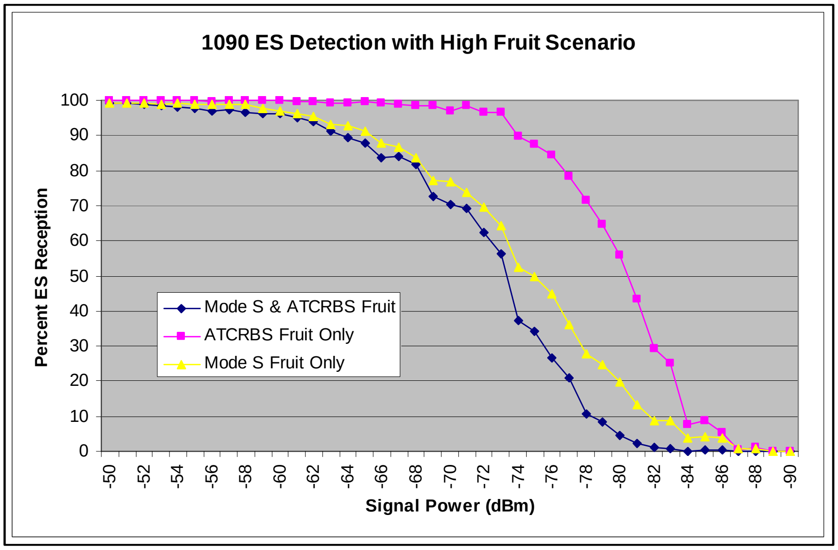
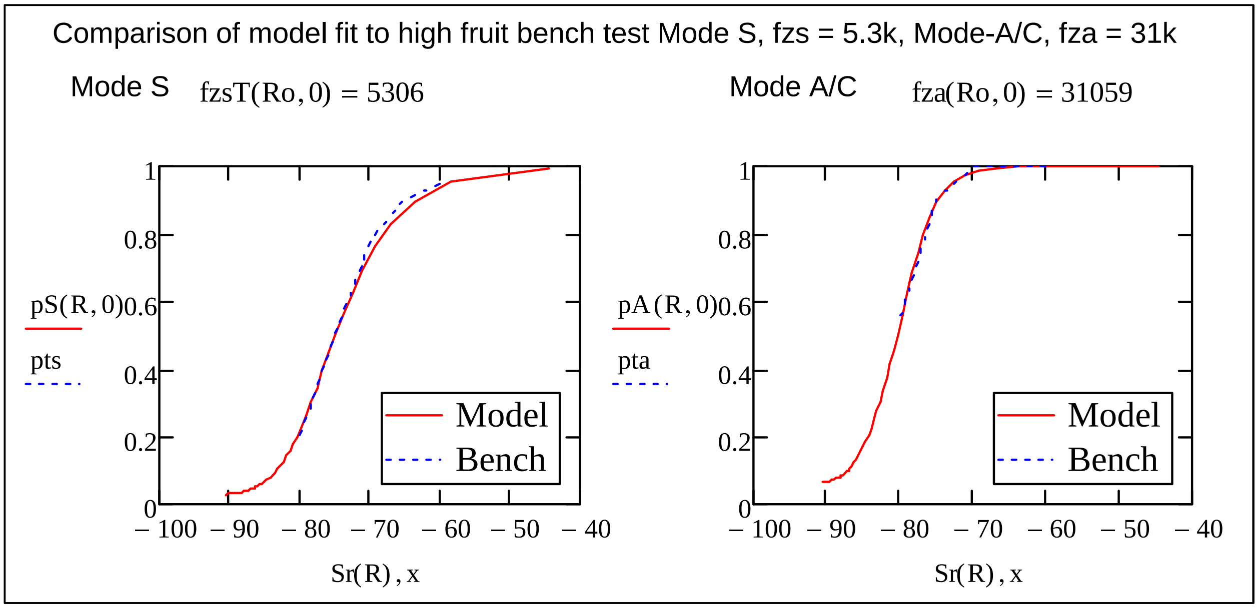


Figure 18. Message Success Rate vs. Received Signal Level for an A3 Receiver in the High Interference Environment for Each Type of Interference

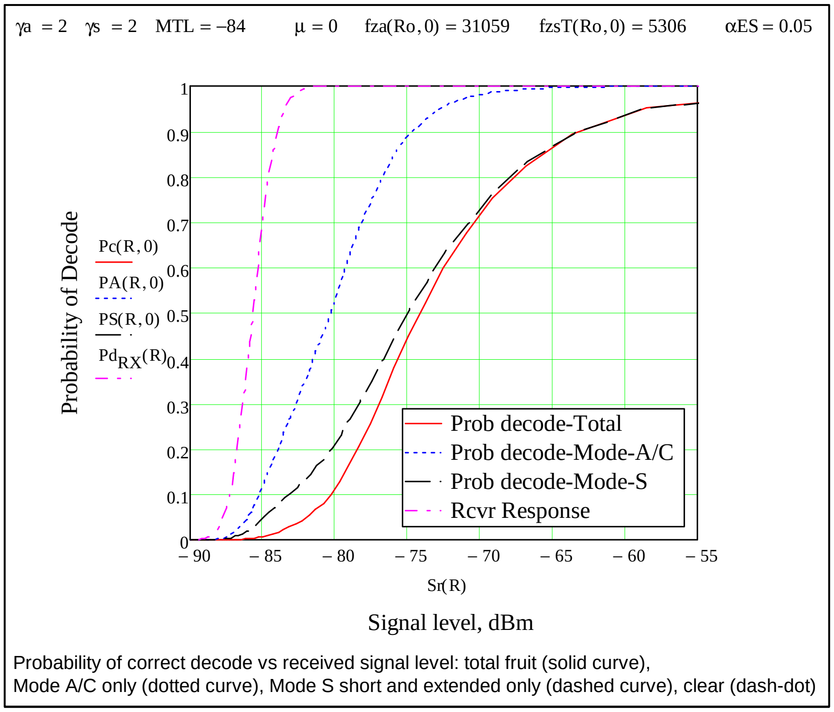
Figure 19 shows the MITRE Model compares very closely with these Figure 18 High fruit rate measurements for both the given Mode-A/C and Mode-S fruit rates.



Comparison of model fit to high fruit bench test Mode S, fzs = 5.3k, Mode-A/C, fza = 31k

Figure 19. Comparison of MITRE Decoder Model with High Fruit Rate WJHTC Bench Measurements

The total probability of decode for the MITRE Model in the High fruit environment is shown with these separate components and the receiver sensitivity in Figure 20.



Probability of correct decode vs received signal level: total fruit (solid curve), Mode A/C only (dotted curve), Mode S short and extended only (dashed curve), clear (dash-dot)

Figure 20. MITRE Receiver/Decoder Model Total Performance in High Fruit Environment

WJHTC bench measurements for the probability of decode in Very High Mode-A/C and Mode-S fruit rates are compared in Figure 21 with the High fruit rate bench results previously shown in Figure 18.

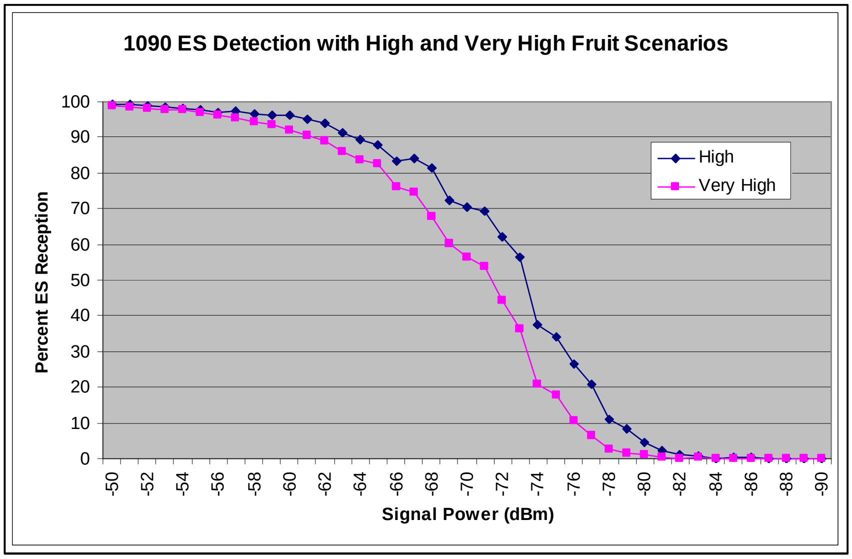
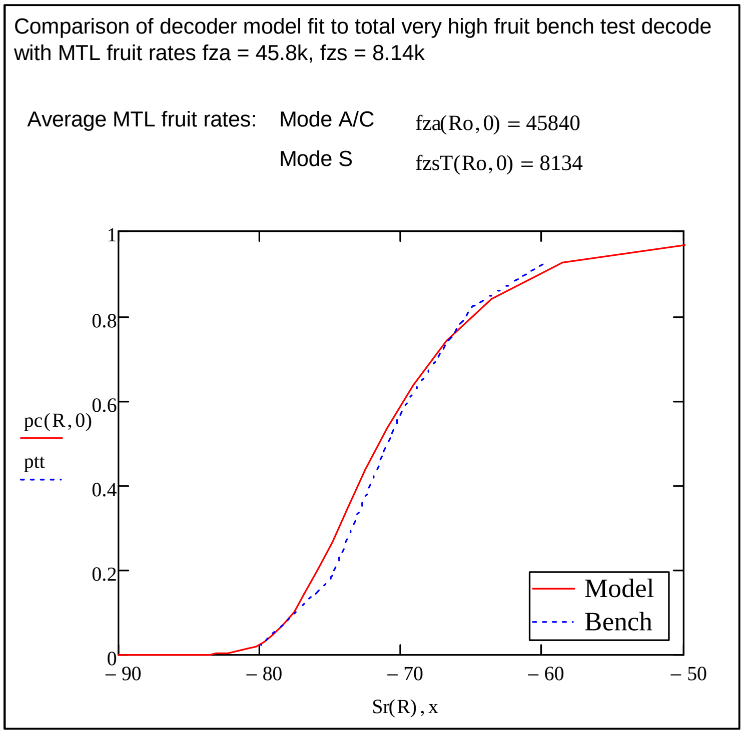


Figure 21. Message Success rate vs. Received Signal Level for an A3 Receiver in High and Very High Interference Environments

Figure 22 compares the MITRE Model probability of decode with the Very High fruit rate bench measurements shown in Figure 21. Again, model results are consistent with the bench measurements at these Very High fruit rates.


Comparison of decoder model fit to total very high fruit bench test decode with MTL fruit rates fza = 45.8k, fzs = 8.14k

Average MTL fruit rates: Mode A/C $\mathrm{fza}(\mathrm{Ro},0) = 45840$

Mode S $\mathrm{fzsT}(\mathrm{Ro},0) = 8134$

Figure 22. Comparison of MITRE Decoder Model with Very High Fruit Rate WJHTC Bench Measurements

Based on this decoder model capability, estimated probability of decode versus range for the 2011 flight test interference environment discussed above is shown in Figure 23 compared with the WJHTC test flight measured values. The dotted curve also shown in the figure is the receiver sensitivity response in a clear channel condition.

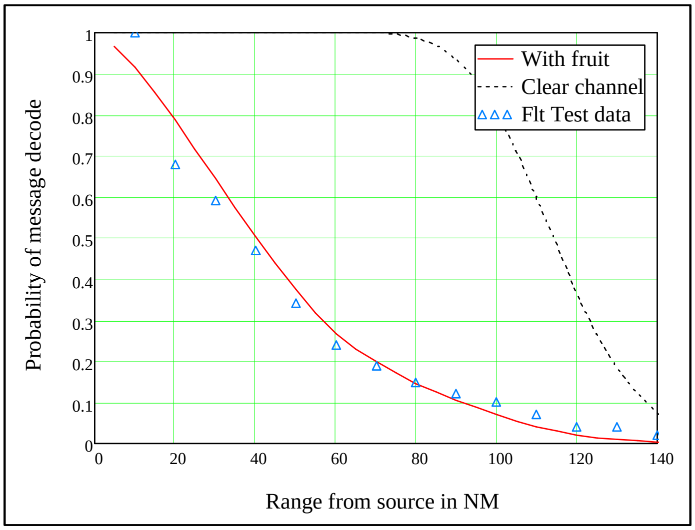


Figure 23. Model Estimated Probability of Decode in 2011 Flight Test Interference Environment Compared with WJHTC Measured Values

3.4 Model Validation Summary

MITRE Model use in representation of future interference levels based on parametric descriptions of the environment is expected to be accurate based on experience modeling current environments and comparisons with WJHTC test flight measurement. Reliable measurements required to validate the decoder component of the model are limited to comparisons with available bench measurements and flight test data from WJHTC. Although limited, the model and data seem to be in reasonably close agreement.

This decoder model is required to extrapolate expected performance in a given fruit environment to probability of message decode versus range. Performance assessments in the next section must therefore be considered the best available estimates until more independent validation data are available to further verify the decoder model.

4 Wake Vortex/Meteorology Alternatives Evaluations

Estimating the future 1090 MHz interference levels is a complex and controversial topic, and to some extent, depends upon choices made by the Federal Aviation Administration (FAA) determining how the channel will be used. These issues are being examined currently by the "1090 MHz Spectrum Mitigation Alternatives Analysis Working Group." Final assessments are not yet available from this group, but they have defined a number of baseline cases determined by known changes that will be made to the system and assumed traffic Growth Factors (GFs) relative to current traffic levels. Details related to this parametric characterization of possible future interference levels are described in the "1090 MHz Spectrum Congestion Mitigation Analysis Baseline and Future Growth Scenarios Model Summary" distributed by the above Spectrum Mitigation Group. The following WV/MET alternatives evaluation will use the interference conditions described in this reference as the 2020 Baseline, and the 2020 Baseline with traffic Growth Factors 2.0 and 3.0. The interference level for the 2020 Baseline assumes the traffic level is the same as that measured in 2011 WJHTC test flights and all the currently planned changes to the interrogator environment have been implemented.

4.1 2020 Baseline Scenario Interference

4.1.1 Interleaved Air Reference Velocity Wake Vortex Alternative

The probability of ARV message decode required to meet OSED updates are shown in Figures 3 through 5 to be a minimum of 0.4 over a maximum air-air range of 20 NM. The expected ES decode capability in the Baseline 2020 interference scenario along with the MET format and normal SV update requirements can be determined from Figure 24. The required 0.4 decode probability for WV support out to a range of 20 NM is easily achieved in this case since it is well below the expected ES message decode probability.

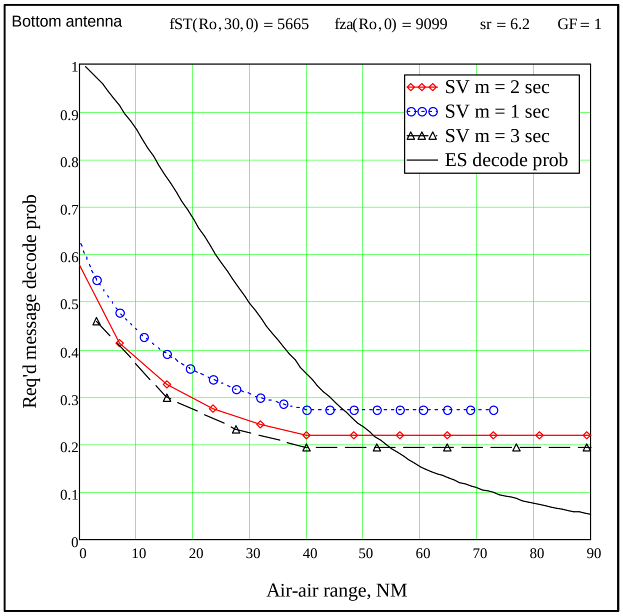


Figure 24. Baseline 2020 Probability of ES Message Decode vs. Range Compared with Minimum Decode Probabilities for a SV Update with 1, 2, and 3 second Velocity Lags

The impact of this alternative on ADS-B users of GPS derived SV surveillance is determined by any loss in coverage due to the increase in this required probability of decode versus range with the interleaved ARV. Comparing Figure 11 for the interleaved ARV with Figure 10 for normal conditions shows the once per three second interleaved ARV has no measureable effect on normal ADS-B application support shown in Figure 24.

The proposed interleaved ARV message therefore meets the requirements for WV support in this Baseline 2020 scenario and causes no measureable loss of coverage for normal SV updates.

4.1.2 Additional Meteorology Format Message Broadcasts

Since the Figure 3 required MET 1 OSED proposed broadcast rate just meets the ES decoder capability in Figure 24, a conservative estimate of the additional fruit created by the MET Format 1 and 2 message broadcasts assumes all ES users broadcast these formats at the rate of 0.38 mess/sec/aircraft required to meet the probability of decode requirements given in Figure 5. This results in the total ES broadcast rate of 6.58 mess/sec/aircraft rather than the normally assumed 6.2 mess/sec/aircraft. The effect of the resulting increase in fruit rates on probability of ES message decode is shown to be negligible in Figure 25. The WV/MET support requirements given in Figure 5 are thus easily met as shown in Figure 25.

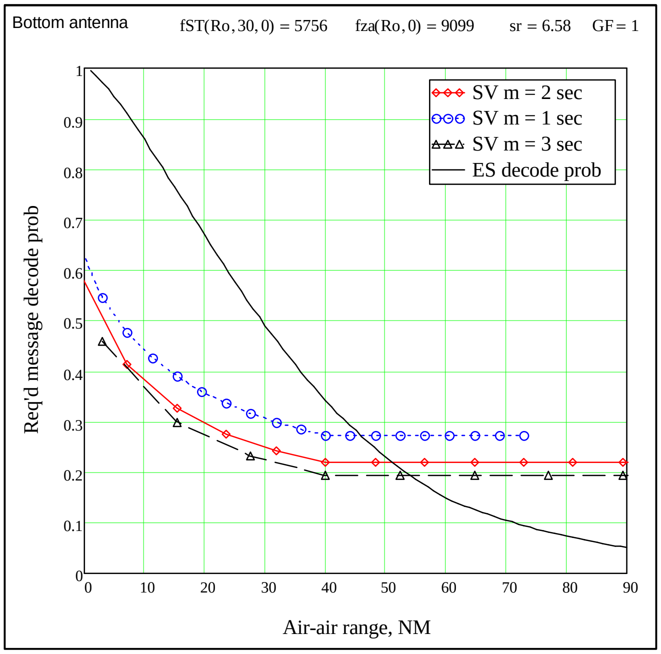


Figure 25. Baseline 2020 Probability of ES Message Decode vs. Range with MET Format Broadcast Compared with Minimum Decode Probabilities for a SV Update with 1, 2, and 3 second Velocity Lags

The increased broadcast rate of MET 1 message of 0.33 mess/sec/aircraft and the OSED proposed rate for MET 2 meet WV/MET support requirements in the 2020 Baseline scenario. The increased Mode-S fruit rate of 5756 mess/sec due to these additional broadcasts compared with the original rate of 5665 mess/sec has no measureable impact on decoder capability in this case.

4.2 2020 Baseline Interference with Traffic Growth Factors

4.2.1 Growth Factor 2 Scenario

The 1090ES message decode probability versus range for the interference environment defined by the Baseline 2020 scenario with a traffic GF of two is shown in Figure 26. This assumed traffic increase by a factor of two significantly reduces the ES range capability and now Figure 5 SV/MET support minimum decode requirement of approximately 0.4 at a 20 NM separation is only marginally met. Although the SV decode capability is limited in this case, the differential effect of the interleaved ARV message is unnoticeable.

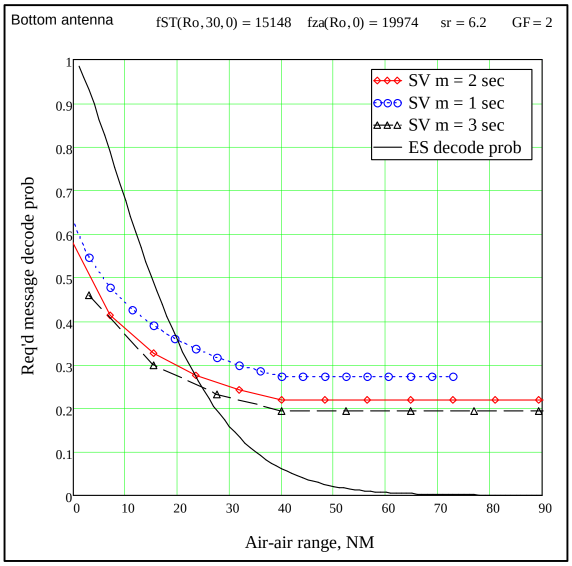


Figure 26. Baseline 2020 with GF = 2 Probability of ES Message Decode vs. Range Compared with Minimum Decode Probabilities for a SV Update with 1, 2, and 3 second Velocity Lags

Figure 27 for the increased broadcast rate due to the MET format messages shows it again has no measurable effect on ES decoder capability.

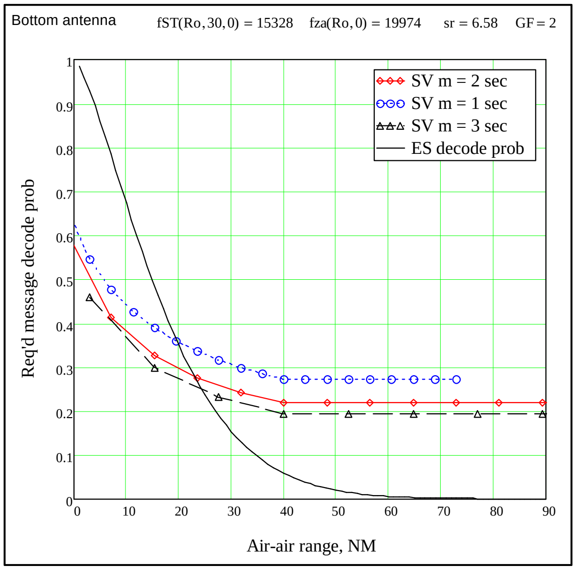


Figure 27. Baseline 2020 with GF = 2 Probability of ES Message Decode vs. Range with MET Format Broadcast Compared with Minimum Decode Probabilities for a SV Update

4.2.2 Growth Factor 3 Scenario

The higher interference level associated with a further increase in traffic density by an assumed *GF* of three causes a drastic reduction in 1090ES message decode capability as shown in Figure 28. The WV/MET support requirements are not met in this case. Although the normal SV coverage in Figure 28 is limited to only10-15 NM, the interleaved ARV would not further reduce this by any measureable amount.

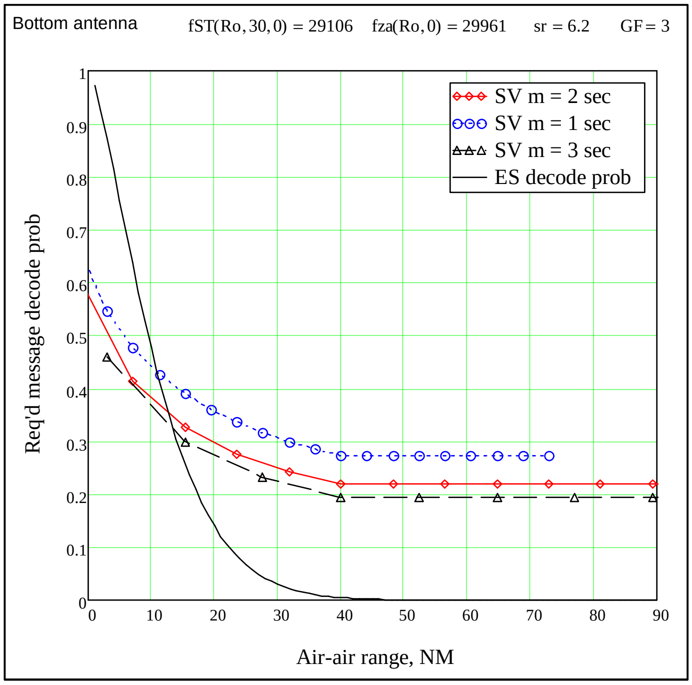


Figure 28. Baseline 2020 with *GF* = 3 Probability of ES Message Decode vs. Range Compared with Minimum Decode Probabilities for a SV Update with 1, 2, and 3 second Velocity Lags

5 Conclusions

Meteorology (MET) data update support requirements were derived from the Wake Vortex (WV)/MET Operational Services and Environmental Document (OSED). Message decode requirements for MET 1 and 2 as well as Air Reference Velocity (ARV) were then determined. Capability of 1090ES to support these WV/MET requirements required comparison of these minimum support decode probabilities with expected ES message decode probabilities in future scenarios.

Expected fruit rates in several future scenarios determined by the 1090 Megahertz (MHz) Spectrum Mitigation Working Group were estimated by The MITRE 1090 MHz co-channel interference model described in Section 3.2. ES message decode probabilities in these interference environments depends upon the message decoder capability. Section 4.1 shows 1090ES can support the WV/MET Alternative requirements for MET formats 1 and 2 and for the ARV in the 2020 Baseline scenario without penalty to normal 1090ES user capability. Section 4.2 shows only a marginal capability for this support with a traffic growth factor of two, and essentially no support capability for a growth factor of three.

Appendix A Glossary and Abbreviations

Acronym	**Definition**
ADS-B	Automatic Dependent Surveillance-Broadcast
ARV	Air Reference Velocity
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
CAASD	Center for Advanced Aviation System Development
CL	Confidence Level
CPR	Compact Position Report
ES	Extended Squitter
FAA	Federal Aviation Administration
GD	Global Decode
GF	Growth Factor
GPS	Global Positioning System
IFF	Identification Friend or Foe
LOS	Line of Sight
MASPS	Minimum Aviation System Performance Standards
MET	Meteorology
MHz	Megahertz
MLT	Modulated Lapped Transform
MOPS	Minimum Operational Performance Standards
MTL	Minimum Triggering Level
NM	Nautical Miles
OSED	Operational Services and Environmental Document
RTCA	Radio Technical Commission for Aeronautics
SSR	Secondary Surveillance Radar
SV	State Vector
TCAS	Traffic Collision Avoidance System
WJHTC	William J Hughes Technical Center
WV	Wake Vortex

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