Appendix J
Accuracy and Update Period Requirements Analysis

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J.1 Overview

This appendix summarizes the rationale for Table 3-4, which specifies requirements for accuracy and report update period. These requirements were based on analysis and simulation of the scenarios given in Section 2.

This Section provides a summary of the methodology and assumptions used in the analyses presented in Sections J.2 and J.3. Section J.2 presents general analyses of the use of barometric vs. geometric altitude, use of bank angle, and latency. Section J.3 presents analyses of stressful scenarios described in Section 2. Analysis of each scenario results in statements of standards for ADS-B position accuracy, velocity accuracy, update period, and probability of update. Given that ADS-B, as defined in Section 1, acts as a conduit for information, it cannot improve on the accuracy of the information from the source. The requirements for ADS-B accuracy are therefore based on an error budget that allocates a portion of the total tolerable error to the contribution from ADS-B.

J.1.1 Methodology

Much of the analysis that follows made use of a Monte-Carlo simulation that was originally developed for TCAS, then modified for ADS-B analyses. This simulation models two-aircraft encounters, either airborne or on the airport surface. The trajectories of both aircraft can be specified, including turns, speed changes, and altitude rate changes. The simulation includes measurement noise, simulates varying update period and receive probabilities, and models latency for both aircraft. The simulation also models random variations in aircraft trajectories about the nominal paths (this part of the model is called plant noise). Plant noise simulates the effects of wind gusts and minor pilot deviations.

For simulation of air-to-air applications, one aircraft is designated as “own” and the other is designated as the “intruder.” Own aircraft state vector updates are modeled as being received reliably and at a high rate (at least once per second). The amounts of noise and latency can be different for the two aircraft, a difference that is needed in simulating air-to-air applications.

The analysis process begins with a specific stressful scenario from Section 2. The simulation is used to evaluate the sensitivity to various ADS-B parameters (position accuracy, velocity accuracy, report update period, and probability of report). Using the Monte-Carlo technique, each scenario is run many times with random perturbations applied to the stochastic variables, including plant noise. (Because of plant noise, the scenario itself becomes randomized within limits, as well as the measurement noise, received report sequence, etc.)

In most cases, the simulation of an application performs linear projections into the future using the state vectors of both aircraft. The linear projections are used to determine the point of closest approach including the horizontal miss distance (HMD), the vertical miss distance (VMD), and the time to the closest point of approach (TCPA). Threshold values are established for these three variables, and an alert is triggered if the projected HMD, VMD, and TCPA are all smaller than the thresholds. As a simulation is being run for a conflict scenario, warning time for the alerts is recorded. After a conflict simulation run is completed, statistics are calculated on alert warning times. Sensitivities of the alert warning time to data errors and update rates were then analyzed. False alarm scenarios were analyzed in a similar way; in this case however, false alarm rates, rather than alert warning times, were recorded and studied.

Based on suggested design goals for acceptable warning times and false alarm rates, recommendations were made as to required values for data errors and update periods. Finally, where possible, comparisons were made against existing, operational systems. This helps to ensure that applications using ADS-B data are likely to perform at least as well as existing systems.

J.1.2 Simplifying Models and Assumptions

It is an assumption of this analysis that both position and velocity components of the state vector will be available in ADS-B reports, as is required by the MASPS in Section 3. No smoothing of the state vector data was performed; the measurement errors of the report are assumed to apply to the data which is used by the application.

A linear, orthogonal, Cartesian coordinate system was assumed for the horizontal measurements. Although latitude and longitude is not a perfectly Cartesian system, the Cartesian assumption reasonably models independent measurement errors in latitude and longitude in most locations on the earth. Measurement inaccuracies are modeled by additive random errors, using the following notation.

σ_p = standard deviation of latitude error (m)
= standard deviation of longitude error (m)

σ_v = standard deviation of latitude-rate error (m/sec)
= standard deviation of longitude-rate error (m/sec)

~~We will a~~Also ~~refer to~~defined are σ_p as the standard deviation of position measurement error, and σ_v as the standard deviation of the velocity measurement error. These four errors are added to each aircraft for each measurement. Each error has a normal distribution, with zero mean. The four errors are uncorrelated with each other and uncorrelated in time.

J.1.3 Limitations

For each application, ~~we have indicated~~ suggested design goals are indicated; however, it is important to note the following points, summarized in Figure J-1. First, the simulations indicate the sensitivities of ADS-B conflict detection warning times to data accuracies and report update periods. They are not intended to imply that the procedure simulated will be operationally viable. The refinement of these scenarios, as well as the resulting design goals and consequent requirements, is an ongoing process.

Second, the requirements which are derived are not necessarily optimal. There are four variables which were assessed. These variables were changed two at a time rather than four at a time. Time considerations prevented the simultaneous analysis of all four variables (i.e., position accuracy, velocity accuracy, update period, and receive probability). Instead, a 1 second update period with a 0.95 Probability of receipt was selected as a baseline. The sensitivity to position and velocity error was then analyzed based on the results observed. Requirements for position and velocity errors were then suggested. ~~We applied t~~The suggested position and velocity accuracies were applied in a second simulation run where ~~we varied~~ update period and receive probability were varied.

In many cases, ~~we applied~~ engineering judgment was applied in making ~~our~~ these suggestions. For example, if a particular update rate was close to the agreed design goal, ~~we may have felt that it was~~this was deemed acceptable despite the fact that it did not meet the design criterion exactly.

= ~~We have performed a~~A parametric sensitivity analysis has been performed for some stressful scenarios; not an end-to-end requirements analysis.
- ~~Our s~~Suggestions are based on the sensitivities of the particular scenarios that were examined.
- ~~We do~~It is not claimed that any particular operation will be supported by ~~our~~ the suggested design goals.
- ~~Our s~~Suggestions are based on scientific study, with engineering judgment applied.

= Believe ~~we have struck~~ a good balance has been reached between what is reasonable and what is achievable.

Figure J-1 Limitations

J.2 General Considerations

Before describing the individual, specific scenarios which were evaluated ~~we will examine~~ three important considerations which were considered will be examined. These are:

a. The use of barometric versus geometric altitude (Section J.2.1);

b. The use of turn rate or bank angle (Section J.2.2), and

c. Effects of latency error biases and random report time errors (Section J.2.3).

J.2.1 Barometric Versus Geometric Altitude; Altitude Rate

~~We assessed t~~The trade-off between supplying barometric versus geometric altitude in ADS-B transmissions was assessed. ~~We a~~Also, assessed was the utility of altitude rate. ~~Our~~ The conclusion was that both barometric and geometric altitude values should be supplied, and that altitude rate should also be supplied. Barometric altitude must be supplied for compatibility with existing ATC automation. In addition, when selective availability is present, geometric altitude may be too coarse for use in surveillance applications.

However, ~~we~~ it should be noted that there are many potential advantages of geometric altitude which makes it reasonable to require geometric altitude reporting. First, the immediate availability of an accurate altitude rate without differentiating position data is an important advantage. Second, geometric altitude and altitude rate will not suffer from some of the difficulties inherent in barometric altitude reporting, such as altimetry errors due to calibration errors and pressure error gradients, which can be significant factors affecting the stability and accuracy of altitude reporting.

As an example, according to [1] barometric altimetry errors are the cause of most unresolved US TCAS II encounters. Use of geometric altitude may help to alleviate this difficulty. Consequently, one of the most promising avenues for further improvements in collision avoidance performance may be through the use of geometric altitude. ~~It is our assessment that~~Since geometric altitude can be of significant value to the overall surveillance problem~~ and~~, provisions should be made for its reporting in ADS-B. Figure J-2 provides a summary of these considerations.

Figure J-3 illustrates one of the difficulties with barometric pressure based altitude reporting. The figure illustrates the types of errors that are typically associated with a temperature inversion when using a standard temperature and pressure model for altitude estimation. The data used for this graph was supplied by the National Center for Atmospheric Research (NCAR) in Colorado, and is based on an actual Rayosonde balloon flight in Akron, Colorado, on February 8, 1994.

The abscissa indicates the actual geometric altitude of the balloon, while the ordinate represents the error in the altitude that would be estimated using a standard temperature and pressure model, as is used in barometric altimetry. What is important in the graph from a surveillance perspective is that the error changes as a function of altitude. The error gradient results in an error in estimated altitude rate. Altitude rate is a key factor in predicting a conflict between two aircraft.

= Transmission of barometric altitude required for compatibility with existing ground based ATC.

= Barometric altitude has limitations for surveillance.
- Barometric altimetry errors can be significant.
- Barometric pressure error gradients can be significant.
- Barometric altitude requires position differentiation to obtain a rate – can result in noisy rates.

= GPS based geometric altitude / rate has potential for:
- More stable, accurate rates
- No altimetry error concerns
- No pressure error gradients

= Requirement is that both be reported, if available.

Figure J-2 Barometric vs. Geometric Altitude: Summary

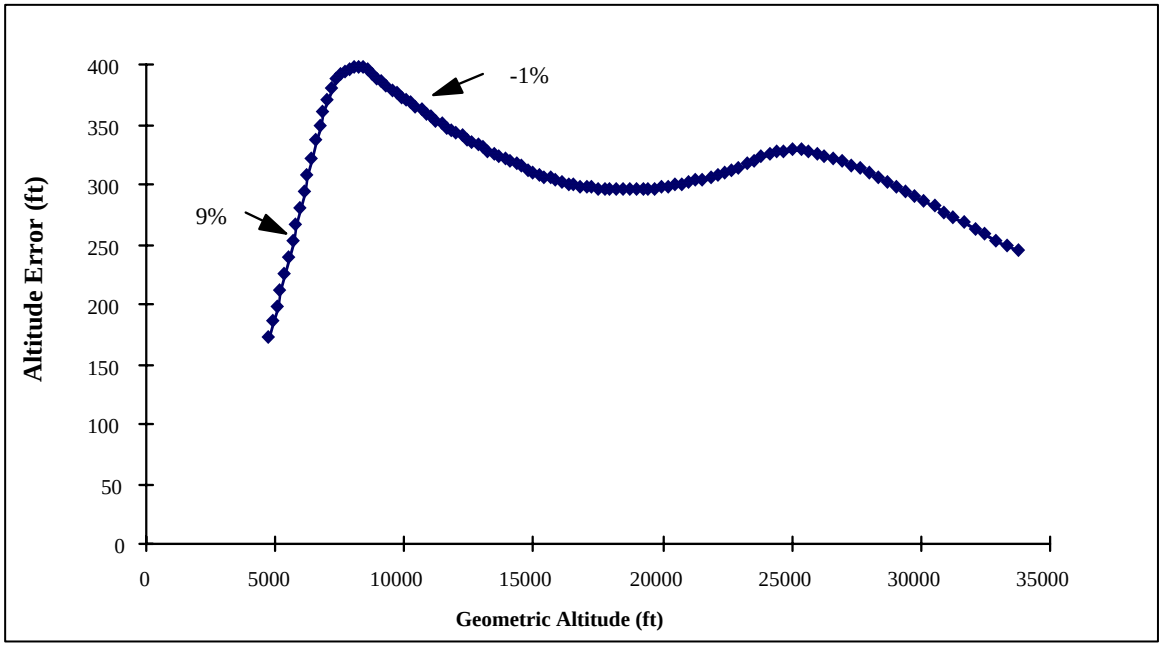

Figure J-3 Barometric Pressure Error Gradient Example
2/8/94, Akron, CO 18:00 GMT (Temperature Inversion)

In fact, if the error gradient, e.g., the slope of the curve in the figure, were constant the affect on surveillance applications would be minimal. However, it is the change in the gradient that causes an error in conflict prediction. It was found that in some of the worst case weather conditions in some of the worst locations recorded world-wide [2] that the change in the pressure gradient could be as high as 10%. It was found that the accuracy in predicting conflicts over such a gradient error change could be seriously compromised. The example is a nominal continental US temperature inversion. The change in the pressure error gradient is 10%, as seen from the annotation of the figure. Therefore the pressure error gradient changes expected to be seen under normal conditions can have a serious effect on altitude conflict prediction. This is one of the reasons geometric altitude and altitude rate are included in the ADS-B transmission.

Aside from the Gradient error question, also examined, using Monte-Carlo simulation techniques, was a conflict scenario in order to compare the conflict alert performance of geometric altitude, geometric altitude rate, and barometric altitude and altitude rate. The simulations conducted below used a process noise model for the vertical of two aircraft, based on a simple second order control model using a damping ratio of 0.6, a time constant of 20 seconds, and a 95% containment value for altitude of 125 feet.

Experiments were run using a 3 second report update period with 95% probability of reporting. The scenario used is similar to that of Figure J-16 with the addition of the process noise described above. FigureJ-4 below depicts a typical sample path used in the analysis. The results reported below are based on 500 Monte-Carlo iterations of the scenario. Each iteration of the scenario represents an obvious conflict, in fact, each is an NMAC.

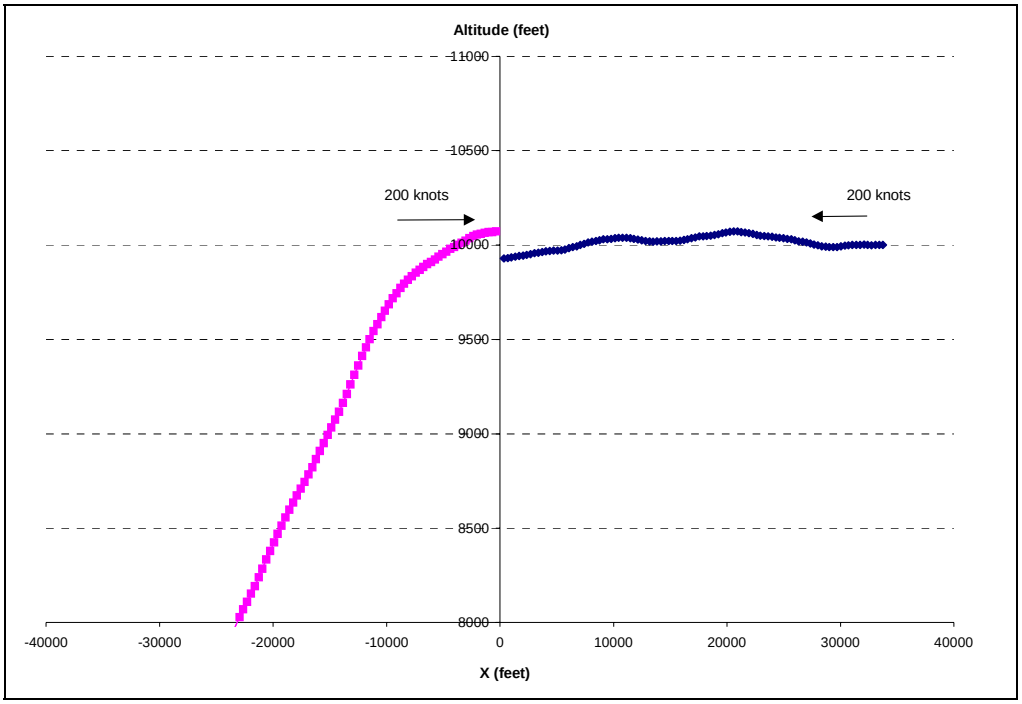

Figure J-4: Altitude Conflict Scenario Sample Path

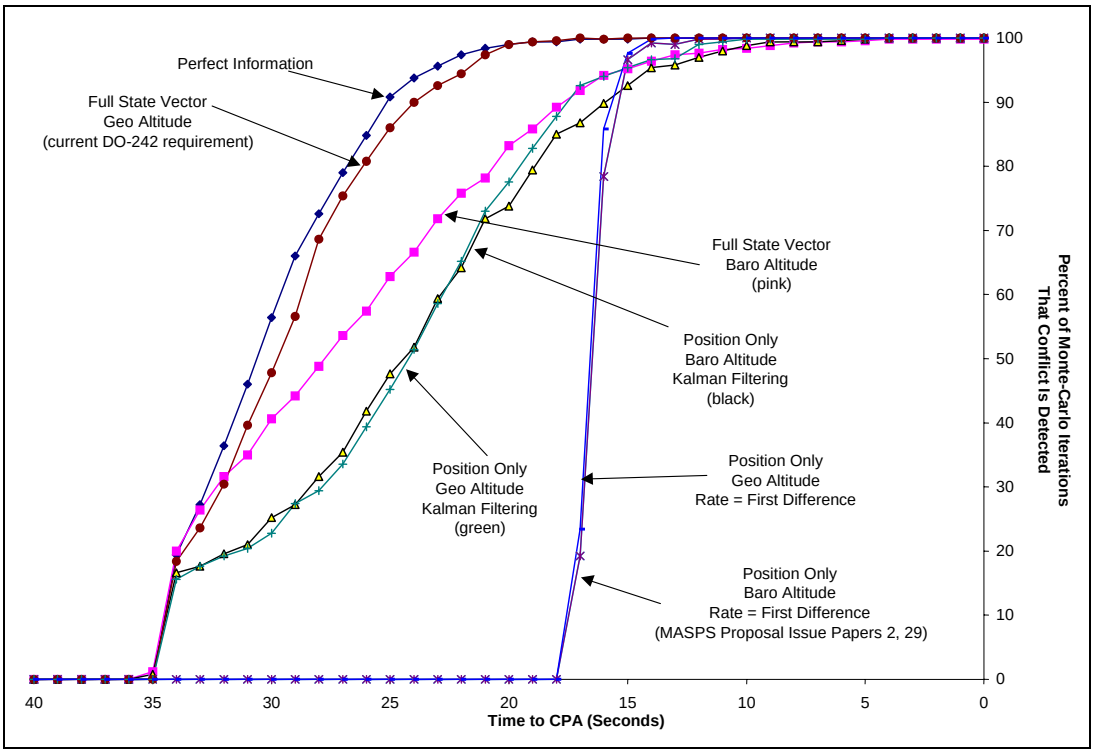

Figure J-5: Monte Carlo Simulation Results

A simple conflict detection algorithm was employed that alerts when predicted vertical miss distance and predicted time to closest point of approach fall below threshold values. For these experiments, the threshold on vertical miss distance was 600 feet and the threshold on estimated time to closest point of approach was 35 seconds.

Figure J-5 shows simulation results for several information and tracking alternatives. The figure depicts as a function of time to closest point of approach (abscissa) the percentage of Monte-Carlo iterations on which a conflict was detected (ordinate). Higher percentages earlier in the scenario represent better alerting performance.

The line in the figure labeled "perfect information" depicts results for an update rate of 1 report per second, both altitude and altitude rate being reported, and no error in the reported altitude information. The curve labeled "Full State Vector, Geo altitude" represents the current MASPS requirements for a 3 second update period with 95% probability of update, the MASPS tolerance for additional altitude errors, and reported geometric altitude based on GPS/WAAS accuracies.

Serious degradation of alerting times results with barometric altitude because of barometric altimetry errors. The model used for altimetry errors is consistent with that used in modeling TCAS. Even with full state vector information, barometric altitude results in significantly lower alert times than geometric altitude for this scenario.

Removing full state vector reports further reduces alerting performance. Two alternatives were examined using altitude-only reporting, rather than altitude plus altitude rate reporting. In the curves labeled "Kalman filtering," a Kalman filter was applied to smooth the reported altitude data. However, filter lags through the maneuver cause degradation in alerting performance.

Use of first differences to derive vertical rate is examined in the curves labeled "Position only, rate = first difference." These curves represent the performance of the proposals outlined in issue papers 2 and 29. These offer the worst performance observed in the study, and would result in significant degradation in alerting performance as compared with the current MASPS requirements.

In conclusion, the utility of both geometric altitude, and both barometric and geometric altitude rate have been demonstrated. The MASPS contain requirements for these variables because of their benefits in supporting conflict prediction.

J.2.2 Use of Bank Angle or Turn Rate

~~We will now discuss t~~The inclusion of bank angle, turn rate, or acceleration in ADS-B transmissions was also considered. ~~Our conclusion has been~~It was determined that ~~that~~ although bank angle may be desirable in certain instances, ~~but~~it should not be a required minimum data element. Figure J-6 illustrates the non-steady nature typical of aircraft turns. Idealized turn models usually simulate aircraft as rolling into a specified bank angle, holding that bank angle over a period of time, then rolling out of the turn. In fact, as demonstrated by the example, aircraft typically do not turn to a specific bank angle and hold it in a steady state for a period of time.

Figure J-6 was extracted from a 737 simulator based flight conducted in the NASA Airborne Information for Lateral Spacing (AILS) program. The abscissa is time in seconds, while the ordinate represents bank angle. The extent of the turn was 30 degrees, during which the pilot was turning onto final approach. There is almost no portion of the turn for which a constant bank angle is maintained.

Figure J-7 illustrates the effect of using turn rate to attempt to predict a conflict when the intent of the maneuvering aircraft is unknown. To derive Figure J-7~~-~~ ~~we analyzed~~ a two aircraft scenario was analyzed where one of the aircraft executes a 30 degree turn which resulted in loss of horizontal separation. The 30 degree maneuver was modeled using the bank angles shown in the previous slide.

In applying bank angle or cross-track acceleration in a prediction model, a typical simplifying assumption is to assume a constant bank angle. One also has to assume that the turn is going to end at some point in the future to make a prediction. What ~~we have~~was done in the analysis above is to assume three cases (1) bank angle is unused, (2), that the current bank angle continues for 5 more seconds, and (3) that the current bank angle continues for another 10 seconds. ~~We then updated t~~The intruder state vector was updated accordingly and made~~ke~~ a conflict prediction.

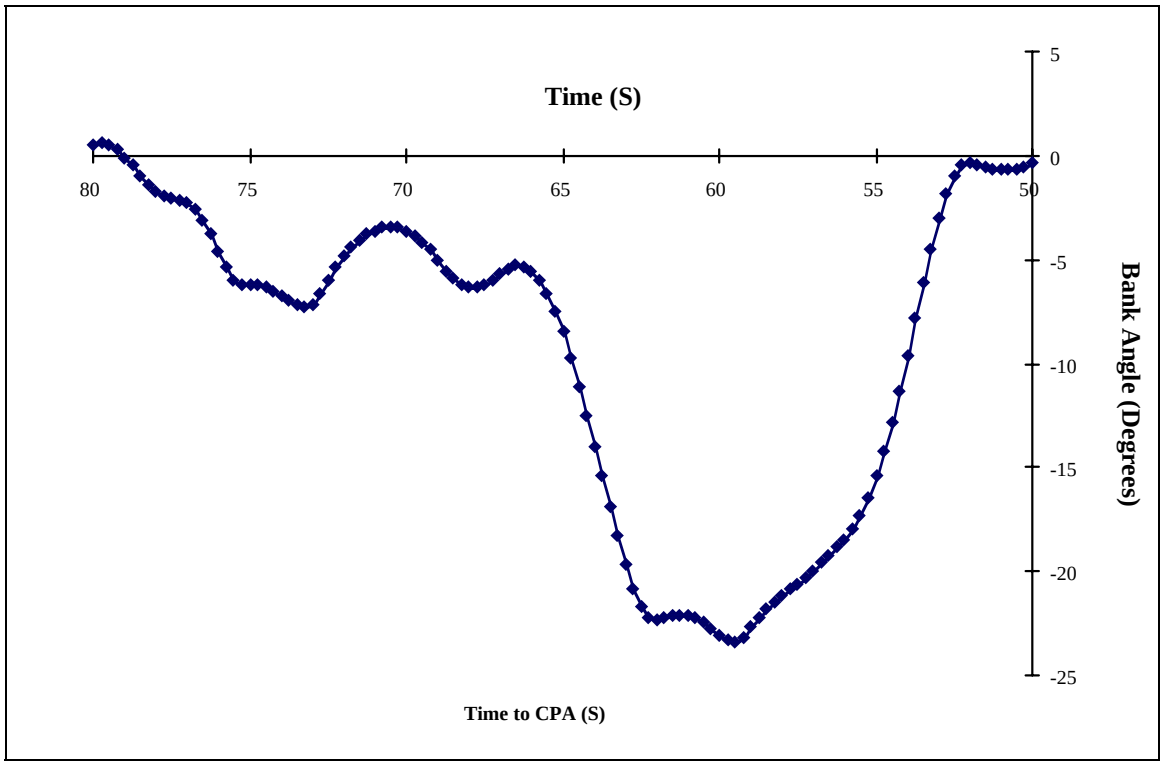

Figure J-6 Profile of Typical Bank Angles During Turn

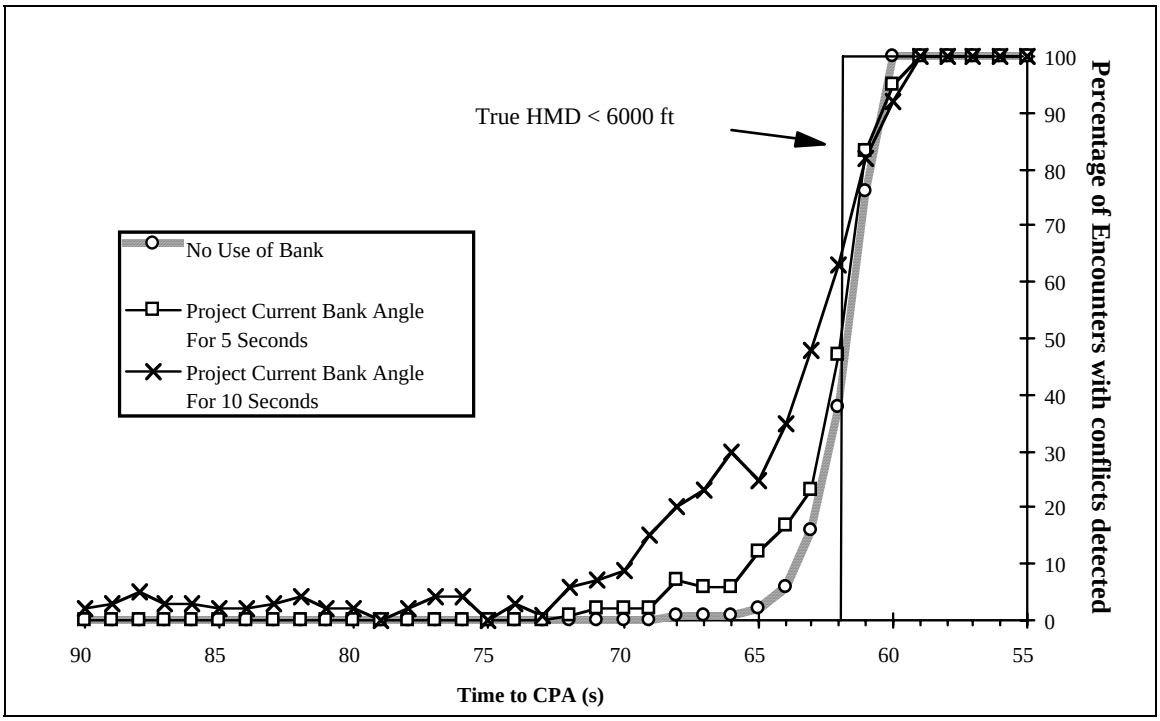

Figure J-7 Use of Bank Angle/Turn Rate:
Effect on Conflict Prediction for a Maneuvering Intruder

The abscissa of the graph is the time to CPA. The ordinate is the proportion of conflicts predicted in our simulation. The graph indicates that use of the assumption that the current bank angle will continue for 10 more seconds provides an early conflict prediction in only a small (about 20%) of the examples. In fact a detailed look at the proportion of encounters predicted reveals that the use of bank angle resulted in a later detection as the conflict progressed close to 60 seconds before CPA. This is because, without intent information, the use of acceleration caused the prediction to go around the turn farther than where the pilot actually stopped turning.

Figure J-8 indicates the false alarm rates for a non-conflict scenario where acceleration was used. In this case no deliberate maneuver was attempted. Recorded accelerations from a representative linear flight were used to model typical bank angles. In this case ~~we again attempted~~ the same set of experiments were attempted as were conducted in the conflict scenario.

What ~~we~~ was observed is that the use of bank angle can generate a high false alarm rate. The longer the acceleration is assumed to continue the higher the potential false alarm rate.

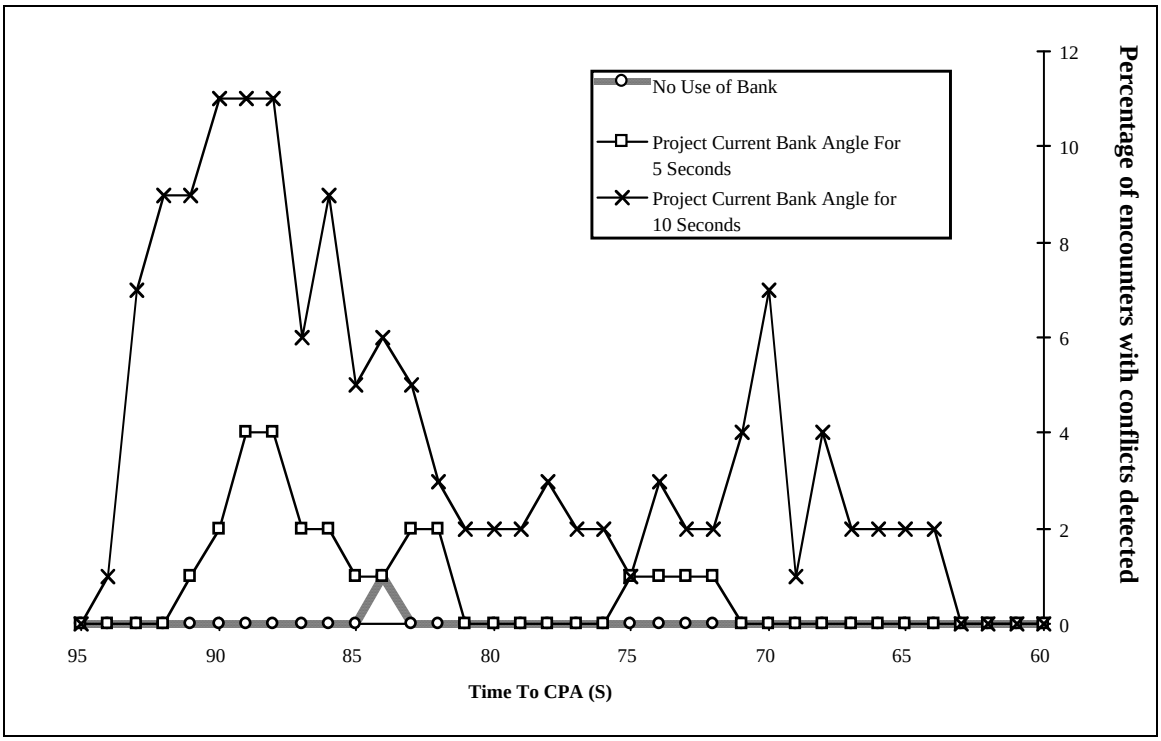

Figure J-8 Use of Bank Angle/Turn Rate:
Effect on False Alarms for Linear, Head-On Encounter

Overall, ~~we saw~~there was no compelling advantage ~~to~~ for the use of turn rate, bank angle, or equivalently, acceleration in the general conflict scenario. Meanwhile, ~~we observed~~ a large increase in false alarm probability was observed.

Therefore, ~~we are doubtful~~it was determined that acceleration, bank angle, or equivalently, turn rate should not be a required ADS-B transmission parameter for most applications. ~~We~~ There are ~~aware of~~ algorithms which make use of bank angle for specialized applications, such as independent parallel approaches. Therefore, ~~we feel that~~ provisions should be made for the inclusion of bank angle, turn rate, or cross-track acceleration in ADS-B but that it should not be made a general requirement, especially for low-end equipage classes. It should be noted that if intent information is considered in the future, turn rate information may provide benefit not shown here.

~~An important caveat to the analysis above should be noted: We did not include in our analysis the use of intent information. The addition of intent may make the use of turn rate more helpful than seen here.~~

J.2.3 Effects of Latency and Report Time Error

Latency, as defined in Section 3, is the time from the moment a particular measurement is valid until the time the measurement is available for use by an ADS-B application. The amount of latency effects the timeliness of information issued to an application. There ~~will~~ are additional effects if the amount of latency is not accurately known by the application; unknown latency contributes to report time error.

There are many aspects to latency and a full treatment of all of its effects would be quite extensive. The accompanying figures are intended to show the effects of latency in certain basic cases. Figure J-9 limits attention to constant latency and the condition that position latency and velocity latency are equal. Figure J-10 illustrates an example with stochastic report time error.

Figure J-9 illustrates a two-aircraft scenario in which ADS-B information is transmitted from one aircraft to the other. The receiving aircraft is equipped with a collision avoidance application using the surveillance data from ADS-B. The flight paths are those of the airborne collision avoidance scenario described below (Figure J-12).

When each new surveillance report is received by the application, a computation is made of the projected miss distance (M) and time to closest approach (TCPA). These are the quantities plotted in Figure J-9. A negative value of M indicates counter-clockwise passage. These quantities are compared against threshold values, and an alarm is issued if the projected M and TCPA penetrate this alarm boundary. The actual time remaining before the collision is also indicated in the figure by tick marks.

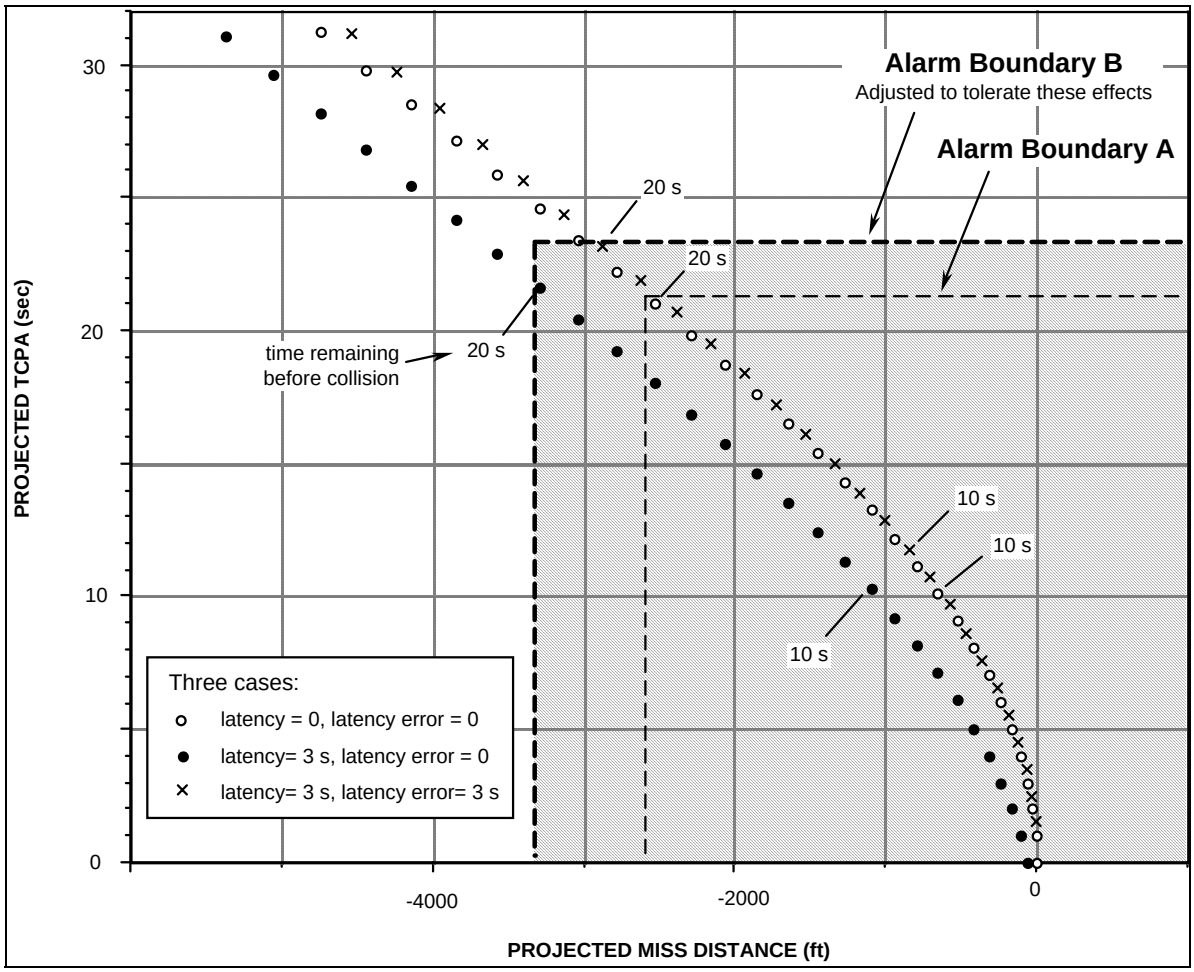

Figure J-9 Latency and Latency Error

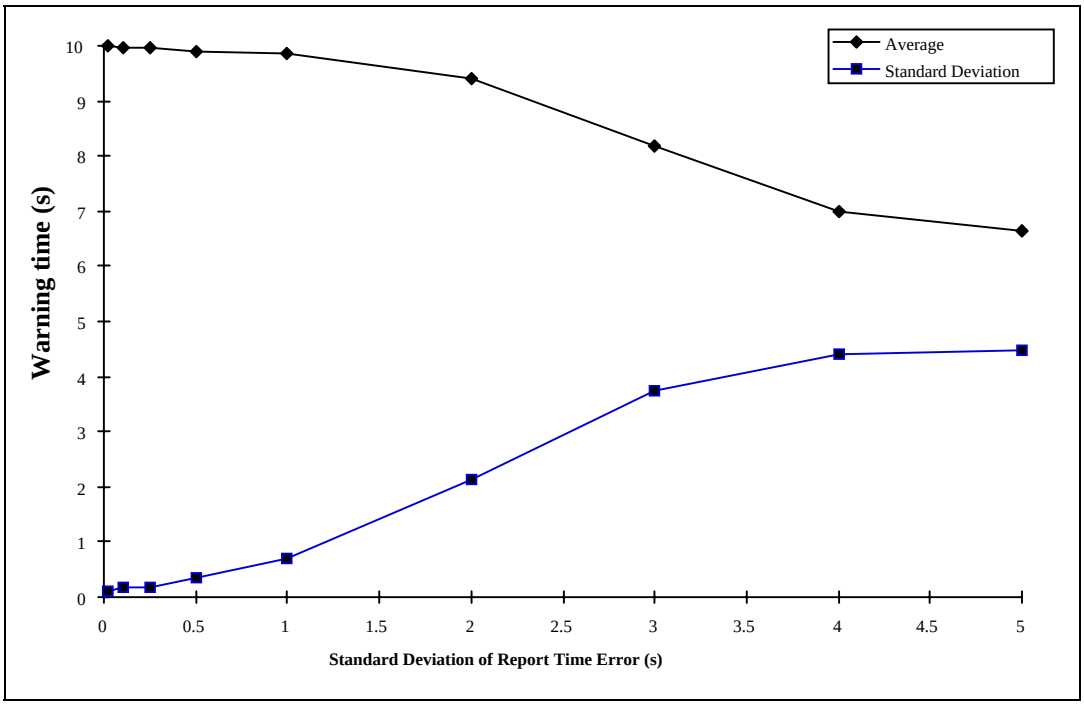

Figure J-10. Example of the Effect of Random Report Time Error on Warning Time for a Maneuvering Intruder

When each new surveillance report is received by the application, a computation is made of the projected miss distance (M) and time to closest approach (TCPA). These are the quantities plotted in Figure J-9. A negative value of M indicates counter-clockwise passage. These quantities are compared against threshold values, and an alarm is issued if the projected M and TCPA penetrate this alarm boundary. The actual time remaining before the collision is also indicated in the figure by tick marks.

Note that latency effects may also occur for the position-velocity information of the receiving aircraft. These effects should be modeled in the analysis of performance for systems using ADS-B. Because this information is supplied by on-board wired connections, without requiring radio transmission, it is not subject to the main phenomena that can limit ADS-B information. Therefore in a well designed system the latency effects for own state vector will be smaller than the latency effects of the ADS-B information. For this reason, and also because the receiving aircraft is flying straight in this scenario, latency and report time error of the receiving aircraft are modeled as zero in the analysis shown in Figure J-9.

Figure J-9 shows three cases, beginning with a basic case in which latency and report time error are zero. For example, at the time 20 seconds prior to collision, the projected M and TCPA are (M, TCPA) = (-2530 ft, 21 sec). Thus if the alarm boundary were as indicated by “Alarm Boundary A” in the figure, the alarm would be triggered at that time, 20 seconds before collision. Note that the projected TCPA is slightly different from the actual time to collision, which is a consequence of the curved flight path.

In the second case, latency = 3 sec. and report time error = zero (that is, the application has a knowledge of the value of latency and uses this value in making the projections to estimate M and TCPA). The results indicate an increase (degradation) in TCPA and also an increase (degradation) in M.

In the third case, latency = 3 sec. and report time error = 3 sec. (that is, the application uses zero latency in its projections). The results indicate a further degradation. As indicated in the figure, the alarm boundary can be adjusted to tolerate both of these effects. Using "Alarm Boundary B" the alarm would be triggered at least 20 seconds prior to the collision for all three cases.

The results in these three cases can be summarized as follows, at the time 20 seconds before the collision.

Table J-1 Effects of Latency

Position Latency (s)	Velocity Latency (s)	Position Report Time Error (s)	Velocity Report Time Error (s)	TCPA (s)	M (ft)
0	0	0	0	21.0	-2530
3	3	0	0	21.6	-3300
3	3	3	3	23.1	-2870

Therefore a 3 second latency and a fixed 3 second report time error would cause a loss of warning time of about 2 seconds for this collision avoidance scenario. More generally, the effect of latency of amount L and report time error of up to the same amount is to delay the warning by an amount less than or equal to L.

As illustrated in Figure J-9, the alarm boundary can be designed to allow for these effects. Of course an expansion of the alarm boundary would tend to cause an increase in alarm rate. In summary, several seconds of latency and report time error would cause a minor degradation in warning time or increase in alarm rate or both.

Figure J-10 illustrates the consequences of random report time errors. ~~Our~~ The scenario for this example was a 30 degree blunder by an intruder in an independent parallel approach scenario. Figure J-10 illustrates that errors of less than 0.5 seconds, RMS, in the report time had no significant effect on conflict warning times for this scenario. Note that report time error was modeled as a zero mean Gaussian random variable with standard deviation as a parameter (the abscissa in the figure); position and velocity latency were assumed to be zero for both aircraft.

The reason for the small effects of random report time errors are that the error primarily effects the along track position and velocity estimates. This is of little consequence for a turning maneuver, since the estimates that are of the most significance relate to the cross track position, and more importantly, the rotation of the velocity vector.

J.3 Specific Scenarios

~~We will now move on to the discussion of the~~ There were also specific scenarios ~~which we~~that were analyzed~~. Each scenario was examined~~ with regard to loss in alert time, as well as false alarm probability. These metrics were analyzed for their sensitivity to report update period and position and velocity accuracy.

Figure J-11 illustrates the concept of "acceptable surveillance delay." This concept will be used through the remainder of our discussion of the specific scenarios. The idea of acceptable surveillance delay is that, for an operation which involves potential conflicts, a required warning time must be developed. A portion of that warning time must be allocated to delays due to the surveillance system. The curve is designed so that, for any operation with less than 10 seconds of warning time, no more that 0.5 seconds of delay will be attributable to the surveillance system. For operations with more than 10 seconds of warning time, an additional 10 percent of delay is allowed for each unit increase in warning time. For example, a 20 second warning time will allow a 1.5 second delay due to the surveillance system (0.5 seconds for the first 10 seconds of warning time, and 1 second for the second 10 seconds of warning time).

The delays are capped at a maximum of 10 seconds. That is, the surveillance system will not delay a warning by more than 10 seconds. It should be noted that the curve presented in Figure J-11 is somewhat arbitrary, although it is felt to be reasonable. This curve represents best engineering judgment, and is intended to serve as a guideline rather than a hard and fast requirement. No claim is made that any particular operation will be supported by the curve of Figure J-11.

J.3.1 Airborne Scenarios

J.3.1.1 Conflict Detection—Future Collision Avoidance Scenarios

Future collision avoidance scenarios were selected as being stressful cases for conflict detection. Examination of a 180 degree turning blunder, an altitude conflict, and finally a set of false alarm scenarios were used to determine requirements for the conflict detection applications.

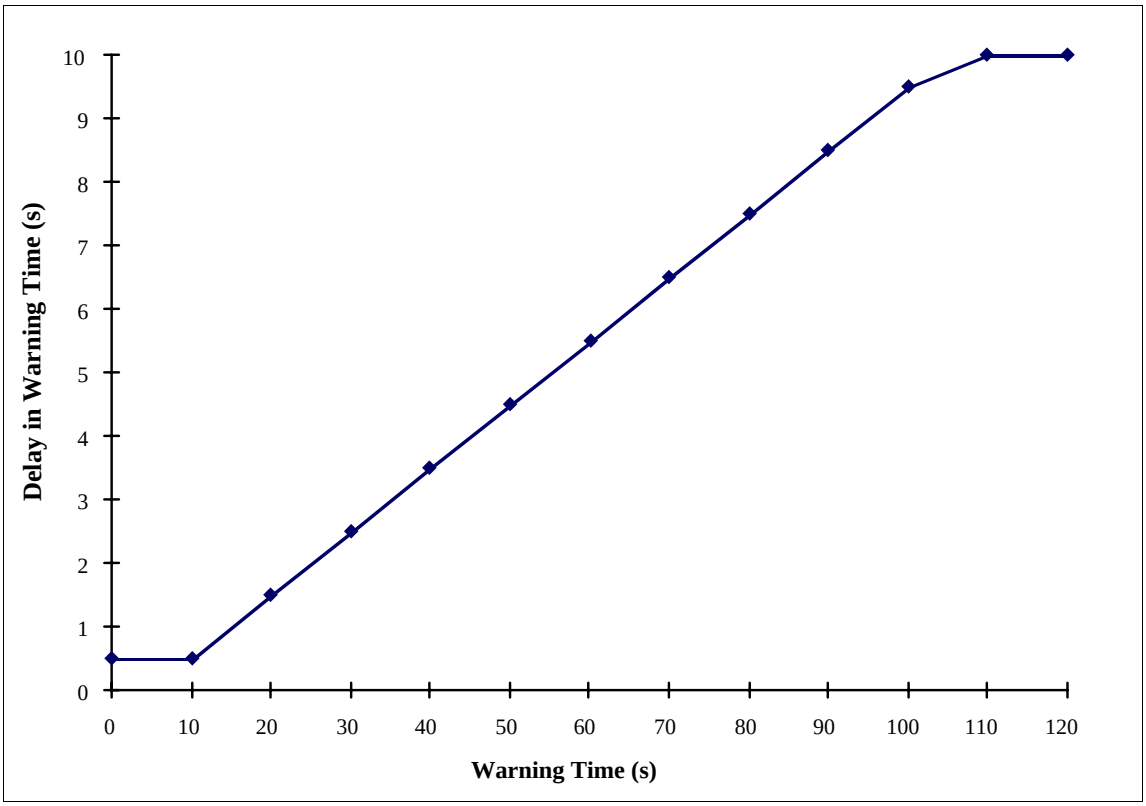

Figure J-11 Acceptable Surveillance Delays as a Function of Warning Time

J.3.1.1.1 Conflict Scenario—180 Degree Turn Blunder

For the collision avoidance application, ~~we considered~~ a scenario involving a 180 degree turn by the intruder was examined. Each aircraft is traveling at 150 kts. ~~We considered a~~A warning was considered to be necessary when the projected HMD was less than 1,500 ft with a projected time to CPA of less than 25s. Figure J-12 illustrates the scenario.

Figure J-13 presents the warning time sensitivity to position and velocity errors. ~~We see~~There is little effect of positional errors less than 40 m for this geometry. In addition, a velocity standard deviation of less than 3 m/s appears to be adequate. Figure J-14 illustrates sensitivity of warning time to report update period and probability of receipt. The design goal is reasonably met with an update period of 3 s with a high report receipt probability (.95).

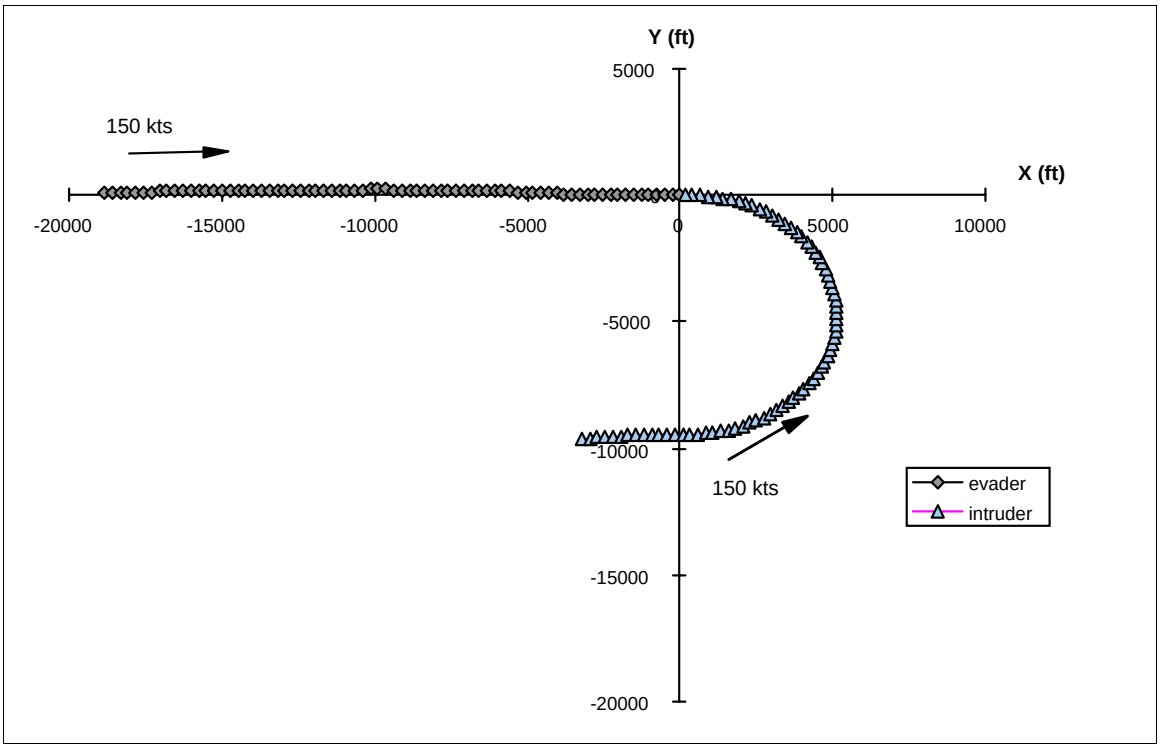

Figure J-12 Future Collision Avoidance Scenario Altitude = 2,000 ft (Both Aircraft)

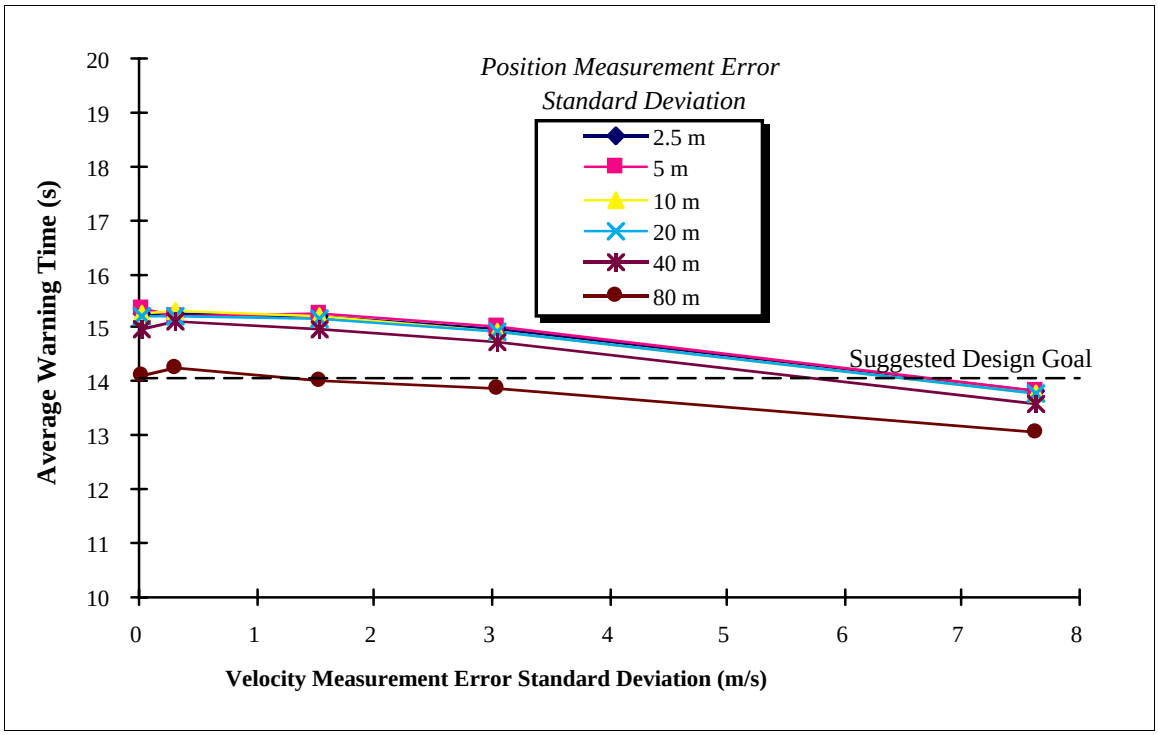

Figure J-13 Collision Avoidance Sensitivity to Position, Velocity Errors

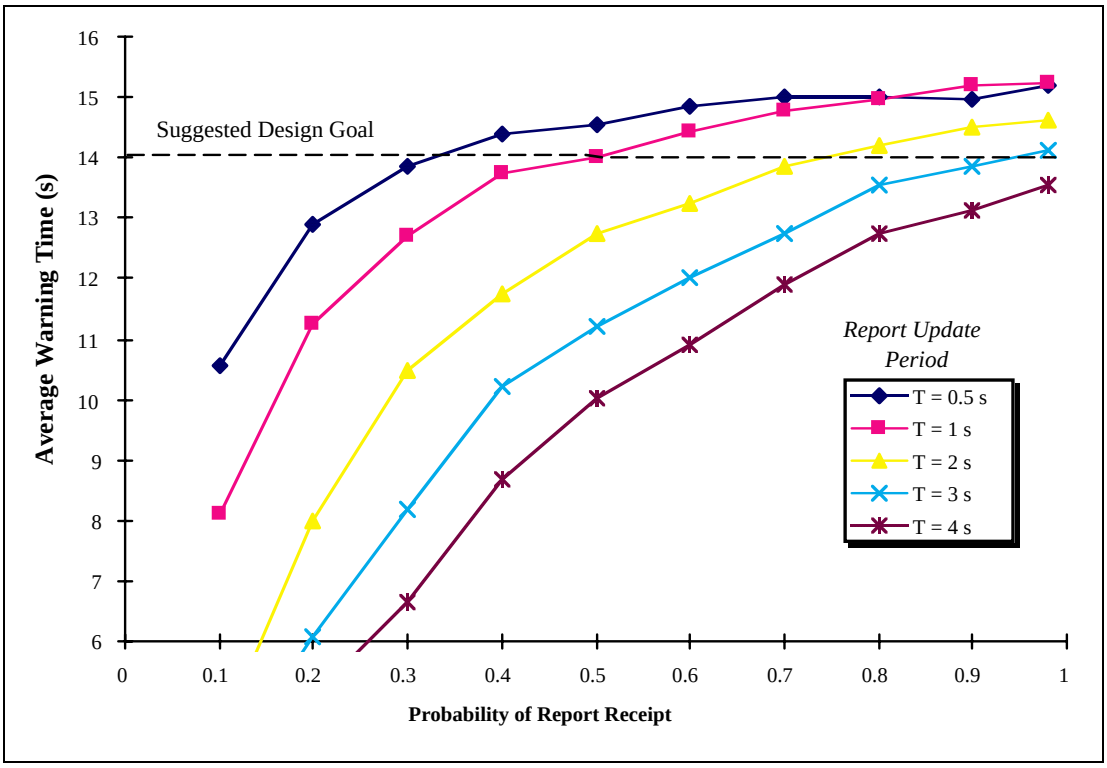

Figure J-14 Collision Avoidance: Sensitivity to Report Update Period, Receipt Probability

Table J-2 lists values for report update period and update probability which meet the desired warning time for the scenario

Table J-2 Report Update Period, Update Probability Values Which Achieve Desired Warning Time for Future Collision Avoidance

Update Period, s	Update Probability
3	0.95
2	0.8
1	0.5
0.5	0.35

Based on the suggested report update period and update probabilities listed, ~~we have conducted~~ an empirical fit of an analytic expression to the simulation results has been conducted. The expression is based on the required probability to achieve an update within TC seconds with a probability of 0.99. TC represents a coast period—that is, the maximum allowable time between state vector report updates. The formula for the expression is given below in equation (1):

$$(1-P)^{(TC/T)} <= 0.01 \qquad (1)$$

where:

P = probability of update
TC = required maximum coast interval
T = update period

A value of TC=6 seconds provides a good fit to the values listed in Table J-2. A plot of the simulation results comparing a curve generated by varying T in equation 1 with TC=6 is provided in Figure J-15. The equation provides an excellent fit to the simulation values. The equation represents a simple way of specifying requirements, and allows for any value of update period, rather than fixed values. The equation also allows another interpretation of the simulation results: it is helpful to assist warning time by limiting the coast period. This result is in concert with the analysis presented in Appendix M. In Table 3-4(a) of Section 3, required update periods and probabilities are specified using the equation, rather than the specific values listed in Table J-2. ~~We will derive similar curves for the other applications which we examine using simulation studies.~~

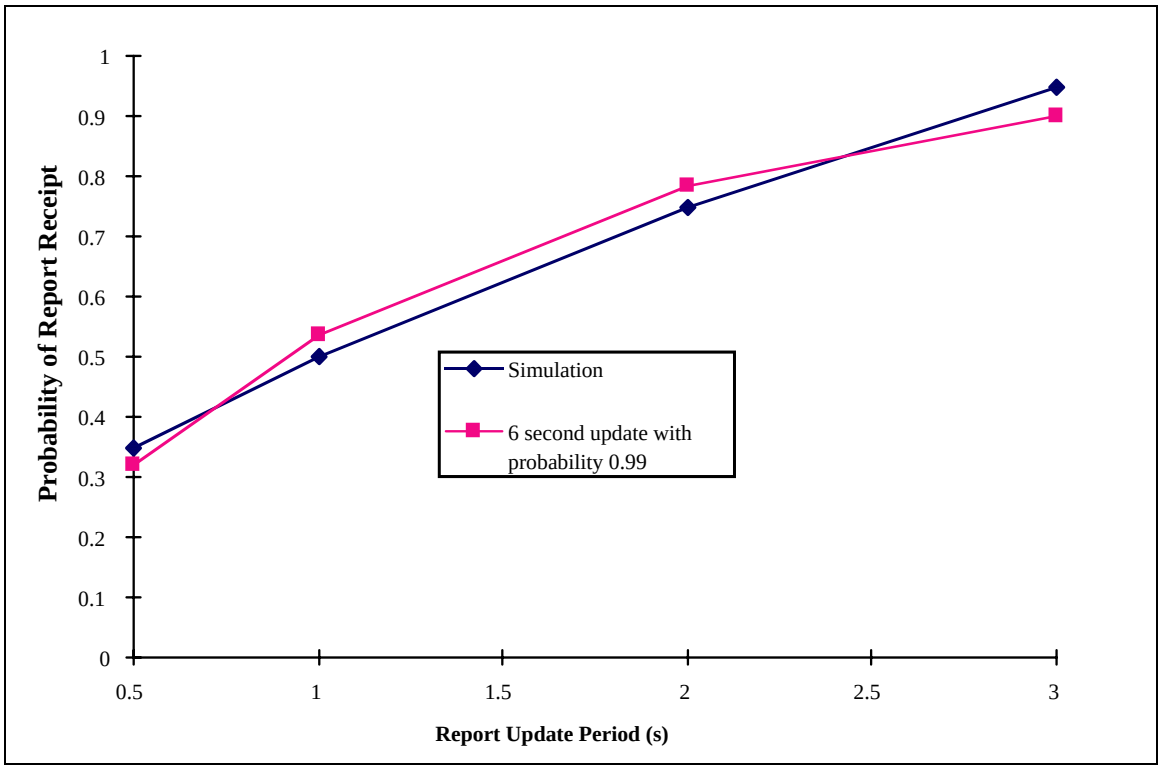

Figure J-15 Update Period Requirements Analysis

J.3.1.1.2 Altitude Conflict

In order to evaluate the sensitivity of conflict warning times to altitude and altitude rate errors, ~~we simulated~~ the altitude conflict depicted in Figure J-16 was simulated. In this example, an intruder aircraft levels off at the evader (own) aircraft's altitude. If the intruder did not level off, it would have passed through own's altitude by more than the altitude threshold (600 ft) used in this example. ~~We used the~~The ADS-B simulation was used to analyze how quickly an alert could be generated ~~that~~ where the two aircraft would not achieve 600 ft of separation.

The vertical acceleration of the intruder is 1.25 ft/s/s. This is typical of altitude accelerations in the U.S. Horizontally, the encounter is head-on. Each aircraft travels with a horizontal speed of 200 knots.

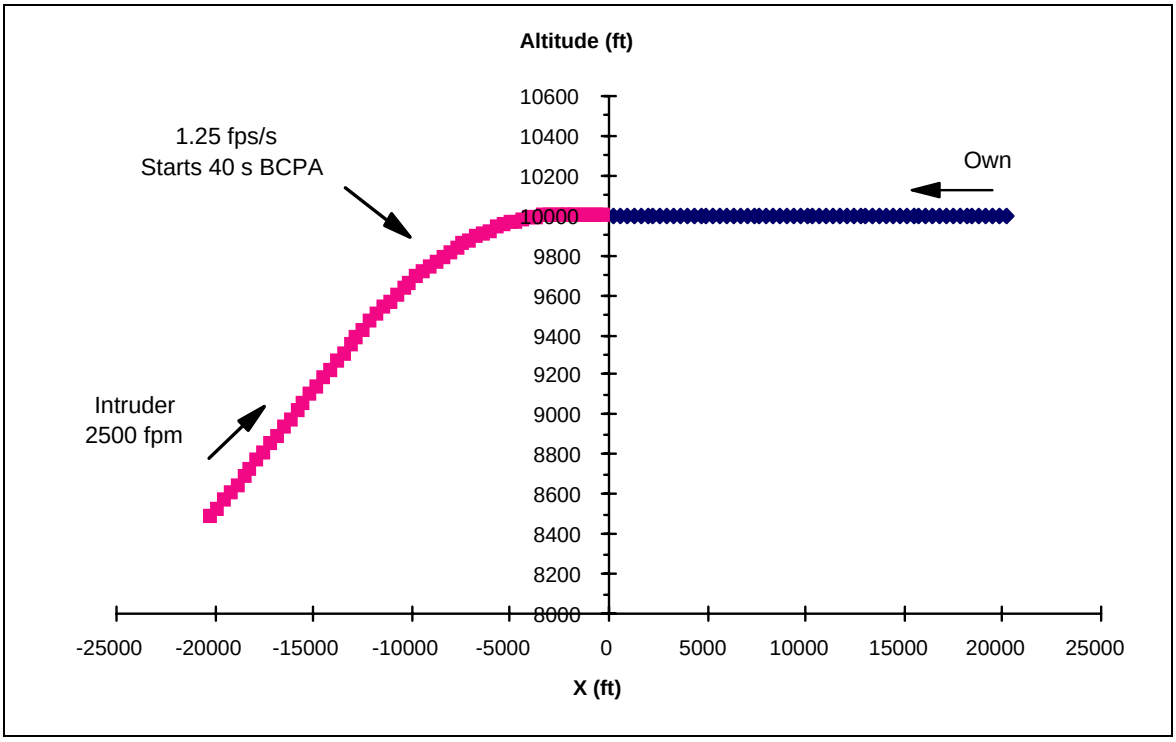

Figure J-16 Altitude Conflict Scenario

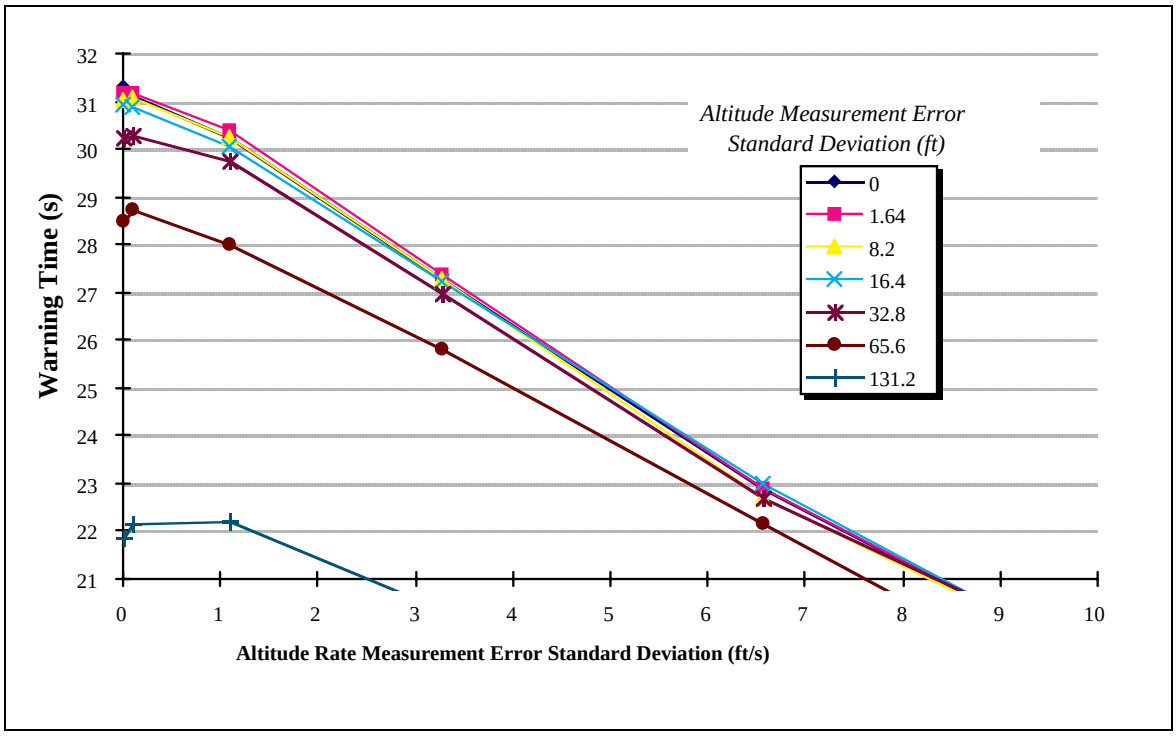

Figure J-17 Altitude Conflict: Warning Time Sensitivity to Altitude, Altitude Rate Errors

The results of simulations of this scenario (Figure J-17) indicate that altitude errors above 32 ft (10 m) can cause degradation in the alert time. In addition, altitude rate errors of more than 1 fps can cause degradation in the alert time. Therefore ~~we have~~a recommended ~~as a~~ design goal is that altitude errors be less than 32 ft RMS and altitude rate errors be less than 1 fps (60 fpm) RMS.

~~We did not indicate the~~A "suggested design goal" for this example is not given -based on the acceptable delay curve. The reason for this is that the warning time for this scenario will be a function of when the altitude acceleration takes place. Warning times could either be shorter or longer depending on when the maneuver starts. Therefore ~~we are suggesting~~it is suggested that the design goals primarily based on the sensitivities observed with the desire that warning time not be seriously compromised.

J.3.1.1.3 Collision Avoidance, False Alarm Scenarios

In addition to the conflict scenario, ~~we have~~also analyzed was a number of false alarm scenarios. These are useful in determining the sensitivity to position and velocity inaccuracies.

The simplest case, shown in Figure J-18, consists of two aircraft encounters in which the aircraft are flying in opposite directions, both at 150 knots. Miss distance was varied from encounter to encounter. The surveillance update rate was 1 report per second.

As described in Section J.1 above, position and velocity inaccuracies are modeled as additive errors, characterized by σ_p = standard deviation of position error (m) and σ_v = standard deviation of velocity error (m). These errors were added just for the data from the transmitting aircraft. As usual, these four errors (two for position and two for velocity) were uncorrelated with each other and uncorrelated in time for the initial runs of the simulation. Correlation effects were addressed subsequently as described below.

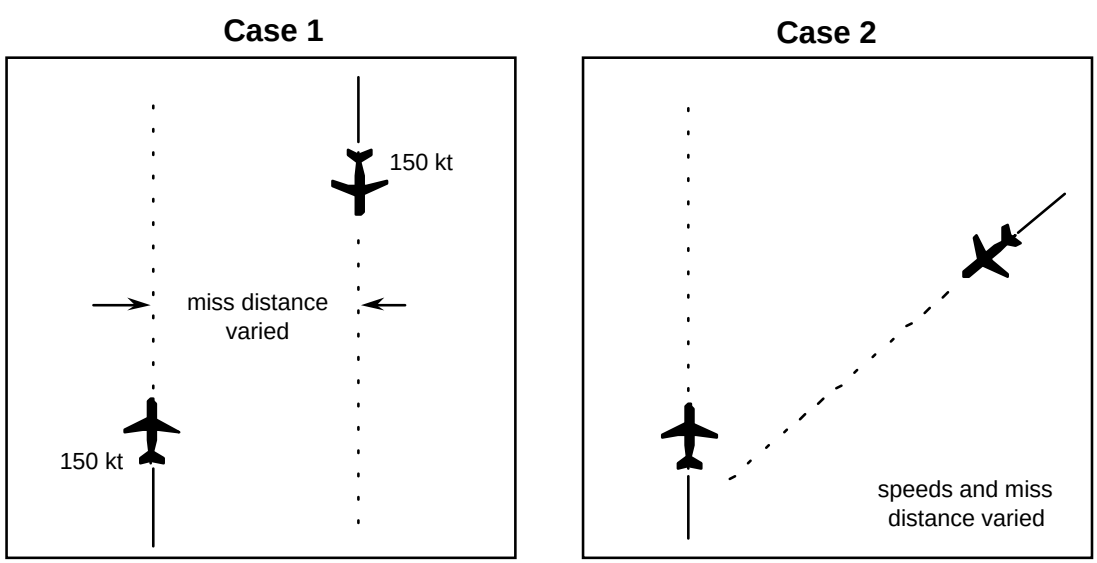

Figure J-18. Scenarios Used to Assess Alarm Rate

The alarm boundary is based on the collision avoidance analysis above. An alarm is triggered if the projected miss distance is less than 1200 m, and the projected time to closest approach is less than 25 seconds. To assess the sensitivity to the surveillance errors, the alarm rate was examined as a function of σ_p and σ_v.

A simple analysis indicates that these surveillance errors cause the alarm rate to increase by a factor F, given by the formula

$$F = \frac{\text{alarm rate with errors}}{\text{alarm rate without errors}} = 1 + \sqrt{(A\, s_p)^2 + (25\, B\, s_v)^2} \quad / \, 1200\text{m} \qquad (2)$$

where A and B are constants on the order of 2 and 1.5 respectively. This result applies to the case in which the family of miss distances is modeled by a uniform distribution.

Monte-Carlo simulation was used to validate this result and to estimate the values of the constants A and B. The results for this basic case are: A = 2.0, B = 1.36. Furthermore, the analysis indicates that the alarm-rate factor F is independent of speeds, and this was validated by simulating cases including different speeds and different aircraft headings (case 2 in Figure J-18).

The results of both the analysis and the simulation are plotted in Figure J-19. This shows the alarm rate as a function of σ_v for several values of σ_p.

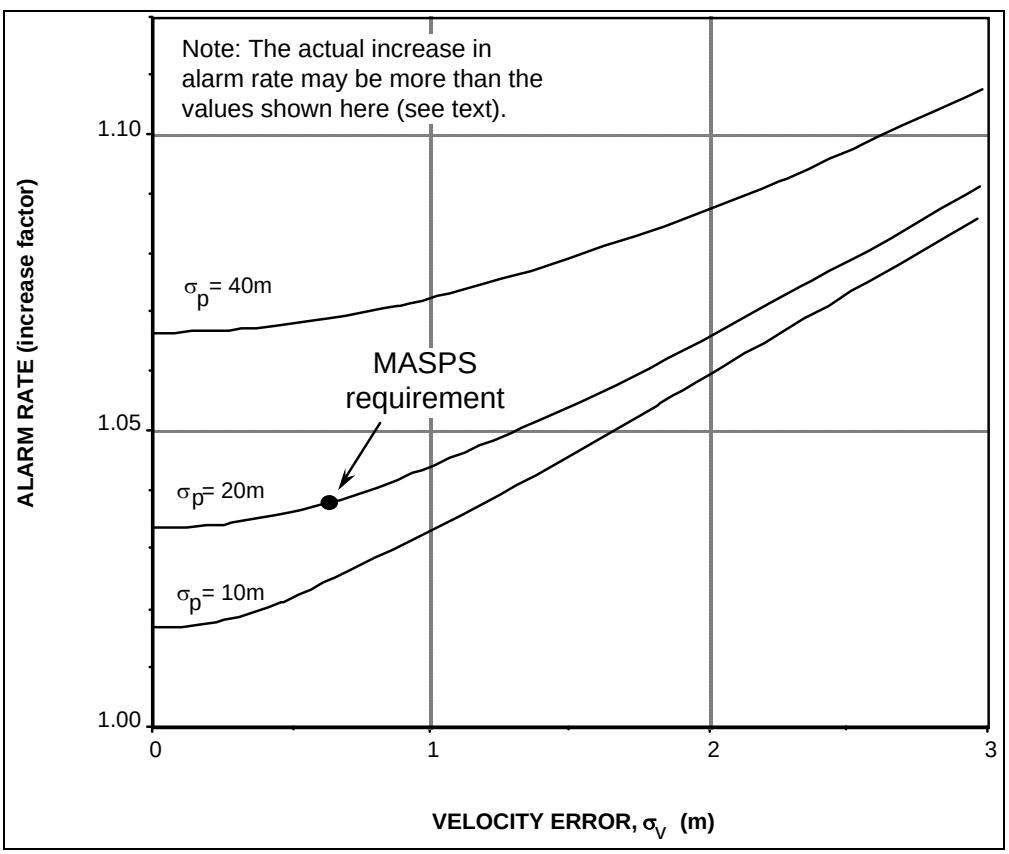

Figure J-19 Sensitivity to Errors In Position and Velocity

Correlation of errors from report to report was also studied, because it is typical of GNSS measurements for the errors in position and velocity to be nearly constant for periods on the order of 10 seconds. It was found that such high correlation eliminates nearly all of the increase in alarm rate given by the above formula. Therefore much larger errors could be tolerated, provided they were highly correlated in time.

On the other hand, quantization caused by a limited number of bits in the transmitted messages will contribute errors that are not highly correlated in time. Effects of quantization were assessed by additional simulation runs, and found to be nearly the same as the results given above for uncorrelated errors.

The above results were based on a simplified model in which miss distances are uniformly distributed. This is not realistic, because it assigns the same probability to zero miss distance as to any other value. The actual distribution of miss distances will be different for different regimes of flight, but in all cases the result will be an increase in the alarm rate factor above the simplified result given above.

Based on these considerations, and also allowing for a further increase in alarm rate attributable to errors in the state vector of the receiving aircraft, the requirements for surveillance errors were set at

$\sigma_p = 20$ m
$\sigma_v = 0.6$ m/sec

Note that these assignments are somewhat arbitrary, but represent best engineering judgment. Other combinations of σ_p and σ_v would provide comparable alarm rate, and other values of alarm rate might be suitable as well.

J.3.1.1.4 TCAS Comparison

~~We have performed a~~A preliminary comparison of ADS-B with TCAS is provided here. For ADS-B simulations, ~~we used~~ the ~~required~~ proposed values for ADS-B accuracy and update period established for conflict detection were used. The intent of this study was to determine if ADS-B can be expected to meet or exceed TCAS performance. ~~We~~ It is assumed that ADS-B must perform at least as well as TCAS to be accepted into the airspace.

To perform the comparison, ~~we used~~ a subset of the MITRE TCAS U.S. database [4], a database of 4,300 encounters which are representative of encounters observed in the U.S, was used. The database was derived from Automated Radar Tracking System (ARTS) data from 12 sites around the U.S. The ARTS data was filtered for two aircraft encounters which would have triggered a resolution advisory with the version 6.00 TCAS logic.

From the U.S. database, ~~we selected~~ 1,326 encounters ~~the US database~~were selected. These encounters represent all encounters took place in altitude layer 3 (between 5,000 and 10,000 ft above ground level). TCAS has warning thresholds which are altitude layer dependent. ~~We used t~~Two versions of these encounters were used. The first version was the original encounter. In second version, ~~we offset~~ the position of the second aircraft was offset such that horizontal and vertical miss distance was zero at closest point of approach, i.e., each encounter in the modified set was a collision. From here on ~~we will refer to~~ these two data sets will be referred to as the "US database" and "Simulated Collision" data sets, respectively.

~~We used t~~The US database was used to compute the "advisory rate." This is the rate at which advisories are generated for the data set. Each Monte-Carlo repetition of each encounter is counted as an "advisory opportunity." Each case in which an advisory is generated is counted. The total number of advisories generated divided by the advisory opportunities is reported as the "advisory rate." ~~We~~ Also examined was the advisory rate for TCAS II version 6.04A, TCAS II Version 7, and for ADS-B with the requirements described in Section 3.1.4. Alarm boundary thresholds for ADS-B were set equal to those of TCAS for altitude layer 3. An alert is therefore generated when the projected horizontal miss distance is less than 3,342 ft, the projected vertical miss distance is less than 600 ft, and the estimated time to closest point of approach is less than 25 seconds.

~~We used t~~The simulated collision data set was used to assess the "delayed alert rate." ~~We defined as a~~ A delayed alert is defined as a collision encounter for which warning time is less than 20 seconds. This represents a 5 second delay from the desired warning time of 25 seconds at altitude layer 3. Since each encounter in the modified database is by construction of a collision, ~~we divided~~ the total number of delayed alerts is divided by the total number of Monte-Carlo encounters simulated to obtain the delayed alert rate. Again, using the TCAS alarm boundaries in ADS-B, ~~we compared~~ TCAS II version 6.04A, TCAS II version 7.00, and ADS-B were compared.

Figure J-20 shows the simulation results for advisory rate. In moving from TCAS Version 6.04A to TCAS version 7, unnecessary advisories were reduced by incorporating complex algorithms to estimate horizontal miss distance based on range data. The development of these algorithms was at one time thought to not be achievable. A 3 year effort was required to complete the Miss Distance Filter algorithms. The net result was a significant reduction in unnecessary advisories. The filtering and conflict detection algorithms required for ADS-B are, by comparison, simple. Yet a similar reduction in unnecessary advisories is achieved by making use of ADS-B data.

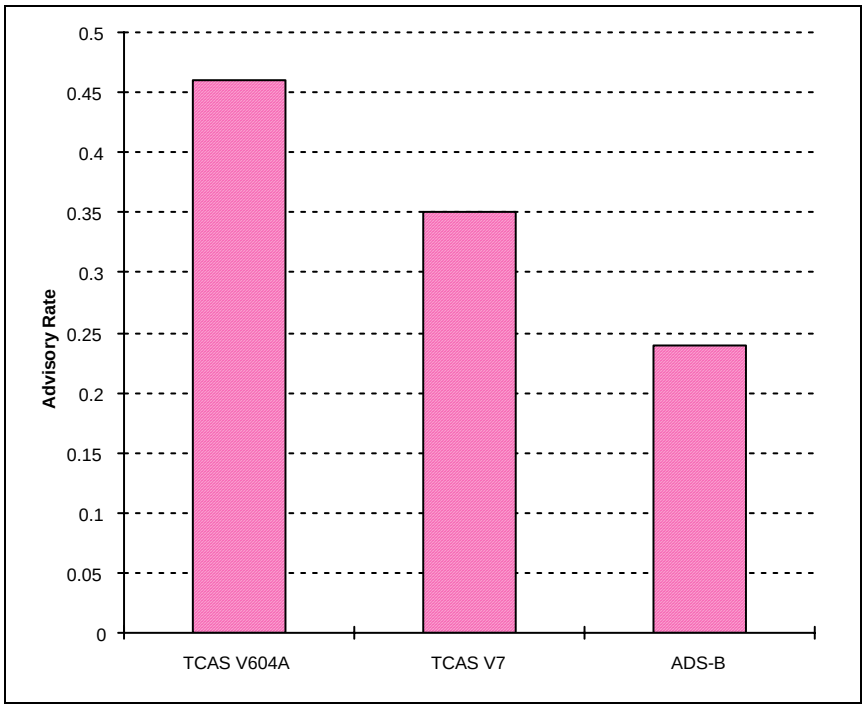

Figure J-20 Advisory Rate, US Database, Altitude Layer 3

Figure J-21 examines results for delayed alerts. ~~We~~ It is observed that an almost four-fold reduction in delayed alerts with ADS-B. Note that there is wide latitude to adjust ADS-B alarm boundaries to trade-off delayed alerts versus alert rate, and still perform better than the existing TCAS II systems in both measures. For example, if a lower alert rate is desired, this could be accomplished while keeping delayed alerts at or below existing TCAS II levels.

J.3.1.2 Separation Assurance and Sequencing—Free Flight Example

Free flight applications were considered to be stressful for separation assurance applications. Free flight conflict and false alarm scenarios were developed to assess requirements for separation assurance and sequencing. It was assumed that separation standards would eventually be tightened over today's standards (3 nmi terminal, 5 nmi en route).

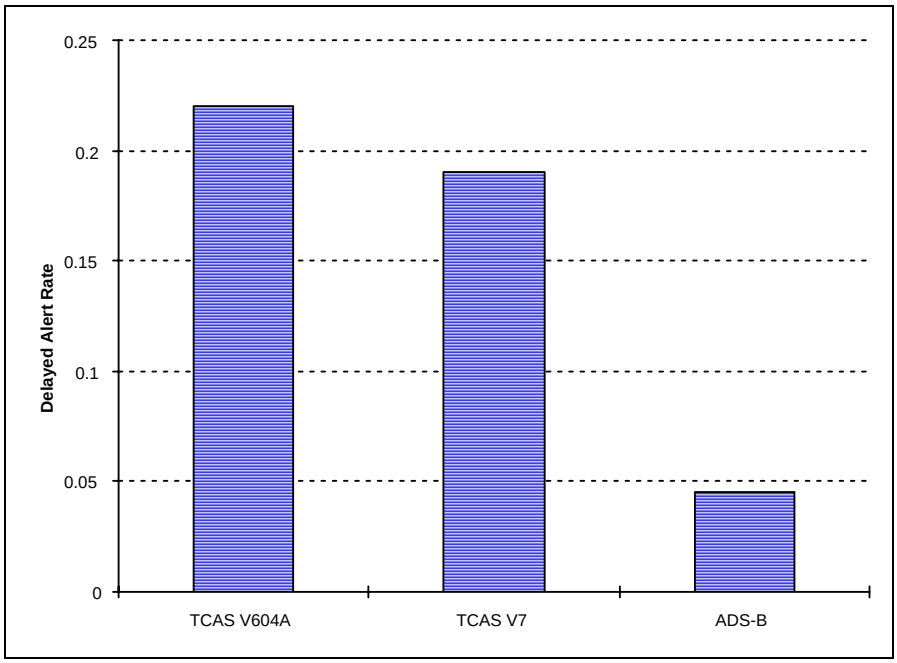

Figure J-21 Delayed Alert Rate, Simulated Collision Database, Altitude Layer 3

J.3.1.2.1 Free Flight Conflict

To examine ADS-B needs in a for separation assurance and sequencing in a free flight context, ~~we~~ also examined was a scenario involving a 90 degree turn with high-speed aircraft (Figure J-22). For this scenario, ~~we~~ it is assumed that the horizontal separation threshold was 2 nmi and the warning time threshold was 2 minutes (120 s).

In this scenario, ~~we observed~~ no decrease in warning time as a function of positional data errors (Figure J-23) was observed. Fairly high velocity errors (about 6 m/s) were also adequate to provide acceptable delay as per our "acceptable delay" criterion. In examining the sensitivity of the free flight conflict warning time to update period and probability of receipt, ~~we find that~~ update periods as high as 7 seconds are acceptable (Figure J-24).

~~We~~ It is also observed that small update periods with low probability of receipt are acceptable by the criteria and the simulations ~~we~~ conducted in this study. Issues such as track acquisition and maintenance are examined in Appendix M.

J.3.1.2.2. Free Flight False Alarm with Reduced Separation Standards

~~We also~~Also examined was a false alarm scenario for Free Flight (Figure J-25). In this example, the aircraft both travel at high speed and the actual HMD is 13,500 ft. ~~We~~ It was assumed that the separation standard was 12,152 ft (2 nmi). ~~We counted t~~The number of alerts were counted~~,~~ and ~~observed~~ the sensitivity to position and velocity errors were observed for this scenario.

Before ~~we describe~~describing the false alarm results, one important note of interest in this example is that even with perfect surveillance it will be impossible to avoid false alarms with long warning times. ~~We show~~As shown in Figure J-26~~ that~~, if a projection beyond 2 minutes is attempted, false alarms begin to grow significantly. ~~We assumed n~~No data errors at all were assumed for this example ~~and~~ as well as a 1 second update period.

The reason for the false alarms is the random perturbations in the aircraft trajectories due to wind gusts, pilot deviations, etc. (called "process noise" in the simulation). Process noise is modeled as a white noise random process in our simulation. Process noise is modeled as random accelerations applied over a discrete time interval. At each new time epoch, a new random acceleration is selected. For this example, the random acceleration had a standard deviation of 0.005 Gs applied over time epochs of 2 s. 0.005 Gs represents about one-third of a degree of bank angle. The use of the process noise model attempts to realistically limit the false alarm rate which can be claimed for a given data accuracy.

Figure J-27 illustrates false alarm rates for the false alarm scenario of Figure J-25. 40 m of positional data accuracy is desirable, combined with 0.3 m/s of velocity accuracy to limit false alarm probability. As for the conflict case, these results were based on an alarm boundary of 12,152 ft. (2 nmi).

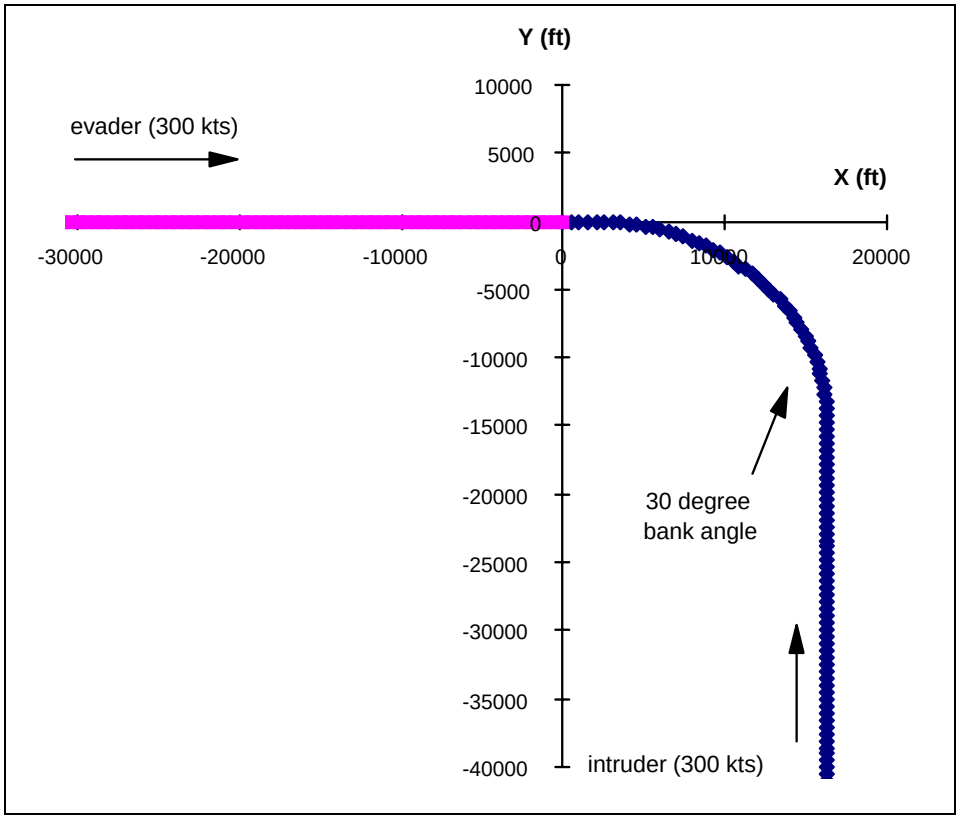

Figure J-22 Free Flight Conflict Scenario

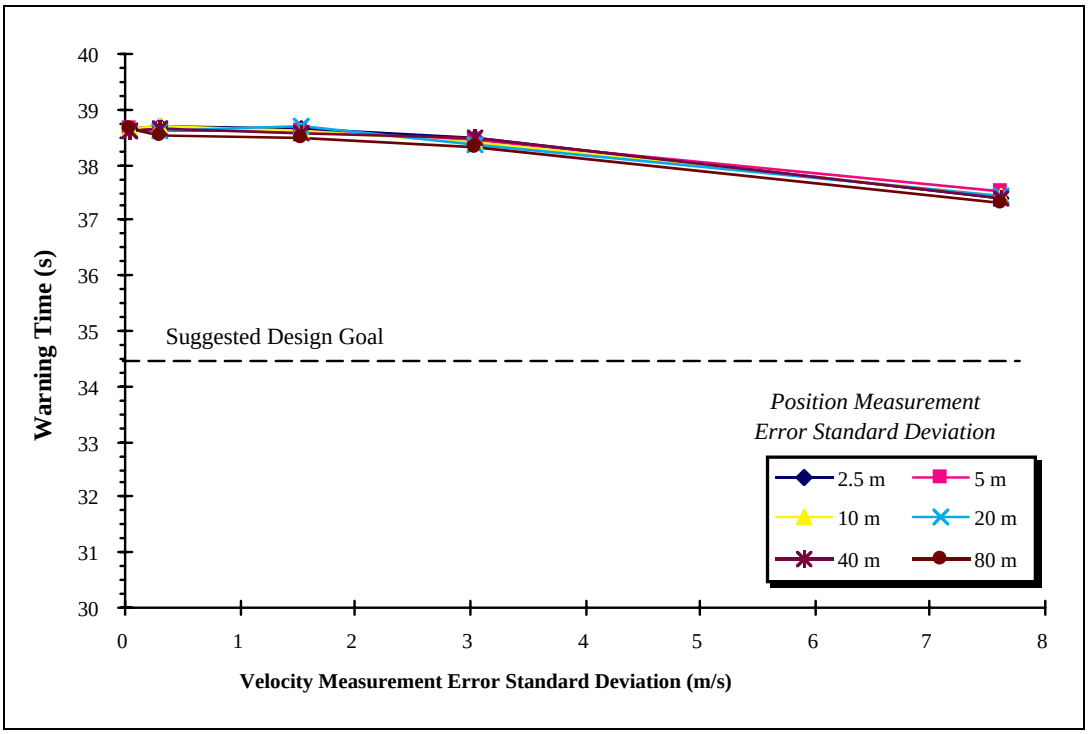

Figure J-23 Free Flight Conflict Sensitivity to Position and Velocity Errors

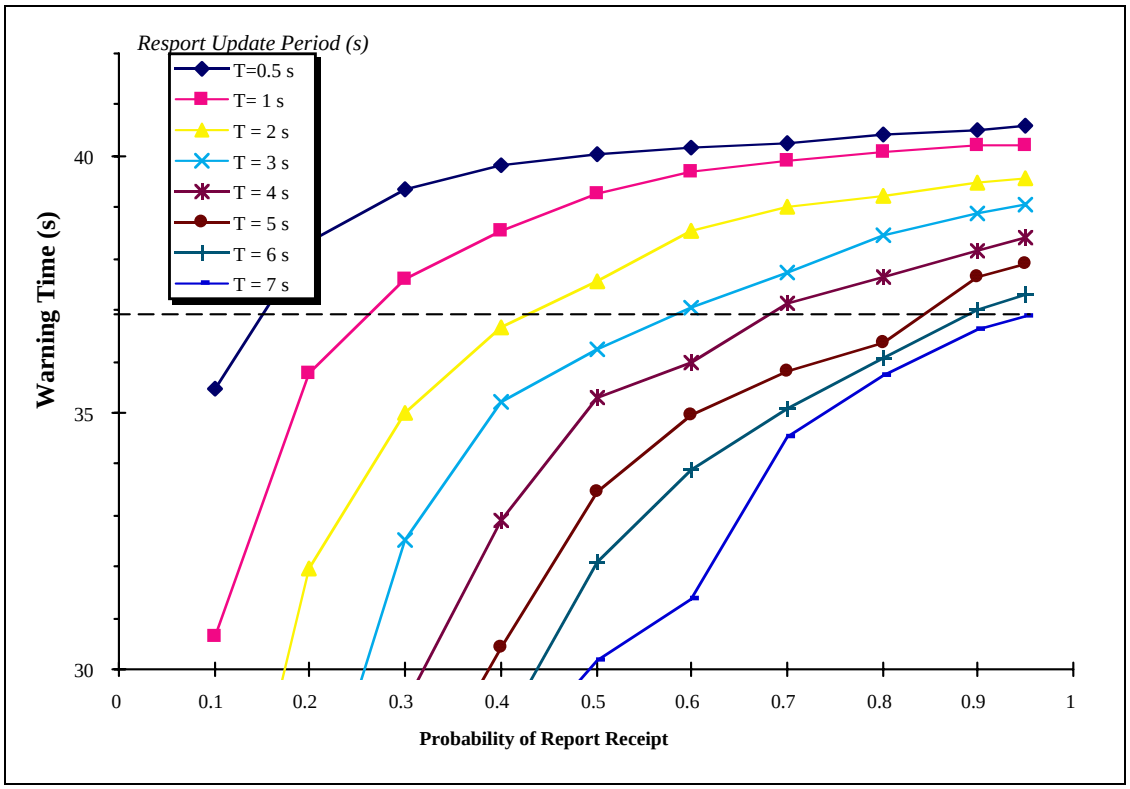

Figure J-24 Free Flight Conflict Sensitivity to Report Update Period, Probability of Receipt

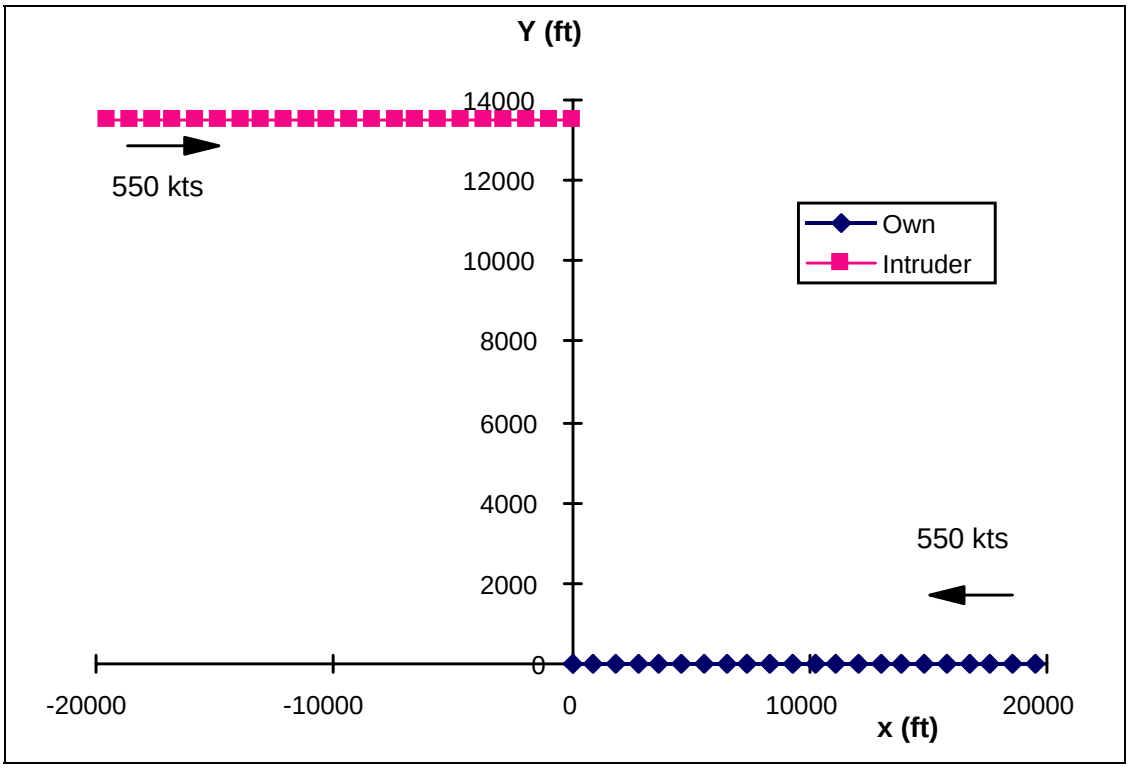

Figure J-25 Free Flight–False Alarm Scenario

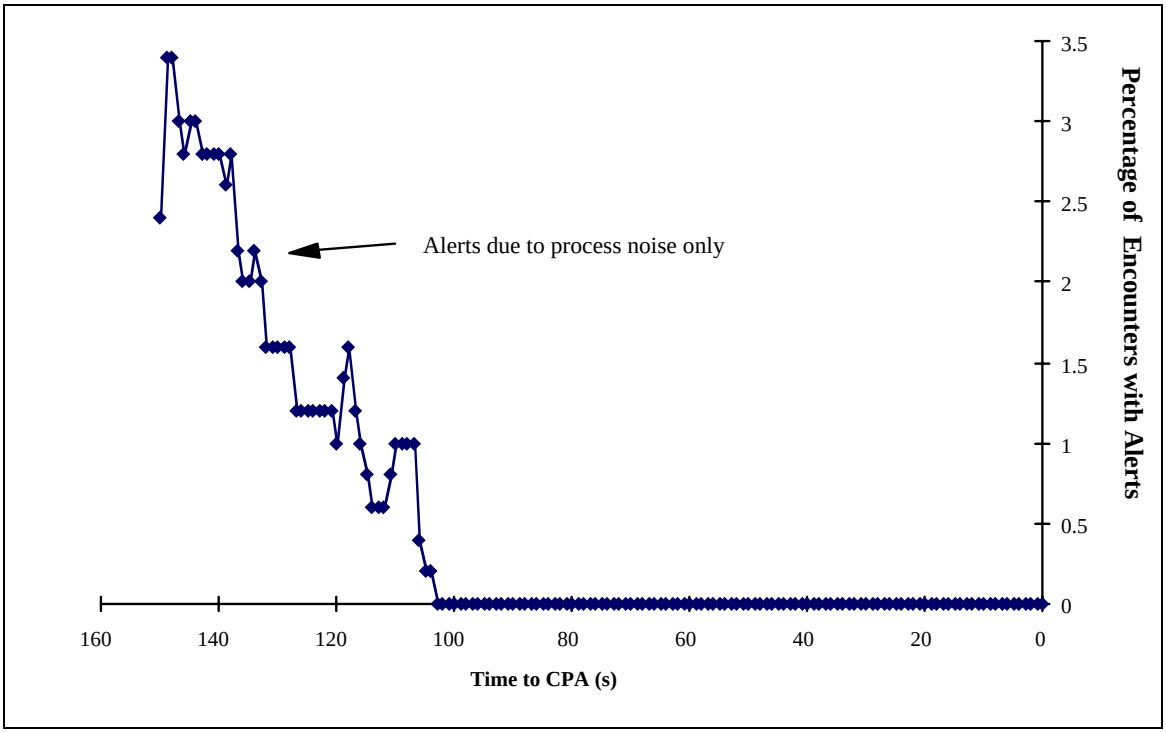

Figure J-26 Free Flight–False Alarms with Perfect Data (T=1s)

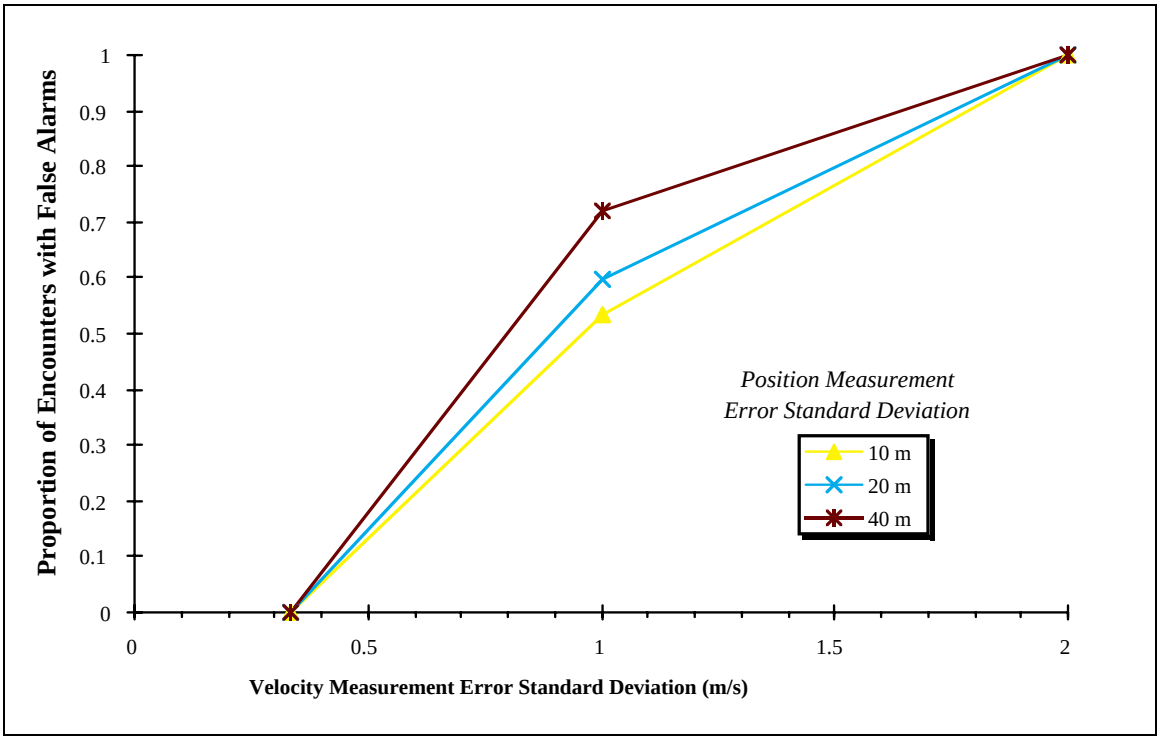

Figure J-27 Free Flight False Alarm Sensitivity to Position and Velocity Errors

As ~~we have~~ observed in the other cases, it is the conflict scenario that drives the update period design goals and the false alarm scenario that drive the accuracy requirements. Based on these results, a maximum positional error of 40 m, RMS, is required, in combination with a maximum velocity error of 0.3 m/s, RMS. Table J-3 lists simulation values for report update period and update probability which achieved the design goal.

Table J-3 Report Update Period and Report Update Probability Simulation Values for Free Flight

Update Period, s	Update Probability
7	0.95
6	0.9
5	0.85
4	0.7
3	0.6
2	0.45
1	0.25
0.5	0.15

As in the collision avoidance example (Section 3.1.1), ~~we derived~~ a curve was derived which fits the data in Table J-3 based on a maximum coast period. Equation (1) in Section 3.1.1.1 was again used. In this case, ~~we found~~ an excellent fit was found to the values listed in Table J-3 for a coast period, TC, of 14 seconds. Figure J-28 compares the simulation results with the requirement, which states that the coast period, or inter-arrival time between report updates, must be less than 14 seconds with a probability of 0.99 or greater.

J.3.1.3 Independent Parallel Approach

~~We will~~Also examined were two closely-spaced, independent parallel runway scenarios. The two runway separations examined are 1,000 feet and 2,500 feet. ~~We analyzed a~~A blunder and false alarm scenario for each runway spacing were analyzed.

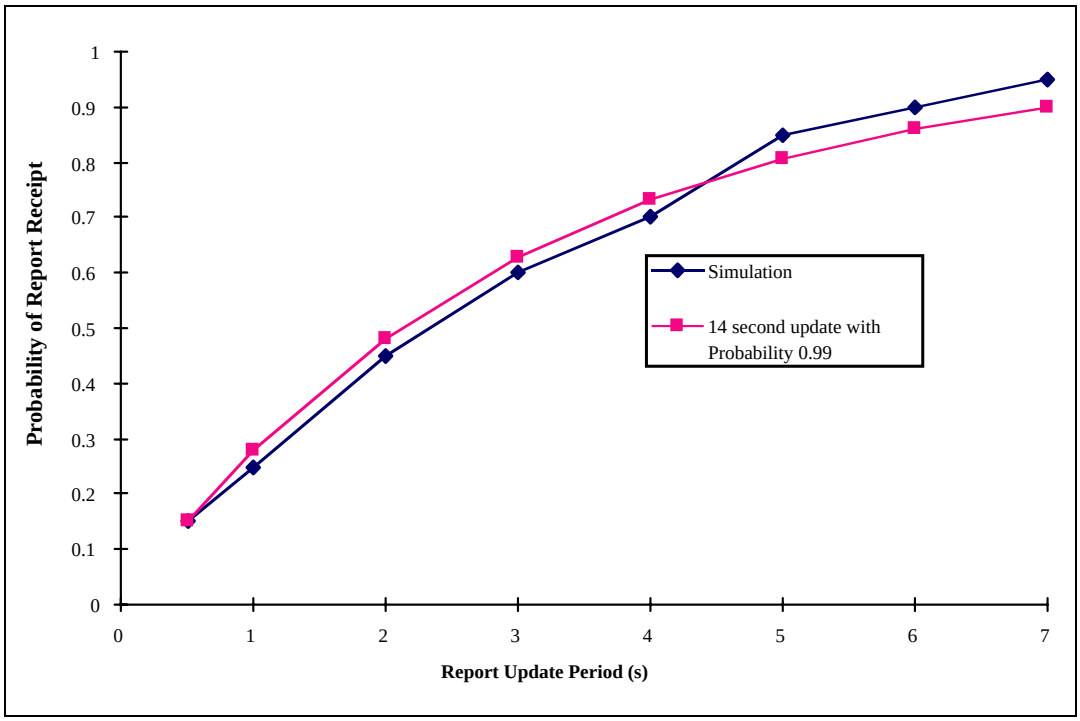

Figure J-28 Update Period Requirements, Free Flight

J.3.1.3.1 1,000 ft Blunder

The blunder scenario is constructed as illustrated in Figure J-29. The “evader” or “own” flies along a runway which is spaced by the runway separation from the “intruder,” in this case 1,000 ft. The intruder, flying at a speed which is 30 kts higher than the evader, blunders at 3 degrees per second with a total angular deviation of 30 degrees. The intruder passes between 400 ft behind or in front of the intruder. The passing point is uniformly distributed in the simulation.

Using the state vector report, the simulation's alerting algorithm solves for horizontal miss distance and triggers a warning when the horizontal miss distance is projected to be less than 500 ft while the time to closest point of approach is less than 25 s. Altitude is not considered in this simulation, as the two aircraft are assumed to be at co-altitude throughout.

Figure J-30 shows the sensitivity of warning time for the 1,000 ft runway separation to position and velocity errors. These curves were generated with a report update period of 1 second.

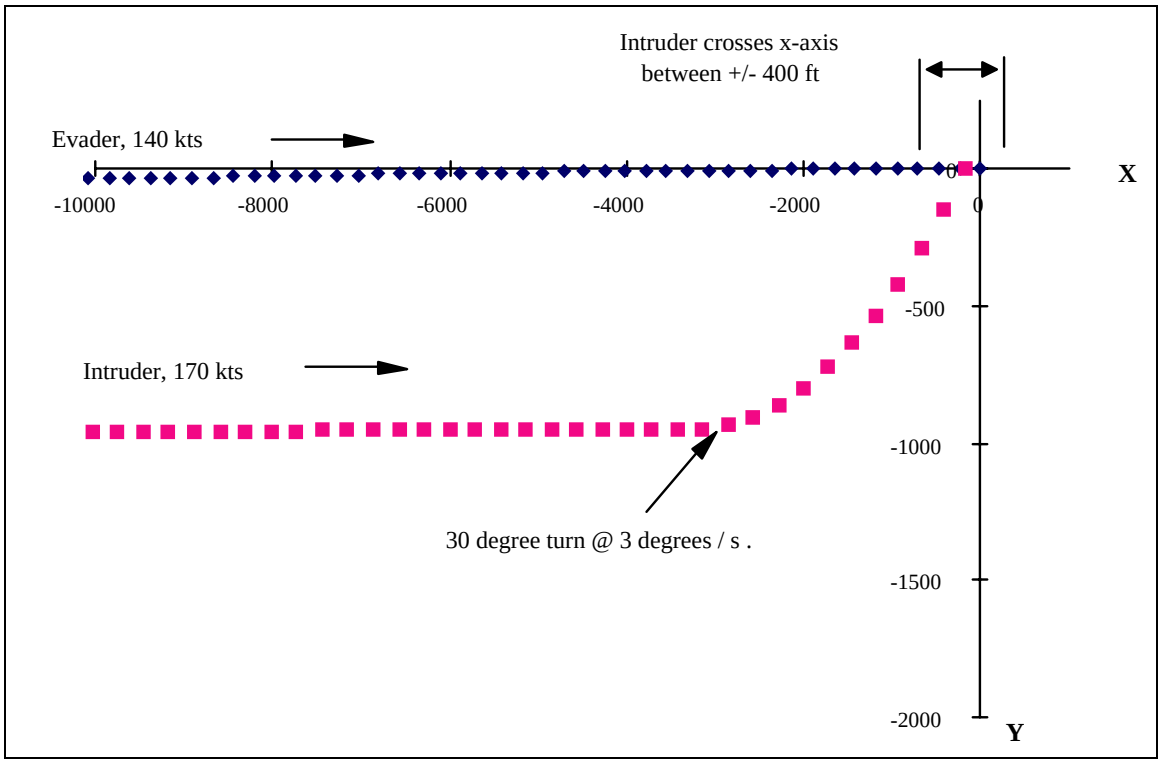

Figure J-29 1,000 ft Independent Parallel Runway Blunder Scenario

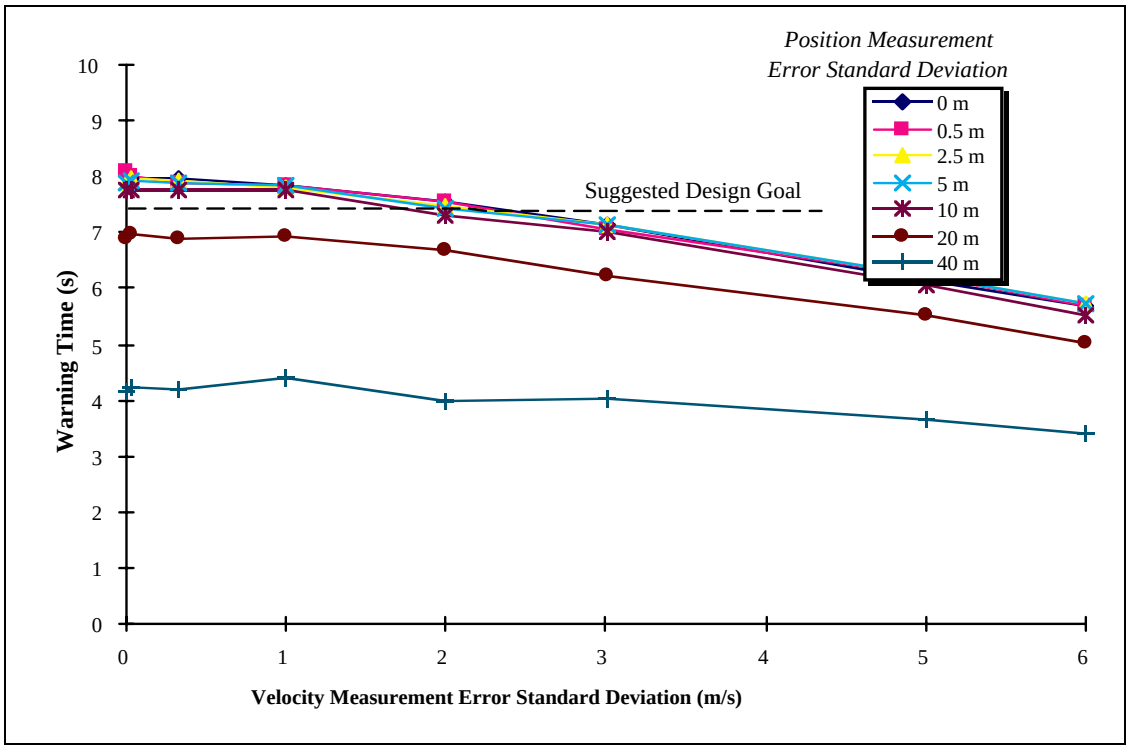

Figure J-30 1,000 ft Independent Parallel Runway: Warning Time Sensitivity to Position, Velocity Errors

~~We observe s~~Some sensitivity of warning times to positional data errors are observed when the data errors grow to more than 10 m. Also observed is ~~We see~~ sensitivity to velocity errors of more than 1 m/s. The suggested design goal, based on the "acceptable delay" curve, is met with positional data errors of up to 10 m and velocity data errors of up to 3 m/s.

Figure J-31 shows the sensitivity of warning times, for 1,000 ft runway separations, to update period and probability of receipt of the state vector report. ~~We see that~~A ~~a~~ 1 s report update period provides close to the desired warning time with receipt probabilities greater than 0.8. A 2 second update period does not meet the suggested design goal for this scenario, as about a 1 second delay from the best recorded values was observed.

~~We~~ It should be noted that ~~we must consider that~~ this scenario is probably operationally not feasible. ~~We~~ It was found that 5th percentile warning times are less than 5 seconds for this scenario. 5 seconds is the nominal expected pilot delay used in previous TCAS safety studies. Therefore, it is highly probable that the crew would not have time to respond to the warning before a collision is imminent in this scenario.

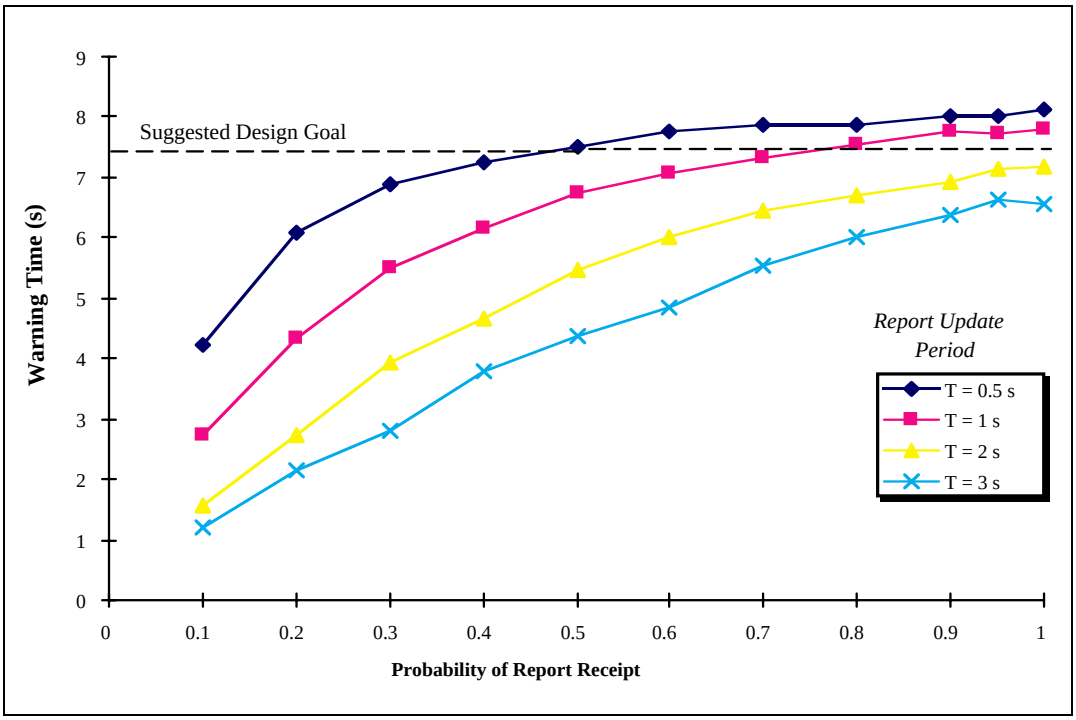

Figure J-31 1,000 ft Independent Parallel Runway Warning Time Sensitivity to Update Period, Probability of Receipt

J.3.1.3.2 1,000 ft False Alarm

In addition to examining the parallel approach conflict case ~~we~~ also examined was a false alarm scenario. The false alarm geometry illustrated in Figure J-32 consists of the two aircraft landing on their assigned runways. The source of false alarms consists of two elements: (1) data errors in the transmitted ADS-B information and (2) plant noise in the true tracks that would allow a prediction of a conflict when none will occur, even with perfect measured data. The simulation's plant noise model varies the true aircraft trajectories on each repetition of the scenario. The deviations from the runway center line are intended to reasonably model typical aircraft landings.

The position deviations from the runway center line observed in Figure J-32 are due to the plant noise model. Note that these deviations are exaggerated, as the aspect ratio in the above figure is not 1:1.

Figure J-33 shows the resulting false alarm rates for the false alarm scenario. The graph depicts false alarm rates for the case where there is no Kalman filtering (smoothing) of received ADS-B data. ~~We suggest a~~A design goal of less than a 0.01 false alarm rate is suggested for the 1,000 ft independent parallel approach case. This design goal is achieved with positional errors of 20 m combined with velocity errors of 1 m/s.

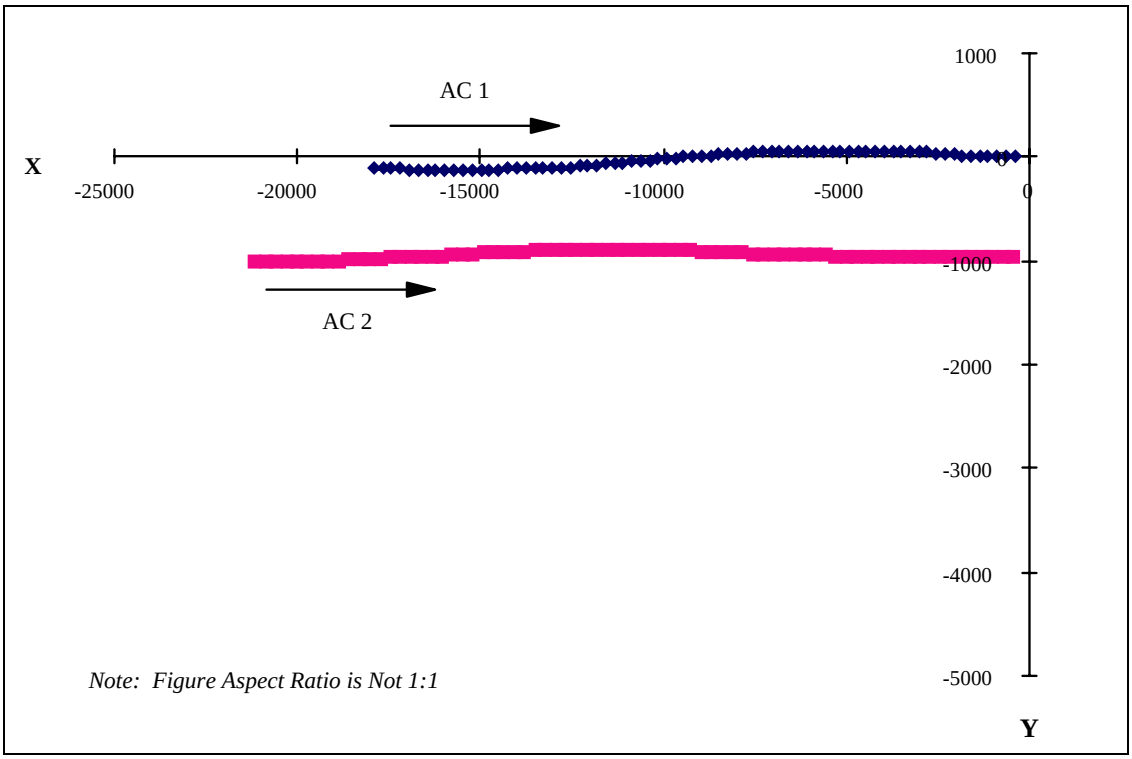

Figure J-32 1,000 ft Independent Parallel Approach False Alarm Geometry

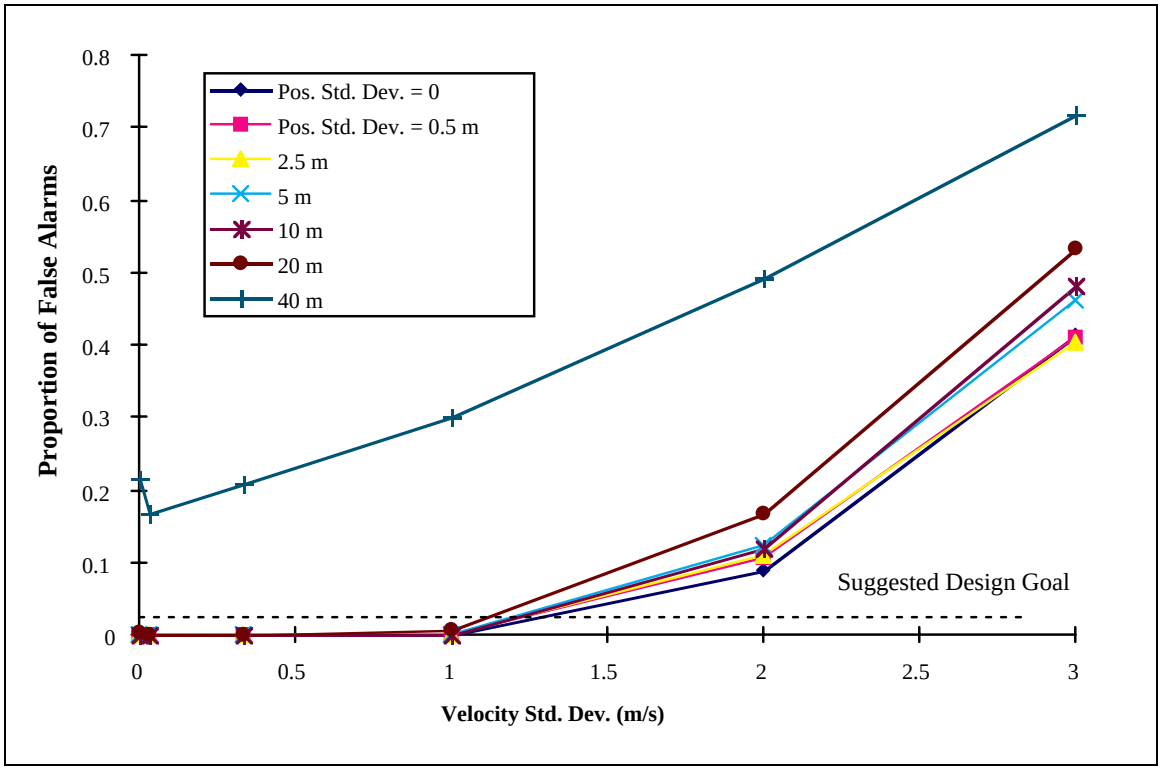

Figure J-33 1k ft Independent Parallel Approach False Alarm Rate

J.3.1.3.3. 2500 Ft Blunder

~~We a~~Also examined was what many consider to be an important potential near-term independent approach scenario. In this case, ~~we analyzed~~ a 2,500 ft runway spacing was analyzed. In Figure J-34~~,~~ is another ~~we again~~ analysis of~~ze~~ the sensitivity of conflict detection warning times to position and velocity errors. Figure J-34 was created based on results with a 1 second state vector report update period with a 0.95 probability of receipt.

The warning times that were achieved may be acceptable for a realistic operation, although extensive safety analysis would need to be conducted to verify this. ~~We n~~Now observed is sensitivity to position errors above 40 meters, 1 sigma, and to velocity errors above 1 m/s. 5th percentile warning times (not shown) are approximately 17 seconds with position errors of 40 m and velocity errors of 1 m/s.

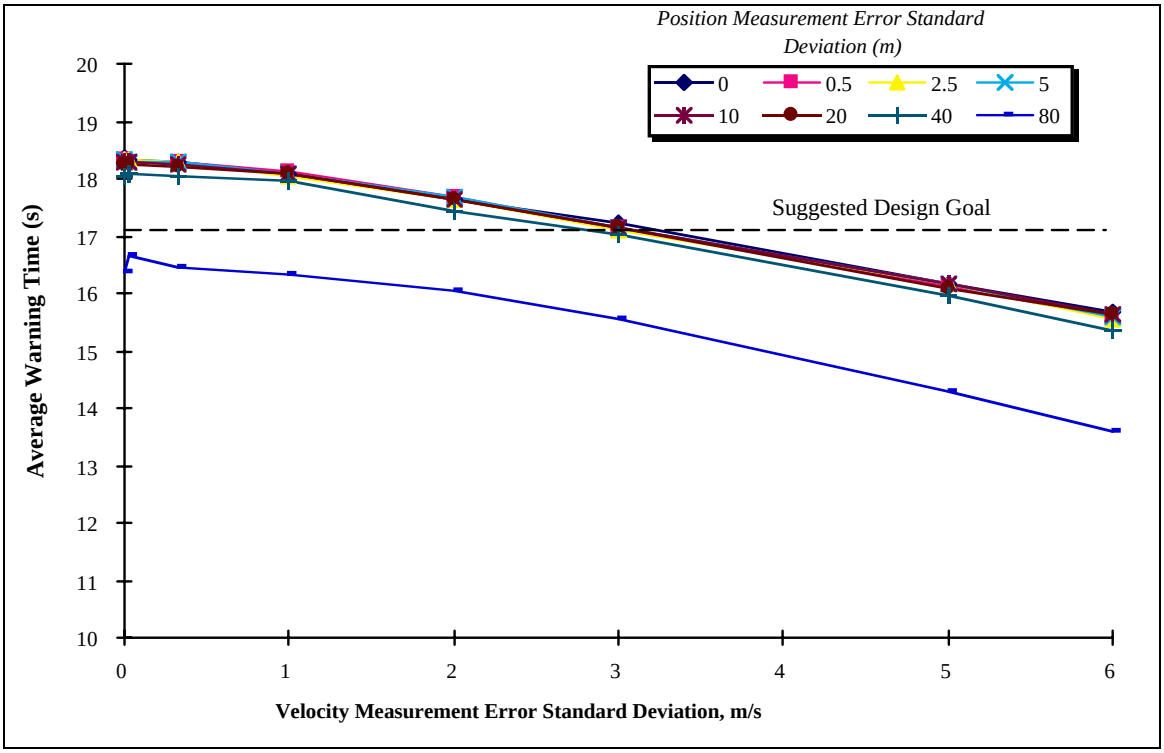

Figure J-34 2,500 ft Independent Parallel Runway: Sensitivity to Position, Velocity Errors

Figure J-35 illustrates the sensitivity of conflict warning time to report update period and probability for the 2,500 ft independent parallel runway blunder scenario. ~~We o~~Observed were adequate warning times relative to ~~our~~ the criterion at update periods of 3 seconds or below.

J.3.1.3.4 2500 ft False Alarm

~~We also~~Also examined was false alarm probability for the 2,500 ft independent runway scenario, illustrated in Figure J-36. ~~We~~ It was found that false alarms could be limited to an acceptable rate (about 1/1000) with position errors at or below 20 m and velocity errors below 0.3 m/s. A false alarm rate of 1/1000 may be operationally acceptable. Therefore it is the false alarms that set the limit on acceptable data errors for this scenario.

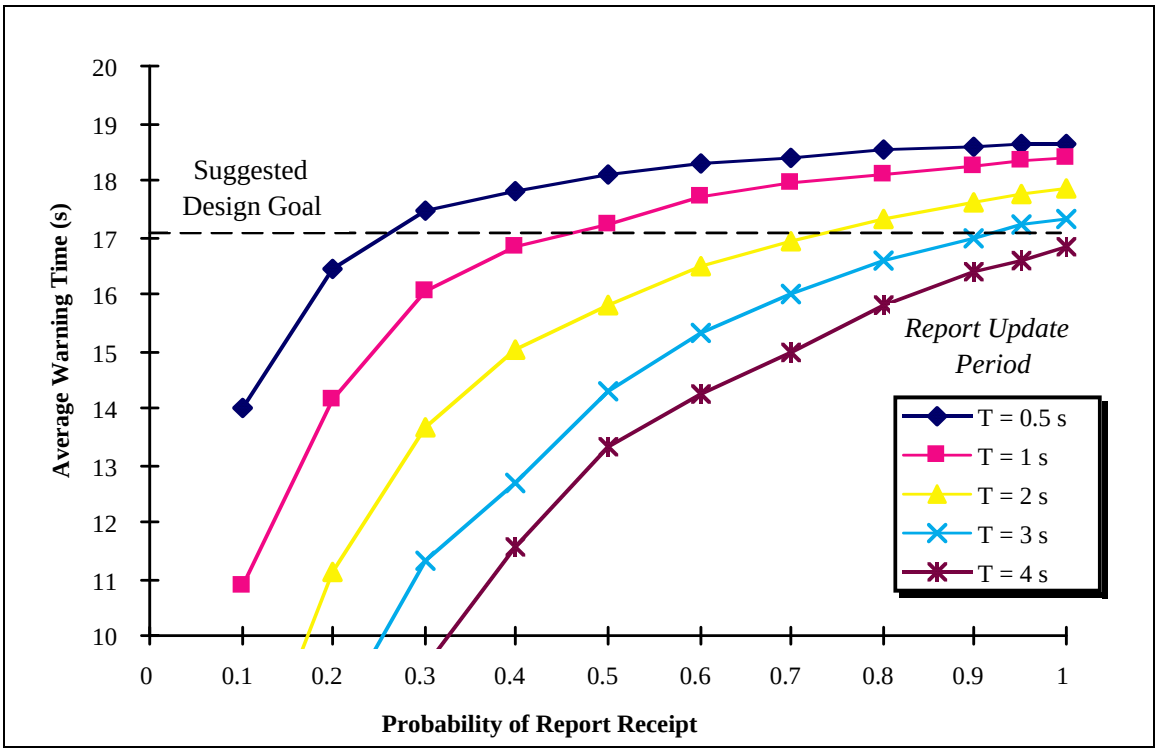

Figure J-35 2,500 ft Independent Parallel Runway: Sensitivity to Report Update Period, Pr(r)

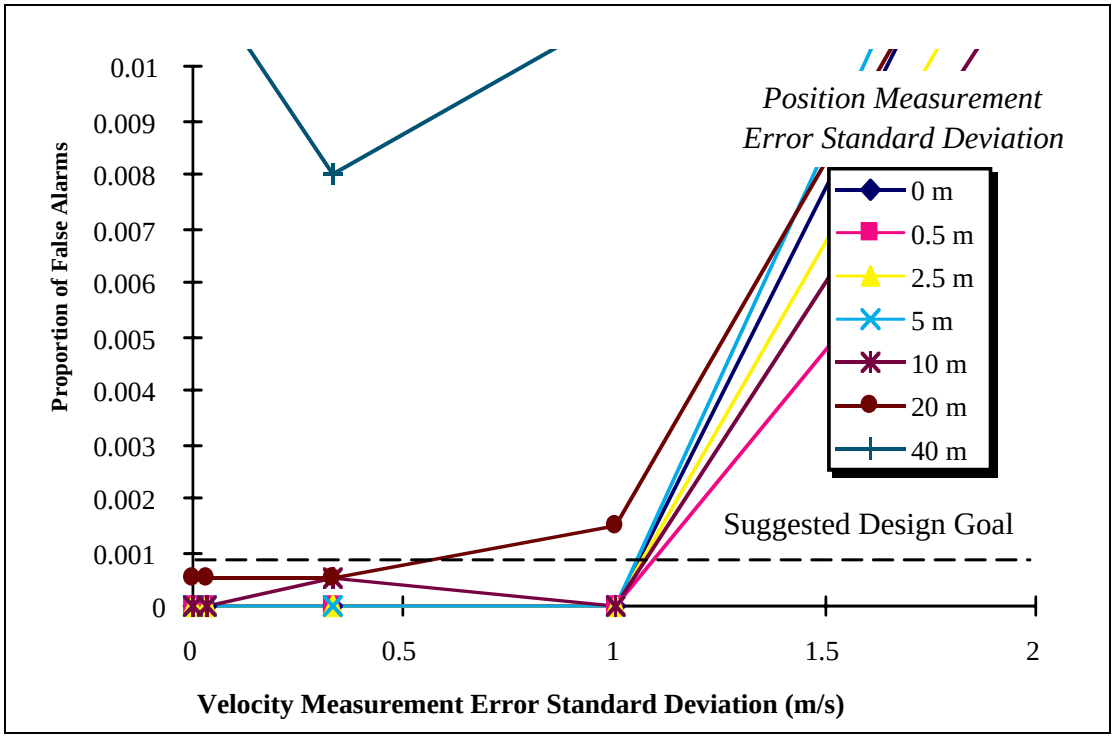

Figure J-36 2,500 ft Independent Runway False Alarm Scenario: Sensitivity to Position, Velocity Errors

J.3.1.3.5 Requirements, Independent Parallel Approach

Based on the results presented, the maximum positional error for these applications is 20 m, RMS. The maximum velocity error is 0.3 m/s, RMS. Table J-4 lists values for required report update period and receive probability. Note that ~~we have made~~ the update period and receipt probability requirements have been made a function of runway separation.

Table J-4 Simulation Update Period, Update Probability Combinations, Independent Parallel Approach

Runway Spacing = 1000 ft		**Runway Spacing = 2500 ft**	
Update Period	Update Probability	Update Period	Update Probability
0.5	0.5	0.5	0.3
1	0.8	1	0.5
2	n/a	2	0.7
3	n/a	3	0.9

Note: n/a = not applicable

As ~~we have~~was done for the other applications described, ~~we derived~~ a curve was derived which fits the data in Table J-4 based on a maximum coast period (Section J.3.1.1). Equation (1) in Section J.3.1.1.1 was again used. In the case of the 1000 ft runway spacing, ~~we found~~ an excellent fit was found to the values listed in Table J-4 for a coast period, TC, of 3 seconds. For the 2500 ft runway spacing, a coast period, TC, of 7 seconds provides a good fit to the simulation data. Figure J-37 and Figure J-38 compare the simulation results with the requirements for the 1000 ft and 2500 ft runway spacings, respectively. The requirements of Section 3 Table 3-4 state that the coast period, or interarrival time between report updates, must be less than 3 seconds for a 1000 ft independent parallel runway spacing, and must be less than 7 seconds for a 2500 ft independent parallel runway spacing.

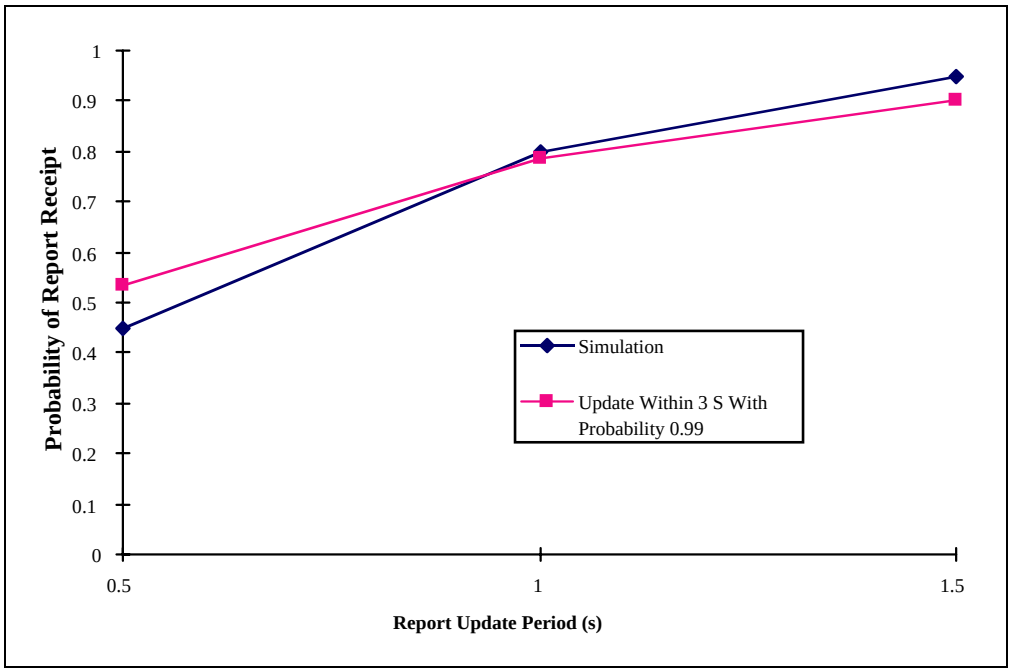

Figure J-37 Update Period Requirements, 1000 ft Independent Parallel Runways

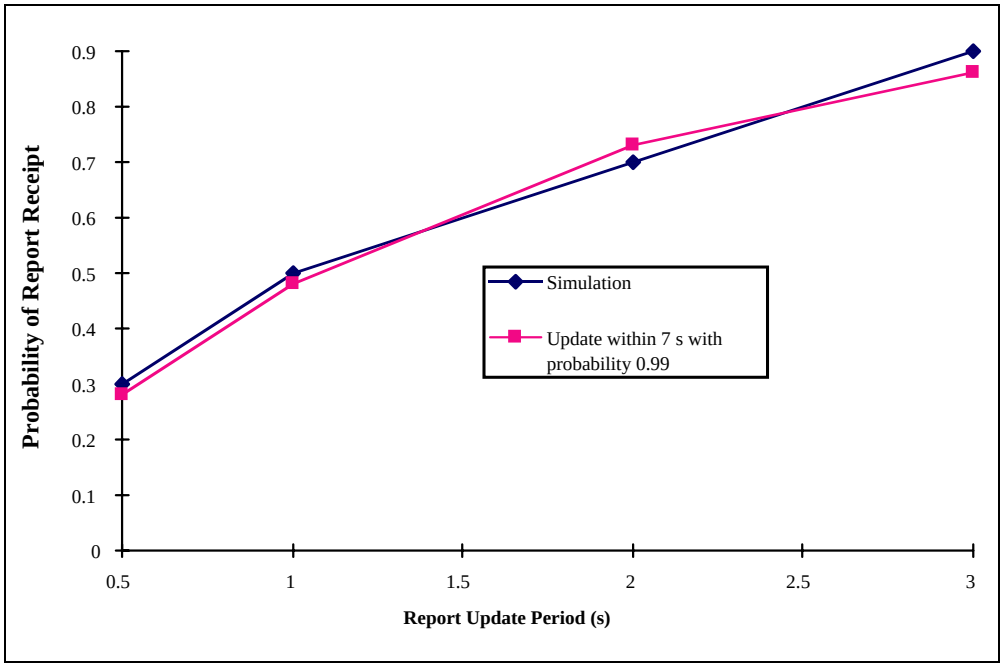

Figure J-38 Update Period Requirements, 2500 ft Independent Parallel Runways

J.3.1.3.6 Comparison w~~W~~ith Parallel Runway Monitor (PRM)

In order to help validate ADS-B requirements for closely spaced independent parallel approaches, a comparison was made between ADS-B and SSR as the source of surveillance information for Parallel Runway Monitoring (PRM). Existing PRM systems use SSR for surveillance, based on an electronically scanned antenna, making measurements once per second [3].

The case analyzed here is illustrated in Figure J-39. Two parallel runways have a spacing of 3400 ft. A surveillance system provides information to controllers on the ground, monitoring the aircraft on approach. A No Transgression Zone (NTZ) 2000 ft. wide is established between the runways. In the event of a blunder, in which an aircraft deviates from the nominal flight path, an alert is generated if the aircraft either penetrates the NTZ or is projected to enter the NTZ in less than 10 seconds, using linear projection of the aircraft path from the available surveillance information. In addition to the 10 second alert threshold, which is used in the existing PRM, this analysis considers other values, in order to make useful comparisons for both warning time and false alert rate.

In this analysis, surveillance is periodic. For the existing PRM, the surveillance period is 1 second. For ADS-B, different values of surveillance period were considered, and results were generated as a function of this parameter. Surveillance inaccuracies are modeled as random Gaussian noise of zero mean added to position and velocity. For ADS-B, the standard deviation of position errors (1 dimensional) = 20 m. The standard deviation of velocity errors = 0.3 m/sec. For the existing PRM, the standard deviation of position errors (1 dimensional) = 9 m, which is a simplified model based on azimuth accuracy of 1 mr, one-sigma, at a range of 5 nmi. In the existing PRM, the surveillance provides only position information. Velocity is estimated by tracking. An alpha-beta tracker is used with constant gains, alpha = 0.3, beta = 0.245. Latency in ADS-B is modeled as follows.

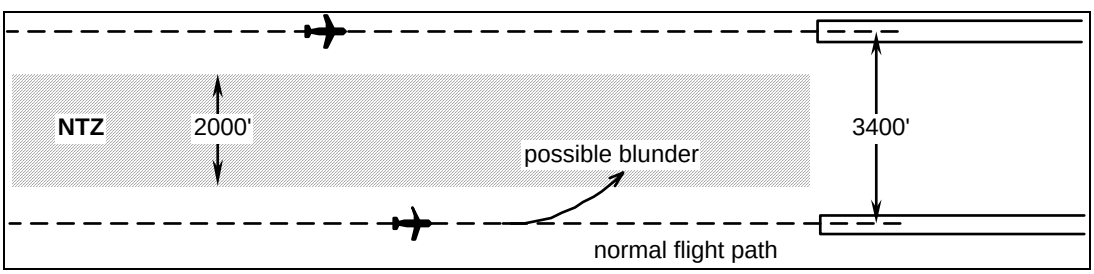

Figure J-39 Scenario for Analysis of PRM

Position latency = velocity latency
Average latency = 0.7 sec (based on the table in Appendix L)
Variable latency = 0 (a simplified model)
Report time error = 0 (a simplified model)

These values are applicable to high-end avionics, which is appropriate for a PRM application. Latency in the existing PRM is modeled as a constant 0.1 sec. The test for triggering alerts is

$$x/(-xd) < 10 \text{ sec.} \qquad (3)$$

where

x = distance to the edge of the NTZ
xd = rate of change of x

To account for latency, the values of x and xd are projected to the current time before applying the above formula.

To assess the PRM performance in providing timely warnings in the event of a serious blunder, the following model was used. An aircraft on a landing approach suddenly begins a blunder in the form of a constant-rate turn toward the other runway, as illustrated in the figure. Speed is 120 knots, and turn rates of 1.5°/sec and 3.0°/sec are considered. The time of the beginning of the blunder is random and independent of the timing of the periodic surveillance.

The false alert rate was also assessed. A motion model was adopted in which the flight path for each landing aircraft includes a deviation toward the other runway. The model for this deviation, which is based on a number of flight paths observed in PRM testing at Memphis International Airport, consists of a smooth path, curving toward the other runway, reaching a maximum deviation, and then returning to the nominal flight path. The flight path is given by

$$x = 700 - M\,(1/2 - 1/2 \cos(2\,p\,t / D)) \qquad (4)$$

for time t between 0 and D. The parameter M is the maximum deviation, and the parameter D is the duration of the path deviation. Both parameters are constant during any one landing, but are varied from landing to landing. D is a random variable, uniformly distributed between 50 and 90 seconds, and M is a parameter used for presenting the false alert rate results.

Results were obtained using a Monte Carlo simulation. For each assignment of parameter values, 1000 trials were run, beginning with statistically independent initial conditions. These results are plotted in Figure J-41 for cases in which the alert threshold is 10 seconds. The upper plot shows the warning time results. From the 1000 blunders simulated, the average warning time was computed, as well as the 10 and 90 percentile values. This plot also includes the individual values of warning time from the first 20 trials. Warning time results were also generated for the existing PRM, and these are plotted along the right hand side of the figure.

These results (for constant alert boundary of 10 seconds) indicate that warning time is best when surveillance rate is high (small values of surveillance period, T). Comparing ADS-B with the existing PRM, the warning time would be the same if the ADS-B surveillance period were about 1 sec. Comparing T = 1 sec. and T = 3 sec. for ADS-B, the results indicate a degradation in the average warning time of about 1 second, which seems reasonable given the independent phasing of surveillance.

On the other hand, the results in the lower plot indicate that the false alert rate is significantly lower (better) for ADS-B. This benefit is a consequence of the fact that ADS-B transmits velocity directly from the aircraft to the ground, eliminating the need to estimate velocity by tracking.

From all the results in Figure J-40, which are based on a 10 second alert threshold, it is not clear how to compare ADS-B with the existing PRM. ADS-B with a 3 second surveillance period provides an improvement in false alert rate but there is a degradation in warning time. For this reason, the study was extended to include other values of the alert threshold.

Other values of the threshold were tested, in order to find conditions for which the ADS-B false alert rate is equal to that of the existing PRM. The results indicate that the following threshold values will all provide the same false alert rate:

Alert threshold =	15 sec. for ADS-B using T = 1 sec.
	18 sec. for ADS-B using T = 3 sec.
	10 sec. for existing PRM (T = 1 sec.)

Then, using these new values, the warning time simulation was run again, producing the results plotted in Figure J-41.

The results indicate that expanding the alert boundary has a beneficial effect for improving warning time in ADS-B. Using this constant-false-alert formulation, the warning time using ADS-B is better than in the existing PRM, even if the ADS-B surveillance period is T = 3 sec. The results also show that a substantial further improvement in warning time is possible by using T = 1 sec. in ADS-B.

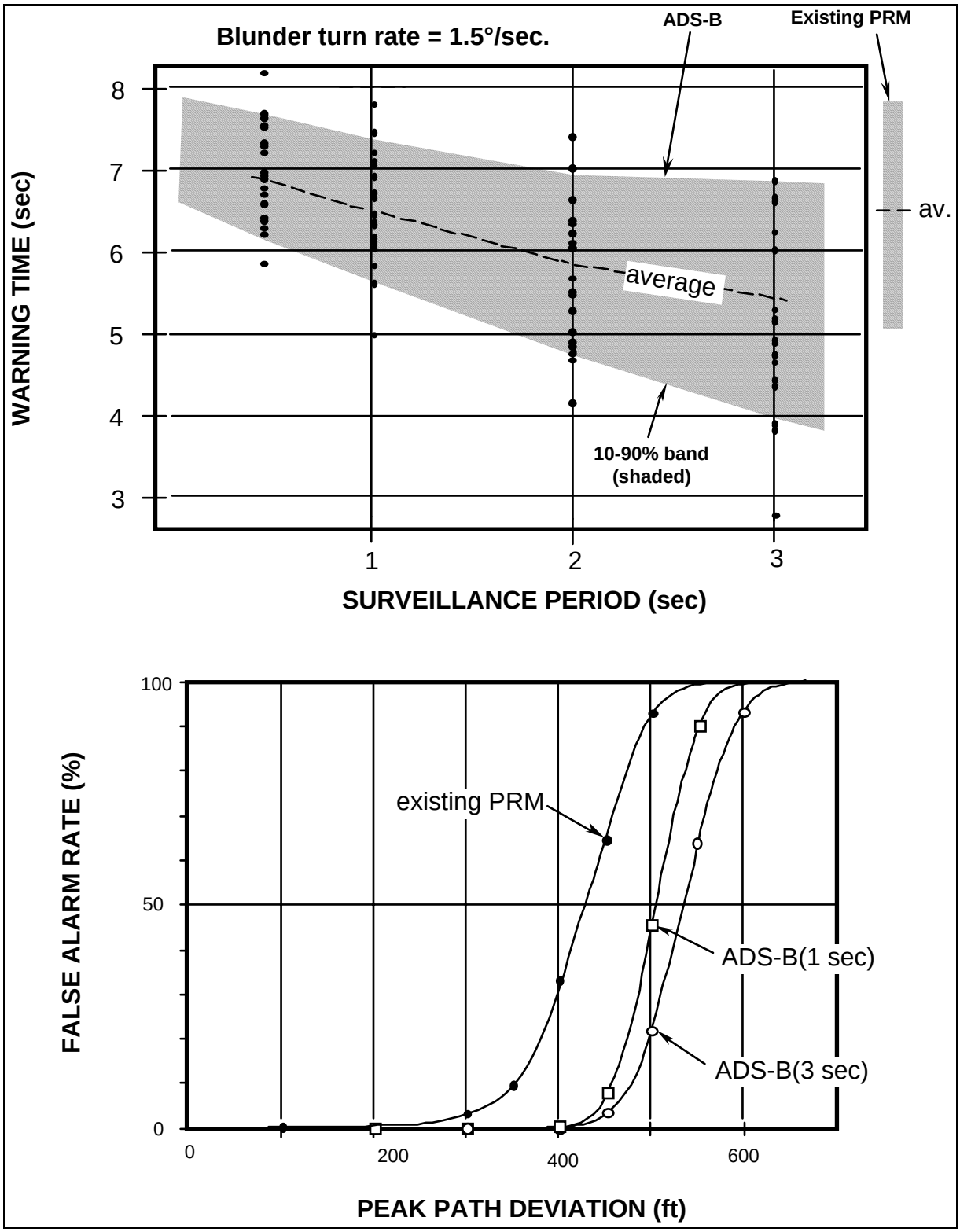

Figure J-40 Simulation Results for Fixed Alert Threshold (10 Sec)

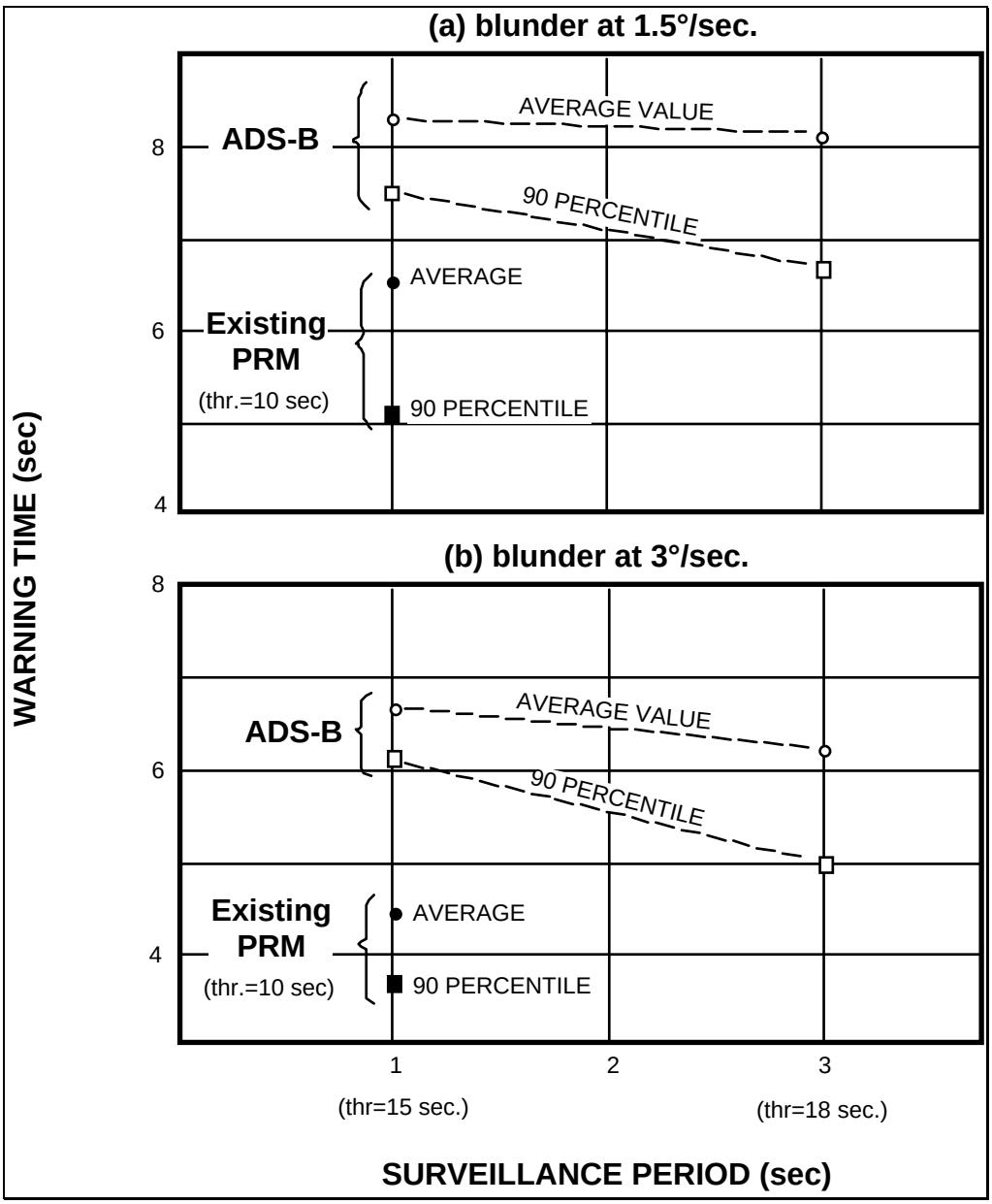

Figure J-41 Simulation Results for Constant False Alert Rate (Different Thresholds)

J.3.2 Surface Scenarios

Two surface scenarios were analyzed: first the blind taxi scenario, and second, a runway incursion scenario.

J.3.2.1 Blind Taxi

The first surface scenario which was analyzed is the "blind taxi" scenario. In this case the objective is to allow aircraft to follow each other on the surface during extremely low visibility conditions. Several assumptions were made regarding aircraft taxi speeds, decelerations, pilot response times, etc., which are listed in Figure J-42.

~~We evaluated t~~This scenario was evaluated using two different values for "data latencies." ~~We~~ It is assumed that data latencies ~~to~~ include any navigation system latencies, buffering of data at the source, transmission delays, buffering of data at the receiver, application processing time, and any latencies associated with displaying information or an aural annunciation of the information. In addition to data latencies, pilot response times and braking system response times were considered.

~~Our~~ The objective was to attempt to detect that the lead aircraft was braking. The tailing aircraft would have the automation to detect lead aircraft braking and either display the information to the pilot or announce it. Due to pilot response delays, braking system delays, and data latencies, there is delay between the time the detection of lead aircraft braking occurs and the time the trailing aircraft begins to brake. Under our assumptions this time would be between 2.5 and 3.5 seconds. Delays in detecting lead aircraft braking will result as a consequence of imperfect information being transmitted and due to ADS-B update periods. It is our intent to budget reasonable values for delays in detecting lead aircraft braking due to ADS-B.

= Aircraft taxi at up to 30 knots

= Braking deceleration = 1 m/s^2

= Pilot Response Time = 0.75s

= Braking System Response Time = 0.75s

= Delay in alert due to data latencies, pilot response, control system response means that trailing aircraft will "catch up" with leading aircraft.

= "Accordion" concept – 2 separation standards required
- "Rolling" separation
- "Resting" separation

= Data latencies are assumed to be 1s to 2s. Total delay before trailing aircraft begins to decelerate is 2.5 to 3.5s.

Figure J-42 Surface Scenario 2—Blind Taxi

It is useful to observe that since the trailing aircraft will catch up to the lead aircraft, two separation standards will be needed. The first is the "rolling" separation – the separation to be maintained when the aircraft are stopped. ~~We have labeled~~ T~~t~~he resulting procedure is labeled the "accordion," and ~~have~~ this is illustrated ~~this~~ in Figure J-43.

Figure J-43 (a) shows the configuration of three aircraft actively taxiing at 30 knots. The aircraft are separated in-trail with a rolling separation of 150 m. Figure J-43 (b) shows the configuration after the lead aircraft (AC 1) and the first trailing aircraft (AC 2) are stopped and the second trailing aircraft is decelerating. At this point the accordion is "compressing" as the first two aircraft are now separated by the resting separation of 50 m and the third aircraft in line is separated by 100 m. Figure J-43 (c) shows the "folded" configuration where all aircraft are stopped. The accordion will again unfold as the aircraft begin to roll and attain the rolling separation again.

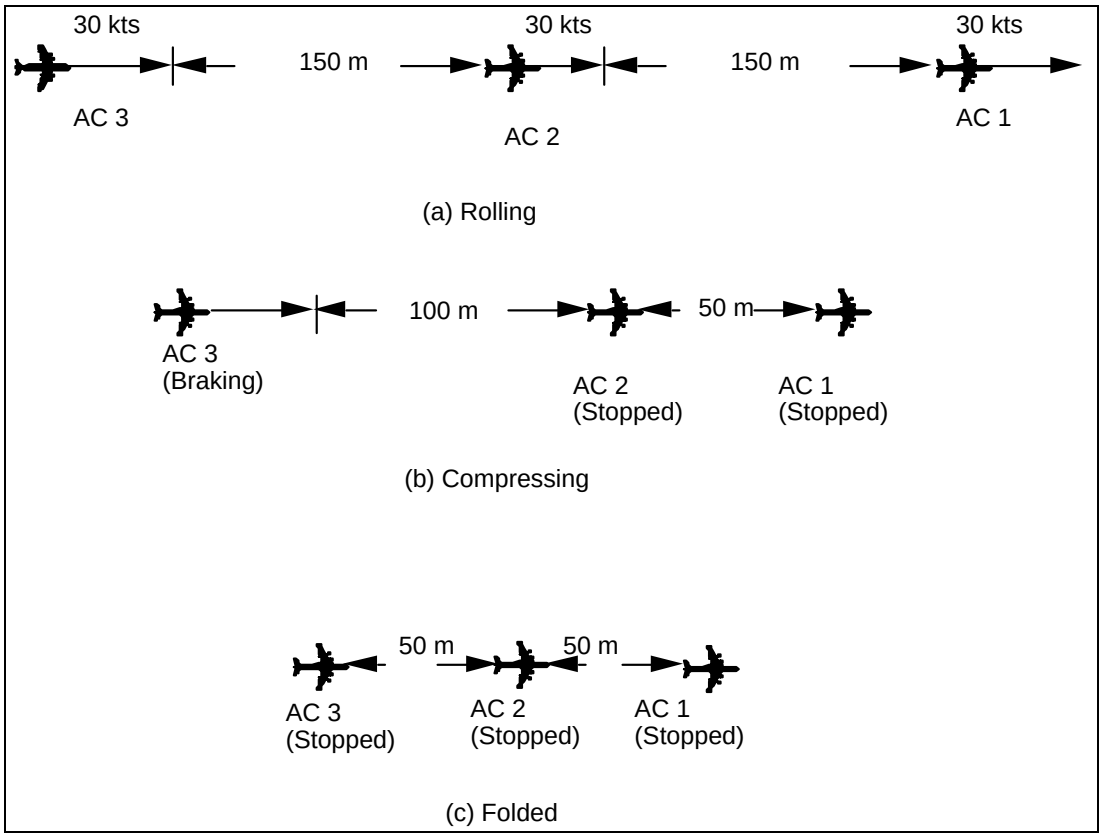

Figure J-43 Accordion Concept

~~We f~~First it was attempted to set the rolling separation to 100m. If ~~we~~ it is assumed that the maximum assumed data latency ~~of~~ is 2 s, the earliest that the trailing aircraft can begin braking is 3.5 seconds after the lead aircraft begins braking (assuming zero delays due to ADS-B inaccuracies and update periods and a perfect detection algorithm). If this were the case, ~~we would observe~~ the geometry depicted in Figure J-44 would be observed. As the trailing aircraft comes to a stop it violates the desired resting separation. Clearly, this scenario (e.g., a 100 m rolling separation) is not feasible if the latency is 2 seconds or more. Therefore, it is our assessment that a rolling separation of 100 m combined with a resting separation of 50 m is probably not realistic. These separations cannot be supported by an ideal ADS-B system (with 0 error and infinite update rate).

Since 100 m does not appear to be feasible, ~~we~~ next analyzed were the requirements for a 125 m rolling separation. Equivalent to analyzing the required warning time, ~~, we can find~~ the range behind the lead aircraft at which ADS-B must provide the braking signal to the following aircraft can be found. This calculation can be made with consideration given to the delays listed earlier. Table J-5 lists the required detection range values for a 125 m rolling separation. Note that the values listed in the table have been adjusted for all delays listed in earlier. Therefore, ~~we can consider~~ the values listed in the table above can be considered to be the allocation to ADS-B surveillance and blind taxi application processing.

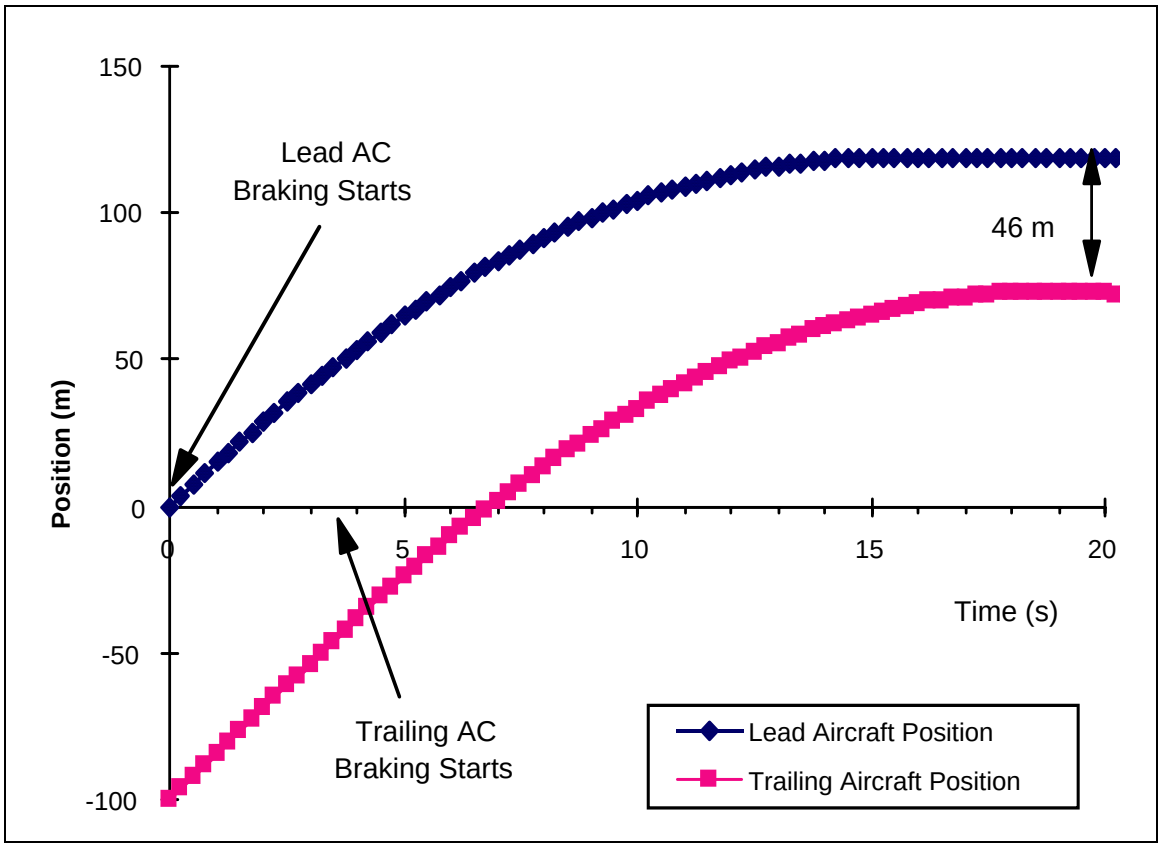

Figure J-44 Separation vs. Time with 100 m Rolling Separation, 2 s Total Data Latency

Table J-5 Required Range at Alert

Latency = 1 s	Latency = 2 s
117 m	121 m

Figure J-45 shows the range at which lead aircraft braking is detected as a function of state vector accuracies for a 125 m rolling separation. Required braking detection range is met for all examples shown if the data latencies are held to 1 second or less. If data latencies are held to 2 seconds, 20 m positional accuracy is required, but all values of velocity data errors supported early braking detection. However, as will be shown in the following figure, these high values of velocity errors lead to unacceptably high false alarm rates.

~~We also~~Also~~-~~ analyzed were false alarms for the blind taxi scenario. ~~We counted a~~A false alarm was counted whenever one or more declarations of lead aircraft braking were made before the lead aircraft actually started braking. ~~We counted t~~The number of encounters in which a false alarm occurred were counted, then divided the number of encounters with false alarms by the total number of encounters simulated. Figure J-46 illustrates that false alarm rates grow quickly for our example when RMS velocity measurement errors exceed 0.3 m/s. Therefore ~~we~~ it is suggested that velocity errors be limited to 0.3 m/s, RMS, for the blind taxi application.

Update period requirements depend on the assumed data latencies. If data latencies are held to 1 second or less, update periods will need to be 2.5 s or less, as illustrated in Figure J-47. If data latencies are as high as 2 s, then update periods will need to be about 1.5 seconds. Note that all report update periods were simulated with a probability of receipt of 0.95.

J.3.2.2 Runway Incursion

Another surface scenario ~~we have~~ examined is the runway incursion scenario. An attempt was made to predict, with a five second warning time, that a taxiing aircraft would incur the runway.

In the scenario ~~we have~~that was chosen, an aircraft is behind the hold short line, approximately 50 m from the runway edge. The aircraft accelerates at a rate of 1 m/s^2, and crosses onto the active runway. The prediction algorithm attempts to predict the incursion with a five second lead time.

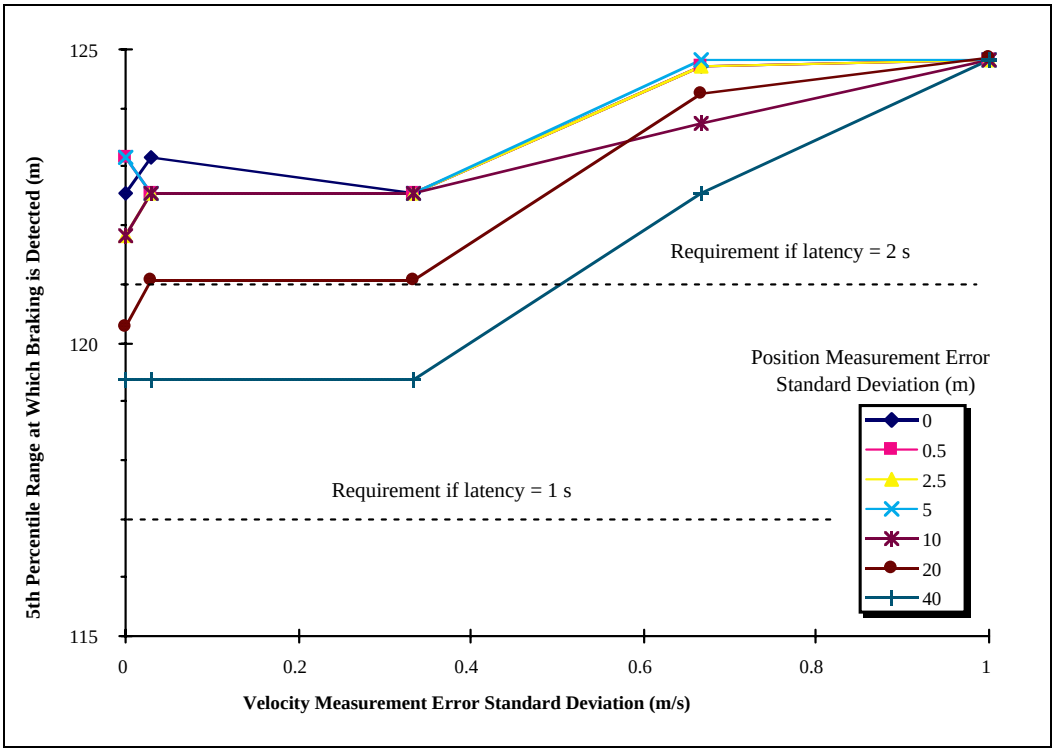

Figure J-45. Range at Which Braking Detected, 125 m Rolling Separation, as a Function of Position, Velocity Error

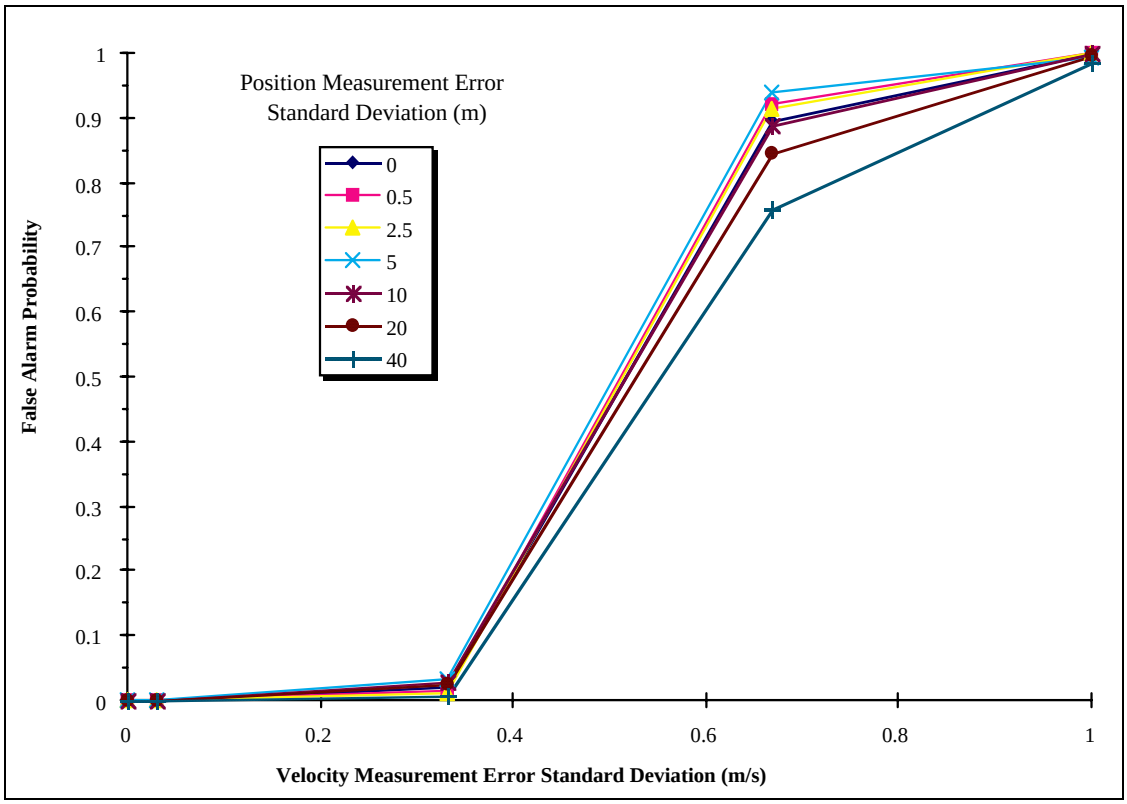

Figure J-46 False Alarm Rates, 125 m Rolling Separation

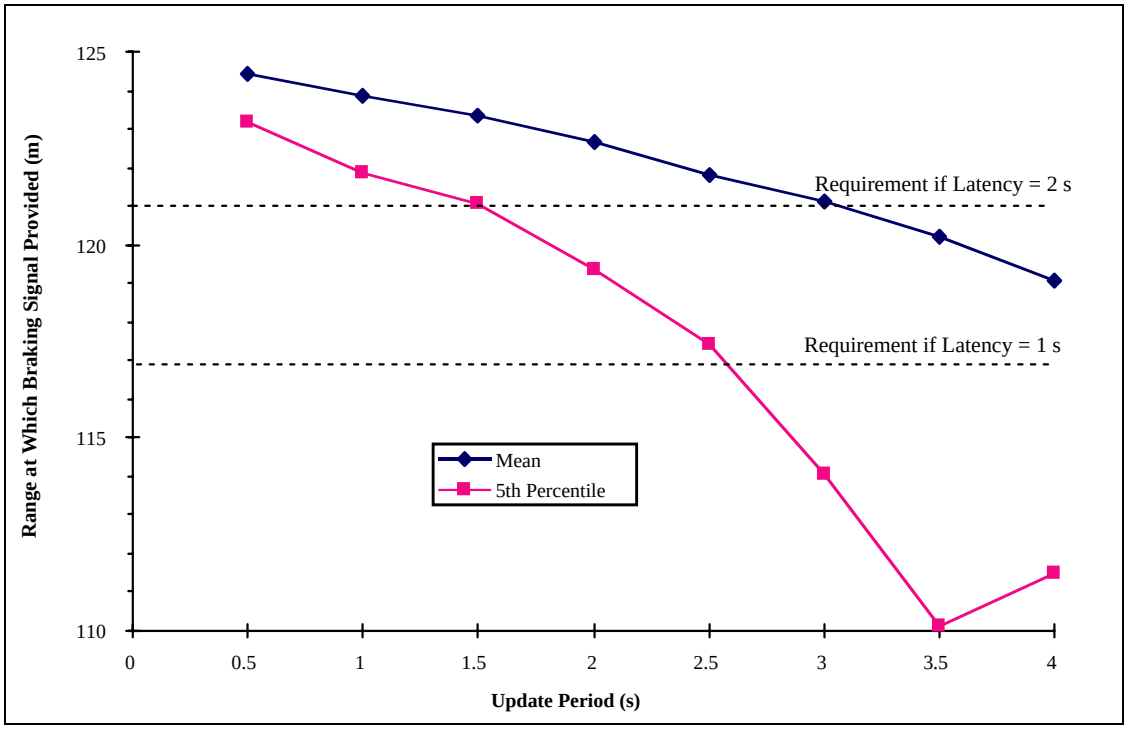

Figure J-47 Required Received Report Update Period, 125 m Rolling Separation

It is self evident that while the aircraft is standing still, position accuracy will be of utmost importance. In order to claim at least equivalence with the existing ASDE-3 radar, it is felt that ADS-B position accuracy for the surface must be at least equivalent to that of ASDE-3. Position measurement errors based on field data evaluations for ASDE-3 are provided in [5]. 95% errors are at least 14 m (mean plus 2 standard deviations, see [5] Table J-1). It seems feasible and reasonable to provide smaller positional error for the surface from ADS-B. 2.5 m RMS error should be practically achievable in a locally differentially corrected environment, and provides errors which are about 1/3 the error in the current ASDE. It is important to point out, that this analysis assumes all positional errors are with respect to a certified navigation center of the aircraft. This navigation center is expected to be available in the ground automation systems' database, along with relevant geometrical data such as wing span[ATO1], fuselage length, etc. ADS-B is not expected to provide the navigation center information or aircraft dimensions in broadcasts.

Since the blind taxi operation established a need for 0.3 m/s velocity error on the surface, ~~we will~~ it is assumed for the runway incursion scenario an RMS positional error of 2.5 m and an RMS velocity error of 0.3 m/s. ~~Our~~ The sensitivity analysis, shown in Figure J-48, indicates that these data errors will cause almost no degradation in warning time for the runway incursion scenario.

Figure J-48 also shows the decrease in warning time as a function of update period. As per Figure J-48, with warning time less than 5 seconds, ~~we allow~~ a 0.5 second degradation is allowed. A 1.5 second update period achieves this goal.

J.3.2.3 Surface Requirements—Summary

~~We have established~~ T~~t~~he following requirements have been established for surface operations. Position error requirements are based on at least equivalence with ASDE-3; velocity error requirements are based on the blind taxi analysis, and the update period requirements are based on an analysis of the runway incursion scenario.

- Position accuracy: 2.5 m, RMS, from the certified navigation center of the aircraft
- Velocity accuracy: 0.3 m/s, RMS
- Update Period: 1.5 seconds with 0.95 probability of update

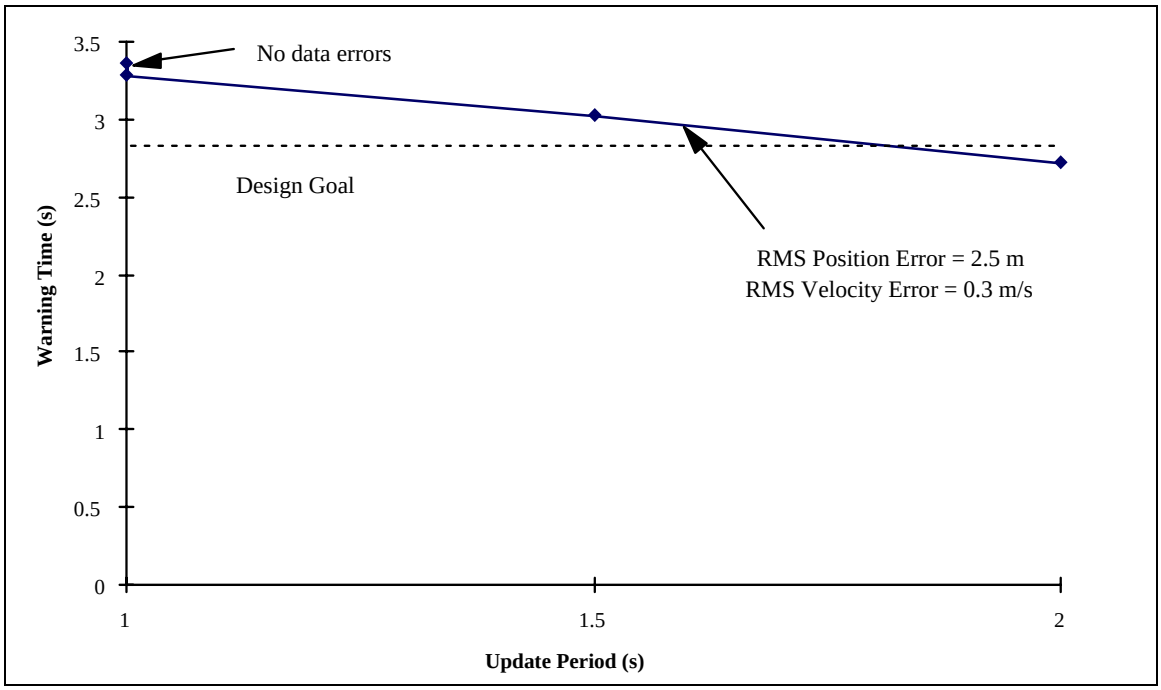

Figure J-48 Runway Incursion Warning Time Sensitivity to Update Period (95%)

J.3.3 Requirements Analysis

Now that ~~we have suggested~~ design goals have been suggested for several applications, ~~we proceed to~~next is a discussion on how these design goals relate to the MASPS tables. ~~We t~~The design goals indicated in the preceding analysis are incorporated into Table 2-8. As described in Section 3.1, Tables 2-8 and 2-9 describe end-to-end design goals for support of ADS-B applications. Section 3 is intended to describe the budget of these design goals allocated to ADS-B. Table 3-2 and Table 3-3 were constructed by assuming that (1) a GNSS satellite navigation system is the primary navigation input to ADS-B and (2) ADS-B should be allocated an error budget consistent with the worst case navigation error that will support the design goals of Section 2. That is, if the navigation system accuracy is equal to or better than that assumed in the construction of Table 3.-2, ADS-B will be able to support the operational goals of Section 2. If the navigation system accuracy is worse than that assumed in Table 3-2, operational procedures may need to be modified. Figure J-49 summarizes the relationship between these sets of tables.

- = Table 2-8 contains design goals for system needs for each application.
- = Table 3.3-1 contains required error allocation to ADS-B to achieve the needs of Table 2-8.
- = Assumed GNSS is the primary navigation support to ADS-B.
- = Pick maximum GNSS error (SA On/ SA Off/ WAAS/ Local Area Differential corrections) that can support Table 2-8 applications.
- = Error allocated to ADS-B is RSS difference between Table 2-8 requirement and GNSS accuracy.

Figure J-49 Relationship between Table 2-8 and Table 3-2

The example presented in Figure J-50 illustrates the derivation of the parameters listed in Table 3-2. For this example ~~we used~~ the position error design goal of 20 m listed in (revised) Table 2-8 is used. Examination of expected GPS positional errors gives ~~us~~ 1-sigma 1D errors as follows:

- SA On: 37 m
- SA Off: 6.4 m
- WAAS: 1.8 m
- LAAS: 0.3 m

- = 20m RMS error requirement
- = GPS, SA On: 37m; SA OFF: 6.4m (1 sigma, 1D)
- = SA Off is maximum navigation error that can support 20m accuracy
- = ADS-B allocation = SQRT (20m * 20m – 6.4m * 6.4m) = 19m
  - - round off: 20m error is ADS-B requirement
- = ADS-B will:
  - - Achieve design goal with SA off, WAAS, or LAAS
  - - Cannot achieve design goal with SA On
    - = May need to adjust operational procedure with SA On (Increase separation, etc.)
    - = SA On will be useful with suitable adjustments to procedures

Figure J-50 Example: Horizontal Position Error

In looking at this set of values ~~we see~~it is seen that SA off is the maximum GPS navigator error which will support the desired 20 m accuracy. Assuming SA off ~~we can then~~an allocation to ~~allocate to~~ ADS-B can be made for a maximum permissible degradation. The 6.4 m used by the navigation system ~~We~~ is subtracted (in an RSS calculation) from the 20 m design goal ~~the 6.4 m used by the navigation system~~. This allows the ADS-B system to degrade positional accuracy by about 19 m. ~~We~~ This is then rounded ~~this value~~ to 20 m.

If the navigation system accuracy is SA off or better, ADS-B will then be able to support the desired operation suggested in Section 2. If an aircraft or aircraft pair is operating with less accurate navigation data, the operational procedure will need to be adjusted. This does not preclude the use of navigation data with more than SA off data errors. The MASPS requirement is intended to guarantee that, when appropriate navigation source inputs are available, ADS-B will be suitably designed for support of the desired operations discussed in Section 2.

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[1] McLaughlin, Dr. M. P., *TCAS v7 Safety Study Overview*, RTCA Paper No. 159-97/SC-147-674, 28 May 1997.

[2] Dobyne, J., *The Accuracy of Barometric Altimeters with Respect to Geometric Altitude*, Institute of Navigation, Proceedings of the International Technical Meeting, September 1998.

[3] FAA Precision Runway Monitor Program Office, *Precision Runway Monitor Demonstration Final Report*, DOT/FAA/RD-91/5, February 1991.

[4] McLauglin, M. P., *The TCAS Safety Database*, WN 95W0000118, The MITRE Corporation, September 1995.

[5] Jones, D. R., Young, S. D., *Flight Demonstration of Integrated Airport Surface Automation Concepts*, Proceedings, AIAA/IEEE Digital Avionics Systems Conference, November 1995.