Appendix H
Track Acquisition and Maintenance Requirements

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1 Introduction

ADS-B surveillance information required to support various operational needs ~~may be~~is transmitted ~~as~~ differently depending on the data link ~~message types~~. If information is transmitted using different message types, ~~T~~the receive processor must correlate information contained in the different message types from different aircraft and associate this information with the correct source aircraft. These correlated, time registered data are then provided to the on-board user application in the form of ADS-B reports. Depending upon the design, the ADS-B receive processor may also support additional functions that are traditionally considered to be part of surveillance tracking. The following discussion first reviews the familiar role of trackers employed in radar surveillance and then identifies some of the ways the ADS-B tracker function differs from radar tracking. ADS-B link reliability required to support ADS-B tracking is then discussed in Sections 2, 3, and 4.

Radar trackers are a familiar part of both skin paint (PSR) and cooperative (SSR) radar surveillance systems, but ADS-B report information content and quality of the information differs appreciably from the target estimates available from a radar sensor. The following discussion identifies some of these differences, discusses the impact of these differences in defining ADS-B tracker requirements, and illustrates how tracker-related features influence the determination of acceptable ADS-B link interference limits.

1.1 Radar Trackers

Radar surveillance systems output position (and sometimes other parameters such as altitude and radial-velocity) estimates on each target detected during a beam scan. Extraneous detections (clutter in the case of PSR and FRUIT replies in the case of SSR) are also output during the beam scan. Trackers are used to suppress these extraneous detections while maintaining surveillance on targets of interest. The process of sorting out extraneous detections from desired detections is based on the expected behavior or scan-to-scan consistency of desired target detections in contrast with the more random nature of undesired detections. This sorting, or track acquisition, process requires that at least m out of n successive scan detections have some kind of correlation in order to initiate a new track. This correlation requirement reduces the probability that extraneous detections (false alarms) will be forwarded to displays or surveillance algorithm using this data.

Radar trackers also smooth target position estimates and derive target velocity estimates based on successive position estimates. This derived velocity is updated with each position estimate and can be used to coast the tracked target through periods of missed updates as long as a new update is obtained before the track coast period has exceeded some operationally accepted interval. For example, the acceptable coast interval may be limited by the required track correlation bin size, or by the time allowed before detection of a worst case threat maneuver by a track in the coast state. Coast periods for the relatively close TCAS target separations are limited to less than ten seconds; coast periods for en route radar traffic environments, on the other hand, are tens of seconds. Similar time considerations apply to initial acquisition of pop-up targets or reacquisition of dropped tracks.

1.2 ADS-B Trackers

ADS-B surveillance and supporting tracker considerations differ from radar in several respects:

- ADS-B extraneous decodes are produced by undetected message errors; these are extremely rare with use of forward error detection codes. All correctly decoded ADS-B messages contain valid surveillance related information on some aircraft within detection range.
- ADS-B information exchanges are of three types: 1) State Vector data (SV) which are broadcast at a relatively high rate, 2) Mode Status data (MS), and 3) On Condition (OC) data. MS data, or MS+OC data may be contained in the same message as SV data in some designs, or MS and OC data may be broadcast as separate messages at a lower rate. All messages in any design contain the transmitting aircraft address. Different operational capabilities require receipt of different levels of information. For example, SV data alone aids visual acquisition of targets and supports basic conflict avoidances; higher levels of operational capability require augmentation of SV data with MS data, or MS + OC data.
- Different ADS-B message types from the same aircraft are unambiguously associated with the same aircraft track through the above mentioned aircraft address contained in each message. Since ADS-B SV messages contain high accuracy velocity data, there is no need for tracker derived velocity estimates based on the difference in successive position updates. A tracker employing extrapolation, correlation, and smoothing is required, however, to reassemble segmented position and velocity SV messages if they are used.

1.3 Operational Needs

Dynamic considerations associated with following an aircraft maneuver using ADS-B based surveillance are similar to those for radar tracking. Certain benefits are, however, obtained from the complete target state vector~~, intent,~~ and other operational information provided in received ADS-B messages. Acquisition ranges and the information exchange requirements for the operational applications of interest are summarized in Table 3-4(a).

~~Simulations to date (see Appendix J) indicate that s~~Surveillance on target separations out to about 20 nmi may be supported by only the position, velocity, and aircraft address information contained in the full state vector (SV) message. These tracks, once acquired, may be maintained by reception of at least one full SV message update within the permitted track coast interval. An acceptable coast interval is somewhat dependent on the operational application supported, but might typically be defined as two update opportunity (or broadcast) intervals. IFR traffic separation requirements impose the need for information in addition to the SV, such as aircraft identification and flight status that is included in the augmenting Partial Mode Status (MS-P) message type. Since MS-P information is relatively static and is directly associated with SV messages through the common aircraft address, it does not require the same broadcast rate as SV messages. Both SV and MS-P messages must be received, however, to support this IFR operational need.

Predicting aircraft separations based on SV information alone is limited to the above mentioned separations of about 20 nmi by false alerts due to aircraft plant noise (normal variations in the track angle during flight) and the fact that the aircraft of interest may maneuver during the approaching encounter alert interval. Beyond 40 nmi, ~~Simulation experience and engineering judgment indicate that exchanging current trajectory change point (TCP) information can restrict these false alerts and aid separation management for separation ranges out to about 40 nmi. This TCP intent information is included in the full Mode Status (MS) message type. Additionally, a lower SV receive update rate can be acceptable in support of surveillance on aircraft separated by longer ranges. After initial SV and MS acquisition, received SV updates corresponding to these longer permitted coast periods are therefore adequate to maintain the tracks.~~

~~Beyond about 40 nmi, the look ahead time for separation prediction is so long that air space deconfliction must be based on the exchange of flight plan information. This strategic planning information is given by the trajectory change point + 1 (TCP+1) data in the On Condition (OC) message type. A~~after initial SV, MS and OC data are acquired, a received SV update interval equal to that of current en route radars seems adequate at these separations. Permitted coast intervals are correspondingly longer.

As discussed above, while maneuver dynamic data contained in SV messages alone support track requirements for separation from nearby aircraft, different operational concerns drive requirements for initial acquisition and track of more distant aircraft. In the latter case, if the operational application requires a specified alert and response time (determined by operational considerations), then the time required to accumulate the required SV, MS and OC information must be added to the operationally required alert time when determining the maximum detection range required for the supported application.

Various combinations of ADS-B state vector broadcast update rates, MS and OC broadcast arrangements, and probabilities of correct reception can satisfy the above stated track acquisition/reacquisition and track maintenance requirements. The following examination determines minimum acceptable values supporting tracker operation. These message reception probabilities may limit the effective range of a particular design when it operates in a high interference environment. Several design alternatives (representing possible random access and TDMA system designs) are ~~examined~~ shown to illustrate ~~acceptable tradeoffs~~performance tradeoffs. ~~We first~~It is ~~-~~assumed that all the required information is contained in either a full state vector report or in segmented state vector reports. Operations requiring the reassembly of augmenting information exchanged in additional message types are then considered.

~~L.2~~2 Approach

~~L2.1~~2.1 Assumptions

The information elements required for various surveillance applications and the coverage ranges of interest are summarized in Table 3-4. It has been previously shown that ~~R~~required SV update intervals for conflict avoidance ~~(~~is 3 seconds and~~)~~, optimized separation is about ~~(about 6 sec),~~6 seconds. ~~and airspace deconfliction (12 sec) are discussed in Appendix J and Section 3.3. Appendix J examines these update requirements~~ on the basis of acceptable loss in alert time for a specified threat target maneuver. From the ADS-B report assembly perspective, we are also interested here in 1) how long it takes to acquire the SV and any necessary augmenting information for the application of interest, and 2) the probability that the acquired track will be dropped if not updated by an SV message within the assumed coast period of two report update intervals. Acquisition time requirements for this examination are assumed to be 6 seconds at a 99% confidence level for conflict avoidance (this is slightly higher than the 95% value given in Table 3-4) and~~,~~ 15 seconds at a 95% confidence level for optimized separation~~, and 30 sec (95%) for airspace deconfliction~~. A reasonable value for the acceptable probability of a dropped track depends on the operational environment, but is taken here to be 0.01. Only random interference is considered. That is, all targets are assumed to be within detection range and received messages are above the link fade margin.

2.2 Design Alternatives

The following analysis determines the lowest acceptable probability of correct message decode, P_s, required to meet tracker requirements for the following message broadcast design alternatives:

1. SV messages are segmented with alternate broadcast of position and velocity messages at intervals of 0.25 sec between segment transmissions. MS and OC messages are each transmitted in separate messages at intervals of T_s= 5 sec for each if either is transmitted alone, or on intervals of 2.5 sec. if both message types are required. That is, the interval for both MS and OC transmissions is 5 sec. The net transmission rate for segmented SV, MS, and OC messages is thus 4.4 Hz per aircraft supporting applications ~~engaged in deconfliction~~requiring additional information that is conveyed in an additional MS or OC message ~~applications~~. The rate is 4.2 Hz for all others broadcasting SV and MS data. These assumptions represent a possible random access design.

2. Full SV data and MS data (partial or full) are combined in one message and broadcast at intervals of 1 sec or 3 sec. Separate OC messages are interleaved with these SV/MS messages as needed on a T_s= 6 sec frame interval in these two designs. The one second interval represents an alternate random access design. The three second interval could be representative of a TDMA design.

3. Each message contains all SV, MS and OC data and ~~are~~ broadcast at intervals of 3 sec. This represents an alternate TDMA design.

3 Analysis

3.1 Performance with State Vector Only

Based on TCAS and simulation experience, assume an ADS-B tactical separation track is updated at intervals of t sec, and is dropped if an SV update is not received within $T_d = 6$ sec. An ADS-B design with a state vector update interval, t, (t= 1/update rate) has $m_d = T_d/t$ opportunities to update the track before it is dropped. For at least one success in m_d tries, the probability of maintaining a track during the permitted coast interval is then

$$P_d = 1 - (1 - p)^{m_d} \qquad ; m_d = T_d/t \tag{3-1}$$

where p is the single report probability of correct reception and each try is assumed to be independent.*

Full State Vector

Because an ADS-B report provides full dynamic information on the aircraft of interest, a single full SV message is adequate for SV data acquisition. Track acquisition or reacquisition within some fraction, α, of the coast period requires at least one out of m full state vector updates. The probability of acquisition is thus given by

$$P_{acq} = 1-(1-p)^m \tag{3-2}$$

where $m = \alpha T_d/t$. When $\alpha = 1$, $m = m_d$.

Segmented State Vector

Acquisition of segmented state vector reports is a little different. In this case, both the position report segment and the velocity report segment must be received and correlated to initiate track. For interleaved segmented reports and the same broadcast rate,

$$P_{acq} = [1-(1-p)^{m/2}]^2 \tag{3-3}$$

since both segments must be received and each segment is transmitted only m/2 times in the permitted acquisition interval.

Minimum Acceptable Decode Probabilities

Equation (3-2) and (3-3) show the probability of receiving at least one full state vector update out of m opportunities to receive an update as a function of the single try probability of receiving an update, p. If, as in equation (3-1), $m = m_d$, then (3-2) and (3-3) give the probability of maintaining a track requiring an SV update within $T_d = m_d t$ seconds. With a little manipulation, (3-2) may be rewritten as

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* The assumption of independence applies for random interference or low S/N considerations. Link fading must be treated separately.

$$P_f = 1 - q^{1/m_d} \tag{3-4}$$

where $q = 1 - P_{acq}$ and is the probability the track is dropped if not updated within T_d sec. The single report probability $p = P_f$, is the minimum probability supporting an acceptable probability of track loss, q with a full SV broadcast every t sec.

Now consider a segmented SV design alternately transmitting position and velocity messages at a rate of n segments in t seconds. The probability of a full SV update in t sec is then given by (3-3) where m=n. An update capability equivalent to that of the full SV design within $T_f = m_d t$ sec may then be determined by setting this value equal to P_f in (3-4) and solving for the required probability of decoding each of the segmented SV messages, P_s. The resulting minimum value for segmented SV messages is

$$P_s = 1 - \left(1 - \sqrt{1 - q^{1/m_d}}\right)^{2/n} \tag{3-5}$$

3.2 Performance with Augmenting Messages

Acquisition requirements for more distant aircraft that are not in immediate conflict may, as discussed above, be stated in terms of being (say) 95% confident of acquisition of the required information elements by the time the aircraft is within the required surveillance range. If P_{acq} is the probability of SV acquisition in an interval, αT_d, and initial acquisition is required within a time, T_{acq}, we may approximate the cumulative probability of State Vector information acquisition by assuming T_{acq} to contain h acquisition cells αT_d long. Thus, $h = T_{acq}/(\alpha T_d)$, and the cumulative probability of SV acquisition within a time, T_{acq}, is

$$P_{cum} = 1 - (1 - P_{acq})^h \tag{3-6}$$

where P_{acq} is again given by (3-2) for full state vector reports, and (3-3) for segmented reports.

Since separation assurance applications require SV+MS data, and since ~~deconfliction~~ applications ~~capability~~ at longer ranges ~~typically requires~~may require OC as well as MS+SV information, track acquisition is not achieved in these cases until the augmenting message(s) is/are also received. Augmenting information may be exchanged in two ways:

- Include MS and OC data along with SV data in a single message broadcast at a rate 1/t
- Augment SV data (broadcast at a rate 1/t) with separate MS and OC messages interleaved with SV messages at a lower rate ($1/T_s$), for example once every five or six seconds.

In the first case where a single message contains SV+MS+OC information, extended range initial acquisition is also given by (3-6). The second case may be implemented in any of a number of different ways. To illustrate, consider the design based on segmented SV messages broadcast at an average 0.25 sec interval between SV segments, and with MS and OC messages interleaved on a T_s= 5 sec average frame time as needed. The cumulative probability of acquiring SV+MS information within T= h x 5 sec is then

$$P_{CSM} = [1-(1-P_{sv})^h]\,[1-(1-p)^h] \qquad (3\text{-}7)$$

where P_{sv} is the probability of acquiring SV data within 5 sec given by (3-3) as

$$P_{sv} = [1-(1-p)^{10}]^2 \qquad (3\text{-}8)$$

and the second term in (3-7) is the probability of receiving the MS message within a period of h x 5 sec. If MS and OC data are contained in separate interleaved messages, then the $[1-(1-p)^h]$ term in (3-7) is squared to account for the joint probability of receiving both MS and OC as well as SV messages within T= h x 5 sec.

4 Results and Discussion

Equations (3-2) and (3-3) are plotted in Figure H-1 for the segmented SV design with an update interval, t_s= 0.25 sec, and for full SV designs with update intervals t_f= 3 sec and 1 sec. As a matter of interest, a full SV design with t_f= 0.5 sec is also shown for comparison with t_s= 0.25 sec segmented SV design. Each curve shows the probability of obtaining at least one SV update within 3 sec as a function of the single message probability of correct decode, p. These values correspond to the requirements for a basic conflict avoidance capability operating without required IFR augmenting information.

As discussed above, the minimum required probabilities of message decode may also be related to operational needs by examining the single message decode probability required to assure that 99% of the tracks are updated within the specified coast interval of twice the operationally required update interval. Figure H-2 shows this minimum acceptable value dependence on 2x update interval for the above designs (equations 3-4, and 3-5). Here, as expected, each design accommodates some decrease in the required minimum value of p for SV or segmented SV messages as the permitted update interval increases. These acceptable p values, however, only apply in cases where all the operationally required information is contained in a single message type. If different message types are used, at least one message of each required type must be decoded for acquisition.

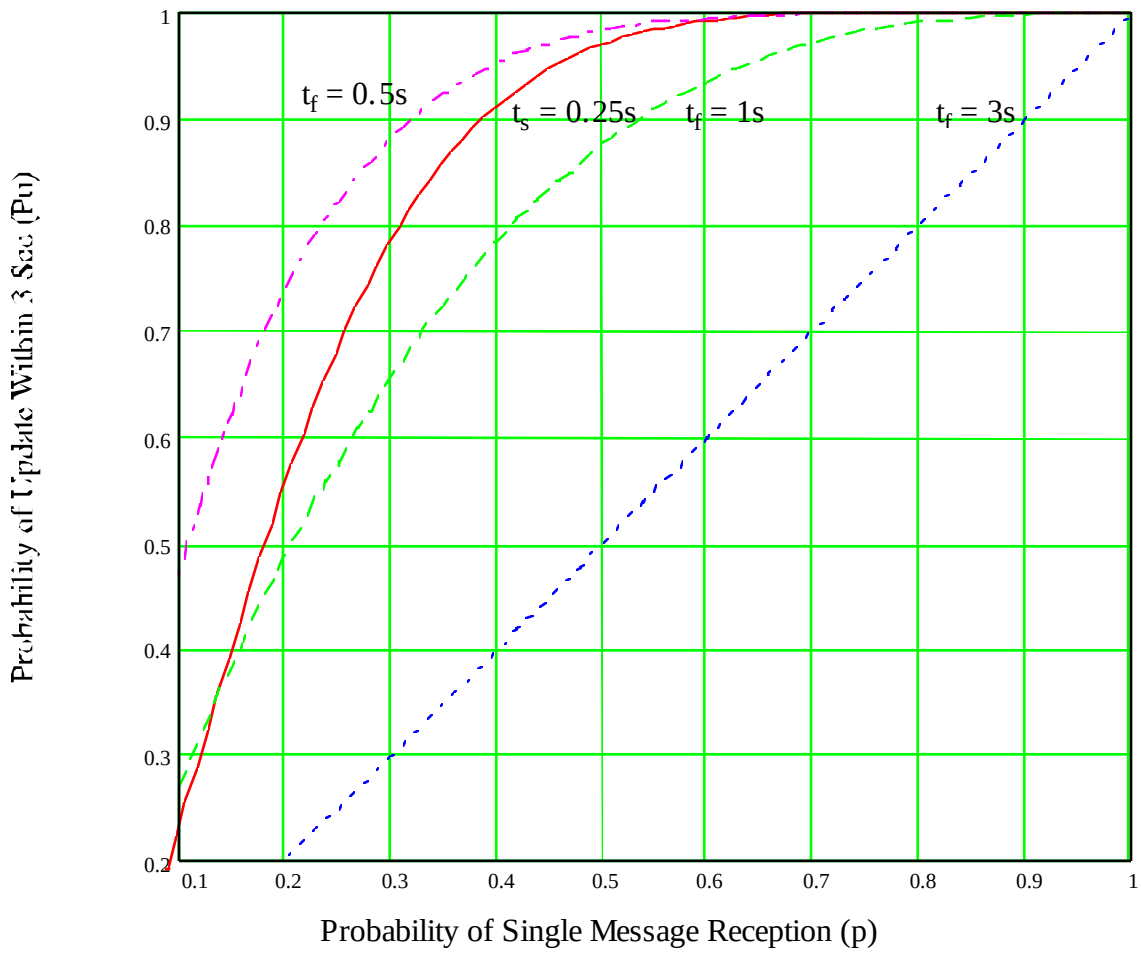

Figure H-1 Probability of Update Within 3 Sec Interval vs. Single Message Reception Probability for Several Broadcast Intervals

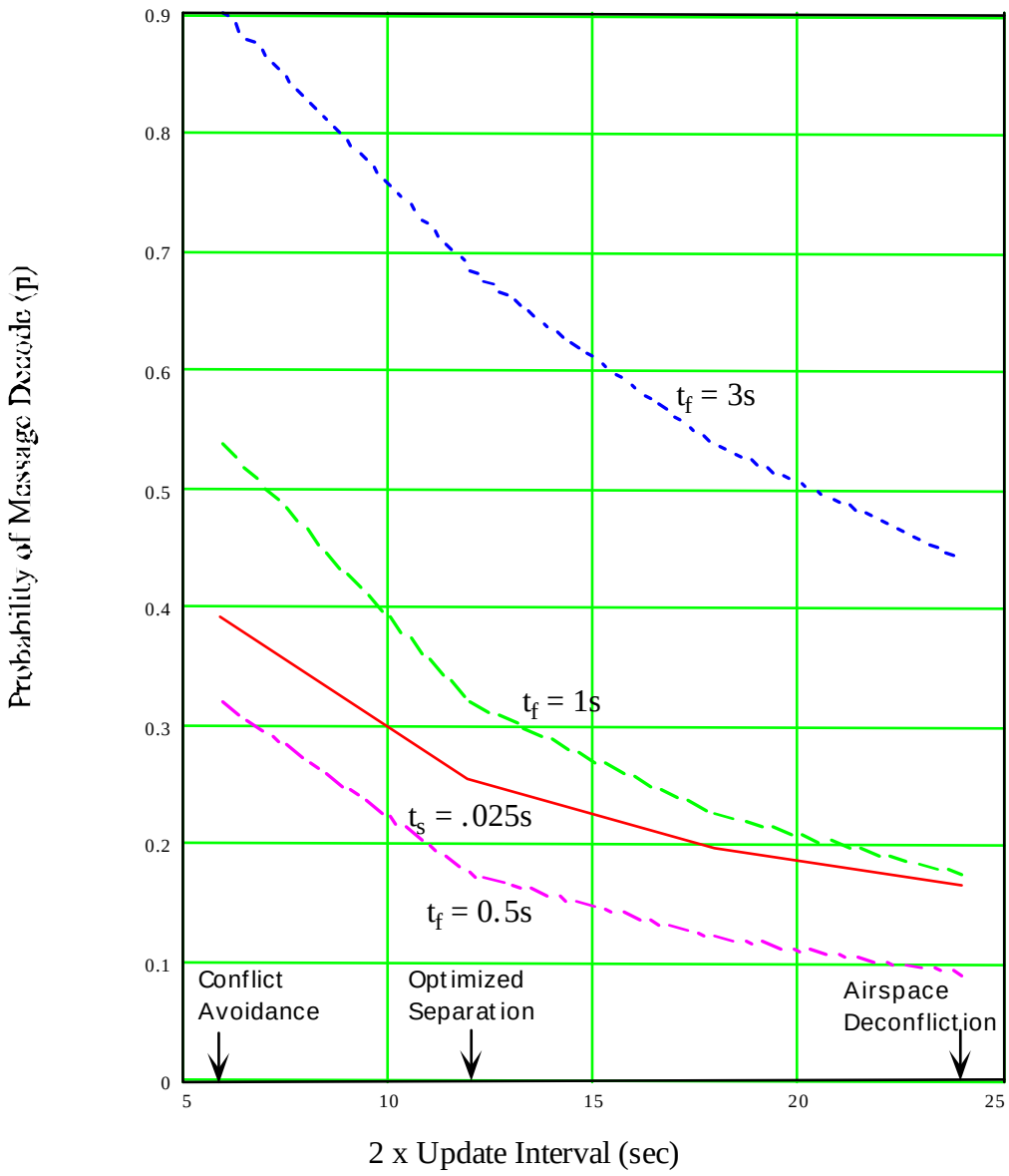

Figure H-2 Required Probability of Message Decode vs. Twice the Required Update Interval for 99% Confidence Track is Updated Within Twice the Update Interval

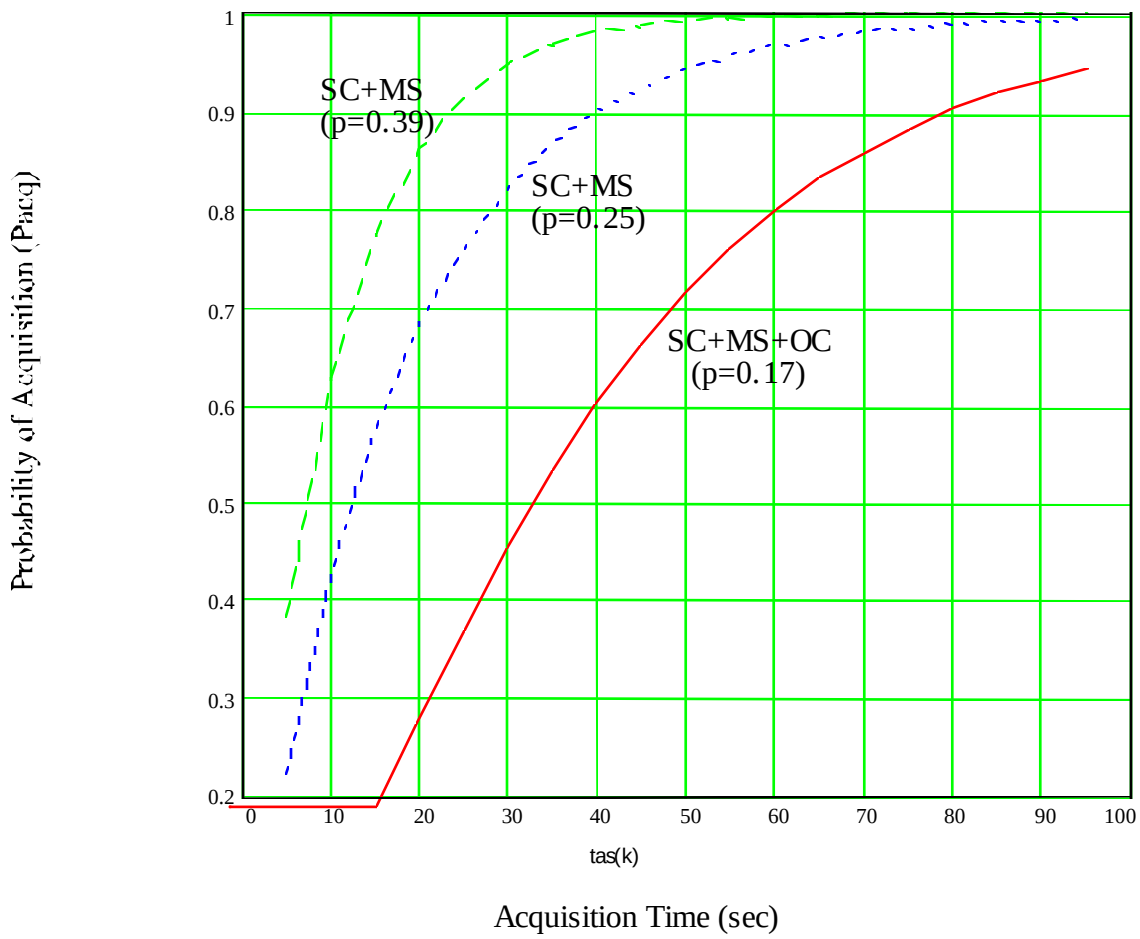

Figure H-3 Probability of Acquiring Multiple Message Types for Segmented State Vector Design with t_s=0.25s and Augmenting Messages Interleaved on a T_s= 5 sec Basis

Although the minimum acceptable probabilities of decode, p, given in Figure H-2 show what is required to support SV track maintenance requirements for conflict avoidance update intervals of 3 seconds, ADS-B Separation update intervals of 6 seconds, and ~~airspace deconfliction~~longer range update intervals of 12 seconds, all surveillance services except basic conflict avoidance require augmenting the SV update data with MS-P, MS or OC type information. Figure H-3 illustrates how low values of p, which are acceptable interims of the SV update requirements alone, limit the acquisition process when multiple message types must be received in order to aggregate all the associated surveillance and intent information required for ~~the airspace deconfliction~~potential longer range applications. This figure is plotted for the segmented SV design and shows the probability of acquiring the full state vector, SC, as well as the required augmenting messages within the indicated acquisition time. Here we note that although p= 0.17 supports the 24 sec ~~deconfliction~~ coast time of Figure H-2, the time to acquire the needed SC+MS+OC data ~~for airspace deconfliction~~ with this value of p is 95 seconds at a 95% confidence level. Either the system detection range must be adequate to support this long acquisition time, or operations must be limited to conditions where a higher level of p is obtained in order to acquire all required data within a shorter time say, 30 seconds. The other two curves on Figure H-3 show similar problems for the other operational services of interest: conflict avoidance, and optimal separation

Figure H-4 shows the same acquisition time relationship for the two designs combining SV and MS into one SV/MS message and augmenting this with an interleaved OC message at T_s= 6 sec as needed ~~for airspace deconfliction~~. In this case the p= 0.44 value required for t_f= 3 sec track update also supports acquisition of OC data within 30 seconds at a 95% confidence level. However, the lower value of p= 0.18 for the t_f= 1 sec design (acceptable for SV/MS update requirements) leads to long delays in OC data acquisition

5 Summary

Table H-1 summarizes these results by comparing minimum acceptable p values determined only by SV track update requirements, with corresponding values derived on the basis that the augmenting MS and OC message acquisition times are the determining factors. The table is based on the assumed requirements of a 6 sec acquisition time for conflict avoidance, a 15 sec MS acquisition time for ADS-B optimum separation, and a 30 sec MS+OC acquisition time for ~~airspace deconfliction~~longer range applications. As an illustration, at a 1200 kt closure rate, a 30 sec acquisition time adds 10 nmi to the required coverage in order to meet the desired alert time.

Inspection of Table H-1 shows that, using the assumed acquisition times and MS and OC message transmission periods, augmenting message acquisition considerations are more demanding than track maintenance requirements for the segmented SV (t= 0.25 sec) design. This is also true for ~~airspace deconfliction~~longer range applications with the SV/MS (t= 1 sec) design. Several possibilities may be considered in these cases:

1. Detection ranges may be extended to accommodate the long acquisition times.
2. The design SV and MS+OC interleave rates may be changed.
3. Support of the intended operational capability may be restricted to low interference environments where higher values of p ~~obtain~~can be achieved.

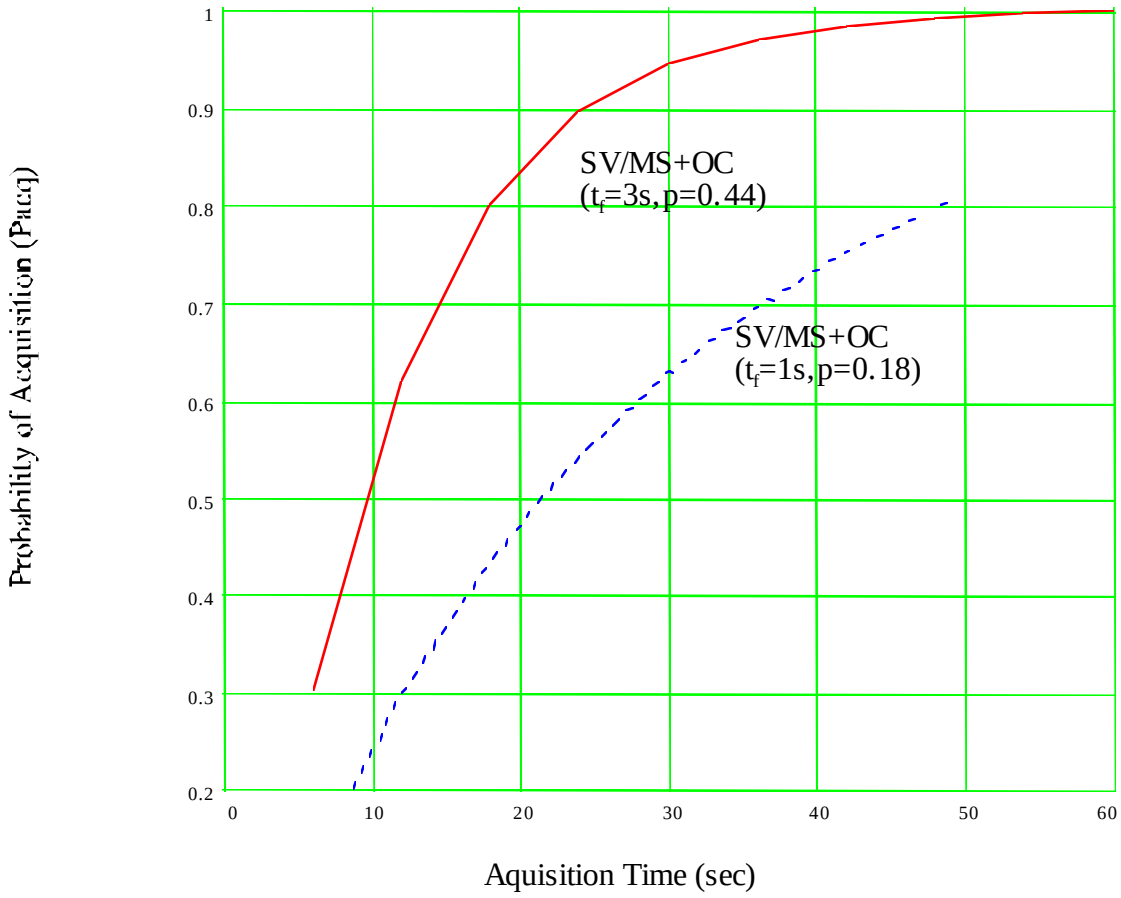

Figure H-4 Probability of Acquiring Augmenting Message for Full State Vector Plus Mode Status Design for t_f=3 sec and 1 sec with Augmenting Message Interleaved on a T_s= 6 sec Basis

Table ~~LH~~-1 Summary of Message Probabilities of Correct Decode Required for Each Design Alternative in Support of Desired Operational Capabilities

Design Alternative	Basic Conflict Avoidance T_d= 6 sec (99%) T_{acq}= 6 sec (99%)	Optimized Separation T_d= 12 sec (99%) T_{acq}= 15 sec (95%)		Potential ~~Airspace Deconfliction~~Longer Range Application T_d= 24 sec (99%) T_{acq}= 30 sec (95%)	
	SV or SV/MS for T_d	SV or SV/MS only for T_d	SV+MS for T_{acq}	SV or SV/MS only for T_d	SV+MS+OC for T_{acq}
Segmented SV t= 0.25 sec T_s= 5 sec	0.39	0.25 (note 1)	0.63	0.17 (note 1	0.46
SV/MS t= 1 sec T_s= 6 sec	0.53	0.32	n/a	0.18 (note 1)	0.45
SV/MS t= 3 sec T_s= 6 sec	0.9	0.69	n/a	0.44 (note 1)	0.46
SV/MS/OC t= 3 sec	0.9	0.69	n/a	0.44	n/a

Notes:

1. *These values only support an indication of target presence. They will not support the intended application.*

2. *n/a indicates service requirement determined by T_d requirement.*

In summary ~~we should also again note that the values in Table -1 must be compared with similar parameters developed in Appendix J where requirements are examined on the basis of lost alert time for specified threat scenarios. F~~, for any design, final system requirements must reflect the most demanding requirement determined by track maintenance, track acquisition time, and lost alert time considerations.