Required Total System Performance and Results of a Short Term Conflict Alert Simulation Study

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Abstract

This paper documents work sponsored by the FAA, as part of the FAA's Concept Validation Plan. It proposes performance metrics relating improvements in technical capability of air and ground elements to traffic spacing under current and future operational concepts. The metrics proposed and defined are the Required Total System Performance (RTSP), and its component metrics; Required Navigation Performance (RNP), Required Communication Performance (RCP) and Required Surveillance Performance (RSP). The paper discusses the potential need for additional metrics for ATM functions such as conflict probing and resolution. A Short Term Conflict Alert (STCA) controller function was modeled to analyze the effects of radar surveillance performance on conflict detection. The report documenting this work in detail can be found at http://www.boeing.com/commercial/caft/reference/documents/rtsp.pdf

Introduction and Background

Current separation standards have evolved over the past 40 to 50 years, reflecting an ATM infrastructure that incorporates a complex set of procedures, technological systems, and human performance. An RTSP perspective has been proposed [1] as an attempt to establish a coherent and rational set of separation assurance criteria. This lays the groundwork for the development of new standards and requirements that incorporate technical, procedural, organizational, and human factors considerations of future CNS/ATM systems.

The establishment of the 5 nmi horizontal separation minima in the US National Airspace System (NAS) was not founded on formal analysis but, according to Rockman [2], "…by the fact that radar target arcs of more distant targets appear wider on the radar screen, and this is most certainly why a larger separation minimum was deemed necessary for targets sufficiently far from the radar site." Historically, the basis of the 3 nmi in the terminal area and 5 nmi in en-route horizontal separation minima was an informal, qualitative evaluation reflecting limitations of the radar surveillance and human monitoring system and not on formal, analytical, simulation-based or other quantitative studies [3]. Thus the standards were implicitly based on radar accuracy, display target size, and concomitant controller and pilot consensus.

The Required Total System Performance Concept

The principal motivation behind the RTSP concept is to construct a consistent, rational, normalized, standard set of performance metrics applied to any airspace region. From its inception, the focus was on navigation-based metrics, namely RNP (Required Navigation Performance), promoted under the aegis of ICAO [4] with analytical support from RTCA Special Committee 181 (Minimum Aviation System Performance Standards for Navigation) [5]. RNP has been applied towards the definition of oceanic separation standards, where ATC intervention is limited due to lack of surveillance and communication [6-8]. It was soon recognized that for radar-controlled airspace, RTSP would include considerations beyond navigational accuracy to establish separation criteria. The broader definition includes ATC surveillance, controller-pilot communication and other performance factors [1]. Ultimately, these performance metrics will form a consistent benchmark to evaluate separation minima and safety in terms of collision risk. The overall evaluation of aircraft collision risk will then be based on aircraft navigational accuracy, temporal and spatial exposures to conflicts stemming from route configuration, traffic density, and ATC intervention strategies, aided and informed by a network of surveillance and communication technologies.

The Reich analytical model [9] has traditionally been used for calculating collision risk in the oceanic environment in the context of 60 nmi horizontal (lateral) separation standards for the North Atlantic Track System. For the domestic NAS en-route and terminal area airspace environment, the Reich model does not capture factors such as RSP and RCP [5, pp. 5-6]. A more comprehensive model for assessing separation minima must be developed that includes

radar monitoring and surveillance performance, pilot and controller communication performance, and ATM factors and human workload. The performance of the complex human/machine system must also be assessed under rare-normal conditions such as weather, and non-normal procedural, systemic, and equipment failure scenarios.

Figure 1 shows some of the key performance factors that are part of the RTSP framework [10]. It is seen that a number of factors reflecting CNS and ATM systems, processes, and procedures are required at the various levels of air/ground interaction to support the top level tasks of detection (monitoring, surveillance), intervention (conflict resolution), and prevention (planning to prevent controller overload) in the context of en-route and terminal area airspace operations, conditions, and configurations.
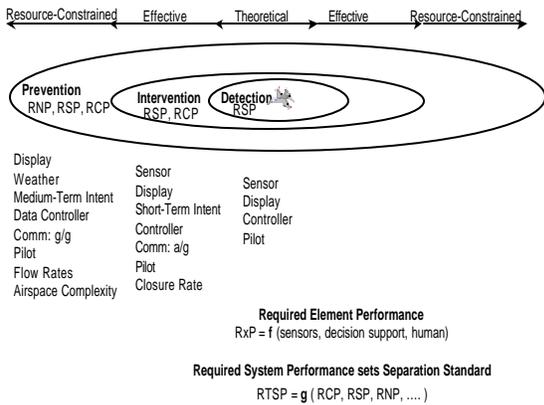

Figure 1. RTSP Performance Factors and Traffic Spacing

A control process view of the NAS separation assurance function is shown in Figure 2, illustrating the interactions of various functional elements involved in assuring separation in an ATC sector. As new aircraft arrive at a sector boundary, the separation assurance agent must predict the trajectory of the aircraft and probe for potential conflicts. Given the typical size of an en route sector, this prediction is performed over a time horizon of between 5 and 20 minutes. Note that the conflict detection takes into account the separation goals in the sector and at particular waypoints, which normally are higher than the required minimum, and are often determined by flow rate constraints due to downstream capacity limitations. If likely conflicts are found, a resolution must be decided, and a corresponding clearance issued to the aircraft. The aircraft then navigates according to the clearance received, resulting in an aircraft state that should confirm closely with what the separation agent

planned. To monitor the aircraft conformance, an aircraft state sensor (currently radar) provides an estimate of current position and velocity, and thus any significant deviations from plan can be detected, resulting in potential conflict detection and resolution action. Additionally, the aircraft crew may request a change in flight plan due to weather or other airborne operational goals, thus again triggering prediction and detection activity.

Figure 2 thus illustrates three primary events that generate conflict detection and resolution activity. The figure also denotes the RxP performance factors associated with particular functional elements. RNP is clearly associated with flying the aircraft, RCP is associated with air/ground clearances and flight plan change requests, and RSP is associated with both airborne and ground aircraft state sensors. The figure associates RMP (Monitoring Performance) with the conformance monitoring function, and indicates with the RAP (Air Traffic Management Performance) index that several additional functions that collectively plan for separation assurance must be incorporated in the overall separation function. The RTSP index, quantifying the performance of the separation assurance function, can thus reflect the composite performance of this overall process, across normal, rare- and non-normal conditions.

Preliminary documentation on RCP is found in FAA AC 120-COM [11], Appendix 5. Common RCP metrics include communication delay, integrity, and availability. Delay is channel transfer delay, integrity is the probability that the wrong party will receive a voice communication, and availability is the probability that the channel will either fail or be adversely affected by an external party. A problematic issue that is yet to be addressed within the purview of RCP is the translation of a message from a sender to a receiver.

RTCA SC 186 is developing a definition of RSP, and this is also being done in a working version of AC 120-CNS [11]. This definition of RSP involves basic surveillance and monitoring that may include on-board collision avoidance systems such as TCAS, altitude alerting, conflict alert, conflict probe and others. It should be noted that they apply RSP to the collision risk of an individual aircraft vis-à-vis another aircraft, or obstacle, rather than a population of aircraft. Thus it would appear that RSP also could incorporate what is proposed as RAP in Figure 2. As with RNP, the performance elements of RSP are defined in terms of accuracy (radar noise, sweep or scan rate), integrity (false returns, transponder undetected errors), and availability (probability of detected loss of function).
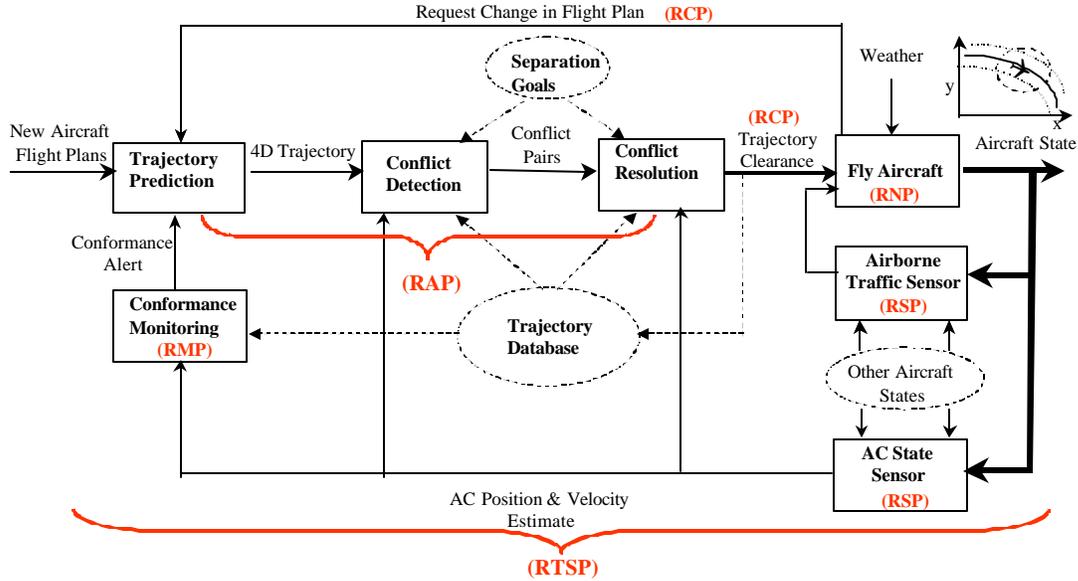
Figure 2. Separation Assurance Functional Elements and RxP Performance Indices

Radar-Based Conflict Probe Separation Assurance Analysis

This section presents some key results of an RSP-based conflict probe dynamic Monte Carlo simulation of a Short Term Conflict Alert (STCA) function. The STCA simulation model contributes to the understanding of conflict probe decision support with current radar-based surveillance, and its possible effects on separation minima in en-route airspace.

En-route Horizontal Surveillance and Separation Assurance Modeling

The primary function of aircraft separation assurance is to maintain maximum safety levels while operating efficiently in oceanic, en-route and terminal area airspace, as well as on the airport surface. The analysis presented here is limited to en-route airspace. A generic sequence of events for the maintenance of distance-based separation minima is shown in Figure 3, to illustrate basic time and distance relationships. When two aircraft are on a potential collision course, a number of events occur: 1) conflict detection between T_1 and T_2, 2) Closest Point of Approach (CPA) determination, estimated between T_1 to T_3, 3) controller and pilot communication on resolution action, T_2 to T_3, and 4) conflict resolution initiated by pilot at T_3. To insure that the separation minimum is not transgressed, a "lookahead" or trajectory prediction is made prior to both aircraft reaching the conflict zone. This lookahead time in a typical control sector ranges from 3 to 20 minutes, depending on the sector traffic load and other dynamic factors. For encounters that

have a prediction time less than 3 minutes, the on-board TCAS function starts to play a significant role.
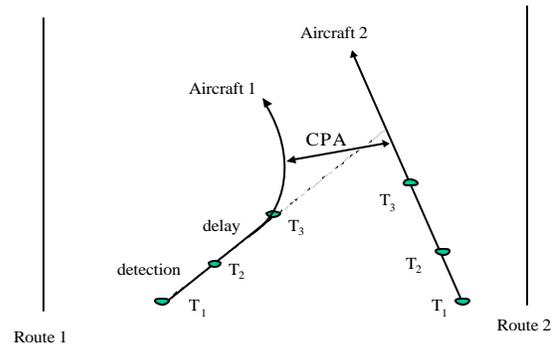

Figure 3. Conflict Detection, Communication Delay, CPA Estimation, Conflict Resolution

Table 1 shows a partitioning of the traffic management and separation assurance functions into four time horizons: 1) Imminent conflict, 2) Short Term conflict prediction, 3) Medium Term prediction, 4) Long Term. These time horizons are associated with the ATM functions of Planning or Flow Management, Detection and Prediction, and Intervention, and the table entries indicate the primary performance factor associated with each time horizon. Each of these four temporal levels is necessary for the continuous management of en-route traffic. For example, the imminent level may be technologically supported by some airborne collision avoidance system such as TCAS II, while the mid

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and short term may have ground based decision support tools such as conflict probe.

Time Horizon	Long Term (MultiSector)	Medium Term (Sector)	Short Term (Conflict Pairs)	Imminent (Conflict Pairs)
Primary Function	Lookahead Time: 20 – 60 min	Lookahead Time: 5 - 20 min	Lookahead Time: 2 – 5 min	Lookahead Time: < 2 min
Planning; Flow Management	Flight Plan	Trajectory Prediction		
Detection / Prediction		Conflict Probe	Short -Term Conflict Alert	
Intervention			Communi-cation	Collision Avoidance

Table 1. Four Levels of Traffic Management and Lookahead Times

Rockman [12] inferred the value of the en route and TMA horizontal separation minima by analyzing pair wise encounters in the imminent time horizon range. He showed for what range of crossing angles and speed an imminent conflict is recoverable given an initial separation at the minimum, with assumptions about surveillance performance and intervention delay times. The STCA model presented here applies to the lookahead horizon of 2 to 5 min and characterizes conflict detection of a pair of aircraft measured by two basic statistical metrics: 1) probability of missed conflict detects; 2) time-to-conflict warning distribution.

<u>Short Term Conflict Alert (STCA) Model for RSP-Based Separation Analysis</u>

The STCA model was derived from an earlier study [13], that was primarily concerned with evaluating the performance of a medium-term en-route controller or sector planner. This controller conducts, among other tasks, handoff coordination, trajectory prediction, and conflict prediction within a 20-minute time horizon. The STCA model presented here is set within a horizon of 2 to 5 minutes. The current STCA simulation model does not include conflict resolution.

Figure 4 is a simple representation of the basic scenario that is modeled. It indicates that as the pair of aircraft fly from their initial state, defined by a mean path entry point and 95% lateral position error uncertainty (normally distributed), and progress along their flight paths, a region of conflict is estimated, within the 5 nmi separation standard, where conflict is detected with a certain level of performance to be evaluated.
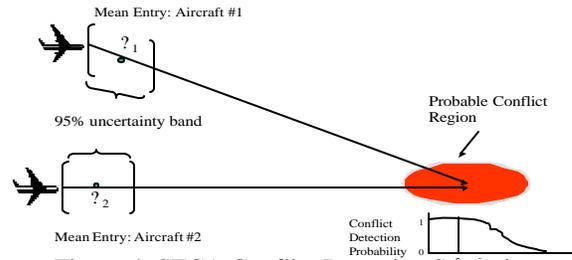
STCA CONFLICT DETECTION SCENARIO

Figure 4. STCA Conflict Detection Scenario

The STCA model is an EXCEL-based Monte Carlo simulation of pairs of aircraft flying through en-route airspace with 5 nmi separation standard, with initialized encounter paths or trajectories as a function of path crossing angles. Figure 5 shows the basic STCA simulation model flow diagram.
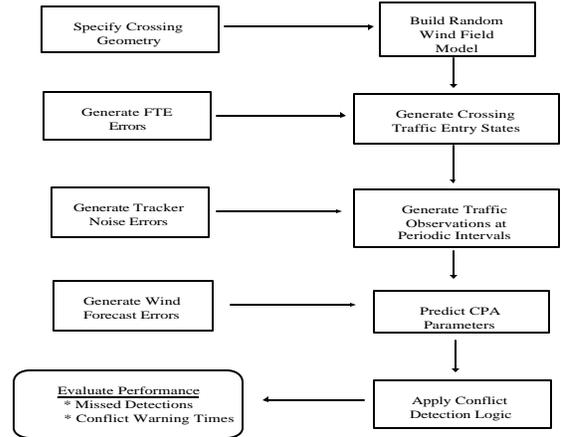

Figure 5. STCA Simulation Model Flow Diagram

Other model features include a wind field structure, flight path errors, radar tracker noise errors, and traffic observations at periodic intervals, wind forecast errors, CPA prediction parameters, and conflict detection logic. In short, the STCA simulation model approximates the current conflict detection and prediction behavior of a tactical sector controller with a binary state conflict probe logic decision process in a stochastic simulation environment. The binary outcome states are either 1) "conflict detect," or 2) "no-conflict detect" states. Moreover, the model measures separation standard (5 nmi) violation by the forecasted CPA and CPA-time, the time remaining from conflict decision to the estimated time remaining to CPA. The undetected violation or transgression of the separation minima is computed as a "probability of missed detection" which is a measure of failure of the conflict detection process. How well does the conflict probe perform in

the determination of the probability of conflict of aircraft pairs? This performance question is graphically depicted in Figure 6, which shows the probability of conflict detection plotted as function of True CPA.
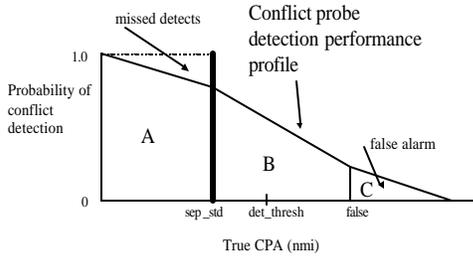

Figure 6. Conflict Probe Detection Performance

The conflict probe detection performance profile shows the likelihood of a correct conflict detection as a function of the closest point of approach between both aircraft. The three regions A, B, and C define certain boundaries that are described as follows: "A" marks the region where there is a violation (conflict region) of the separation standard (sep_std) or when the True CPA is less than or equal to 5 nmi. The difference between the performance profile and dashed line representing 1.0 or 100% conflict detection performance is the "missed detect" probability; the second region "B" is a region where there are "near non-conflicts." This signifies that at True CPAs greater than 5 nmi and less than the "false" alarm threshold the conflict probe predicts a "near non-conflict" with a certain probability of detection. The "det_thresh" is a parameter that represents the minimum true CPA distance or threshold when the controller is concerned of a possible conflict further downstream. In other words, the controller's focused attention in monitoring the traffic flow is a function of how far apart the aircraft are from each other as measured by True CPA. This information is estimated from the radar surveillance information visible on the radar display. Region "C" is labeled as "far non-conflicts." Conflict predictions from this region are considered to be "false alarms."[1]

One of the primary performance metrics for a STCA controller is the "missed detect" probability (generally required to be at least 0.2%; inversely a probability of conflict detect rate of 99.8%). Figure 7 further illustrates the above by showing the relative position of both aircraft (shown as arrows), defined by True CPA, which either cross the shaded region

(conflict state) A, or just miss this region (near non-conflicts) and are in region B, or are in region C (far non-conflicts).
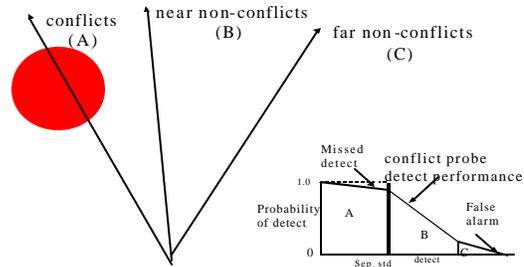

Figure 7. STCA CPA-based conflict and Non-Conflict Aircraft pair States

It may be instructive to contrast the above conflict detection performance (Figure 6) with an ideal or perfect conflict probe performance profile. Figure 8 shows such an idealized conflict probe performance. It is immediately evident that precisely at the boundary defined by the separation standard where the True CPA reaches 5 nmi, the conflict probe perfectly, that is, at a 100% probability of detection, predicts a conflict between a pair of aircraft. This idealized performance limit is also instructive when we compare the performance of current or baseline radar (SSR) with an enhanced radar (Mode S monopulse) performance.
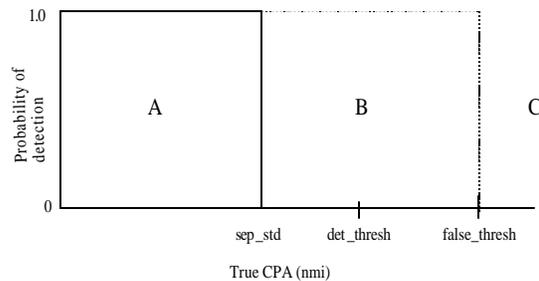

Figure 8. Ideal Conflict Probe Performance profile

The other basic metric for the STCA conflict probe performance is the distribution of conflict detection warning times shown in Figure 9. This is the estimated time remaining from conflict decision to predicted conflict. This is determined when the difference in predicted position between both aircraft is less than the 5 nmi separation standard. The distribution of conflict warning times helps to evaluate whether a STCA controller is capable of intervening in a timely manner to resolve the pending conflict [14].
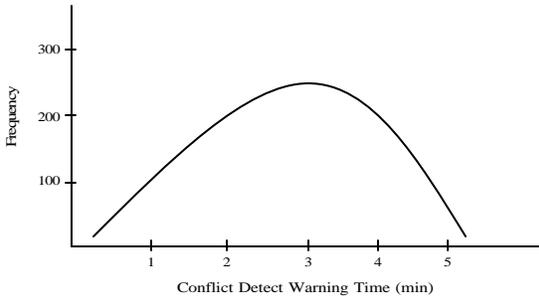
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[1] False alarm rates were not part of our STCA metrics but are included for reference only; it has particular relevance for a mid-term conflict probe with 20 to 30 min of lookahead times.

Figure 9. Notional Detection Time Distribution[2]

Results of STCA RSP-based Monte Carlo Simulation Study

In this section we summarize the significant findings of our STCA Monte Carlo simulation in terms of two primary metrics: 1) the performance of the STCA conflict detection process, 2) the distribution of conflict detect warning times. These two metrics contribute to a preliminary understanding of current STCA controller performance operating in en-route airspace for both current separation standards and the potential for operations with reduced separation standards enabled by enhanced radar performance.

STCA Conflict Detection Performance

Figure 5 depicts the basic STCA simulation model flow. A basic initializing parameter is the path-crossing angle between the two aircraft flying in horizontal flight in a linear path shown in Figure 4.

The parameter of "closing speed," or the rate with which the aircraft approach each other, is a function of the initial path-crossing angle. Figure 10 shows this relationship. At shallow crossing angles the closing speeds are lower.
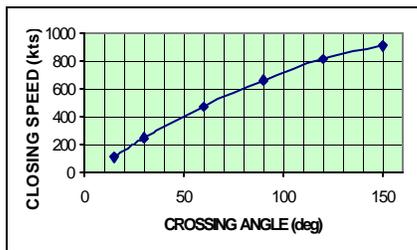

Figure 10. Closing Speed as a Function of Aircraft Pair Crossing Angle

In typical encounters, aircraft crossing angles for horizontally separated aircraft are generally distributed along the range of values shown in Figure 10. The performance of the conflict probe varies as a

function of crossing angle. A nominal performance profile is shown in Figure 11. These results are based on 1000 Monte Carlo runs. The crossing angle for this specific case is set at 30 deg.
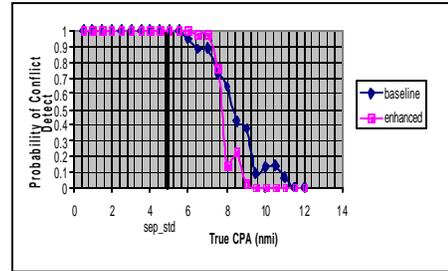

Figure 11. Conflict Detection Performance Profile

Both aircraft airspeeds are 480 kts. The performance profiles approximate a baseline or current (SSR) accuracy ($\sigma = 0.25$ nmi) and an enhanced (Mode S Monopulse) radar ($\sigma = 0.10$ nmi). It is immediately evident that the performance of the enhanced radar in terms of conflict detection is better than the baseline as indicated by a higher probability of conflict detection near the separation standard, or conversely lower probability of missed detection.[3] Shallow crossing angles produce relative path uncertainty of both aircraft. This is shown in Figure 12 for a crossing angle of 5 deg. In contrast, the STCA performance for a 30 deg. crossing angle drops sharply due to limitations in relative path discrimination by the radar tracker.
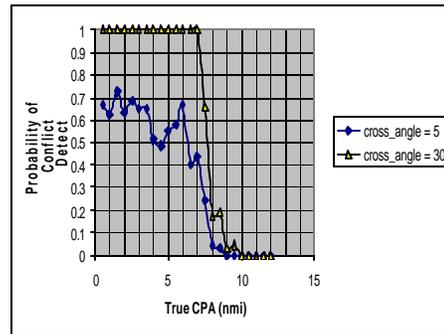

Figure 12.Effect of Crossing Angle on STCA Performance

Figure 13 shows the performance of the conflict detect warning time for both radar configurations. In general terms, it is observed that the enhanced radar produces a narrower distribution vis-à-vis the baseline implying a more accurate determination of

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[2] Figure 9 is a depiction of a typical conflict detect warning time profile and is not based on actual data.

[3] The "squiggles" in the performance profile are due to statistical processing and do not directly represent radar performance.

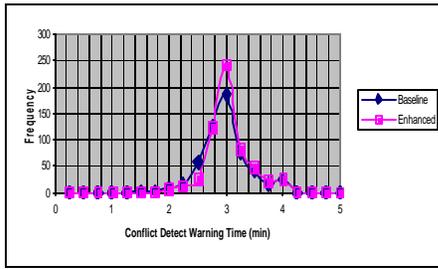conflict warning times. The average times are about 3 minutes for both radars.

Figure 13. Distribution of Conflict Detection Warning Times

To help decipher the minimum and maximum values of conflict detect warning times this plot must be re-scaled. A re-plot of Figure 13 with a different Y-axis scale is shown in Figure 14. From this perspective we can see that the baseline radar conflict probe detect configuration estimates a few conflict warning times that are less than 2 minutes while the enhanced radar estimates all its warning times above 2 minutes[4].
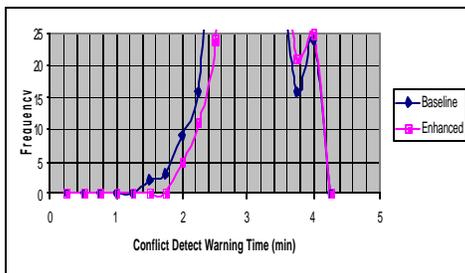

Figure 14. Re-scaled Distribution of Conflict Detect Warning Times

The low values of conflict detection times for the baseline radar suggest a performance insufficiency of the controller in conducting a timely conflict resolution strategy after detection and prediction. This lack may be characterized to be equivalent to nuisance warning times [15]. As stated above, the typical STCA controller values for the lookahead time are approximated to be within the range of 2 to 5 minutes producing an average value of about 3 minutes as shown in Figure 13.

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[4] The simulation parameter "minimum lookahead time" is set to 1 min to optimize the conflict warning time detection performance; the actual warning time distribution (e.g. Figure 15) minimum is 2 minutes or the actual minimum time for timely decision by the STCA controller; the enhanced (Mode S) radar shows five counts of 2 minute minimum conflict warning times; the baseline radar shows a number of "nuisances" below 2 minutes; this is considered too late for the timely resolution of conflicts.

The performance sensitivity of the STCA model to "maximum lookahead time" (time at which conflict probing is initiated) is shown in Figure 15. It is evident that under 4 or 5 minutes, the STCA performance degrades sharply This signifies a performance inadequacy, in conflict warning time, in predicting the state of a possible conflict when probing is initiated too close the encounter time.
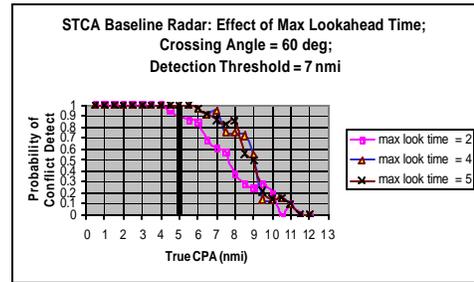

Figure 15. STCA Performance as a Function of Maximum Lookahead Time

Reduction in Separation Minimum

Questions may be raised as to how this STCA model could help inform issues of en-route airspace capacity enhancements. For example, what effect would a reduction of the separation standard have on the conflict probe performance? Figure 16 shows the performance profiles of the enhanced radar with different separation standards. The relative performance for all three conditions is similar within the statistical limits of the Monte Carlo simulation.
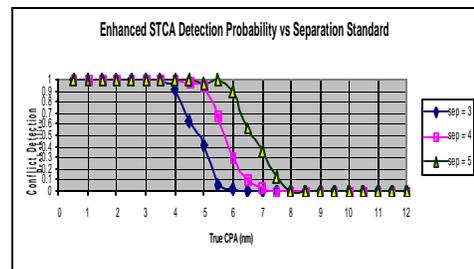

Figure 16. Effect of Different Separation Standards on Conflict Probe Performance for Enhanced Radar

Based on Figure 16, it may be concluded that it would be possible to reduce the separation standard to 4 or even 3 nmi without significant performance degradation of the STCA conflict probe, given the operations of an enhanced radar. However, to actually propose reductions in en-route route minima to values of 4 or even 3 nmi will require a complete evaluation of the effects of rare-normal and non-normal conditions and configurations assessed in various complex traffic flow structures. The

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separation assurance models presented in Figures 1-2 are proposed as a framework for a model-based assessment of safe separation standards, and a STCA model will be one of the components represented in such a closed-loop model.

Reduced Detection Threshold

Another possible question is related to the monitoring behavior of the STCA controller. In the simulation the parameter "det_thresh" roughly represents the distance (7 nmi) relative to the actual conflict boundary (5 nmi), (about a 2 nmi difference), at which the STCA controller initiates his or her conflict detection task and decision process and still manages to perform adequately. In other words, the STCA controller achieves a high level of conflict detection probability (>99.8%) and conversely a low probability of missed detections (<0.2%) given the current or baseline radar (SSR) performance (accuracy). Figure 17 shows a plot of the <u>average</u> probability of missed detects for the baseline (SSR) radar as a function of the same parameter relative to the separation standard. As the detection threshold decreases from a nominal or 7 nmi to lower values, the average probability of missed detects increases to unacceptable levels given this baseline (SSR) radar configuration (greater than about 0.2% missed detects occurs around 6.7 nmi)[5].
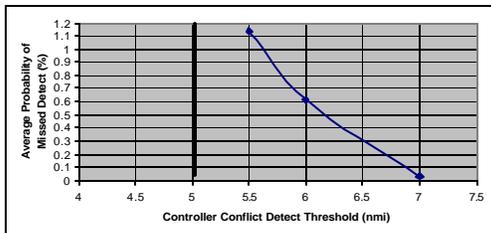

Figure 17. Average Missed Detection Probability of Baseline Radar as a Function of Conflict Detection Threshold

Conclusions

The above discussion has presented some of the principal Monte Carlo simulation results of a STCA controller in the performance of the tasks of conflict detection of a pair of aircraft in horizontal en-route airspace whose trajectories may be in conflict. From the basic findings of this simulation study and in the historical operational context a number of preliminary conclusions may be drawn:

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[5] Similar results for the enhanced radar require significantly more Monte Carlo runs (N ~ 10,000) to measure in a statistically significant manner the missed detection performance since the missed detection rates are much lower.

1. The STCA RSP-performance modeled Monte Carlo simulation provides a representation of tactical conflict decision-making performance, with a level of fidelity that is adequate to show first order effects of surveillance accuracy on detection performance.
2. Given the performance differences of the baseline (SSR) and enhanced (Mode S) radars some indications are noted with respect to the possibility of reduction of lateral separation standards and thus the potential increase in airspace capacity.
3. Finally, although a contribution is made in determining operational requirements and limits via this STCA model, a number of additional modeling features and traffic structures have to be incorporated in order to have a more comprehensive understanding of the relationships between separation standards, operational efficiency, and increased en-route airspace capacity.

Recommendations for Further Investigation

This report focused only on the lateral component of separation minima. Expanding the scope of the above study with greater realism may further inform the complex safety and capacity interactions. Consistent with the essential motivation of an RTSP mode of analysis, the following is a minimal list of recommendations for future studies intended to incorporate additional explanatory factors of the relationships between separation standards, safety and capacity:

1. Separation assurance effects of turns and other maneuvers must be evaluated.
2. Vertical trajectories need to be simulated in conjunction with horizontal traffic flows.
3. Conflict resolution strategies and behavior of controllers, pilots, and concomitant aircraft performance characteristics must be modeled.
4. Separation assurance requirements assessment should include the effects of rare and non-normal environmental conditions and CNS/ATM system configuration states.
5. In addition to the inclusion of radar performance models in the STCA simulation, other technologies should also be modeled (ADS-B).
6. A set of typically encountered traffic scenarios should also be used to test various ATM strategies in different en-route and TMA traffic structures.
7. The separation assurance model presented in Figures 1-2 is proposed as the overall needed modeling framework, with appropriate representation of, as a minimum, all the elements illustrated.

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Author Biographies

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