A METHODOLOGY AND INITIAL RESULTS SPECIFYING REQUIREMENTS FOR FREE FLIGHT TRANSITIONS

Dr. Anthony Warren

Boeing Commercial Aircraft Group

MS 05−KA, P.O. Box 3707

Seattle, WA 98124

ABSTRACT

This article summarizes results from a study of proposed operational concepts and requirements to achieve en route Free Flight through a series of transitional steps. The transition path to Free Flight envisioned in this article assumes an orderly development of technologies to meet requirements which will enable growth in en route capacity and progressive reduction in routing constraints. A simulation model of the Cleveland Air Route Traffic Control Center was used to study proposed transition alternatives, and to specify operational requirements for a phased transition from the current ATC system to mature Free Flight. The concept of medium term (10−30 min) separation assurance for initial Free Flight, and implementation using a medium term conflict probe is discussed. Technical requirements for CNS / ATM infrastructure to achieve the envisioned initial transition to Free Flight are then summarized. This article describes the methodology and initial results deriving airborne and ground−based requirements for cooperative development of the future NAS Air Traffic Control system.

INTRODUCTION

A number of concepts and methodologies have been proposed for moving towards a more user oriented ATC system. The Automated En Route Air Traffic Control (AERA) program in the United States and other programs abroad have advocated the use of medium term conflict probe and conflict resolution aids for increasing en route ATC efficiency and to enable greater freedom in implementing user preferred routings[1]. RTCA Task Force 3 has advocated a wide spectrum of methods to reduce user limitations in the NAS system, including the development of mutual airborne surveillance for separation assurance [2]. The great challenge is to find a transition strategy for both users and service providers which will provide economic benefits to justify infrastructure investments, while accommodating the great diversity of existing airspace users and their need for ATC services.

Our studies examined several operational concepts for separation assurance which require the development of new airborne or ground based infrastructure, i.e. conflict probe, mutual airborne surveillance, and use of advanced CNS (Communications / Navigation / Surveillance) technologies. The major results of this study are preliminary operational requirements for separation assurance during a proposed transition to Free Flight, and specification of CNS technical requirements for infrastructure development during an initial transition step toward Free Flight [3].

Our study is limited to Free Flight implementation concepts which enable en route User Preferred Trajectories (UPT). Inherent in these concepts is the notion of intent. We assume an aircraft is flying a strategic flight plan, or will provide to ATC some level of tactical intent whenever an aircraft expects to deviate from it’s strategic flight plan. Aircraft intent is essential in our studies for enabling more efficient use of en route Center resources, i.e. off−loading controller workload through automation concepts such as medium term conflict probe and conflict resolution across sector boundaries.

METHODOLOGY

The methodology employed in our study was to simulate various Free Flight transition options and evaluate en route encounters parametrically as a function of traffic load. A simulation of aircraft operations in the Cleveland Air Route Traffic Control Center over a one day period was developed and close encounter statistics for 1995 operations were benchmarked. We then studied the effect of traffic growth over time, and the effect of implementing various transition options to Free Flight. Figure 1 summarizes the methodology that was used to translate en route encounters for each transition option into separation parameters. The basis of this process was to limit the number of encounters at each transition stage to that of the 1995 benchmark. For each transition option, we assumed a level of implemented CNS technology such as radar or ADS based surveillance and an RNP level for navigation. The probability of detecting conflicts as a function of closest approach distance was evaluated with a conflict probe simulation. Then, separation parameters were derived for each option and transition time, consistent with the CNS infrastructure assumed.

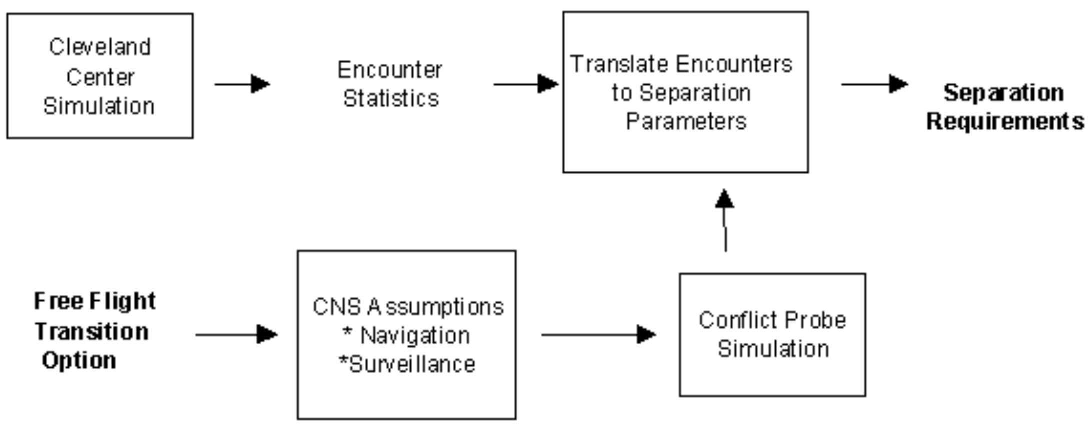

Figure 1 : Methodology to Obtain Requirements for Free Flight Transitions

This paper investigates concepts which will permit reducing the size of aircraft protection zones, eliminating the need for a substantial proportion of en route interventions. Other techniques such as dynamic resectorization and use of controller automation tools will also be needed to manage controller workload and increasing traffic growth over time. However, this paper is concerned with deriving separation requirements as transition goals to meet anticipated traffic growth. Further studies are needed to generate and validate CNS / ATM subsystem requirements which will achieve these goals and to assess whether such requirements are operationally and economically achievable.

CLEVELAND CENTER SIMULATION

An initial simulation study was undertaken to evaluate operational requirements for separation assurance, based on modeling en route flight operations in a high density Center in the current NAS system, and with various Free Flight transition options. We evaluated aircraft close encounter statistics for 1995 benchmark traffic and for traffic growth to 200% of the 1995 benchmark. Assuming a nominal 5% per year growth in traffic, then by 2002, the year assumed for initial Free Flight operations, traffic will have grown by 140%. By 2010, the year assumed for mature Free Flight operations, aircraft traffic will have doubled. Thus, we have chosen to evaluate the operational requirements for initial Free Flight using 140% traffic statistics, and the operational requirements for mature Free Flight using 200% traffic statistics. While some increase in sector intervention rate may be possible, this study assumes the benchmark rate should be maintained as an operational requirement.

There are four routing / altitude options for transitioning to Free Flight analyzed in our studies. The first option, denoted **Baseline** constrains the trajectories by terminal exit and entry conditions to efficiently manage terminal flows, and constrains cruise altitudes to 1000 or 2000 foot steps, segregated by east or west flying routes. This option permits the users freedom in selection of lateral routes and cruise airspeeds, and requires the least amount of ground and air infrastructure for implementation. The second option, **Baseline Plus RVSM** (Reduced Vertical Separation Minimum) reduces the vertical separation minimum and the vertical steps in cruise altitude above FL290 to 1000 feet. This option permits Baseline flight operations and more efficient use of cruise flight levels. The third option, **En Route UPT** (User Preferred Trajectories) removes the constraints on user preferred cruise altitudes, i.e. the user is free to select preferred altitude and speed cruise parameters as well as lateral path routing. This option permits greater freedom in route selection but may require substantial ground and air infrastructure to achieve greatly reduced lateral separations and to manage potentially difficult encounter geometries. The fourth option, **En Route UPT Plus RVSM** permits En route UPT flight operations with reduced vertical separations. This option represents a possible end state for mature Free Flight.

The basis of our study is a simulation of the aircraft operations in the Cleveland ARTCC (Air Route Traffic Control Center) over a one day period. The ten high altitude sectors in this region are shown in Figure 2. These sectors start at FL240 and include the airspace above FL240. The air traffic for this region was obtained from the Official Airline Guide (OAG), for a representative day in August, 1995.

Non−scheduled IFR flights through the Cleveland Center were not modeled in this study. More than 4500 flights were simulated for the 1995 benchmark study. Of these, 25% are interflights between airports within Cleveland airspace, 57% are external arrivals or departures from an airport in the region, and 18% are overflights.

In our model all flights are assigned direct routes and follow great circle paths between departure and arrival airports. Aircraft fly undisturbed flight paths, i.e. potential conflicts are detected but not resolved. As the simulation proceeds, the closest point of approach (CPA) between nearby aircraft pairs are monitored. If the CPA distance for a pair is less than 10 nm, and vertical separation is less than the vertical standard assumed, then an encounter is recorded. The encounter data are used to estimate the number of ATC interventions for a given separation requirement. Although many factors determine controller workload, it is assumed that encounters may be used as an important indicator of workload for establishing separation requirements. Other areas, such as automation of sector transfers and improvements in communications may also be needed to achieve overall reductions in workload and increases in traffic throughput.

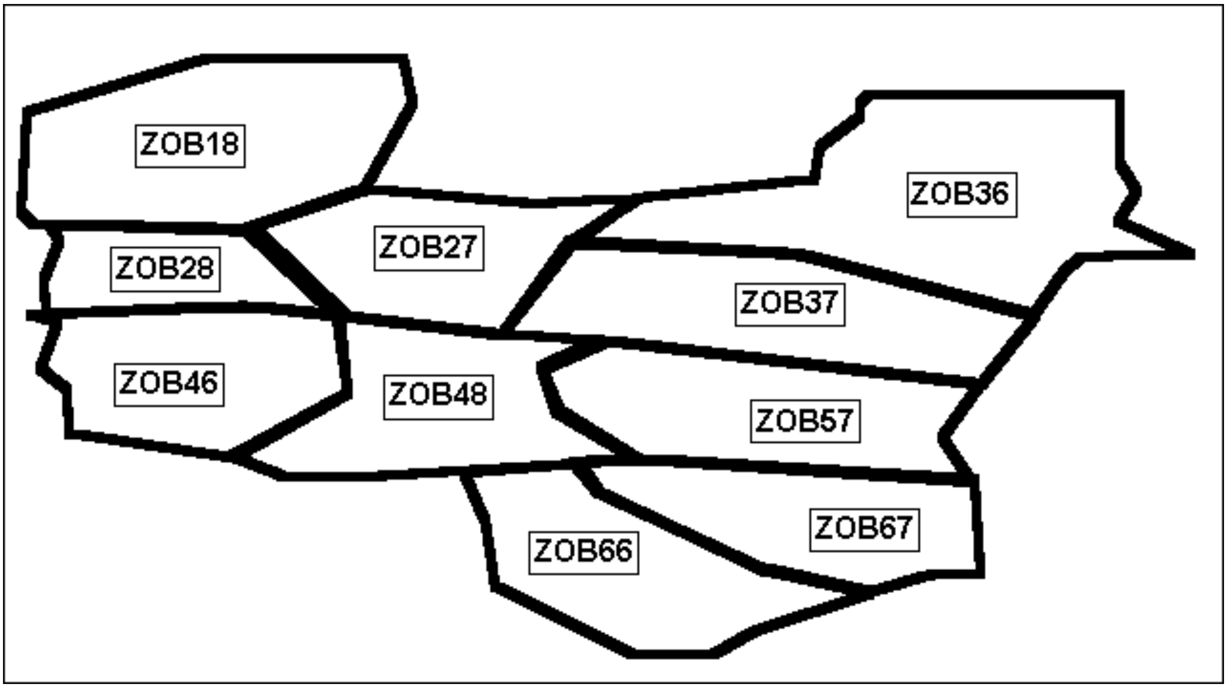

Figure 2 : Sectors Used in the Cleveland Center Study

There are four different simulations that model the four free flight options. The results for the benchmark studies were obtained with the baseline free flight simulation using 1995 traffic levels. For the benchmark case we have assumed that the number of encounters with direct point−to−point routes is roughly equal to the number of encounters with conventional routes. This assumption is based on results from a previous study that shows both sector loading and number of proximity events are similar for a conventional route system versus direct routing [4]. Our studies also do not model winds aloft or adverse weather conditions which may significantly alter traffic loading patterns.

Simulation Study Results

The initial benchmark studies evaluated the types of encounters which occur most frequently. Aircraft encounter statistics were generated for several Monte Carlo trials where the departure times were randomized. The encounters were then characterized by encounter geometry and by en route flight phase. Encounter geometry was evaluated by counting in−trail, crossing, or opposing encounters based on crossing angle between aircraft ground tracks. Flight phase was characterized by climb, cruise, or descending flight for each aircraft involved in an encounter. Figure 3 shows the benchmark encounter results evaluating encounter frequency versus flight phase. This chart shows that most encounters involve at least one aircraft in vertical transition. Of the 967 average encounters, only 166 or about one−sixth are encounters between aircraft in cruise flight. These simulation results reflect the high density of aircraft arriving or departing from airports in this airspace, compared to overflights.

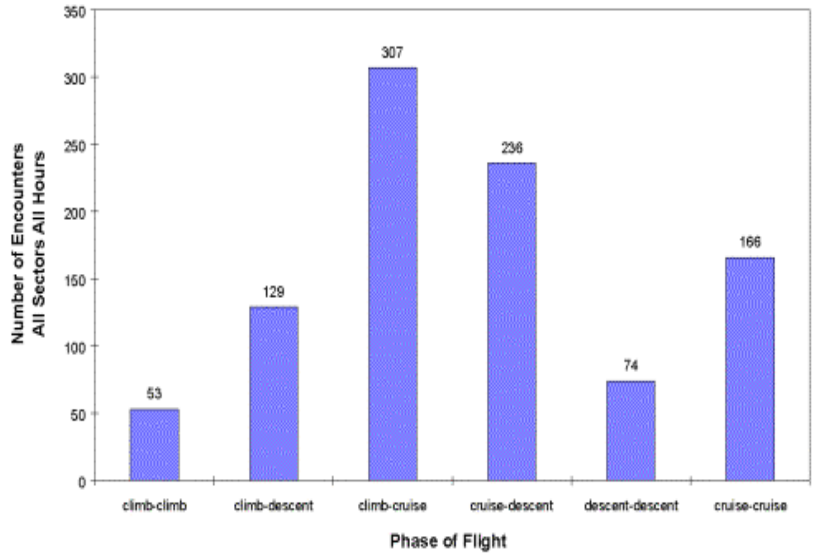

Figure 3: Benchmark Encounters By Flight Phase

In the benchmark case there are procedural controls that limit the free flow of aircraft, and also limit the number of encounters. One procedural control placed on current traffic is the segregation of cruise altitude based on direction of flight. Flights flying east are given cruise altitudes that differ from those flying west by at least 1000 feet (2000 feet above FL290). Removing the segregated altitude restriction greatly increases the number of encounters. The differences are shown in Figure 4.

The biggest impact is in the increased number of opposing conflicts, i.e. more than three times as many opposing conflicts occur as in the benchmark case. These studies illustrate the challenge in moving from procedural, constrained flight to less−constrained free flight concepts. As we remove flight restrictions, we assume a reduction in separation standards to stabilize sector conflict rate and controller workload.

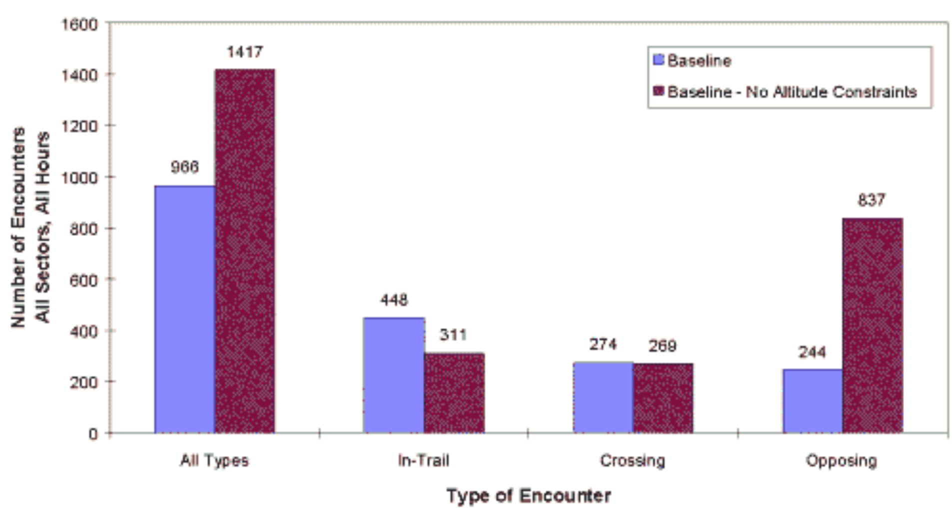

Figure 4: Effect of No Altitude Constraints

The most important study results from the Cleveland model are the scaling law for encounters as a function of CPA distance (Figure 5), and the time phased growth in close encounters due to traffic growth, and due to implementation of successive Free Flight transitions (Figure 6). These simulation results allow us to develop operational requirements for Free Flight transitions, and to specify preferred transition phases.

The scaling law for encounters defines the relationship between number of encounters and the CPA distance between aircraft. In our early studies, we found that the cumulative number of encounters is approximately proportional to CPA distance. However, additional analysis showed that the number of encounters is better estimated using a power law with CPA exponent = 4 / 3. Figure 5 shows results of the benchmark simulation compared to the 4 / 3 power law.

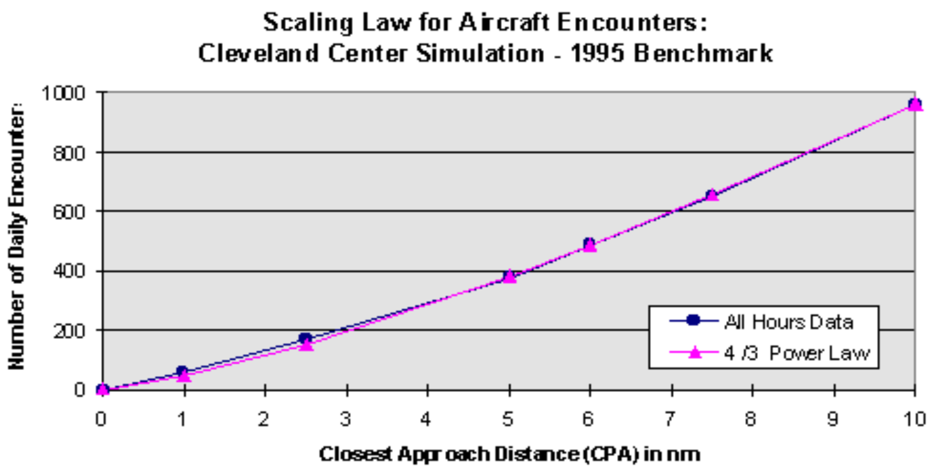

Figure 5: Power Law Provides Good Fit for Encounters Versus CPA Distance

The encounter statistics for the 1995 benchmark and for traffic growth for the four proposed implementation options is shown in Figure 6. The relationship between growth in traffic and number of encounters is nearly quadratic for all four scenarios. The implications of this chart are twofold. The first is that separation standards will probably need to be reduced as traffic grows, in order to prevent excessive growth in intervention rate and controller workload. The second is that there is a preferred order for transitioning to mature Free Flight, beginning with the Baseline option which is most easily implemented, then transitioning to Baseline Plus RVSM which reduces the encounter rate compared to Baseline Free Flight, and finally, transitioning to En Route UPT Plus RVSM which will require substantial infrastructure development and reduction in separation standards to further limit workload growth.

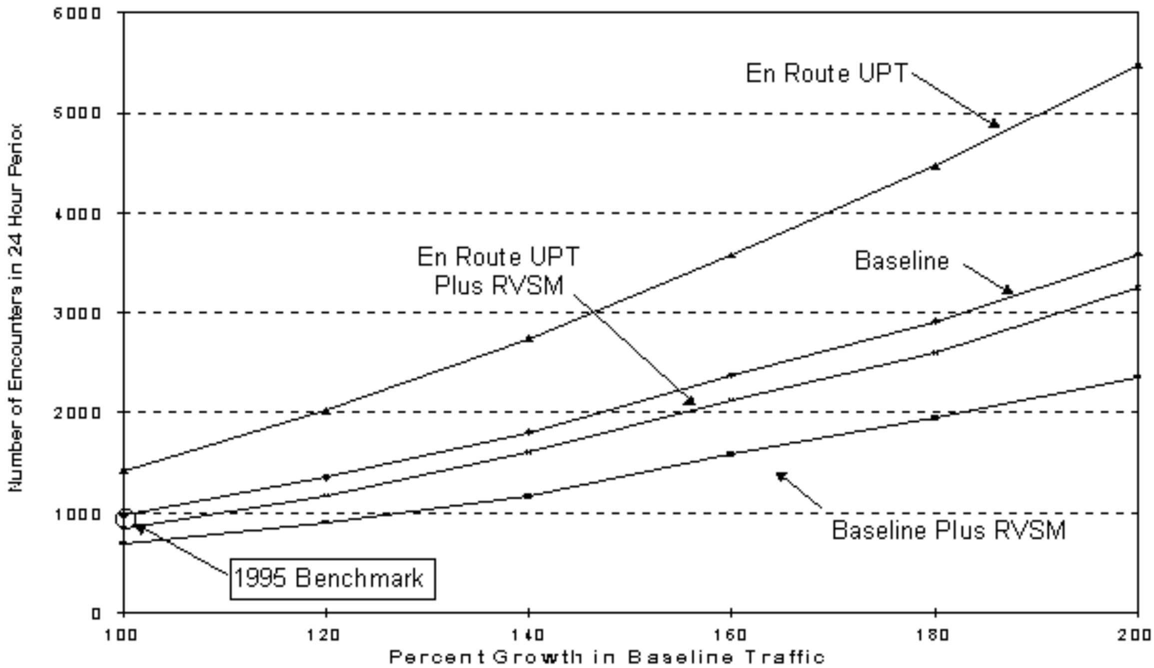

Figure 6: Encounter Growth Statistics − Four Free Flight Options

There are several caveats which should be noted in interpreting the results in this section. One is that we have treated all encounters as equally significant for controllers, whereas workload is dependent on encounter type and complexity. For example, opposing encounters and multi−aircraft encounters will require more controller attention than simple two aircraft merging or crossing encounters. Secondly, there can be a significant difference between encounters modeled in our studies, and potential conflicts requiring tactical intervention. In current practice, interventions are based on potential conflicts with large allowances for surveillance errors. Our simulation studies did not account for uncertainty in estimating the time of level crossings for aircraft in vertical transition. In order to reduce interventions involving climbing and descending aircraft, it may be necessary to reduce vertical path uncertainty, in addition to implementing RVSM. These items will require further study.

FREE FLIGHT OPERATIONAL REQUIREMENTS

In order to translate a desired encounter rate into separation standards, it is necessary to quantify the role that surveillance plays in separation assurance. In the current NAS system, the horizontal standard for en route radar control is 5 nm. For the study, we have assumed controllers will not intervene when the predicted CPA distance of an aircraft pair is more than 10 nm, but will intervene when the predicted CPA distance is less than 10 nm to assure safe separation. The establishment of an effective threshold above which a controller or conflict alerting process will not intervene is critical to free flight operations and is here called the intervention standard. For the benchmark study, the assumed intervention standard is 10 nm. Our conflict probe studies − described in a later section − focus on the requirements for CNS infrastructure which will support desired separation and intervention standards. The assumption here is that surveillance which supports a medium term conflict probe will also support short term separation assurance by a sector controller and short term Conflict Alert.

If the number of interventions is to be limited as traffic grows and procedural constraints are removed, then the separation parameters must be reduced to compensate. If we compare the number of benchmark encounters in Figure 6 with the number of interventions allowed for Baseline operations with 140% traffic growth, we find that the number of interventions needs to be scaled by approximately 1000 / 1800 ~ 56%. Using the scaling law in Figure 5 relating number of close encounters to CPA distance, and baseline probe performance as summarized in Figure 8, we can estimate the number of interventions for the Baseline CNS assumptions, and show that this objective is achieved with sep std = 4 and int std = 7.5 nm.

Similarly, we can derive separation parameters for each of the other Free Flight options. Selected separation parameters obtained from the Cleveland simulation study and conflict probe studies are shown in Table 1. The options where the difference between the separation and intervention standard is greater than 3 nm can be satisfied with conventional radar surveillance. However, the options where the difference is 1.5 to 2.0 nm require improved velocity tracking (GPS / ADS−B level performance).

Table 1: Derived Separation Parameters for Free Flight Options

IOC Date	Baseline	Baseline + RVSM	Enroute UPT	Enroute UPT + RVSM
2002 (140% Traffic)	4 nm − SepStd 7.5 nm − Int Std	5 nm − Sep Std 10 nm − Int Std	3 nm − SepStd 4.5 nm Int Std	4 nm − Sep Std 8 nm − Int Std
2010 (200% Traffic)	2 nm − Sep Std 3.5 nm − Int Std	3 nm − Sep Std 5 nm − Int Std	1 nm − Sep Std 2.5 nm − Int Std	2 nm − Sep Std 4 nm − Int Std

The preferred options in Table 1 are shown shaded. The preferred options for Mature Free Flight are those which incorporate RVSM, since these options require the least reduction in horizontal separation parameters. However, ADS capability will probably also be needed to achieve the separation requirements shown for Mature Free Flight.
This option may require that the sector controller transfer separation assurance to an air−air based function for some conflict geometries. Each of the proposed transition steps must be validated by in−depth studies which show that operational benefits and capacity increases are achievable.

Transition Path to Free Flight

The proposed transition path to mature Free Flight is summarized in Table 2. Our studies show that the first two transition steps, which focus on reduced horizontal and vertical separations, are very effective means of reducing tactical interventions. Consequently, these steps are recommended for increased efficiency in Center operations, both to support Free Flight operations and to manage controller workload in high density traffic. Implementing En Route UPT is more difficult, since it allows same altitude, opposing traffic conflicts.

For the Initial Free Flight implementation, the Baseline option is preferred since this step can be implemented using existing radar technology. The Baseline option will require precision navigation (RNP−1) equipage in order to accommodate opposing traffic conflicts. Our conflict probe studies show that substantial improvements to the radar tracking system and implementation of several Center automation functions will be needed to accommodate a 4 nm separation standard and to reduce the intervention standard to 7.5 nm. However, there is not a high technical risk in implementing these improvements since all the basic technologies are available today.

Table 2: Selected Operational Requirements for Transition to Free Flight

Free Flight Transition Stages	IOC Date	Traffic Level	Separation Standard	Intervention Standard
1995 Benchmark	Today	100 %	5 nm	10 nm
Initial Free Flight: (Baseline − Direct Routing)	2002	140 %	4 nm	7.5 nm
Intermediate Free Flight: (Baseline Plus RVSM)	2006	170 %	3 nm / RVSM	5 nm
Mature Free Flight: (En Route UPT Plus RVSM)	2010	200 %	2 nm / RVSM	4 nm

The preferred Free Flight concept may change significantly, however as we move towards mature Free Flight, and traffic growth necessitates further reduction in separation standards. The problem with the Baseline concept for mature Free Flight is that even with significant changes in onboard avionics and situation awareness, cruise altitudes remain limited to 4000 foot discrete steps above FL290. Consequently, it makes sense to implement RVSM and reduced horizontal separations as a system−wide infrastructure upgrade, for aircraft flying at or above FL290. The preferred intermediate step to Free Flight is the Baseline plus RVSM concept, since it has definite economic value for users, with the least reduction in separation parameters to accommodate future traffic growth. This step is recommended as a candidate transition for airborne / ATM system upgrade at some future time, encompassing RVSM altimetry, enhanced GPS navigation, and ADS or ADS−Broadcast avionics for enhanced surveillance.

The transition to Mature Free Flight is completed using the En route UPT plus RVSM concept, which again requires reduced separation standards compared with the Baseline plus RVSM concept. However, the horizontal separation standards are much less severe than those for the En route UPT concept without RVSM. This concept may require high integrity Alert Zone monitoring and guidance to manage same altitude opposing encounters. Thus, this option is implemented last in our transition plan.

The Alert Zone monitoring concept outlined in our NASA study [3] assumes that all aircraft operating in designated Free Flight airspace would periodically broadcast their current position, velocity and flight intent. Aircraft equipped for air−air separation management would monitor nearby aircraft for possible airspace conflicts with the ownship. If the path of a nearby aircraft is predicted to enter into a 3 dimension protection zone around the ownship or an extended dimension Alert Zone, and if the time to closest approach is small (< 2 minutes) then an alert would be issued to the ownship pilot, and heading guidance cues would be displayed to avoid conflict with the nearby aircraft.

SEPARATION ASSURANCE CONCEPT

The transition path to Free Flight envisioned in our study is based on augmenting the way that separation between aircraft is achieved in the current NAS system. In the current system, the sector controller has prime responsibility for separation. System capacity is limited by the capability of sector controllers to manage separation. The concept utilized in this report is to partition separation assurance into several time scales, and develop distinct methods for managing separation at each time scale. However, the sector controller will retain primary responsibility for separation.

The task of performing separation assurance can be conceptually divided into four time scales: strategic planning, medium term separation assurance, short term separation assurance, and immediate separation and conflict avoidance. See Table 3. In our concept, a medium term conflict probe is used to detect and resolve potential path conflicts prior to the application of short term separation. Similarly, immediate separation is a function which could be provided by appropriately equipped aircrews using airborne surveillance prior to and during close encounters between two aircraft.

Several enhancements to the current system of short−term, tactical separation will probably be needed for Free Flight operations. One is that decision support tools such as a future intent display may be needed to support reduced separation standards. Reduced separations, in turn, will probably be needed to keep workload from growing substantially as Free Flight is successively implemented, and as traffic grows over time. The process of reducing separations is limited by inherent time lags in the control loop, i.e. detecting traffic problems, communicating resolutions to the pilot, and pilot and airplane response times. This situation is most critical with opposing conflicts, where the time scales for problem resolution are compressed. Consequently, the evolution to mature Free Flight will require additional system augmentation to manage opposing conflicts and reduced separation encounters. Transfer of separation responsibility from the sector controller to equipped aircrews for the purpose of managing short term encounters is envisioned in the author’s Alert Zone concept [3].

An advantage of having several redundant systems responsible for separation assurance is less dependence on one critical subsystem. For example, the conflict probe does not have to detect all potential conflicts since the sector controller can easily manage short term conflicts, provided that the number of such conflicts is reasonably contained. Similarly, airborne surveillance and alert zone guidance could provide a high integrity system for managing opposing encounters which are difficult for current ground based ATC systems.

Table 3 : Separation Assurance Time Partitioning

Time Scale	Current Separation Method	Future Separation Method
Strategic Planning (> 30 min)	Central Flow Management	Central Flow Mgmt + Dynamic Density
Medium Term Planning & Separation	Center TMU	Center TMU + Conflict Probe
Short Term Separation	Sector Controller + Conflict Alert	Sector Controller+ Conflict Alert

Immediate Separation	Air Crew + TCAS	Air Crew + TCAS + Alert Zone Guidance

MEDIUM TERM SEPARATION CONCEPT

The basic concept for medium term separation is to use 10 − 20 minute path predictions to identify and resolve most potential conflicts before they become short term conflicts. Whether used on a sector basis to clear aircraft paths through a sector, or on a regional basis to provide more strategic planning, a conflict probe will enable airspace problems to be identified earlier and solved more efficiently than with the current system. In the AERA concept[1], once an aircraft path has been validated for safe flight across a sector or over some lookahead period, the conflict probe and path prediction process is not repeated again until an end condition is reached or the aircraft strays from the predicted path. We also assume this concept, except that the time interval for updating conflict decisions is more frequent, i.e. conflict decisions are revisited at least twice over a 20 minute lookahead, since path uncertainty decreases significantly as the predicted encounter time is reduced.

A conflict probe is vital for Free Flight operations since traffic conflicts can occur anywhere in a sector with Free Flight, whereas the high workload conflicts today primarily occur on airways at high density route crossings or merge points. Conflict probe will alert traffic managers and controllers to conflicts well in advance of a potential problem. This operational concept has several advantages: (1) conflicts can be resolved with smaller perturbations to the flight plan than with current methods, since more time is available to achieve the needed separation, (2) sector controllers will be less impacted by high density traffic, allowing more time to apply separation aids and to respond to airspace user requests, and (3) controllers are less likely to intervene tactically, allowing users greater benefit from user preferred trajectories.

We here designate the position which monitors medium term conflicts as the planning controller. (It is assumed that the planning controller and the sector controller are different positions.) The planning controller will have responsibility for medium term flight planning and identifying path resolutions to solve potential airspace conflicts. The planning controller will need automation support in addition to the conflict probe in order to assure that aircraft are following their active flight plan, and that planned flight paths are flow−efficient and safely separated. When these conditions are not valid, decision support is needed to aid the controller in trial path planning, and to negotiate an alternative flight plan when a dynamic path change is needed.

The aircraft in en route Center airspace will be monitored at each surveillance update for conformance with the predicted flight path last determined by the conflict probe. The horizontal conformance bounds on the trajectory can be viewed as either uncertainty ellipses or as lateral and longitudinal parallelograms centered on the predicted path. In our studies we assume that the conformance bounds are elliptical regions, since this simplifies the analysis for detecting aircraft conflicts, and is compatible with covariance analysis for modeling horizontal prediction uncertainty[5]. Vertical conformance bounds for cruise and vertical transitions can be developed similarly, but have not been explicitly modeled in our studies to date.

The use of medium term conflict detection extends separation assurance beyond the limits of current sector boundaries, i.e. this concept is area wide rather than sector wide. As an example, Figure 7 shows a typical case in which two aircraft cross near a sector boundary, and a potential conflict can be solved by a current sector controller before the aircraft enters into the sector where the conflict occurs. In this case, the planning controller could request Sector A controller to vector or slow AC1 in order to resolve the potential crossing conflict in Sector C.

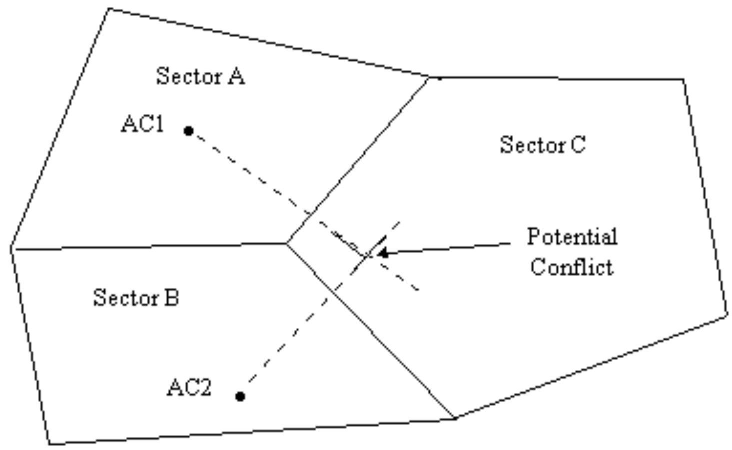

Figure 7: Example Medium Term Conflict Resolution Concept

CONFLICT PROBE SIMULATION STUDIES

In our studies, the conflict detection algorithms model horizontal path prediction uncertainty using covariance calculations for modeling tracker surveillance errors, wind forecasting errors, and aircraft path following errors [3,5]. In this concept, error ellipse path uncertainty regions are computed at the time of closest approach, together with CPA distance for each potential aircraft conflict pair. The thresholds for declaring conflicts and non−conflicts are based on the horizontal separation standard assumed and the estimated CPA uncertainty at closest approach. The thresholds with this method are dynamic and depend on aircraft pair geometry and time to closest approach.

The covariance methodology allows many of the problems with separation assurance to be formulated and solved analytically. For example, calculation of detection thresholds, problem entry and exit times, and graphical display of path uncertainty can be obtained with straightforward analytic calculations. However, this methodology needs to be extended to vertical plane conflict detection for implementation in future probe systems. A current research project is examining the extension of covariance methodology to vertical plane tracking and medium term path prediction.

A Monte−Carlo simulation of the covariance based conflict probe was developed to evaluate probe performance as a function of assumed CNS infrastructure. At each Monte−Carlo trial, a conflict scenario is generated with random variations in wind and lateral FTE to produce variations in crossing geometry. At each probe update time (nominally every one to two minutes from simulation start) random tracker errors in aircraft position and speed are generated and forecasted wind shear errors are generated to model conflict probe estimation errors. The reference and intruder aircraft paths are then predicted forward to estimate CPA distance and CPA time, and conflict detection algorithms are applied to evaluate probe performance.

The system requirements assumed for en route conflict probe are:

- missed detections < 2% of close encounters with true CPA < sep_standard,
- false alerts < 6% of close encounters, i.e. alerts with true CPA > int_standard,
- 20 minute max_lookahead and > 10 minute mean warning time for detecting in−trail, crossing and opposing conflicts.

We have initially selected a 2 % rate on missed detections under the assumption that lower rates are not necessary due to redundancy in separation assurance. In our studies, a false alert is counted for close encounters whenever a conflict is declared and the true CPA exceeds the intervention standard. Mean warning time is the Monte−Carlo average of the time from first conflict alert until predicted loss−of−separation.

The surveillance and wind forecast rms errors for baseline simulation studies are:

- Radar sensor along−track rms error = 0.15 nm
- Along−track wind forecasting error = 6 knots
- Along−track wind shear uncertainty = 4 knots per 100 nm
- Radar tracker steady state velocity error = 3.8 knots (alpha = 0.20 & beta = 0.022 for ~ 2 minute track settling time)

These assumptions are consistent with state−of−the art wind forecasting [6] and target tracking given modern monopulse radar sensors and current technology trackers[7]. Our assumption is that these enhanced systems will be integrated into the ATC Centers in the time period that medium term conflict probe becomes available.

The anticipated performance of the covariance method for en route conflict probe is illustrated in Figure 8. This figure shows conflict detection probability per aircraft encounter as a function of true CPA distance for an in−trail scenario, based on 2100 Monte−Carlo trials. The results show better than 99% detection probability for encounters with CPA < 4 nm, a rapid fall−off in detection probability between CPA= 4.5 nm and CPA = 8 nm, and less than 6% conflict alerts for CPA > 7.5 nm. In this case, conflict probe automation supports a 4 nm separation standard and a 7.5 nm intervention standard. These results show the potential for medium term conflict probe.

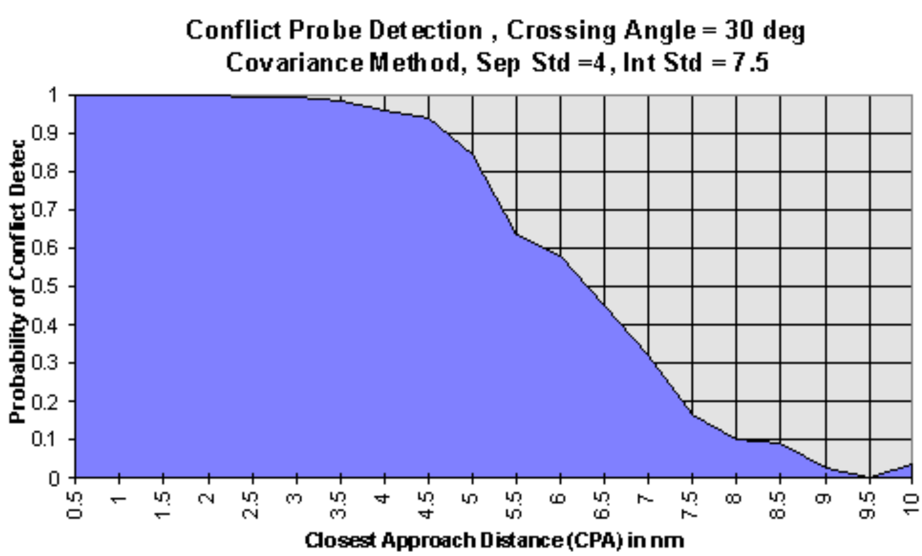

Figure 8: Conflict Detection Performance − Baseline Assumptions

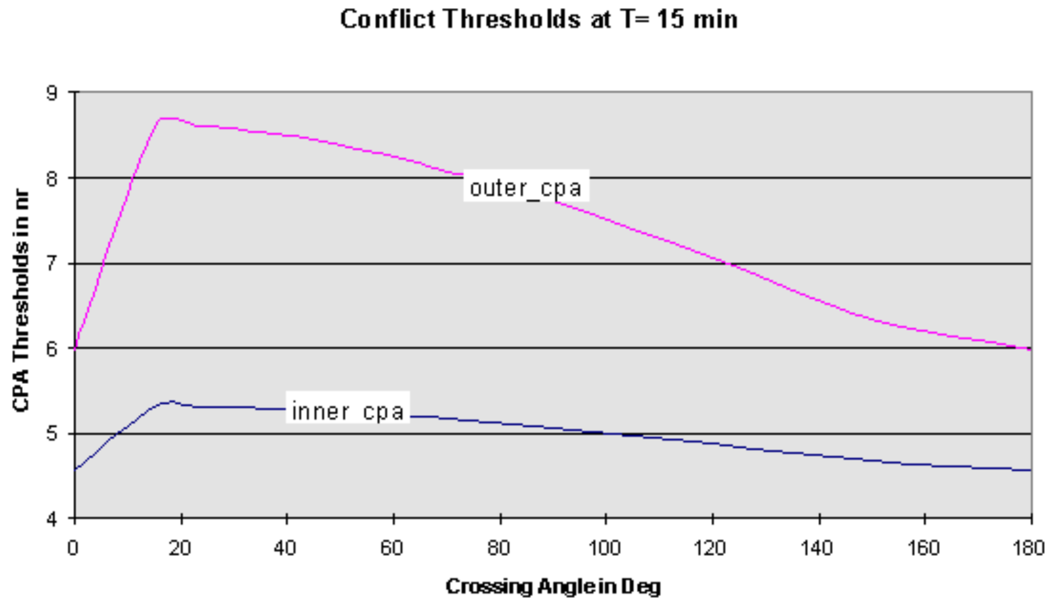

Figure 9: Conflict Probe Baseline Sensitivity to Crossing Angle

Conflict Probe Sensitivity Studies

Our baseline Monte−Carlo studies indicate that conflict detection is most difficult for In−trail scenarios where the crossing angle is less than 30 degrees. This sensitivity to crossing angle was confirmed by evaluating the inner and outer conflict detection thresholds for conflict / no−conflict decisions at a fixed 15 min lookahead time, for crossing angles varying from 0 to 180 degrees. The detection thresholds reflect the uncertainty in predicting CPA distance as a function of conflict geometry and time to closest approach. Figure 9 shows the result of this sensitivity study. It is seen that the detection thresholds (and CPA error uncertainty) increase to a maximum as crossing angle increases from 0 to 20 degrees, remains relatively flat between 20 and 30 degrees, and decreases slowly as crossing angle increases from 30 to 180 degrees. (The sharp rise in thresholds at small crossing angles is due to the large ratio between lateral axis and longitudinal axis errors at 15 min lookahead times.)

This study confirms the difficulty of detecting in−trail conflicts with 15−30 degree crossing angles. Although such conflicts are a worst case from the point of view of conflict detection, they are typically easier to resolve for controllers since more time is available for path corrections. Opposing conflicts, on the other hand, are easily detected but are more difficult for controllers to resolve.

A previous sensitivity study using the covariance method[5] showed that conflict probe performance is very sensitive to assumptions on surveillance and tracking errors. In our recent study we examined the relative effect on conflict probe performance of three technology options for surveillance: (1) retaining the current surveillance and tracking system, (2) enhancing the radar−based tracking software as described above, and (3) implementing ADS or ADS−B surveillance assuming non−augmented GPS avionics aboard participating aircraft. Study results showed that option (1) was not promising for medium term conflict probe, i.e. current surveillance and tracking systems may not support reduced separation standards and probe lookahead times >= 10 minutes. We concluded that enhancements to current NAS trackers are required to support medium term separation concepts.

By contrast, the probe results with ADS−based surveillance show much improved performance compared with the assumed baseline system. With ADS based surveillance and some data smoothing to reduce SA noise, steady state velocity error less or equal to 0.5 knots rms may be attainable. Figure 10 shows the results for ADS equipped aircraft using 2100 Monte Carlo trials. This study assumed the same level of lateral errors and wind forecast errors as the baseline system, so that the study measures the effect of reduced surveillance and tracking errors only. The probe thresholds were tuned for a 3 nm horizontal separation standard and 5 nm intervention standard. It is seen that the conflict probe will support the reduced separation standards if both aircraft are ADS equipped, i.e. missed detection, false alarm, and warning time requirements are all satisfied.

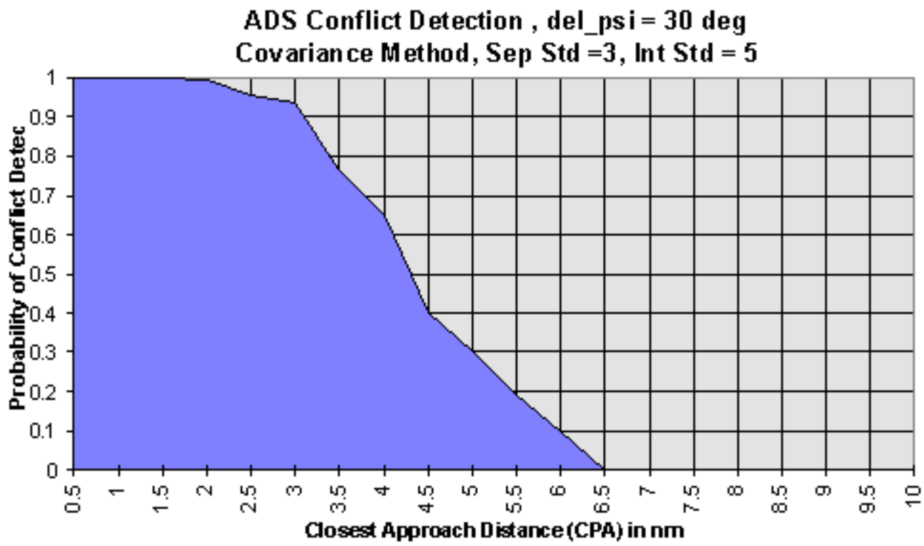

Figure 10: ADS Conflict Detection Performance − 30 Deg Crossing Scenario

TECHNICAL REQUIREMENTS FOR INITIAL FREE FLIGHT

In our recent study, we examined requirements to obtain a desired level of performance for medium term separation assurance, and for associated CNS functions to implement the envisioned initial transition to Free Flight. Derived technical requirements for Navigation, Surveillance, Communications, and Wind Forecasting are summarized, based on initial study results [3].

Navigation Requirements

We have stated a requirement for precision RNAV equivalent to RNP−1 navigation capability for initial Free Flight operations. This requirement is derived from the operational requirement to support a 4 nm horizontal separation standard. Recent RGCSP studies have proposed the use of RNP standards as a basis for reduced lateral route separation, and for reduced longitudinal (in−trail) separation. Route based separation minimums as low as 3.5 nm have been proposed for RNP−1 aircraft with radar conformance monitoring. Thus, RNP−1 aircraft should be capable of supporting the proposed 4 nm separation standard for initial Free Flight.

Users may be allowed to fly basic RNAV / FMS certified aircraft on free flight trajectories for some grandfathered time period, in order to encourage adoption of Free Flight. However, such aircraft may not qualify for the reduced separation standards proposed above, and as a result will tend to increase controller workload in the Centers, compared with current jet route operations. The transition to precision RNAV standards should be achievable by many modern FMS and RNAV systems, since this level of accuracy and integrity should be attainable with dual DME and other multisensor navigation systems, as well as with GPS systems.

Surveillance Requirements

Probably the most important surveillance requirement for initial Free Flight is that of obtaining an along−track steady−state velocity error of 5 knots rms or better. This value is considerably better than current NAS trackers, e.g. the modified tracker used for recent CTAS studies[8] was observed to have a 15 knot rms error for cruise trajectories. The ~5 knot surveillance criterion is the basis for the 4 nm separation / 7.5 nm intervention standard assumed for initial Free Flight, i.e. enhanced surveillance is key to reducing separation parameters for Free Flight operations. On the other hand, simulation studies [7] have consistently shown that the use of modern multi−sensor trackers are capable of achieving this level of tracking performance (or better) using modern ATC radars. Another method of achieving this requirement is to use longer interval data filtering to reduce velocity noise. However, this solution is not recommended for general tracking needs, since fast response is also desirable for tracking maneuvering aircraft. The preferred solution methods are to improve the radar sensor and the ATC tracking software.

Communication Requirements

We do not assume any special voice or data−link communications for Initial Free Flight. In this phase the primary communication between ATC and the aircraft crew will be performed by VHF voice as in current operations. It is assumed that the controller working the conflict probe position has some direct, but non−obtrusive method of communicating a recommended conflict resolution to the sector controller responsible for separation assurance. The sector controller (or assistant) will assess the viability of the recommended resolution and communicate it to the aircrew.

Some means of direct data−link communications will be needed for conflict resolutions in later transition phases. From the point of view of Center operations, Controller−Pilot Data Link (CPDLC) is essential for distributing situation awareness beyond that of the sector controller. Simulation studies [9] have shown that CPDLC allows more efficient usage of controller teams, based on distributed situation awareness of user intent and current flight plan clearances. This is exactly what is needed for medium term separation assurance, since the planning controller using a conflict probe needs some capability to resolve conflicts outside the current sector. Moreover, the implementation of complex procedures such as the use of Required Time of Arrival (RTA) and Top−of−Descent restrictions may require CPDLC for reliability of communications.

Although not required for initial Free Flight operations, the capability to dynamically update the flight plan and to communicate path intent will eventually be needed since medium term separation assurance depends on valid path intent. Thus, capability for domestic ADS communications will also be needed for later Free Flight transitions.

Weather Forecasting Requirements

The National Weather Service is currently developing an advanced weather prediction system for the continental U.S., which is called the Rapid Update Cycle (RUC). The RUC forecasts will use both ground based doppler radars and airborne observations to perform detailed one−to−three hour forecasts for use in aircraft flight predictions. This system will use 60 km or finer grids and 19 flight levels to perform detailed, mesoscale level weather predictions throughout continental U.S. airspace. If current schedules are satisfied, the RUC will become available in the en route Centers before the turn of the century. Thus, we assume that the current 12 hour coarse grid forecasting system will be replaced by the RUC prior to implementation of Initial Free Flight. Our conflict probe studies show that wind component forecast accuracy on the order of six knots rms is desirable to support medium term flight predictions and conflict detection.

CONCLUSION

In this paper we describe a methodology for deriving separation parameters to accommodate proposed changes in en route ATC operations and to accommodate future traffic growth. The methodology selects separation parameters to limit increases in ATC intervention rates to prescribed levels, as the ATC system evolves over time. We have specifically evaluated the effect of four Free Flight options and limited intervention rates to 1995 benchmark levels, to derive a first order transition plan for Free Flight implementation. Other concepts, and methods of limiting intervention rates can also be evaluated using this methodology.

We have specifically focused on the role that medium term separation concepts and medium term conflict probe can play in the implementation of Free Flight. Operational concepts for medium term separation are described and technical requirements for CNS subsystems are specified, consistent with the preferred Free Flight transitions. These studies show the need for surveillance enhancements to support medium term separation concepts.

There are a number of areas where the simulation studies could be improved. For example, the definition of an encounter in our Cleveland simulation could be improved by counting potential conflicts based on prediction uncertainty rather than counting conflicts based on simulated nearest approach. However, the basic methodology described in this paper is probably adequate for first order analysis of future ATM operational concepts and CNS system requirements.

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