

The Automated Airspace Concept

By

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Abstract: *The Automated Airspace concept uses ground-based computers and a ground-to-air data link to provide separation assurance and other selected air traffic services for properly equipped aircraft. The elimination of manual separation monitoring and control of equipped aircraft allows sector capacity, which is currently limited by controller workload, to be increased significantly. In this environment controllers can safely shift their attention to more strategic tasks such as optimization of traffic flow. Controllers will manually control unequipped aircraft operating in Automated Airspace sectors. An independent separation monitoring and conflict avoidance system provides a safety net against failures of the primary ground based computer system as well as failures of certain on board systems and pilot errors. Techniques for conflict detection and avoidance designed to support this concept are described. Operational procedures and responsibilities for controllers and pilots are outlined.*

Introduction

This paper describes a new concept for air traffic control, called Automated Airspace. It has the potential for significantly increasing both terminal area and en route capacity while at the same time enhancing safety and flight efficiency. The key to the Automated Airspace concept is a new approach to separation assurance that, unlike today's system, does not depend entirely on controllers for maintaining safe separation. Instead, ground-based computers that issue clearances to the pilot via a data link provide separation assurance for properly equipped aircraft. Alternatively, the ground-based computers can use the data link to send trajectories directly into the Flight Management Systems of suitably equipped aircraft. Pilots of the equipped aircraft and the ground based automation system are jointly responsible for separation assurance. Controllers in these sectors will be responsible for such tasks as strategic control of traffic flow, handling of exceptional traffic situations, reroutes due to weather as well as manual separation monitoring and control of unequipped aircraft. By relieving the controller of the workload associated with tactical separation monitoring and control for a large proportion of the traffic in his airspace, the capacity constraints due to workload limits can be relaxed, thereby permitting a much larger number of aircraft to operate in Automated Airspace sectors.

The Automated Airspace concept requires new components on the ground and in the cockpit as well as a reliable two-way data link for exchanging information between ground and airborne systems. The primary ground-based component is an Automated Airspace Computer System

(AACS) that generates efficient and conflict free traffic control advisories and associated trajectories for all equipped aircraft operating in an Automated Airspace sector. Many of the functions to be performed by the AACS have already been demonstrated in the Center-TRACON Automation System (CTAS) [1-3]. For example, an advanced version of the CTAS software generates conflict-free sequencing and spacing advisories to help controllers manage arrivals and departures. However, in this application, the control algorithms in CTAS must be upgraded to make them suitable for use as autonomous agents. The clearances and trajectories generated by the upgraded algorithms must meet additional safety criteria that qualify them to be sent to pilots or on board systems via data link without first being validated by a controller. With the operational experience gained in long term use of the CTAS advisories, combined with further progress in control algorithms and air-ground data links, it now appears to be technically feasible to build a more autonomous traffic control system that can be at least as safe as today's manual system.

The most important technical and operational challenge in designing the Automated Airspace system is providing a safety net to ensure the safety of operations in the event of failures of primary system components such as computers, software and data link systems. It includes defining procedures for reverting to safe, though less efficient, back-up systems. In the design of this safety net, the controller will play an indispensable role by assuming separation assurance responsibility for any aircraft that has lost its link to the ground-based system or has experienced other failures. Another element of the safety net is the capability to display the location, heading and speed of nearby traffic on a display in the cockpit, referred to as cockpit display of traffic information or CDTI [4]. CDTI will give the cockpit crew situational awareness of surrounding traffic and thus enable

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the pilot selectively to take responsibility for certain traffic control functions under exceptional circumstances, for example when components of the Automated Airspace system fail. While CDTI will therefore contribute to the safety net of the Automated Airspace concept, it is not intended here to be used routinely in high-density airspace as a stand-alone cockpit-based traffic control tool.

Protection against near term loss of separation due to failures of the AACS or failures of aircraft to correctly execute clearances will be performed by a new ground based system that operates independently of the AACS. This system, called Tactical Separation Assisted Flight Environment or TSAFE, independently monitors the clearances and trajectories sent by the AACS to each equipped aircraft. It also monitors the separation of unequipped aircraft that are being handled manually by controllers. If TSAFE predicts a loss of separation conflict within 1-2 minutes from current time, it will send a conflict avoidance clearance directly to the equipped aircraft. TSAFE will be built as a separate component that is insulated from both hardware and software failures of the Automated Airspace Computer System. It also can be developed as a controller tool for current operations to give controllers more timely and accurate warnings against loss of separation than Conflict Alert provides.

On board system requirements for equipped aircraft will include data links integrated with an ATC clearance read/send device, a traffic display such as a CDTI and, preferably, a Flight Management System. One of the data links must have the bandwidth to accommodate the transmission of automated clearances from the ground while a second data link will provide traffic information on nearby aircraft. Although the choices of a data link technology and the data transmission protocols to meet these requirements are uncertain at this time, it is likely that Mode S, ADS-B and VDL2 will be important candidates for this application.

The automation of separation assurance removes several operational constraints that limit the capacity and efficiency of today's system. With the reduction of controller workload achieved in this environment, controllers can accept more aircraft in their airspace. Therefore, traditional sectors can be combined into larger super-sectors without the risk of overloading controllers. The fixed air route structure of today's en route airspace can be largely eliminated in the super-sectors and replaced by a less structured and dynamically flexible routing system that approaches the ideal free flight environment users have long desired. The implementation of Automated Airspace for landing approaches at major hub airports will make it possible to optimize runway assignments, landing sequences and spacing control to a degree not possible with decision support tools such as those in CTAS, which are limited in their potential by controller workload considerations. This will result in significant increases in throughput and reductions in delays even if separation criteria remain unchanged.

A recent study has estimated the potential capacity gains of the Automated Airspace concept [5]. In this study two adjacent en route sectors that are often capacity limited due to controller workload were examined. Using current traffic flows, route structures and separation criteria as a basis, the study showed that traffic levels in the sectors could be increased to more than twice current capacity without creating an excessive number of new conflicts compared to base line traffic levels. This demonstrated that controller workload and not the availability of conflict free trajectories currently sets the limit on traffic density and throughput in en route sectors

The technologies for implementing the Automated Airspace concept are available or could be developed in a relatively short period. The major technical issues that research must address involve integration of air and ground components and performing a systematic safety analysis. The issue of equipment standards for aircraft must be resolved as soon as possible to give aircraft operators adequate lead time to purchase and install equipment needed for operation in Automated Airspace. Finally, since controllers will experience significant change in transitioning from current to Automated Airspace operations, the human factors issues associated with the controller's changed work environment must be given careful attention. Although the controller's workload will change from performing fewer tactical control tasks in today's system to more strategic tasks in Automated Airspace, the controller's interface to the system must still be based on the human-centered design principles incorporated in advanced decision support tools such as CTAS.

More than a decade ago, in the late 1980's, the MITRE Corporation, in cooperation with FAA, conducted the AERA 3 program that had objectives broadly similar to those of the Automated Airspace concept [6]. Work on the program was terminated around 1991. With the benefit of hindsight, it is now apparent that the basic design knowledge as well as several enabling technologies needed for building AERA 3 did not exist or were still under development in that time period. For example, such essential prerequisites for designing automated air traffic control systems as trajectory synthesis software, algorithms for decision support tools and controller interface design were immature. Furthermore, air-ground data communications technologies, essential for integrating air and ground systems were also insufficiently developed. However, recent advances in automation design techniques and data link technologies, combined with a lack of simpler alternatives for increasing capacity, have improved the prospect for success in designing a system such as proposed in this paper and having it deployed.

The paper begins with a description of the system architecture for this concept and then concentrates on the design of TSAFE with emphasis on strategies and methodologies for near term conflict detection and resolution. The paper concludes with an outline of the operational concept and a candidate design of the controller interface.

System Architecture

In this section the system architecture of the Automated Airspace concept and the functions performed by its major elements are described. Figure 1 shows the major elements of the system and the information flow between elements. The elements consist of the aircraft and its on-board systems, a two-way data link between aircraft and ground systems, and three ground-based elements, referred to as the Automated Airspace Computer System (AACS), the Tactical Separation Assisted Flight Environment (TSAFE) and the Controller Interface. A more detailed diagram would also

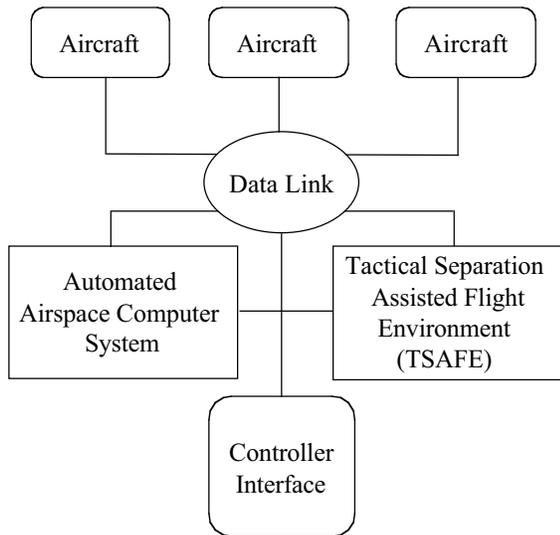


Figure 1: Automated Airspace Architecture

include supporting infrastructures such as surveillance radars, navigation systems, airborne collision avoidance systems, and en route and terminal area computer systems as well as the flow of information between them. While these elements are indispensable for the operation of the system, they nevertheless play only a peripheral role in the design and are therefore omitted from the diagram.

The design of the system architecture was strongly influenced by the need to provide cost effective and secure protection against potential loss of separation associated with critical component failures, software crashes and errors by controllers or pilots. The key element in the system that helps to meet this requirement is TSAFE. This element together with AACS and the Controller Interface provide the essential ground-based functions for the operation of the Automated Airspace concept. In the discussion to follow the functions and design considerations of the main elements comprising the system are briefly described.

The AACS solves air traffic control problems for equipped traffic operating in the Automated Airspace sector. Solutions to many of those problems are being developed for

application in today's system under the aegis of decision support tools for controllers. As the design of these tools has advanced in recent years, it has become apparent that the algorithms and software developed for them can provide the basis for building air traffic control tools that interact autonomously with the aircraft. In this context, autonomous interaction is understood to mean that the solutions generated by these tools provide a level of correctness and a sufficient operational envelope that they can be up-linked to the aircraft without first being checked by controllers. Several decision support tools available in CTAS are candidates for application in AACS. The three CTAS tools that are fundamental to AACS are the Direct-To/Trial Planner [7], the En Route Descent Advisor (EDA) [2] and the Final Approach Spacing Tool (FAST) [3]. After these tools have reached a mature state of development, they will provide the full range of advisories needed to control en route traffic as well as arrival traffic transitioning from en route airspace to landing approach. The set of advisories these tools generate correspond one-to-one to the set of clearances controllers use to solve a variety of traffic control problems. Moreover, since the advisories are derived from the four-dimensional trajectories by a process of sequential decomposition, it is possible to up-link the trajectories to the aircraft in a single transmission, instead of controllers issuing the advisories in a series of clearances. For a range of nominal operating conditions the advisories as well as the entire four-dimensional trajectories are generated to be both conflict free and to ensure efficient flow of traffic.

Therefore, a CTAS-based AACS could serve as the computational engine for automating traffic control under selected conditions. However, before this system can be considered safe for operational use, a critical evaluation of its performance limits and potential failure conditions must be conducted. Such an evaluation, conducted below, reveals that a single-threaded AACS is inadequate for controlling traffic autonomously.

Automation software such as CTAS, unlike an experienced controller, is inherently limited to solve a set of air traffic control problems that fall within the operational envelope determined by the finite parameterization of solutions built into the software. Unfortunately, for complex software comprising several hundred thousand lines of code, the controllable problem set cannot be determined because of the extremely high dimensionality of the input conditions that would have to be evaluated. Therefore, the boundary between the set of solvable and unsolvable problems is unknowable. While the envelope of problems controllers can solve is also limited, it is much larger than the CTAS solvable set. Moreover, human controllers excel at adapting their control strategies to completely new situations, a capability that is beyond existing software design.

Even if the input traffic conditions are closely monitored to keep them within the controllable range of the AACS's operational envelope, unplanned and unpredictable events such as equipment failures or weather may produce

conditions that fall outside the AACS's normal operational envelope. When that happens, traffic flow could become inefficient, chaotic and perhaps even unsafe. These inherent limitations of an autonomous system, used standalone as the AACS, make it unlikely that such a system can ever be certified as safe by aviation authorities. Furthermore, the complexity of the algorithms embedded in the software presents another obstacle to the system passing a certification test. Establishing the robustness and operational envelope of the algorithms and even documenting the design will be difficult. Finally, the test procedures certification authorities will perform to establish the safety of such complex automation software have yet to be determined.

Two steps are proposed to overcome the difficulties with a standalone AACS. These steps are intended to provide an effective safety net for a variety of failures and simplify the certification process. The first step consists of adding independent software and hardware designed to monitor the health and performance of the AACS, to detect imminent conflicts missed by the AACS, and to generate conflict avoidance advisories. This software/hardware addition is referred to here as Tactical Separation Assisted Flight Environment or TSAFE. The second step consists of the ability of the controller to accept separation responsibilities for an equipped aircraft, but only after the aircraft has been issued a TSAFE clearance and is not at immediate risk of losing separation. The transfer of control from AACS to the controller will be handled by functions built into the controller interface. Functions built into AACS and TSAFE and accessible through the interface will also permit the controller to return the aircraft to AACS control when appropriate.

As the system architecture illustrated in Figure 1 shows, the TSAFE element operates in parallel with the AACS. Both receive surveillance data and can exchange data with aircraft via data link. However, TSAFE is designed only to identify and solve problems over a time horizon of less than about 3 minutes, whereas the AACS is designed to cover the entire planning horizon from current time to 20 or more minutes into the future. Because TSAFE's time horizon for problem solving is very short and its function is limited to preventing loss of separation, its software design can also be much simpler than that of AACS. As long as AACS is performing normally, TSAFE will not detect any problems and therefore will not generate advisories. The next section will describe the design of TSAFE and its interaction with AACS in greater detail.

It is important to clarify the relationships and differences between TSAFE and the airborne collision avoidance system TCAS (Traffic advisory and Collision Avoidance System) [8] and to determine if the functions performed by TSAFE could instead be performed by TCAS, thereby rendering TSAFE unnecessary. TCAS issues traffic alerts and advisories to help pilots avoid collisions when the predicted minimum separations are very small and the time to avoid a collision is less than 25 seconds. It considers only the current

relative motion of aircraft pairs and works best in one-on-one encounters when other traffic is not a factor. However, it has several disadvantages when used in dense and highly organized traffic such as in the terminal area. A TCAS maneuver performed in dense traffic can disrupt the orderly flow of arrival traffic, potentially producing chaotic conditions and generating secondary conflicts. While its use as the final safety net to prevent a collision is not at issue, it was never designed to reliably and efficiently handle conflicts involving multiple aircraft. Furthermore, in dense traffic TCAS is susceptible to false alarms, many of which can only be avoided by taking into account the planned trajectories of nearby aircraft. Its limitation to vertical resolution maneuvers also reduces its effectiveness in dense airspace.

TSAFE detects and helps avoid conflicts at least 60 seconds before a loss of required minimum separation is predicted to occur. By incorporating in its algorithms the planned trajectories of nearby traffic, TSAFE can generate conflict avoidance maneuvers that minimize disruptions to the orderly flow of this traffic while also avoiding false alarms more effectively. It is therefore especially suitable for application in high-density airspace, including the terminal area. Since TSAFE compares the planned trajectories obtained from AACS with the actual trajectories flown by the aircraft, TSAFE can identify any aircraft that has failed to track its planned trajectory and take that into account when generating the avoidance maneuver.

In addition to its role as a critical component for the Automated Airspace concept, TSAFE can also be incorporated in the current operational system to give controllers improved protection against operational errors. The architecture for this implementation would be similar to the one in the figure except that conventional controller-pilot voice communications would take the place of the data links to the aircraft. In this role the system would not operate autonomously, but as a conventional decision support tool for controllers. As in the Automated Airspace concept, TSAFE would make use of planned trajectories provided by CTAS or an equivalent trajectory engine to detect short-term conflicts and to generate conflict avoidance advisories. The controller would issue the advisory to the pilot by conventional voice link. Because of its more effective methods for detecting short-term conflicts and its conflict avoidance advisories, TSAFE promises to provide more complete protection against operational errors than the currently operational Conflict Alert function does. The near-term use of TSAFE as a controller tool in the current system also will provide an opportunity to evaluate its effectiveness and improve its performance under current operational conditions. Most importantly, the experience gained from this use will help to determine whether the proposed system architecture and its major building blocks provide the proper foundation for building the Automated Airspace concept.

Design of TSAFE

Because of its safety-critical role in protecting against loss of separation during primary system failures, TSAFE poses the most important design challenge in the development of the Automated Airspace concept. The design must focus narrowly on achieving essential requirements and exclude any function that is not absolutely necessary or can be incorporated in other components. Ideally, the final product should be as simple, reliable and easily verifiable as possible.

The modules comprising TSAFE and its inputs and outputs are shown in Figure 2. Primary inputs are track positions, velocity vectors, and planned four-dimensional trajectories for all aircraft. These inputs are provided by the surveillance system and the AACS, respectively, and are updated in real time. The controller interacts with the system via the controller interface. The output of TSAFE consists of clearances and trajectories that are sent to the Controller Interface, to the appropriate equipped aircraft via data link,

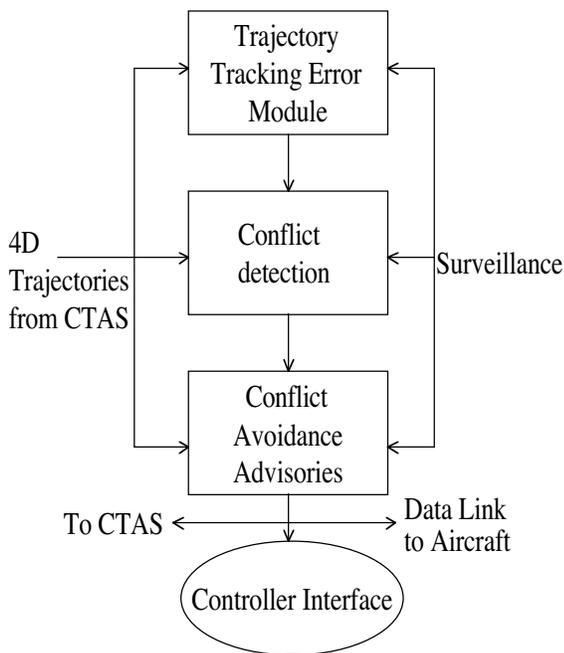


Figure 2: TSAFE Architecture

and to the AACS. In the Trajectory Tracking Error module, TSAFE analyzes the tracks of every aircraft in the Automated Airspace sector to determine whether the tracks match their planned trajectories to within prescribed error tolerances. It sends the call signs of aircraft with excessive tracking errors together with their error classification and error states to the Conflict Detection module.

The Conflict Detection module identifies all aircraft that are at high risk of losing separation within 3 minutes or less. This module is designed to identify only such near term

conflicts, since the Conflict Probe/Conflict Resolution function built into AACS is responsible for finding and resolving conflicts with longer time horizons. Over its short time horizon the conflict search performed by this module is intentionally redundant with the search done by the AACS. This redundant search acts as an independent safety net. It monitors both automatically and manually controlled traffic for short-term loss of separation produced by software or hardware failures of the AACS as well as by operational errors made by controllers or pilots.

For aircraft in conflict identified by the Conflict Detection module, the Conflict Avoidance module generates advisories to eliminate the short-term conflict threats. The advisories provide a conflict-free interval of time of short duration to give the AACS or the controller the opportunity to find a strategic solution to the problem. Limiting the TSAFE solution to a short interval of time reduces software complexity and therefore helps to simplify the design. Further characteristics of the advisories are described in a later section. In addition to sending the advisories to the appropriate aircraft via voice or data link, the module also sends them to the AACS where they are used to update the database of planned trajectories.

Trajectory Tracking Error Analysis

Early and accurate detection of errors in tracking planned trajectories is key to the effective operation of TSAFE. The primary use of tracking error analysis is to help the conflict detection algorithm minimize missed and false alerts and correctly identify real conflicts as early as possible. This section analyzes the relationships between segments of planned trajectories and the types of tracking errors that can occur. Insights gained from this analysis provide the basis for designing the error detection and categorization algorithm that must be built into the Trajectory Error Tracking module.

For purposes of tracking error analysis, planned trajectories are divided into two classes: 1. Steady trajectories, which designate flight at constant altitude and heading, and 2. Transition trajectories, which designate flight segments wherein either altitude or heading is changing. Since the tracking error analysis for the two classes pose significantly different problems, they are examined here separately.

1. Steady Trajectories

This class subdivides further into steady horizontal and steady vertical trajectories. Steady horizontal trajectories are defined as directed straight-line paths in the horizontal plane and steady vertical trajectories as flight at a specified altitude. The error tracking logic detects when the aircraft track position has deviated from the reference values by an amount larger than a prescribed error tolerance. For the horizontal case in en route airspace, the error tolerance is a maximum lateral displacement (~4 nmi) from the reference

line, whereas for the vertical case it is a maximum deviation from the reference altitude (~400 feet). The horizontal error logic also detects deviations of the aircraft heading from the reference heading defined by the directed line segment. When a deviation exceeding the error tolerance is detected, an alert message is generated and sent to conflict detection functions and other clients. Another monitor function could be added to detect deviations from a specified airspeed. However, speed deviation monitoring is not included here because it is considered nonessential for near term conflict detection.

The types of errors that occur in tracking steady horizontal or vertical trajectories can be classified into four tracking error states. These error states and their designations are listed in Tables 1 and 2 for steady horizontal and vertical trajectories, respectively. In each case, the first error state designates the on-track condition, whereas the following three states refer to the possible off-track conditions. The second column in the tables identifies the types of predicted trajectories that are used as the basis for conflict searching. The recommended choices designate the trajectories the aircraft are most likely to fly in the specified error state and are based on extensive analysis of data collected in testing CTAS tools as well as empirical observations of live traffic. It is important to note that for error state 2 in Table 1 two different prediction trajectories are used for conflict detection, one being the dead reckoning trajectory and the other the CTAS-generated trajectory. This dual trajectory strategy for conflict detection is the conservative approach adopted here to identify potential conflicts under conditions of irresolvable ambiguity. The dual strategy is also used for

certain error states arising in the other trajectory types. The third column in each table specifies the conflict detection strategy and look-ahead times for each error state. For horizontal tracking errors Figure 3 illustrates the evolution of the four tracking error states along an example deviation path that begins on a straight-line reference segment and terminates at the end of the segment. Several dead reckoning and CTAS predicted trajectories involved in the conflict search are shown at various points along the deviation path. The type of deviation path shown is often observed during convective weather activity when pilots are attempting to avoid areas of turbulence. Such deviation paths have contributed to loss of separation in the past and thus represent opportunities for TSAFE to provide a more effective safety net against operational errors.

The error states in tracking steady altitude segments listed in Table 2 and illustrated in Figure 4 involve uncoordinated or unintended altitude deviations from the cleared altitude level. Although such deviations occur less frequently than horizontal path deviations, they are easy for controllers to miss. For the climb or descent phase of the deviation the CTAS-generated vertical trajectories are combined with observed altitude rates to determine the predicted trajectories used in conflict search. Since the target altitude level during the unscheduled climb or descent is unknown, all altitude levels that can be reached within the look-ahead time are tested for conflicts. When the altitude is changing and the target altitude level is unknown the look ahead time is reduced to only 3 minutes, reflecting the large uncertainty in the prediction process.

Track Error State	Applicable Trajectories	Conflict Detection Strategy
1. On track, On heading	4 D trajectory	Normal conflict probe detection, full look ahead time ~ 20 minutes
2. On track, Off heading	4 D trajectory	Normal conflict probe detection reduced look ahead time ~ 10 minutes
	Dead reckoning trajectory	Separate conflict check along dead reckoning trajectory; ~ 3 minute look ahead
3. Off track, Off heading	Dead reckoning trajectory	Conflict probe detection disabled; dead reckoning conflict check activated; ~ 3 minute look ahead
4. Off track, On heading to a capture waypoint	4 D trajectory	Conflict probe detection with reduced look ahead time ~ 7 minutes

Table 1: Horizontal Trajectory Tracking Error States

Track Error State	Applicable Trajectories	Conflict Detection Strategy
1. At assigned altitude (Error-free state)	4 D trajectory	Conflict probe detection with normal look ahead time ~ 20 min.
2. Unscheduled climb above (descent below) assigned altitude level	Trajectory prediction based on observed altitude rate envelope	Vertical airspace conflict search, ~ 3 min. look ahead time
3. Unscheduled steady altitude flight above (below) assigned altitude	4 D trajectory at observed altitude level	Conflict probe detection with reduced look ahead time of ~ 6 minutes
4. Descent (climb) toward assigned altitude, following unscheduled altitude deviation	Trajectory prediction based on altitude rate envelope	Vertical Airspace conflict check, ~ 3 min.; conflict probe detection, 6 minutes

Table 2: Vertical Trajectory Tracking Error States

Track Error State	Applicable Trajectories	Conflict Detection Strategy
1. Transition on track and on heading (no errors)	4 D trajectory while position errors within bounds during turn	Conflict probe detection, full look ahead time ~ 20 min.
2. Improper turn initiation	4 D trajectory to capture waypoint. Dead reckoning trajectory	Conflict probing, reduced time. Dead reckoning conflict check ~ 3 minutes
3. Position error during turn exceeds bound	4 D trajectory to capture waypoint. Dead reckoning trajectory	Conflict probing, reduced time. Dead reckoning conflict check ~ 3 minutes
4. Turn terminated at wrong heading	4 D trajectory to capture waypoint. Dead reckoning trajectory	Conflict probing, reduced time. Dead reckoning conflict check ~ 3 minutes

Table 3: Horizontal Transition Error States

Track Error State	Applicable Trajectories	Conflict Detection Strategy
1. Altitude transition on time and on profile (no errors)	4 D transition trajectory; dead reckoning before start of transition	Conflict probing; dead reckoning maneuver criticality check
2. Altitude transition not initiated on time or in wrong direction	4 D transition trajectory; altitude rate envelope	Conflict probing; vertical airspace conflict search ~ 3 minutes
3. Altitude transition profile failure: Profile out of bounds or A/C leveling out early	4 D transition trajectory; altitude rate envelope	Conflict probing; vertical airspace conflict search ~ 3 minutes
4. Assigned altitude capture failure: A/C flies past assigned altitude	4 D trajectory if in level flight; altitude rate envelope	Conflict probing; vertical airspace conflict search if altitude rate not zero

Table 4: Vertical Transition Error States

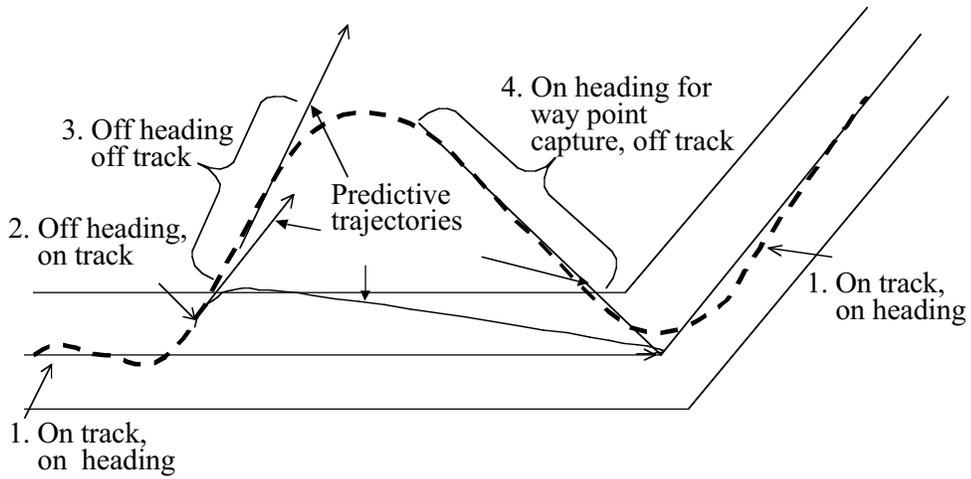


Figure 3: Horizontal Tracking Errors

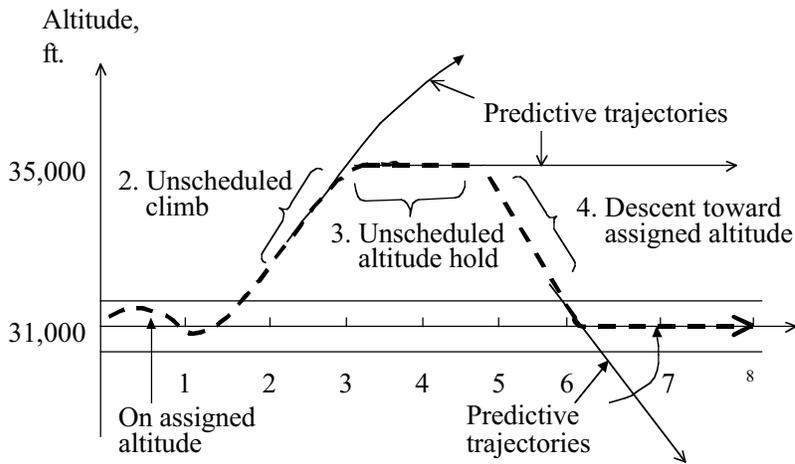


Figure 4: Illustration of Altitude Tracking Errors

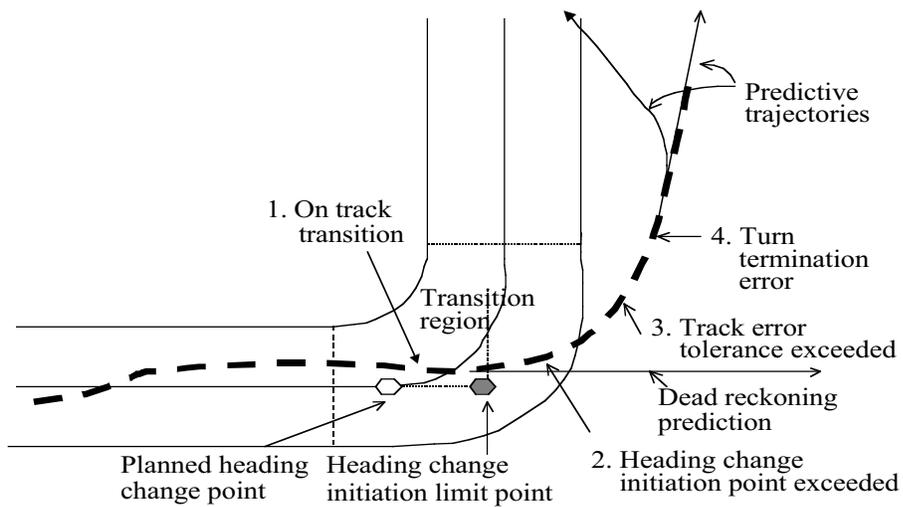


Figure 5: Illustration of Horizontal Transition Errors

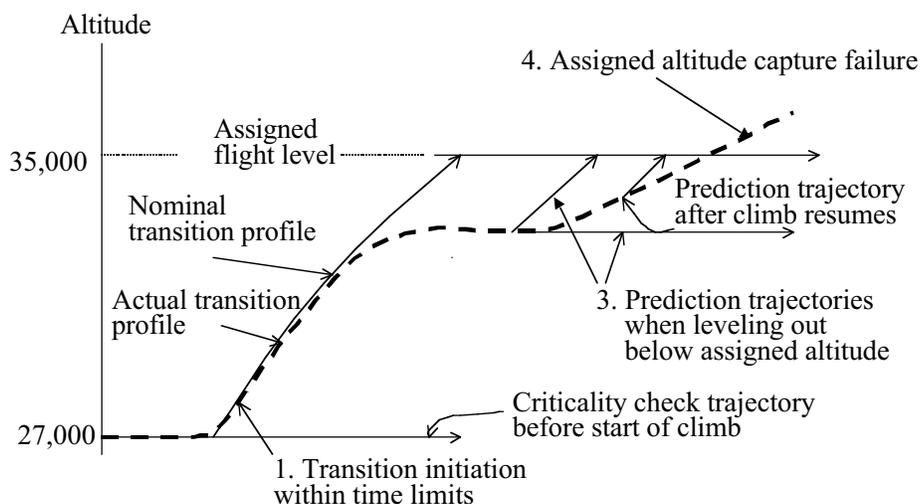


Figure 6: Illustration of Vertical Transition Errors

2. Transition Trajectory Tracking

As previously defined, transition trajectories connect the end point of the current steady flight segment to the beginning of the next steady segment. The starting time and position of the transition trajectory and the conditions to be achieved at the end of the transition are determined by the 4D trajectory, which is provided to TSAFE by the AACS. A transition trajectory initiated by the controller is referred to as a clearance or vector, and is intended to take the aircraft to a new flight level, heading, speed or route segment. In general, the transition trajectory of interest here is any segment of a 4D trajectory where the altitude, heading or speed is changing monotonically to capture new steady values. The transition trajectory ends when the specified steady values have been captured. Transition trajectory error analysis checks for the proper execution of the transition. It determines if the transition starts within prescribed time limits, if the transition variables such as heading or altitude are moving at the proper rates toward the target values and if the transition is terminated at the target values. The tracking errors permitted during the transition will depend strongly on the method used to execute the transition. If the transition originates with a controller clearance and is flown manually by the pilot, the error tolerances will be much larger than if the transition is a segment of a 4D trajectory, which is flown automatically by the FMS. The analysis algorithm outputs alert messages if transition error tolerances are exceeded. These messages are sent to the conflict detection logic and may also be used to alert the controller.

Table 3 lists four types of horizontal transition error states and describes the applicable trajectories and conflict detection strategy for each type. The main problem in horizontal transition error analysis is detecting the initiation and termination of planned heading changes. The detection

algorithm analyzes successive radar returns to determine if a heading change has begun or has terminated. It must be designed to require the fewest possible radar returns in order to minimize detection delays. An example of tracking errors along a transition trajectory consisting of a 90 degree heading change is shown in Figure 5. Each of the possible error states listed in Table 3 is illustrated in the figure. The limit point for heading change initiation defines the position where heading change must be observed to begin in order for the aircraft to complete the turn within the transition boundary. Before the beginning of the heading change is detected, both the predicted transition trajectory and the dead reckoning trajectory are used in conflict search. Conflicts found along the dead reckoning trajectory establish the time criticality of the heading change initiation. Once heading change is observed to be in progress, dead reckoning prediction is terminated and conflict search is performed only along the currently available 4D trajectory. Dead reckoning prediction resumes after the turn detection algorithm indicates that the aircraft has completed the heading change. If, as shown in the figure, the new heading is incorrect and the aircraft's position is outside the maneuver boundary, the AACS or the controller will guide the aircraft back to its planned path.

Vertical transition error monitoring is especially critical to the design of TSAFE because loss of separation incidents often occur while aircraft are changing altitude or just after leveling out at a new altitude. This can be explained by the fact that altitude transitions are more difficult for controllers to monitor than horizontal transitions, since the plan view format of controller displays does not provide a graphical visualization of vertical trajectories. Furthermore, the vertical trajectories generated by trajectory engines such as in CTAS are prone to substantial prediction errors. Such

errors limit the usability of controller tools for managing altitude transitions. These circumstances necessitate an approach that uses maneuver uncertainty regions in vertical airspace instead of predictive trajectories as the basis for conflict search. For this purpose a vertical uncertainty region shaped like the slice of a pie is defined as follows. The apex of the region is located at the current position and altitude of the aircraft. Two directed line segments radiating from the apex form the upper and lower boundaries of the region. The angles of the lines in the vertical plane are defined by the maximum and minimum flight path angles the aircraft is likely to fly during the transition. A line connecting the upper and lower line segments at a distance from the apex corresponding to 3 minutes of flying time completes the specification of the region. The vertical region so defined lies in a plane determined by the current heading angle of the aircraft. The algorithm in the CTAS conflict probe can be adapted to search for conflicts in this region.

Transition error states and conflict search strategies for vertical transitions using the approach described above are summarized in Table 4. An example transition trajectory illustrating two error states is shown in Figure 6. Similar to the horizontal transition case, the first step here is to check for the initiation of the altitude transition and to determine its time criticality. Once initiation has been confirmed, the next step is to monitor the climb (or descent) profile in order to detect anomalies such as leveling out below the target altitude. The last step is to determine whether the aircraft has completed the altitude transition by leveling out at the target altitude or is climbing (descending) past it.

Tactical Conflict Detection

The conflict detection logic for TSAFE must be capable of providing timely and reliable warnings for controllers against imminent loss of separation. The causes for the loss of separation may be pilot deviations from controller clearances or flight plans, controller monitoring failures or potential operational errors embodied in the most recently issued clearance. The detection time horizon for this function is targeted to be about 3 minutes from current time. Several techniques of conflict detection for TSAFE have already been discussed in the preceding section. In this section TSAFE conflict detection is compared with other types of conflict detection currently in use or under development. Additional detection procedures for TSAFE are also described.

TSAFE differs significantly in its purpose and technical approach from both the Conflict Alert capability installed at en route centers and the Conflict Probe approach, as well as the on board collision avoidance system, TCAS. Both Conflict Alert and TCAS predict conflicts by analyzing the current velocity vectors of aircraft pairs that are in close proximity of each other. Pilot or controller intent, even if known, is not considered. The Conflict Probe approach, on the other hand, is designed primarily to detect strategic conflicts, which are conflicts predicted to occur between

about 5 and 20 minutes in the future [1]. The technical basis for strategic conflict probing is analysis of the aircraft's planned trajectory. In conflict probing, flight plans, aircraft performance models and wind models play essential roles. On the other hand, the conflict detection function in TSAFE combines velocity vector and airspace analysis with near term intent information, derived from AACS trajectories, to provide a more reliable procedure for identifying near term conflicts.

Conflicts detected by TSAFE are categorized into two types, high and moderate risk, based on the near term risk they pose for losing separation. A high-risk conflict is one for which loss of separation is less than a minute away and the maneuvering airspace available for conflict avoidance is limited. A high-risk conflict will cause a conflict avoidance clearance to be generated and sent to the equipped aircraft via data link or issued to the unequipped aircraft as a clearance by the controller. A moderate risk conflict is one for which loss of separation is more than a minute away and maneuvering airspace is available. A moderate conflict, if detected, causes an alert message, but not necessarily an avoidance clearance, to be sent to the AACS or the controller via the controller interface.

The detection logic also identifies aircraft pairs that have an increased potential for high-risk conflicts before they become actual conflicts. This logic asks the question: Will an aircraft come into immediate conflict if a transition maneuver to a new steady flight segment is not initiated within a specified time window? If the answer is yes, the logic will calculate the time remaining for the maneuver to be initiated in order to avoid a conflict. The logic thereby establishes the time criticality of a scheduled transition maneuver. If the logic determines that a transition maneuver is time critical, the conflict avoidance module will generate several options for potential avoidance maneuvers and hold them ready to be issued.

Conflict Avoidance

The purpose of this module is to generate a conflict avoidance maneuver in the form of a brief controller clearance. The intent of the maneuver is to direct the aircraft to an altitude level and heading that is conflict free for about 3 minutes. The maneuver is not intended to provide an optimized strategic conflict-free solution that takes account of all predicted trajectories for the next 20 minutes, but rather a solution that avoids an imminent conflict risk for a short period of time and is also relatively simple to compute. This type of solution will give the controller sufficient time to plan a more strategic solution, either manually or by using automation tools at his disposal, such as a conflict probe/trial planner.

The conflict avoidance clearances are of the following two types:

1. Climb (descend) to a specified altitude
2. Turn right (left) to a specified heading

The transition component of the clearances-climb, descend, turn right or turn left - will be generated to avoid the imminent conflict risk and is functionally similar to a TCAS collision avoidance alert, although TCAS gives only vertical maneuvers. The altitude or heading assignment given in the clearance ensures that the aircraft will be operating in a safe region of airspace for a limited period of time after the imminent conflict risk has been eliminated.

The algorithm that generates the conflict avoidance clearances has at its disposal information on the characteristics and apparent causes of the conflict identified by the conflict detection module. Important conflict characteristics include the conflict geometry, miss distance, time to loss of separation as well as aircraft positions and velocity vectors. The causal information includes the identity of the aircraft that has deviated from its planned trajectory or has failed to execute a controller clearance. Other important information includes the identity and planned trajectories of all near-by aircraft that are properly tracking their planned trajectories, as well as any that are not. Furthermore, the geometry and location of airspace regions that are to be avoided during an avoidance maneuver are also known. By factoring all this information into the calculation of an appropriate conflict avoidance clearance, the effectiveness and reliability of the conflict avoidance module is significantly enhanced compared to current operational systems such as Conflict Alert or TCAS.

Controller Interface

The controller interface will include both visual and aural signals. The visual signals will consist of messages and symbols displayed on the controller's monitor and will indicate track deviation errors, conflict severity and the time criticality of alerts for the unequipped aircraft. The aural alerts intended for unequipped aircraft will consist of voice synthesized conflict avoidance clearances. They will be inserted into the controller's voice communication channel and be heard by the controller over his headset.

A longer-term enhancement of the controller interface will involve the use of voice recognition technology. This technology has greatly advanced in recent years and is now used in numerous consumer applications. Voice recognition systems can monitor the controller's verbal clearances to pilots, such as altitude and heading assignments, and automatically enter the clearances into the AACS. They could therefore help to reduce the number of keyboard entries controllers have to make to keep the AACS up to date. The voice recognized clearance could also be compared with the manually entered clearance to identify discrepancies. By having more complete and accurate knowledge of controller intent, the conflict detection algorithm can achieve a higher level of accuracy, with fewer false and missed alerts.

Operational Concept

This section broadly outlines operational procedures, controller responsibilities and computer-human interfaces for the Automated Airspace concept.

Automated Airspace operations take place in a well-defined volume of airspace referred to as an Automated Airspace sector. However, the airspace volume and the traffic density may be significantly greater in an Automated Airspace sector than in a conventional sector. As in today's operations, a controller has broad responsibility for maintaining an orderly and expeditious flow of traffic through the sector. It includes monitoring the inflow, outflow and sector count of owned aircraft to ensure that the traffic density in his sector does not exceed sector capacity. He will also monitor the movement of convective weather, respond to pilot requests for reroutes around weather, resolve conflicting pilot requests and assist pilots in handling emergencies and other abnormal situations.

The major change in operational procedures compared to procedures in today's system involves the controller's handling of the equipped aircraft in his sector. Monitoring and control of separations between equipped aircraft is performed by the ground-based Automated Airspace system that communicates directly and autonomously with aircraft systems via data link. The controller is therefore exempted from the responsibility of controlling the separation between these aircraft as long as they remain in the equipped status category. However, the controller retains authority to re-route equipped aircraft at any time by using interactive tools that are part of the Automated Airspace Computer System. These tools enable the controller to select conflict-free re-route trajectories, coordinate the changes with the pilot and transmit the trajectories to the aircraft via data link. Since the efficient operation of the Automated Airspace system depends on the system's up-to-date knowledge of planned trajectories, the controller must perform all trajectory changes by using the interactive tools. Similarly, the pilots of equipped aircraft are obligated to coordinate all trajectory changes with the ground system before deviating from previously established trajectories. However, it is inevitable that improper or uncoordinated deviations will occasionally occur. The Tactical Separation Assisted Flight Environment (TSAFE) element of the system is designed to detect such deviations and assist the controller in re-establishing an orderly traffic flow.

The controller retains responsibility for monitoring and controlling the separation of unequipped aircraft as well as those equipped aircraft that have reverted to unequipped status because of on-board equipment failures or other reasons. By considering the complexity of the traffic situation and his workload, the controller determines how many unequipped aircraft he can handle in his Automated Airspace sector. If his workload in handling the equipped aircraft is low he may permit more unequipped aircraft to enter. In general, however, equipped aircraft will have

higher priority than unequipped in entering Automated Airspace. In deciding how many unequipped aircraft he can handle, the controller has to plan for the possibility of an unexpected increase in workload due to events such as rapidly changing convective weather activity or onboard failures that may cause several equipped aircraft to revert to manual status. While controllers could use current manual procedures for handling unequipped aircraft, it is more likely that they will perform most control tasks with the aid of decision support tools such as conflict probe/ trial planner. By using these tools, the controller can be certain that modifying the trajectories of the unequipped aircraft will not lead to conflicts with the equipped aircraft. These interactive tools will therefore be a basic requirement for Automated Airspace operations.

As long as equipped and unequipped aircraft are neither operating in close proximity nor are in trail with each other, the controller's attention will be focused primarily on handling the unequipped aircraft. He will monitor separation between unequipped aircraft, resolve conflicts and direct them so as to avoid encounters with the equipped aircraft. However, encounters between equipped and unequipped will sometimes be unavoidable and therefore it is essential that controller procedures for handling such situations be defined. The level of difficulty in handling encounters will strongly depend on the density of traffic and the complexity of the traffic flow. As a rule, an unrestricted mix of equipped and unequipped aircraft will have to be avoided, since it would reduce capacity and efficiency. The complexity of controlling a mix of traffic without some degree of airspace separation between equipped and unequipped aircraft would strongly increase controller workload, thus reducing the number of aircraft allowed to operate in an Automated Airspace sector below its potential maximum. While operationally feasible, an unrestricted mix of traffic would defeat the main benefit of the Automated Airspace concept and therefore must be avoided.

The most effective procedure for handling isolated encounters between equipped and unequipped aircraft will be for the controller to use the trial planner/ conflict probe tool. This procedure is particularly applicable to en route sectors where over-flights make up most of the traffic. By using the trial planner tool, the controller has the freedom to change the trajectories of either or both aircraft involved in the encounter and therefore to choose the best control strategy. Factors such as encounter-geometry, efficiency of trajectories, workload, and effect on other traffic will determine his choice. In one-on-one encounters, the controller may prefer to change the equipped aircraft's trajectory via data link, thereby avoiding the more time consuming and less reliable voice clearance method for issuing changes to the unequipped aircraft.

In traffic scenarios where closely spaced streams of equipped arrival aircraft are converging at a feeder control point in center airspace or at a final approach fix in the terminal area, encounters between the equipped stream of arrivals and an unequipped aircraft are handled by having

the unequipped aircraft avoid crossing the arrival stream of the equipped aircraft. Controllers handle unequipped arrivals in center airspace by controlling them along a separate stream to a separate feeder control point. If the terminal area does not accommodate Automated Airspace operations, the approach controller merges the equipped and unequipped streams after handoff from center. In a terminal area designed for Automated Airspace operations, a separate runway must be set aside to land unequipped aircraft during arrival rushes. Although a controller could occasionally choose to insert an unequipped aircraft manually into a landing stream of equipped aircraft, it would be at the expense of both high workload and reduced capacity.

Another significant difference between current and Automated Airspace operations is the transfer of control process between sectors, referred to as handoff. Handoff coordination into and from Automated Airspace sectors of equipped aircraft is automated regardless of whether the adjacent sectors are automated or manual. Along with automated separation assurance, automation of handoffs is another important function that helps to shift the controller's workload from routine tactical tasks to strategic tasks and handling of exceptional situations. Instead of deciding aircraft by aircraft whether to accept a request for a handoff into the Automated Airspace sector, the controller maintains control over the inflow rate by setting the sector's capacity limit. However, handoffs of unequipped aircraft will continue to be handled manually by controllers. A handoff situation unique to Automated Airspace occurs when an equipped aircraft's status changes to unequipped. The change may be voluntarily initiated by the controller or pilot or may be forced by the system. A forced change typically would occur when on board equipment fails or when TSAFE issues a conflict avoidance advisory to the aircraft. A forced handoff is subject to the condition that TSAFE has issued a clearance to the aircraft that is conflict free for at least 2 minutes at the time of handoff. This time interval is considered to be the minimum period the Automated Airspace controller needs to gain awareness of the traffic situation and be able to safely take over separation assurance responsibility for the aircraft. During the two minutes of conflict free operation following the forced handoff, the controller uses his automation tools to develop a strategic solution for re-integrating the aircraft into the traffic flow. If at a future time the aircraft recovers its ability to operate in the equipped mode, the controller has the option to change the aircraft back to equipped status by handing it off to the Automated Airspace system.

As the discussion above has demonstrated, the requirement for the Automated Airspace system to handle a mix of equipped aircraft and manually controlled unequipped aircraft complicates both the design of the system and the development of controller procedures and interfaces. Nevertheless, this requirement is indispensable to the development of the concept as a practical operational system.

The key to the operation of the Automated Airspace concept is the separation assurance function in TSAFE. As described earlier, it provides a safety net against trajectory errors and control failures when they threaten an imminent loss of separation. As a safety net, TSAFE effects operations only during the infrequently occurring events when the normal processes and systems for ensuring separation have failed. When such events occur TSAFE generates conflict avoidance advisories for both equipped and unequipped aircraft. After issuing a conflict-avoidance advisory to the equipped aircraft via data link, TSAFE sends a copy of the advisory and a handoff message to the controller, who assumes manual control of the aircraft at that time. A TSAFE advisory intended for an unequipped aircraft is sent to the controller via an appropriate computer-human interface. The controller is then responsible for issuing it as a clearance to the aircraft.

The controller monitors and controls the traffic in the Automated Airspace sector through a computer-human interface that combines features found in the traditional plan view radar display with functions designed specifically for Automated Airspace operations. An example of a candidate display configured for the northeastern arrival sectors in the Fort Worth Center is given in Figure 7. Targets with full data tags identify unequipped aircraft for which the controller is responsible for maintaining separation, whereas those with reduced data tags that show only altitude and meter gate sequence number identify equipped aircraft. Equipped and unequipped arrivals are controlled along separate streams, which converge at their respective feeder gates (Karla and Sasie) at the bottom left in the figure. The reduced data tags identifying the equipped aircraft help to minimize display clutter by suppressing superfluous

information while still providing the controller with the basic information he needs to supervise the traffic flow. However, the controller retains the option at any time to display the full data tag by dwelling and clicking on the target. If the reduced data tag of an equipped aircraft target expands to full size and simultaneously changes its color to yellow (not detectable in the non-colored version of the figure) as illustrated by AAL391, it indicates that the aircraft has changed its equipage status from equipped to unequipped and that it has been handed off to the controller. As shown in the figure, the data tag also includes a diagnostic message (data link inoperative) identifying the type of failure that caused the handoff and change in equipage status. To assist the controller in handling the unequipped aircraft, the display includes a list of predicted strategic conflicts. The controller uses the conflict list in combination with the trial planner to manage the unequipped aircraft. In addition to using these tools, the controller can access Direct-To, Descent Advisor, Final Approach Spacing Tool and others included in the Center-TRACON Automation System through the display interface to help him manage a range of traffic problems for both equipped and unequipped traffic. As a further enhancement of the interface, new graphical tools can be added to minimize the controller's workload in managing encounters between equipped and unequipped aircraft.

The operational concept and the interface design described in this section are intended to serve as a starting point for the development process. They provide sufficient design details for building a system that can be evaluated in real time simulations with controllers in the loop. These simulations will be the primary mechanism for developing the final design specifications.

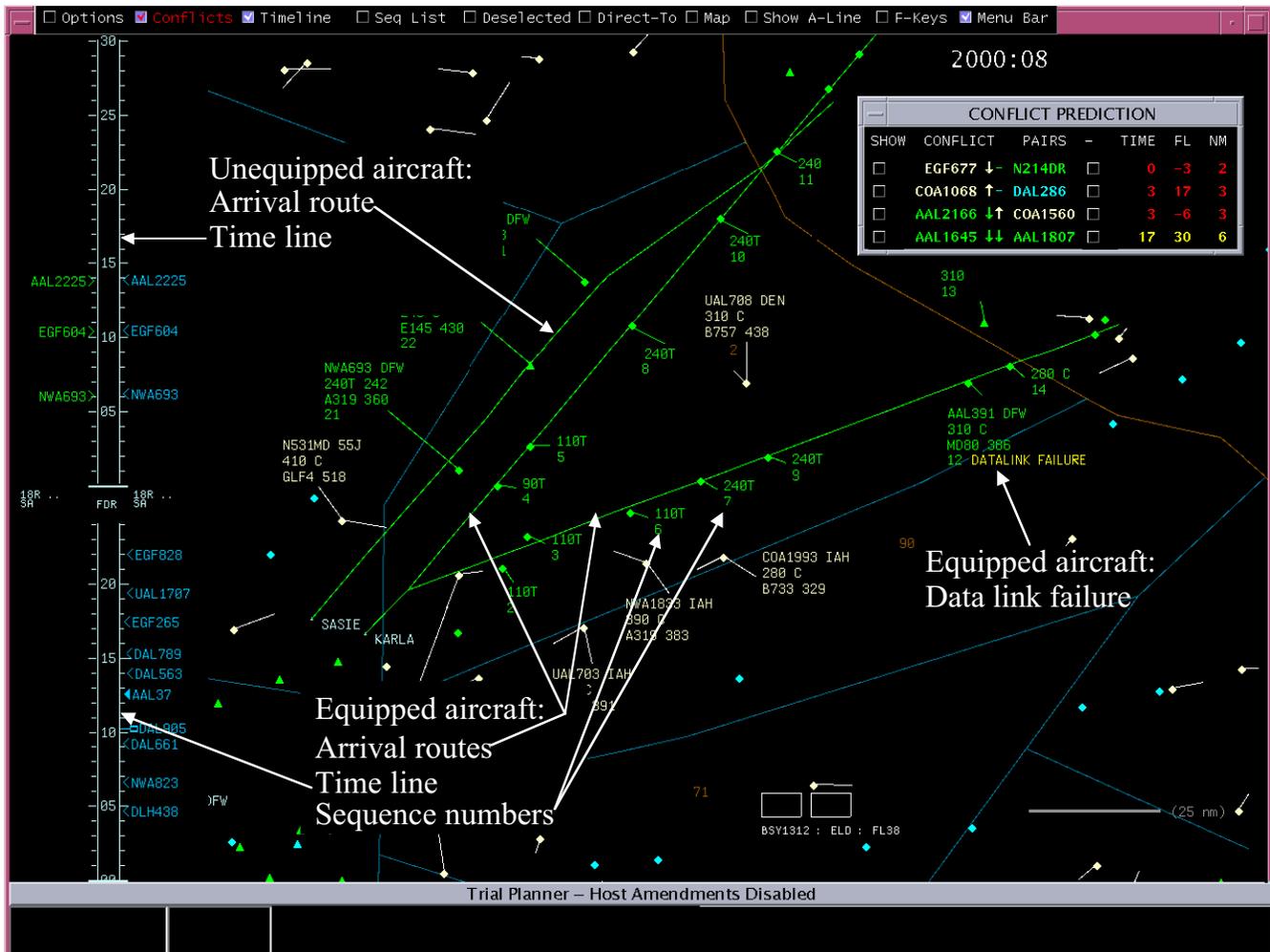


Figure 7; controller display for automated airspace sector

Concluding Remarks

This paper has addressed the problem of how to design an air traffic control system that maintains safe separations in high density traffic without depending on controllers to monitor and control separations of each and every aircraft in his sector. The major problem in designing such a system is defining an architecture that incorporates a safety net for protection against loss of separation in case failures or errors of execution occur in the primary system of separation assurance. This problem is solved by augmenting the primary ground based computer system for automating air traffic control functions, including separation assurance, with an independent system for detecting imminent loss of separation and generating conflict avoidance maneuvers. It was shown that such a system for detecting and avoiding near term loss of separation could be implemented in today's system as a tool to help controllers avoid operational errors.

The traffic control functions performed by this system are designed to handle only those aircraft that are equipped with data link, cockpit display of traffic information and flight management systems. The controller will handle unequipped aircraft and equipped aircraft that have lost a required capability by manual techniques. In this concept the distribution of controller workload will shift away from monitoring separations of each aircraft in a sector toward managing traffic flow and handling those exceptional problems that only humans have the knowledge and skill to solve. This redistribution of workload combined with integration of ground and airborne systems characterizing the Automated Airspace concept lays the foundation for achieving a substantial increase in the capacity of en route and terminal area airspace. By reusing software components and infrastructure technologies developed in support of other programs, an experimental version of the concept could be built and evaluated within a relatively short time.

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Biography

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Heinz Erzberger joined Ames Research Center in 1965 after receiving a Ph.D. in electrical engineering from Cornell University. His early work at Ames was in the field of guidance and control of aircraft. He developed methods and algorithms that help to minimize aircraft fuel consumption and operating costs. His methods are incorporated in the flight management systems of most airliners flying today. In recent years Dr. Erzberger has worked on developing algorithms and architectures for automating air traffic control. He led the design of the Center-TRACON Automation System (CTAS), which comprises a suite of tools for air traffic controllers that reduce delays and smoothen traffic flows. The Federal Aviation Administration is deploying CTAS tools at several airports around the country. He has published over 80 papers and reports and received numerous honors and awards for his research. He is a Fellow of the American Institute of Aeronautics and Astronautics and a Fellow of Ames Research Center. This year the American Society of Mechanical Engineers awarded him the prestigious Holley Medal.