Concept for Next Generation Air Traffic Control System

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The next generation air traffic control system must achieve a large increase in capacity and throughput while improving efficiency and safety. This paper describes the Automated Airspace concept that has the potential to achieve these objectives. A ground-based component, the Automated Airspace Computer System (AACS), will generate efficient and conflict-free traffic clearances and associated trajectories and send them directly to the aircraft via data link. Another ground-based component, the Tactical Separation Assisted Flight Environment (TSAFE), will provide a safety net to ensure that safe separations are maintained in the event of failures in the AACS or in certain on-board systems. TSAFE will independently monitor the clearances and trajectories sent by the AACS to each equipped aircraft, monitor aircraft conformance to those trajectories, and issue warning and resolution advisories to pilots and controllers when appropriate. Because the Automated Airspace concept will reduce controller workload associated with tactical problem solving, controllers will be able safely to shift their focus to more strategic problems, such as traffic flow management and pilot requests. TSAFE also has application in the current air traffic control system as an improved controller tool for detecting near-term conflicts and reducing the potential for operational errors. Changes in controller and pilot responsibilities for operations in Automated Airspace are outlined.

INTRODUCTION

The next generation air traffic control system must be designed to achieve a significant increase in capacity and throughput while providing even higher levels of safety than today's system. Such an

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This paper is based on a presentation given at the USA/EUROCONTROL Air Traffic Management R&D Seminar held in Santa Fe, New Mexico, in December, 2001 [see ATC Quarterly, Vol. 10(2)].

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Received July 2, 2002; accepted August 6, 2002.

increase in performance cannot be achieved simply by evolutionary improvements of the existing operational system. Rather, it requires a new approach that constitutes a paradigm shift relative to the traditional systems and methods of control. The automation of separation monitoring and control should allow airspace capacity to be increased significantly. By delegating the separation assurance function to systems on the ground and in the cockpit, controllers can shift their attention to such tasks as optimization of traffic flow and accommodating pilot requests for route changes. This paper presents an outline for the design of a system, referred to as the Automated Airspace concept, which has the potential to achieve these performance objectives.

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 clearances and associated trajectories for all equipped aircraft operating in an Automated Airspace sector. The trajectories or clearances generated by the AACS are sent via data link to appropriately equipped aircraft where they are executed manually by the pilot or are entered directly into the Flight Management System. Therefore, separation assurance is achieved by equipped aircraft executing clearances generated by the ground-based automation system.

A key component of the Automated Airspace concept is an independent separation monitoring and conflict avoidance system that provides a safety net in event of AACS failures, certain on-board system failures, or pilot errors. This system, called the 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.

The paper begins with a description of the system architecture for this concept and then concentrates on the design of TSAFE. Methods are described for identifying operational situations that can lead to loss of separations and for generating alert messages that give timely warnings to controllers and pilots. The TSAFE algorithms are being evaluated by using archived records of radar tracking data that document incidents of loss of separation in en route airspace. Initial results from the evaluation are described. The paper concludes with a discussion of the major changes in procedures and responsibilities for both controllers and pilots operating in Automated Airspace.

CONCEPT OVERVIEW

The primary ground-based component of the Automated Airspace concept is the Automated Airspace Computer System (AACS). Many of the functions to be performed by the AACS have already been developed for the Center-TRACON Automation System (CTAS) [Erzberger et al., 1997; Green, Vivona, and Grace, 1998; Robinson and Isaacson, 2000]. 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 Automated Airspace, the control algorithms in CTAS must be upgraded to make them suitable for use without controller oversight. The clearances and trajectories generated by the upgraded algorithms must meet additional safety criteria that qualify them for transmission to pilots or to on-board systems via data link without first being validated by a controller. With the experience gained in operational use of the CTAS advisories, combined with further progress in control algorithms and air-ground data links, it now appears technically feasible to achieve this level of performance.

The most important technical and operational challenge in designing the Automated Airspace system lies in 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. This 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 that 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 [Zeitlin et al., 1998]. CDTI will give the cockpit crew situational awareness of surrounding traffic and thus enable the pilot selectively to take responsibility for certain traffic control functions under exceptional circumstances, for example, when components of the Automated Airspace system fail. CDTI will therefore contribute to the safety net of the Automated Airspace concept, but it is not intended to be used routinely in high-density airspace as a stand-alone cockpit-based traffic control tool.

Protection against near-term loss of separation owing to failures of the AACS or to failures of aircraft to correctly execute clearances will be provided by a new ground-based system, TSAFE, which operates independently of the AACS. 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 within 1–2 min from the 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 AACS. As we shall demonstrate in a later section, it also shows promise as a controller tool for current operations to give controllers more timely and accurate warnings of loss of separation than existing tools such as Conflict Alert.

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 (FMS). One of the data links must have the bandwidth to accommodate the transmission of automated clearances from the ground; a second data link will provide traffic information about 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 VDL3 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 significantly increase throughput and reduce delays, even if separation criteria remain unchanged.

A recent study estimated the potential capacity gains of the Automated Airspace concept [Andrews, 2001]. In that study two adjacent en route sectors that are often capacity-limited because of 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 additional conflicts relative to those currently encountered at base line traffic levels. This result 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 a system based on the Automated Airspace concept are available or could be developed in a relatively short time. The major technical issues that research must address involve integration of air and ground components and the performance of a systematic safety analysis. The issue of equipage standards for aircraft must be resolved as soon as possible in order to give airlines and other aircraft operators adequate lead time to purchase and install the equipment needed for operation in Automated Airspace. Finally, since both controllers and pilots will experience significant changes in transitioning from current to Automated Airspace operations, the human factors issues associated with the controller's and pilot's changed work environments must be given careful attention. New pilot responsibilities will include monitoring separation assurance messages and executing conflict avoidance advisories promptly when they are received via data link. Although the controller's workload will change from one of performing fewer tactical control tasks associated with separation assurance in today's system to one of performing 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, the MITRE Corporation, in cooperation with the FAA, conducted the AERA 3 program that had objectives broadly similar to those of the Automated Airspace concept [Niedringhaus, 1989]. 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, at that time. 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 the one proposed in this paper.

SYSTEM ARCHITECTURE

Figure 1 shows the major elements of the Automated Airspace concept 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, the Automated Airspace Computer System (AACS), the Tactical Separation Assisted Flight Environment (TSAFE) and the Controller Interface. A more complete diagram would also show supporting infrastructures such as surveillance radars, navigation systems, airborne collision avoidance systems, and en route and terminal-area

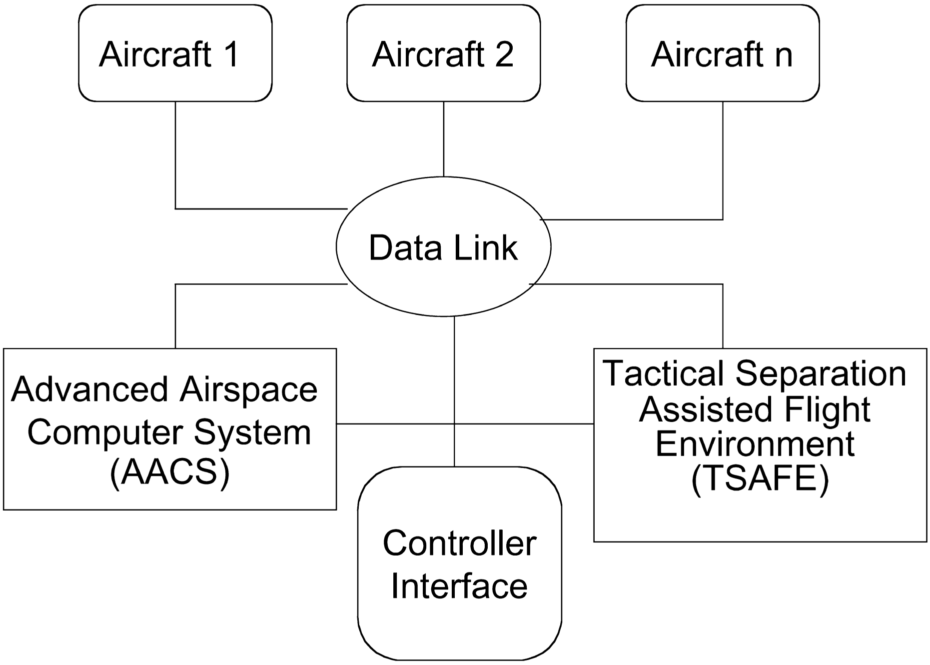

Figure 1. Automated airspace architecture.

computer systems, as well as the flow of information between them. Although these elements are indispensable for the operation of the system as a whole, they nevertheless play only a peripheral role in the design and are therefore omitted from the diagram.

The design of the system architecture was influenced by the need to provide cost-effective 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, provides the essential ground-based functions for the implementation of the Automated Airspace concept. In the discussion to follow, the functions and design considerations of the main system elements are briefly described.

The AACS solves air traffic control problems for suitably equipped traffic operating in an Automated Airspace sector. Solutions for such problems are being developed for application in today's system under the aegis of controller decision support tools. 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 a system that is capable of interacting more autonomously with aircraft. Autonomous interaction requires that the solutions generated by these tools provide a level of completeness and accuracy that allow them to 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 [Erzberger, McNally, and Foster, 2001], the En Route Descent Advisor (EDA) [Green, Vivona, and Grace, 1998], and the Final Approach Spacing Tool (FAST) [Robinson and Isaacson, 2000]. When these tools are fully developed over the next several years, they will provide the advisories needed to control en route traffic, as well as arrival traffic transitioning from en route airspace to landing approach. They will then be able to assist controllers in solving a variety of traffic control problems. Moreover, since the advisories these tools generate are derived from four-dimensional (4-D) trajectories, it is possible to up-link the complete trajectories to the aircraft or up-link them as a sequence of clearances. For a range of nominal operating conditions, the advisories and the 4-D trajectories upon which the advisories are based can achieve a conflict-free and efficient flow of traffic.

Therefore, a CTAS-based AACS could serve as the computational engine for achieving autonomous control of traffic 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. Our hypothesis is that a stand-alone AACS is insufficient to ensure safe separation.

Automation software such as CTAS is inherently limited to the solution of 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. Although the envelope of problems that 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 severe weather conditions, may produce conditions that fall outside that envelope. If that should happen, traffic flow could become inefficient and chaotic, risking the loss of separation. These limitations of a stand-alone AACS make it unlikely that such a system can ever be certified as safe. 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.

Two steps are proposed to overcome the difficulties with a standalone AACS. These steps are intended to provide an effective safety net in event of a variety of failures and to 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 for those situations. This step is performed by the TSAFE system. The second step consists of a procedure that allows the controller to accept separation responsibilities for an equipped aircraft 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 that are built into AACS and TSAFE and that are 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, TSAFE operates in parallel with the AACS. Both receive surveillance data and both 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 min, 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 limited to preventing loss of separation, its software design can also be much simpler than that of the AACS. As long as AACS is performing normally and the equipped aircraft are tracking their assigned trajectories properly, TSAFE will not detect any problems and therefore will not interfere in its operation. The next section describes the design of TSAFE in greater detail.

DESIGN OF TSAFE

Because of its safety-critical role in protecting against loss of separation during primary system failures, TSAFE presents a unique design challenge in the development of the Automated Airspace system. The design focuses on achieving essential requirements and excludes any function that is not absolutely necessary or that can be incorporated in other components.

Before describing the design, it is important to clarify the relationships and differences between TSAFE and the airborne collision avoidance system TCAS (Traffic advisory and Collision Avoidance System) [FAA, 2000]. The most important difference is that TSAFE is designed to prevent loss of separation, whereas TCAS is designed to prevent collisions. TCAS issues traffic alerts and advisories to help pilots avoid collisions when the predicted minimum separations are very small and the time available in which to avoid a collision is less than 25 s. 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 that 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. Its use as the final safety net to prevent a collision is not at issue, but TCAS 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 imminent loss of minimum required separation. 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 traffic while also more effectively avoiding false alarms. It is, therefore, especially suitable for application in high-density airspace, including that of the terminal area. Since TSAFE compares the planned trajectories obtained from the AACS with the actual trajectories flown by the aircraft, TSAFE can identify any aircraft that has failed to track its planned trajectory and can then take that into account when generating the avoidance maneuver.

In addition to its role as a critical component of the Automated Airspace concept, TSAFE can also be incorporated in the current operational system to give controllers improved protection against operational errors. An operational error refers to a traffic incident in which a controller is held responsible for permitting separation to fall below the required minimum. The architecture for this application of TSAFE would be similar to the one proposed for the Automated Airspace concept, except that conventional controller-pilot voice communications would take the place of data-linked communication 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 by an equivalent trajectory engine in order 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 detection of short-term conflicts and its conflict avoidance advisories, TSAFE promises to provide more complete protection against operational errors than does the currently operational Conflict Alert function in the host computer. The near-term use of TSAFE as a controller tool in the current system will also provide an opportunity to evaluate its effectiveness and improve its performance under current operational conditions. Most important, 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 the Automated Airspace system.

The modules composing TSAFE and its inputs and outputs are shown in Figure 2. Primary inputs are track positions, velocity vectors, and planned 4-D trajectories for all aircraft. These inputs are provided by the surveillance system and the AACS, respectively, and are updated in real time. Since TSAFE analyzes trajectories received from the AACS, it does not qualify as a fully independent backup system, nor is it designed to take over all AACS functions during a total failure. Such a requirement would defeat the goal of keeping the design of TSAFE as simple as possible. It is primarily intended to provide protection against near-term conflicts arising from occasional AACS trajectory planning errors or aircraft deviations from planned trajectories. However, immediately after a complete failure of the AACS, TSAFE advisories should also provide sufficient time

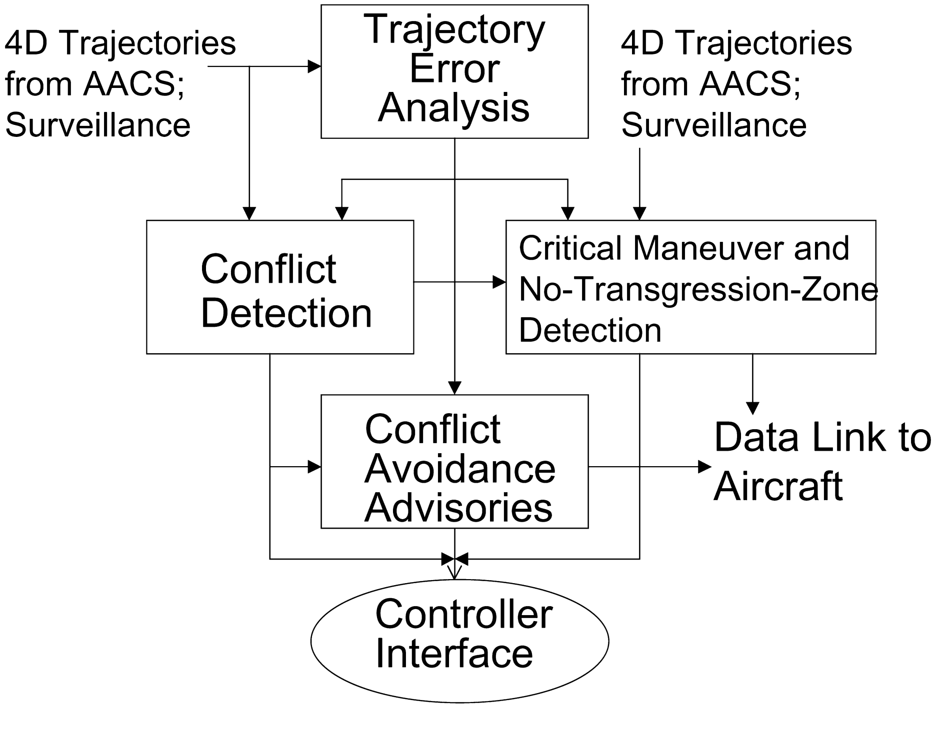

Figure 2. TSAFE architecture.

for controllers to take over manual separation of traffic. The controller interacts with the system via the Controller Interface. The output of TSAFE consists of clearances, trajectories and several types of alert messages that are sent to the Controller Interface, to the appropriately equipped aircraft via data link, and to the AACS.

In the Trajectory Error Analysis module, TSAFE compares the current position, altitude, heading, and speed of every aircraft to the corresponding values of the planned trajectory to determine whether the aircraft is following the planned trajectory within prescribed error tolerances. Excessive errors indicate a loss of intent that strongly influences the conflict-detection strategy. This module classifies errors into several categories based on the degree of deviation from the aircraft's planned trajectory. The greater is the deviation from the planned trajectory the larger is the airspace protected near that aircraft in order to reduce the risk of conflicts. As soon as the algorithm in the module detects that the aircraft has resumed tracking its assigned trajectory accurately, it reduces the protected airspace to normal size. The categorization of trajectory tracking errors and their effect on near-term conflict detection is described and illustrated with several examples in Erzberger [2001]. The module sends the call signs of aircraft with anomalous 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 min or less. This module is designed to identify only such near-term conflicts, since the Conflict Probe/Conflict Resolution function built into the 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 to 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. The causes for the loss of separation may be pilot deviations from controller clearances or flight plans, failures of controllers to monitor unequipped aircraft, or errors embodied in an AACS-generated clearance.

For aircraft that are in conflict and that are identified by the Conflict Detection module, the Conflict Avoidance module generates advisories to eliminate the short-term conflict threats. The advisories provide a short conflict-free interval of time 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 reduces software complexity and therefore helps to simplify the design. 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.

TSAFE differs significantly in its purpose and technical approach from the Conflict Alert function installed at en route centers, the on-board collision avoidance system, TCAS, and the Conflict Probe approach. Both Conflict Alert and TCAS predict conflicts by analyzing the current velocity vectors of aircraft pairs that are close to each other. Pilot or controller intent is considered in only a limited way for Conflict Alert and not at all for TCAS, making these systems susceptible to both false and missed alerts. The Conflict Probe approach is designed primarily to detect strategic conflicts, which are conflicts predicted to occur between about 5 and 20 min in the future [Erzberger et al., 1997]. The technical basis for strategic conflict probing lies in the analysis of the aircraft's planned trajectory. Flight plans, aircraft performance models, and wind models play essential roles in conflict probing; the current velocity vector plays a lesser role. On the other hand, the conflict-detection function in TSAFE combines the velocity vector and airspace analysis with near-term intent information, derived from AACS trajectories and observed deviations from these trajectories, to provide a more reliable procedure for identifying near-term conflicts than is possible with either Conflict Alert or Conflict Probe.

Finally, the TSAFE architecture shown in Figure 2 also contains a function referred to as Critical Maneuver and No-Transgression-Zone Detection. By analyzing the current 4-D trajectories, the Critical Maneuver function identifies the next planned maneuvers that aircraft must perform accurately and on time in order to avoid a conflict. Such maneuvers are defined as critical. It should be noted that the aircraft associated with critical maneuvers generally will not be the same as those found by the conflict-detection function. The existence of critical maneuvers indicates an increased potential for high-risk conflicts to develop rapidly, if the critical maneuver is not performed properly. The No-Transgression Zone identifies airspace regions an aircraft must avoid; it is explained further in a paragraph below.

The Critical Maneuver Detection function searches for aircraft that will come into immediate conflict if a transition maneuver to a new steady flight segment (an assigned heading or altitude) is not initiated at a specified way point or altitude. For all such aircraft, the function also calculates the times remaining before the maneuvers must be initiated in order to avoid the conflicts. The function thereby identifies the time criticality of all transition maneuvers scheduled to be executed within a few minutes. Although probing for critical maneuvers can be applied to every type of planned maneuver or trajectory, we focus here on two important cases involving transition maneuvers: (1) failure to execute a planned turn and (2) failure to terminate a climb or descent at an assigned altitude.

Figure 3 illustrates critical maneuver and no transgression zone scenarios for these cases of horizontal and vertical transition trajectories. For critical maneuvers, the Conflict Avoidance module will pre-compute avoidance maneuvers and prepare them to be issued expeditiously to the aircraft if a maneuver failure is detected. In Automated Airspace, TSAFE will also send a critical maneuver warning message to the corresponding aircraft. The message, which would be sent a few minutes before the planned start of the maneuver, will alert the pilot to the criticality of the impending maneuver. The message will be cancelled as soon TSAFE confirms that the critical maneuver is being executed. In the application of TSAFE to the current operational environment, critical maneuver messages can be added to the controller's plan view display of traffic. We plan to conduct simulations and field evaluations to assess the effectiveness of these messages in helping controllers avoid operational errors.

The no transgression zone alert, illustrated in Figure 3 and intended primarily for use in the cockpit, specifies a region of airspace adjacent to the current position of an aircraft that the aircraft must avoid so as not to create an immediate conflict with another aircraft. This message can also be interpreted as a do-not-maneuver message such as do-not-turn-left, do-not-climb. The message will be displayed in the cockpit only during the period when it is needed and then promptly removed. Essentially, the two TSAFE messages are

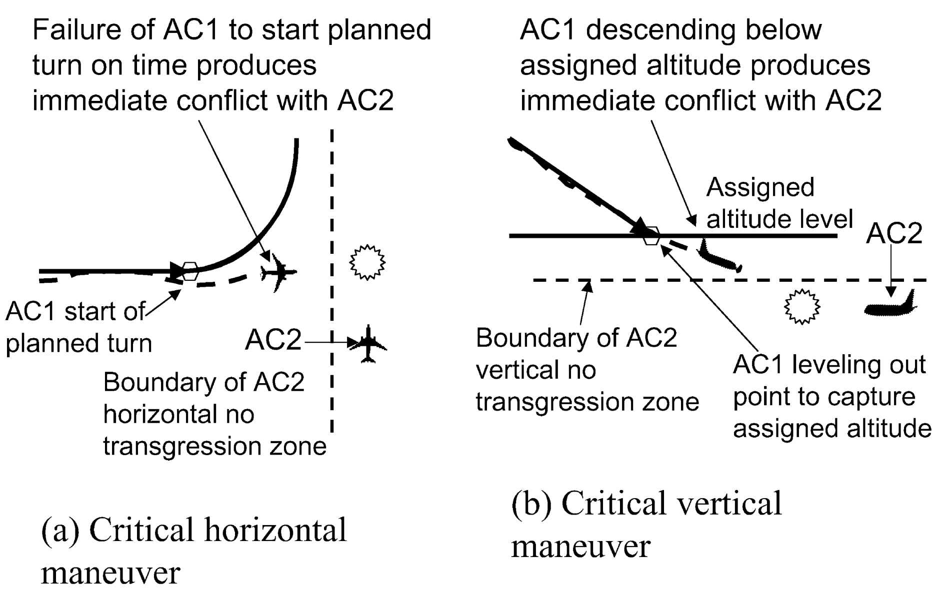

Figure 3. Illustration of critical maneuvers and no transgression zones.

complementary in the sense that the critical maneuver message advises what the aircraft must do and the no-transgression-zone message advises what it must not do if an immediate conflict is to be avoided.

The purpose of the Conflict Avoidance module (Fig. 2) in TSAFE is to generate a conflict-avoidance maneuver when the detection module has detected that a loss of separation is imminent. The intent of the maneuver is to direct the aircraft to an altitude level or heading that are conflict-free for about 3 min. The maneuver is not intended to provide an optimized strategic conflict-free solution that takes account of all predicted trajectories for the next 20 min, but rather a solution that avoids an imminent conflict risk for a short period of time and that is also relatively simple to compute. This kind of solution should give the AACS or the controller sufficient time to plan a more strategic solution using automation tools at his disposal such as a conflict probe/trial planner. It is recognized that the TSAFE-generated short-time horizon solution may make the strategic solutions of other nearby aircraft obsolete. Therefore, the AACS will also have to update the strategic solutions for these aircraft during the three minute grace period.

The conflict avoidance clearances are of two kinds: (1) climb or descend to a specified altitude; and (2) turn right or left to a specified heading. The transition component of the clearances (climb, descend, turn right, turn left) will be generated to avoid the imminent conflict risk and is functionally similar to a TCAS collision-avoidance alert, although TCAS is limited to vertical maneuvers only. 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. It should be noted that speed changes are generally not used here as conflict avoidance clearances because they are ineffective over the short time interval of the TSAFE time horizon. However, they may be useful in special situations involving merges or overtakes in trail.

The algorithm that generates the conflict-avoidance clearances has at its disposal information about the characteristics and apparent causes of the conflict identified by the Conflict Detection module. Important conflict characteristics include the conflict geometry, miss distance, and 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 that has failed to execute a controller clearance. Other important information includes the identity and planned trajectories of all nearby 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 are used as constraints in synthesizing the avoidance maneuver.

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 unequipped aircraft. In this context the equipage standards for unequipped aircraft are assumed to be the same as those required for instrument flight rule (IFR) operations by air carriers in today's system. The aural alerts intended for unequipped aircraft will consist of voice synthesized conflict-avoidance clearances. These alerts will be inserted into the controller's voice communication channel.

EXAMPLE OF TSAFE ANALYSIS

For analysis and testing purposes, we have obtained incident reports and tracking data from the FAA for more than a dozen actual conflicts (breaches of minimum required separation). Analysis of these conflicts shows that altitude transitions are implicated in all except one case. We will use one of these incidents to illustrate the application of the TSAFE warning and alert detection methods. Figure 4 shows the ground tracks, and Figure 5 shows the altitude profiles for the example case. One pair of asterisks on the ground tracks marks the point of loss of separation, and another pair marks the point 3 min before loss of separation. Discrete events are marked on the plots with time tags relative to the time of loss of separation, and controller

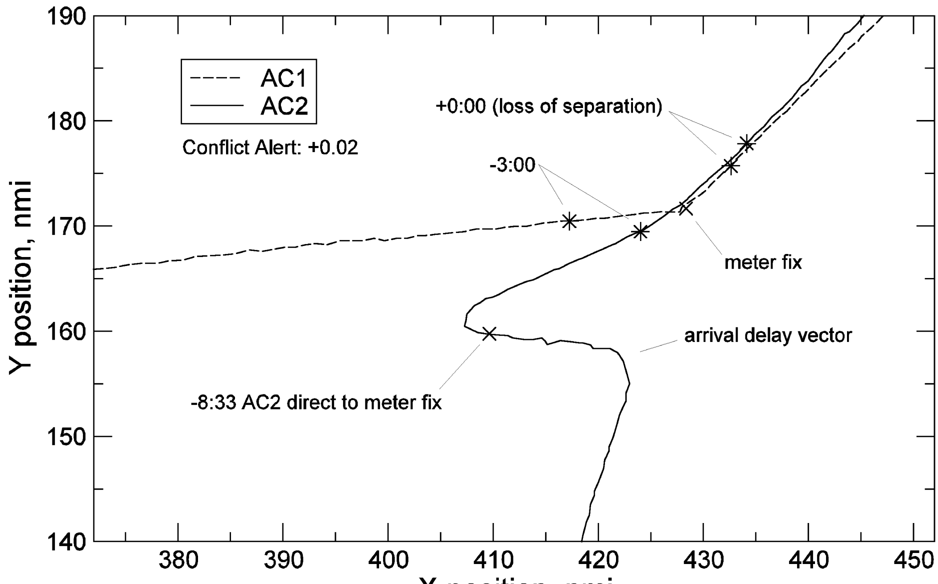

Figure 4. Actual ground tracks showing loss of separation and expected TSAFE response.

clearances are abbreviated. The data file for the incident (which includes tracking data and altitude clearances entered into the host computer by the controller) was “replayed” through CTAS to visualize the incident as a controller would see it and to evaluate the response of TSAFE emulated in CTAS.

This particular conflict involved two arrivals merging at a feeder fix, one descending (AC1), and the other (AC2) flying level at 10,000 ft. AC2 was given a path-stretching (delay) vector, then a clearance direct to the feeder fix at –8:33 (8:33 min before loss of separation). At –5:31, the descending aircraft, AC1, was issued a meter fix crossing altitude of 11,000 ft, which the controller keyed into the host computer. However, the pilot incorrectly read back the assigned altitude as 10,000 ft (the altitude at which AC2 was flying). The controller failed to catch the misread, and that misunderstanding caused the conflict. Without correct altitude data, Conflict Alert (the existing system in the host computer designed to warn the controller of imminent conflicts) did not activate until 0:02 after AC2 had descended through 11,000 ft and separation had already been lost. Furthermore, the CTAS Conflict Probe could not have predicted this conflict in time to prevent it, because CTAS uses the same crossing altitude of 11,000 ft that was entered by the controller. As a result, the airplanes came within 1.0 nmi horizontally and 200 ft vertically, which is considered a severe violation.

The projected TSAFE response to this example scenario is indicated in Figure 5 by two warning messages, the first at –2:00 and the second at –0:15. The first is an example of a critical maneuver message for AC1. As defined in the previous section, a critical maneuver condition exists if failure to perform a prescribed maneuver (failing to level off at 11,000 ft in this case) could create an immediate conflict. TSAFE will identify all critical maneuver conflicts 2 minutes or less before the nominal start of the maneuver. In the Automated Airspace environment, TSAFE would send a data link message to AC1, reminding the pilot of the urgency to level off at 11,000 ft. This message would provide another opportunity for the pilot to become aware of the misunderstood altitude clearance and to correct it. In today’s manually controlled airspace the controller could be warned of the critical maneuver by blinking the altitude field in the aircraft’s data block shown on his plan view display of traffic. That warning would prompt the controller to monitor the aircraft’s altitude profile more closely, potentially resulting in earlier detection of an improper altitude maneuver.

The alert message at –0:15 indicates that a loss of separation is imminent. This message achieves an earlier alert time than Conflict Alert or the existing version of the CTAS conflict probe by using both altitude and altitude rate measurements to anticipate that a violation of the assigned altitude will result in an immediate loss of sepa-

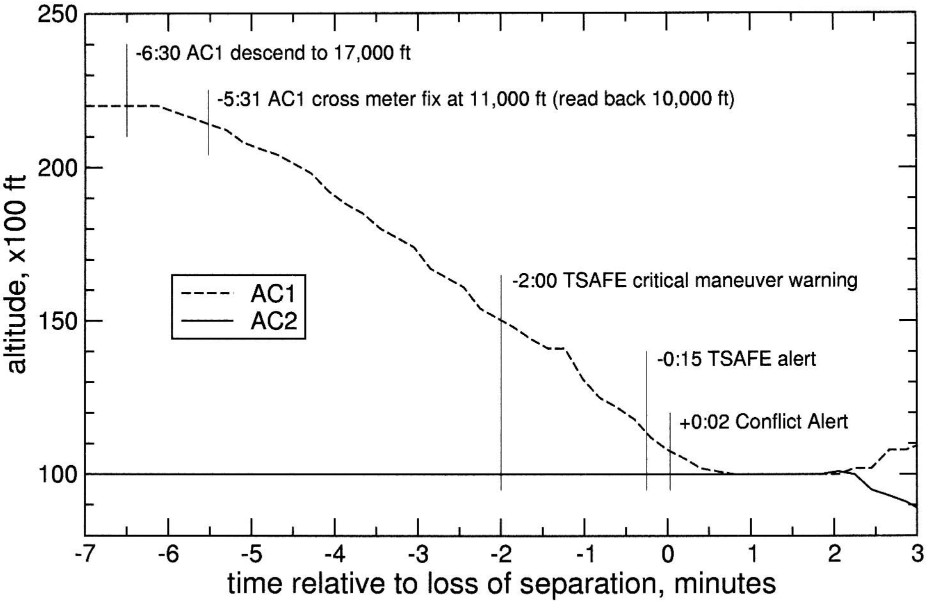

Figure 5. Actual altitude profiles showing loss of separation and expected TSAFE response.

ration. It is determined by calculating the ratio of the change in altitude remaining before reaching the assigned altitude and the current descent rate, where the physical unit of this ratio is time. When that ratio becomes less than a specified threshold value, referred to as tau, TSAFE generates an alert message and sends it to the pilot via data link or, in the current environment, to the controller's display. Analysis of tracking data and descent profiles of airline traffic indicates that values of tau in the range of 10 to 15 s provide a reasonable balance between providing the earliest possible alert time and avoiding an excessive number of false alerts. We set tau equal to 15 s for the analysis of this example. At this value of tau, and an observed descent rate of approximately 2,100 ft/min, the TSAFE alert message is initially triggered when the aircraft crosses 11,500 ft. Both the predicted alert time and the actual time to loss of separation are 15 s in this case, although in general the predicted and actual values will not be identical.

When AC1 descended through 11,000 ft without slowing its descent rate, separation was almost certain to be breached, and TSAFE could have given only about 15 s of warning of the imminent loss of separation. Although that is about 17 s earlier than the warning the existing Conflict Alert gave, it would probably not have been enough to completely avoid the conflict. However, it could have helped to reduce the severity of the loss of separation had the controller or pilot seen the message and acted on it immediately.

In today's system, the detection sensitivity of TSAFE is limited by its dependence on the slow update rate (once per 12 s) and the inaccuracy of barometric altitude measurements, along with the fact that altitude rate can only be determined from barometric altitude (hence it is somewhat noisy). That limits its effectiveness in detecting the failure to flare as the aircraft approaches the leveling-out altitude, for example. If GPS were ever used for altitude measurement and control, its superior accuracy and update rates could make the detection process much sharper and more effective.

If AC1 in the example had been equipped with TCAS, an alert would have been triggered when it was 850 ft above the other aircraft (150 ft below the cleared altitude of 11,000 ft) [FAA, 2000]. However, only AC2 was equipped with TCAS, and examination of its altitude profile shows no evidence that it took evasive action. Unlike TSAFE, TCAS has no knowledge of altitude intent (assigned leveling-out altitude) and therefore could not have alerted on this condition until much closer to a collision. Also, TCAS alert logic is designed to detect potential collisions rather than conflicts. Although TSAFE is not intended to replace TCAS, it could augment it or substitute for it in unequipped aircraft.

CONTROLLER PROCEDURES AND RESPONSIBILITIES

Automated Airspace operations will take place in a well-defined volume of airspace that is referred to as an Automated Airspace sector. However, it is anticipated that the airspace volume and traffic density may be significantly greater in Automated Airspace sectors than in conventional sectors. These sectors may be established by combining several conventional sectors or by resectorization of the airspace. As in today's operations, a controller has a broad range of responsibilities for maintaining an orderly and expeditious flow of traffic through the sector, including monitoring the inflow, outflow, and the number of aircraft in his sector to ensure that traffic density does not exceed sector capacity. He will also monitor the movement of convective weather, respond to pilot requests for re-routes around weather, resolve conflicting pilot requests, and assist pilots in handling emergencies and other abnormal situations.

The major change in operational procedures relative to today's system involves the controller's handling of the appropriately equipped aircraft in his sector. Monitoring and control of separations between equipped aircraft are performed by the ground-based AACS, which communicates directly with the pilot and aircraft systems via data link. The controller is therefore not concerned with controlling the separation between these aircraft as long as they remain in the equipped status. However, the controller can reroute aircraft at any time by using interactive tools that are part of the AACS. These tools enable the controller to select conflict-free reroute trajectories, coordinate the changes with the pilot, and transmit the trajectories to the aircraft via data link. Since the efficient operation of the AACS depends on the system's up-to-date knowledge of planned trajectories, the controller will generally use the interactive tools to perform trajectory changes. Similarly, the pilots of equipped aircraft will 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. TSAFE is designed to detect such deviations and to 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 aircraft 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 resulting from such events as rapidly changing convective weather activity or on-board failures that may cause several equipped aircraft to revert to unequipped status. Controllers could use current manual procedures for handling unequipped aircraft, but 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 more confident that modifying trajectories of 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 not operating near each other or 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 when necessary, and direct the aircraft to avoid encounters with equipped aircraft. However, encounters between equipped and unequipped aircraft will sometimes be unavoidable; 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 on 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.

Another significant change in operational procedures is the process of transferring control between sectors, referred to as handoff. Handoff coordination into and from Automated Airspace sectors of equipped aircraft will be 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 to the 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 needed by the Automated Airspace controller in order to gain awareness of the traffic situation and to be able to safely take over separation assurance responsibility for the aircraft. During the 2 min 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.

An example of a controller display and interface for an Automated Airspace sector operation is described in Erzberger [2001].

PILOT PROCEDURES AND RESPONSIBILITIES

Pilots will operate equipped aircraft in Automated Airspace in essentially the same way they currently operate aircraft that are equipped with flight management systems. Pilots can choose to fly the equipped aircraft manually or in any of several automated flight modes. However, regardless of the level of automation the pilot chooses to use, the equipped aircraft will be expected to track the planned and approved trajectory with an accuracy that will generally be higher than is required of unequipped aircraft. In particular, vertical transition trajectories and turns will be performed with greater predictability and uniformity than they are performed today. Most important, the pilot will be required to obtain approval from the ground system to make changes in, or deviate from, the currently approved trajectory. These procedures are required to ensure that traffic flow remains safe and orderly at the high traffic densities expected in Automated Airspace sectors.

A major change in the operation of equipped aircraft in Automated Airspace is the assignment of certain defined responsibilities for separation monitoring and assurance to the pilot. Pilot workload associated with these responsibilities will be minimized by providing the pilot with advisory and alert messages that are automatically up-linked to the aircraft from the ground. The critical maneuver message will alert the pilot to the potential loss of separation if he fails to perform a prescribed maneuver, and the no-transgression-zone message will specify the types of maneuvers to avoid in order to not create a conflict. Since these messages incorporate the known trajectories of nearby aircraft, they obviate the need for the pilot to continuously monitor the movement of all nearby traffic on a cockpit display of traffic information (CDTI) and to prepare for avoidance maneuvers relative to targets with uncertain or unknown intent. These messages can therefore contribute both to a reduction in the monitoring workload and in the frequency of conflicts caused by pilot blunders or failures of execution. If a threat to loss of separation should nevertheless develop, TSAFE's conflict detection and avoidance function will respond with appropriate advisories to the pilot.

Because the TSAFE conflict-avoidance advisories incorporate all the information that is known about the trajectories of nearby aircraft, they will be more efficient and safer than those a pilot can generate without assistance from the ground. Although separation monitoring, even with the help of TSAFE messages, will increase pilot workload, this increase will be offset by a reduction in workload associated with the traditional types of pilot-controller communications. Furthermore, the greater opportunity for the aircraft to be flown hands-off with the FMS engaged in Automated Airspace will also help to offset the increase in pilot workload.

Several options exist for communicating TSAFE messages to the flight crew. The critical maneuver/no-transgression-zone messages can be shown on the combined navigation and traffic situation displays used by flight management systems. Appropriate symbols for displaying them will have to be designed. These messages could also be inserted into a flight director display. TSAFE conflict-avoidance messages will probably require an aural alert similar to a TCAS alert. Piloted simulations will have to be conducted to evaluate candidate display concepts.

While operating in Automated Airspace, the pilot always retains the option to contact the controller by voice communication to request various services, including controller monitoring of separations for special conditions. The pilot can also request that his aircraft's status be changed from equipped to unequipped status when on-board equipment failures, cockpit emergencies or other abnormal events warrant such a change.

CONCLUDING REMARKS

This paper has addressed the problem of designing an air traffic control system that maintains safe separations in high-density traffic without depending on controllers to monitor and control the separations of each and every aircraft in a 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 the event that failures or errors of execution occur in the primary system of separation assurance. It is proposed that this problem be solved by augmenting the primary ground-based computer system for automating air traffic control functions, including separation assurance, with an independent subsystem for detecting imminent loss of separation and generating conflict-avoidance maneuvers. The subsystem also includes a method for identifying critical maneuvers and restrictions on maneuvers that are essential for avoiding loss of separation. A modified version of this subsystem could be implemented in today's system as an improved tool to help controllers and pilots avoid operational errors.

The traffic control functions performed by this system are designed primarily to handle aircraft that are equipped with data-link, cockpit display of traffic information, and flight management systems. The controller will use manual techniques to handle unequipped aircraft, as well as equipped aircraft that have lost a required capability. In this concept, the distribution of controller workload will shift away from monitoring the separations of all aircraft in a sector and toward the management of traffic flow and handling those exceptional problems that only humans have the knowledge and skill to solve. The pilot of each equipped aircraft will receive information from the ground system to assist him in monitoring his separation from nearby traffic and avoiding conflicts. This redistribution of workload and responsibilities, combined with the integration of ground and airborne systems through a data link, lays the foundation for achieving a substantial increase in the capacity of en route and terminal-area airspace.

ACRONYMS

AACS	Automated Airspace Computer System
ADS-B	Automatic Dependent Surveillance—Broadcast
AERA	Automated En Route Air Traffic Control
ATC	Air Traffic Control

CDTI	Cockpit Display of Traffic Information
CTAS	Center-TRACON Automation System
EDA	En Route Descent Advisor
FAST	Final Approach Spacing Tool
FMS	Flight Management System
GPS	Global Positioning System
IFR	Instrument Flight Rule
TCAS	Traffic advisory and Collision Avoidance System
TRACON	Terminal Radar Approach Control
TSAFE	Tactical Separation Assisted Flight Environment
VDL3	VHF (Very High Frequency) Data Link Version 3

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BIOGRAPHIES

Heinz Erzberger joined NASA 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. The methods and algorithms he developed for computing trajectories that minimize aircraft fuel consumption and operating costs are incorporated in the flight management systems of most airliners flying today. In recent years Erzberger has worked on developing algorithms and systems for automating air traffic control. He led the design of the Center-TRACON Automation System (CTAS), which comprises a suite of tools that assist controllers in reducing arrival delays and detecting conflicts. Most recently he developed the design for the Direct-To tool that assists controllers in assigning direct routes to aircraft. The Federal Aviation Administration is deploying CTAS tools at several airports around the country. He has published over 90 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. The American Society of Mechanical Engineers recently awarded him the prestigious Holley Medal.

Russell A. Paielli received his B.S. degree in Mechanical Engineering from Oakland University in Michigan in 1982 and has worked at NASA Ames Research Center since then. He received his M.S. degree in Aeronautics and Astronautics from Stanford University in 1987. At NASA Ames he has done research in flight control theory and precision aircraft navigation and landing. He is currently in the Automation Concepts Research Branch at Ames and is working on advanced concepts for Air Traffic Management, particularly with regard to conflict prediction and resolution. He is a Senior Member of AIAA.