Separation Assurance in the Future Air Traffic System

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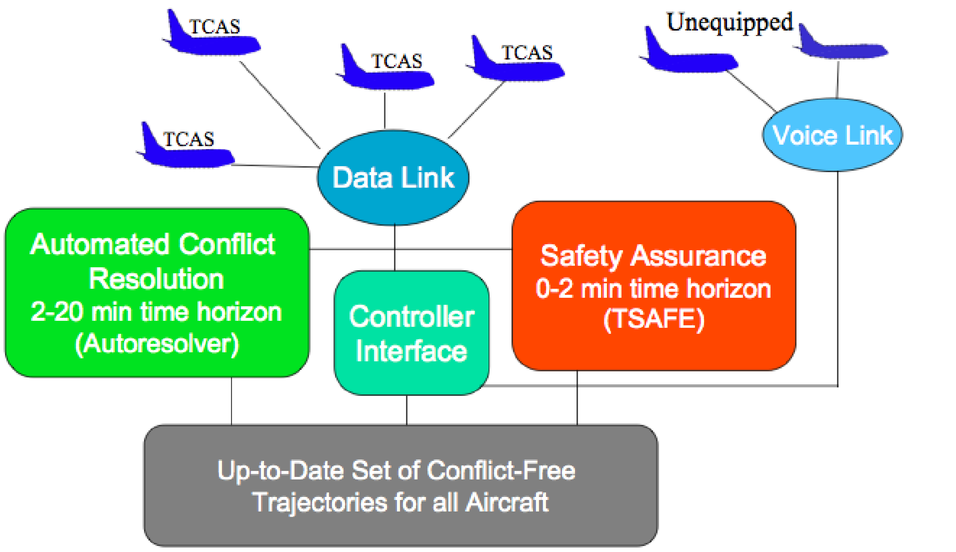
Abstract: This paper addresses concepts and algorithms for automated separation assurance intended for use in the future air traffic system. In order to achieve a high level of safety and protection against failures in an automated system, a proposed design includes two independent methods for detecting and resolving conflicts. One system detects and resolves strategic conflicts while a second independent system detects and resolves conflicts at short range. Furthermore, the paper describes a significant extension of a previously developed strategic resolution algorithm referred to as the Arrival Manager. This new function automatically sequences, merges and deconflicts arrival traffic converging to transition points that feed major airports. The paper concludes with proposals for a series of evolutionary steps leading eventually toward a future air traffic system that incorporates a high degree of automated separation assurance.

1. ARCHITECTURE FOR SEPARATION ASSURANCE

The design of the future U.S. air traffic system, referred to as NextGen, is the subject of current research at universities and research centers around the country. Although the design concepts continue to evolve as research progresses, the final design is expected to include a high level of automation in separation assurance. Such automation will constitute a change from the current method of separation assurance, which is primarily the responsibility of the controller. A consequence of this change is that responsibility for ensuring separation will shift from the controller to an automated system. The major challenge presented by such a shift is the requirement to demonstrate that a system with this level of automation is safer than the current system over a wide range of operating conditions and traffic densities.



•Ground-based systems connected to flight deck by data link provide separation assurance

•Controllers responsible for traffic management and for handling special situations

Figure 1 Major Elements of a Concept for Automated Separation Assurance

Fig. 1 shows the key elements of a proposed ground-centered system for automated separation assurance. In order to provide increased protection against loss of separation during failures, the proposed system incorporates two independent conflict detection and resolution algorithms, each of which is designed to detect and resolve conflicts over different time ranges. The first algorithm, referred to as the Autoresolver, handles conflicts with times to loss of separation in the range of 2 to 20 minutes. This algorithm is intended for resolution of non-urgent conflicts and is the mainstay of separation assurance. Its design and performance in enroute airspace are described in several papers [1-3]. Recently a function for sequencing, spacing and deconflicting arrival traffic, referred to as the Arrival Manager, was developed and integrated into the Autoresolver. The design of the Arrival Manager is the main subject of this paper.

The second algorithm is designed to handle urgent conflicts, which are those with times to loss of separation of less than 2 minutes. Its main purpose is to provide a safety net for those infrequently occurring situations when conflicts are not resolved in a timely manner by the first algorithm. This algorithm is an integral part of the Tactical Separation Assured Flight Environment (TSAFE) in the system shown in Fig. 1. Its analytical formulation is given in Ref. 4. Although the two algorithms perform similar functions they differ substantially in their analytical formulation as well as their software implementation.

As shown in Fig. 1, operational implementation of a system for automated separation assurance requires an air-ground data link that allows ground-based systems to uplink resolution trajectories to systems onboard aircraft. The controller will continue to use a conventional voice link to maintain separation of unequipped aircraft.

All changes to aircraft trajectories initiated by the conflict resolution algorithms or made by controllers or pilots are immediately entered in real time into a repository of currently assigned trajectories maintained by the ground system.

2. DESIGN OF ARRIVAL MANAGER

The Arrival Manager performs arrival scheduling, sequencing, spacing and conflict resolution. It generates a 4-dimensional descent trajectory for each arrival aircraft and has been integrated with a previously developed algorithm for resolving en-route conflicts [1-2].

In order to accommodate in-trail time constraints between consecutive arrivals crossing an arrival fix, a new type of conflict, referred to as a sequencing conflict, is introduced. A sequencing conflict is defined as a violation of a specified value of minimum time separation, ΔT_{min}, between two consecutive arrivals crossing an arrival fix. The minimum time separations are assumed to be provided by an arrival metering system such as the Traffic Management Advisor [5], which is used to manage arrival traffic at large airports in the U.S. A consequence of introducing this additional type of conflict is that arrival aircraft may simultaneously be involved in either or both conventional loss of separation conflicts and sequencing conflicts. The Arrival Manager must be designed to resolve both types of conflicts while maintaining the arrival sequence order specified by the Traffic Management Advisor whenever possible.

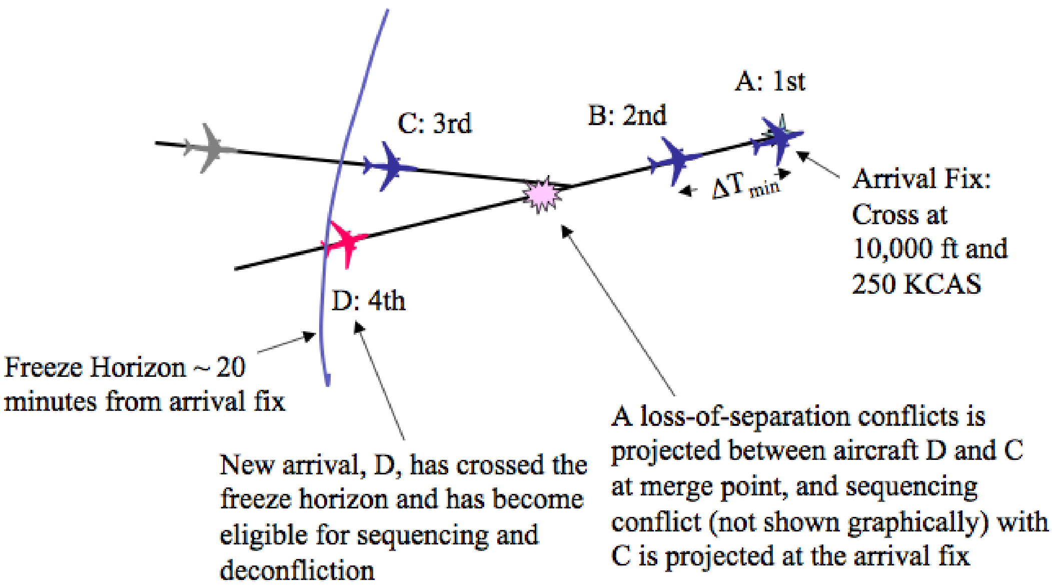


Figure 2 Illustrating the Arrival Sequencing Process

Similar to the Traffic Management Advisor, the Arrival Manager uses a Freeze Horizon to determine when an aircraft first becomes eligible for arrival sequencing and deconfliction. The Freeze Horizon is a user-specified time interval, which is typically set to 20 minutes. For all aircraft heading toward a particular arrival fix, the Arrival Manager periodically (typically once per minute) computes updated values of the estimated times of arrival (ETA) to the arrival fix. When the difference between the ETA for an aircraft and current time becomes less than the Freeze Horizon for the first time, the aircraft is said to have crossed the Freeze Horizon and becomes eligible for arrival sequencing and deconfliction. Fig. 2 shows a Freeze Horizon line, several aircraft heading toward an arrival fix and the minimum time separation, ΔT_{min}, between in-trail arrivals at the arrival fix.

The Arrival Manager differentiates between aircraft that were sequenced and deconflicted at an earlier time, such as aircraft A, B, and C in Fig. 2, and those, such as aircraft D, that have crossed the Freeze Horizon at the current scheduling time and are now eligible to be sequenced. Those that were previously sequenced and deconflicted are treated as having frozen arrival trajectories, which will not be changed to accommodate new aircraft whose ETA's have crossed the freeze horizon for the first time. The strategy of sequencing and deconflicting arrival aircraft only once after they have crossed the freeze horizon ensures stability of trajectories and fairness in the sequencing process. Thus, aircraft D must now be scheduled and deconflicted without changing the trajectories of the frozen aircraft.

In order to keep track of the scheduling status of aircraft, the Arrival Manager maintains a list of frozen aircraft that were previously scheduled. This list is arranged in the order the frozen aircraft have been scheduled to cross the arrival fix. The list also contains two other time parameters for each aircraft. These are the original estimated time of arrival (OETA), which is the ETA that was computed at the time the aircraft initially crossed the Freeze Horizon and the scheduled (frozen) time of arrival (STA), which is the time the aircraft is scheduled to cross the arrival fix.

An essential operation performed by the Arrival Manager is to merge the set of new aircraft that have crossed the Freeze Horizon at the current scheduling epoch into the set of frozen aircraft without causing either separation or sequencing conflicts. The first step in this process is to merge the new aircraft into the list of frozen aircraft in first-come-first-served order. The OETA's of the new aircraft determine where they will be inserted into the STA-ordered list of frozen aircraft. Next, the combined list is examined to identify sequencing conflicts between frozen and new aircraft and between pairs of new aircraft. Each new aircraft is tagged, if it is not conflict-free, with a conflict type identifier: loss of separation conflict, sequencing conflict or a combination conflict. Previously scheduled aircraft that have crossed the arrival fix since the last scheduling epoch are deleted from the list.

The Arrival Manager now proceeds to resolve the conflicts one at a time starting with the conflict aircraft that has the smallest ETA (is closest in time to the arrival fix) and continuing until the last of the new conflict aircraft has been processed. If the Arrival Manager succeeds in finding a trajectory that resolves all the conflicts for an aircraft, it changes the status of that aircraft to frozen and scheduled. Thus, after all new aircraft have been processed the list will contain only frozen and conflict-free aircraft. The Arrival Manager then waits for real time to advance to the beginning of the next scheduling update cycle. When that time is reached the Arrival Manager repeats the process for all new aircraft that have crossed the Freeze Horizon.

The Arrival Manager generates separate lists of scheduled aircraft for all arrival fixes at an airport. Moreover, if separate crossing altitudes are assigned to jet, turboprop and piston aircraft at an arrival fix, as is often the case, the Arrival Manager generates and maintains separate lists for the streams of aircraft assigned to each crossing altitude.

The process that generates conflict-free trajectories for each new aircraft comprises rules and procedures that will be described in a future technical report in more detail. In summary, for either sequencing or combined sequencing and loss-of-separation conflicts, the Arrival Manager first computes the earliest time slot (STA_{min}) for the aircraft to be scheduled that meets the required separation time constraint relative to the STA's of frozen aircraft. The STA_{min} can be earlier or later than the aircraft's OETA, although more often it will be later if frozen aircraft are close by and immediately ahead of an unscheduled aircraft. This is the typical situation during an arrival traffic rush. Then the Arrival Manager instructs the trial trajectory generator to compute a meet-time trajectory that achieves the STA_{min} within specified error tolerances. If this trial trajectory is found to be conflict-free relative to trajectories of all frozen aircraft, the trial trajectory is frozen and becomes the trajectory that is uplinked to the aircraft. At the same time, the status of the aircraft is changed to frozen, and the Arrival Manager proceeds to process the next-in-line new aircraft. On the other hand, if the trial plan trajectory that achieves STA_{min} is still projected to lose separation with a frozen aircraft, then the resolution logic generates a sequence of trial trajectories, each with incrementally greater delay relative to STA_{min}. Each of these is again checked for loss of separation and sequencing conflicts with frozen aircraft. The first trajectory found that is free of both types of conflicts terminates the trial-planning process and results in acceptance and implementation of the

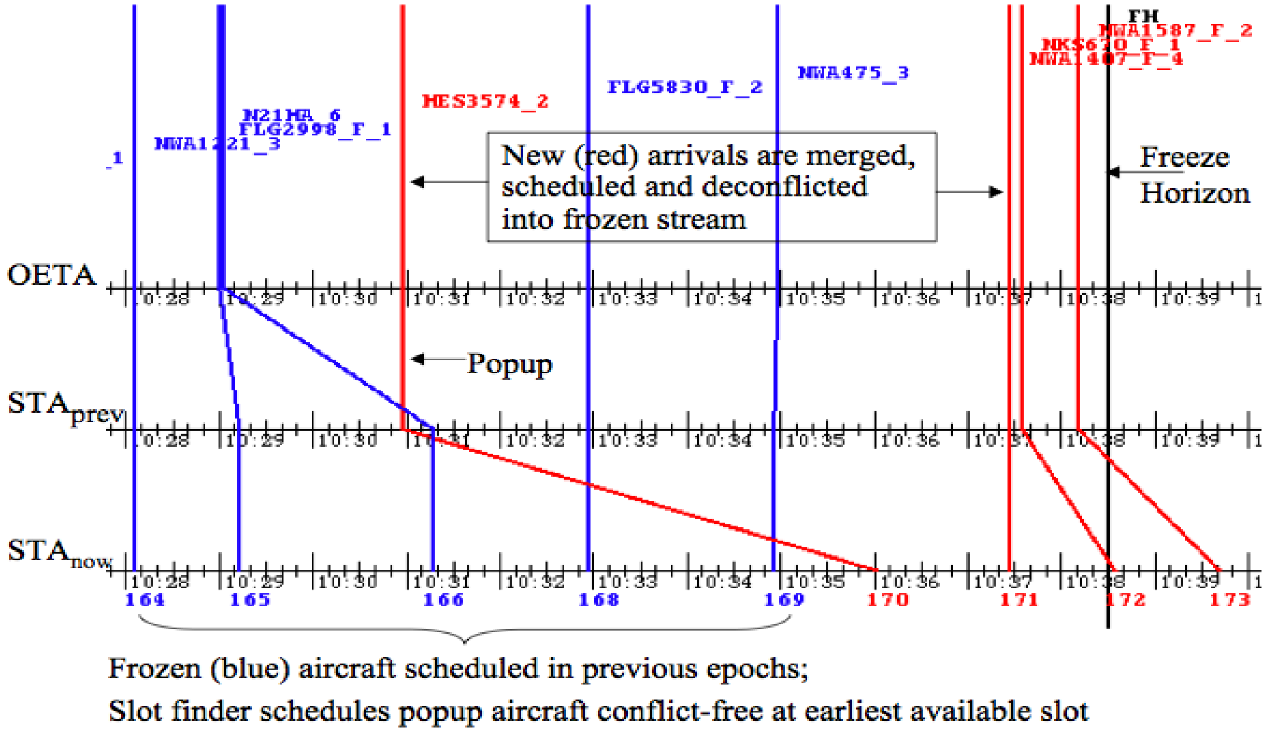


Figure 3 Merging and Scheduling New Arrival Into An Arrival Stream

trajectory. Here it is important to note that because of the sequential procedure for processing new aircraft, conflicts between the aircraft currently being processed and new aircraft not yet processed are ignored.

New arrivals with only loss-of-separation conflicts are handled slightly differently. If such a conflict occurs between aircraft in the same stream class (i.e., aircraft for the same arrival fix with the same crossing altitude), the resolution process uses the same rules for generating trial resolutions as previously developed for arrivals, except that an additional constraint must be satisfied by the trial resolution trajectory. Namely, each trial trajectory is also checked for violation of sequencing constraints with any frozen aircraft in the same stream class. While a conflict may initially present purely as a loss-of-separation conflict, the trial resolutions generated to resolve it often create violations of sequencing constraints with frozen aircraft, which then require additional trial-plan trajectory iterations to resolve.

A time-line plot, an example of which is shown in Fig. 3, provides an insightful graphical illustration of the dynamics of the sequencing process. This plot was generated from the results of a fast-time simulation of the Arrival Manager for traffic into the Detroit airport. The input to the simulation was based on a 24-hour traffic recording from a particular day. Plots such as these are generated automatically by a simulation data analysis system and are posted on a website [6]. In the plot, time at arrival fix crossing is shown in units of hours and minutes and increases from left to right. Current time is 20 minutes to the left of the Freeze Horizon line and is off the plot to allow a better view of the scheduling events of interest. This example was chosen from thousands of such plots generated for a 24-hour run, because it illustrates how the Arrival Manager handles both normal and exceptional scheduling situations. The three time lines in the figure show OETA's and two STA's for each aircraft converging to this arrival fix. The STA_{prev} line shows the frozen arrival schedules for traffic scheduled at the previous and at earlier scheduling event times. It shows how the four new arrivals (red lines) that crossed the freeze horizon since the previous scheduling event would fit into the arrival sequence if their trajectories were left unchanged. The three new arrivals near the freeze horizon represent the normal situation. Since they are in violation of the one-minute sequencing constraint, they must be rescheduled and deconflicted. The effect of this process is shown in the STA_{now} time line. It can be seen that the process has preserved the first-come-first-to-land sequence order based on their OETA order and has resulted in time separations close to the required one-minute minimum time interval.

The fourth new arrival (numbered 170) is designated a pop-up arrival, so named because it entered the sequencing process far below the freeze horizon. Pop-ups are undesirable because they are often difficult to merge into the frozen aircraft stream, but they cannot always be prevented from occurring. This particular popup departed from a nearby airport with a short flying time to the arrival fix. Other reasons for the occurrence of pop-ups are onboard emergencies and aircraft that have diverted to an alternate airport due to weather. In this case, the slot finder function of the Arrival Manager scans the scheduled times of frozen aircraft to locate the nearest available time slot. An acceptable time slot must have at least a two-minute gap between adjacent frozen aircraft. The aircraft has been scheduled for the earliest available slot, which is located after the scheduled time of aircraft 169. A trial trajectory was computed that delayed the aircraft by the amount of time required to meet the specified slot time. The trial trajectory was then checked for loss-of-separation conflicts and was found to be conflict-free in this case, thereby completing the scheduling process for the current time.

It is noted that the sequencing process in the previous scheduling time (STA_{prev}) produced a time separation between aircraft 165 and 166 that is in excess of the required one-minute interval. Such excess time can be a byproduct of the simultaneous resolution of a sequencing and loss of separation conflict.

Whenever the Autoresolver is called upon to resolve a list of conflicts, the order in which the conflicts are resolved follows specific rules. The highest-level rule requires that arrival vs. arrival conflicts have priority over all other conflict types in the resolution process. This rule helps to reduce delays in the arrival queues and ensures an orderly arrival flow. Furthermore, the resolution process starts by resolving conflicts at the fix with the highest arrival traffic count at the airport with the most traffic in the Center. For example, at the Cleveland Center, the Southeast arrival fix for jets at Detroit (DTW) often experiences the highest traffic demand and therefore is selected as the starting point for the resolution process.

While resolving the arrival conflicts in this stream class, secondary conflicts may be created with out-of-stream-class traffic and with non-arrivals. These secondaries are treated as new conflicts and added to the list of unresolved conflicts. They will be resolved in subsequent steps as shall be explained. Next, conflicts in the turboprop stream class at the same arrival fix are resolved, followed by conflicts in the prop stream class at this fix. The same procedure is repeated for all remaining arrival fixes at this airport, where the order in which the fixes are selected is determined by their traffic demand ranking. At each stage in this process, secondary conflicts with aircraft sequenced and deconflicted in previous steps are not permitted, while secondaries generated with traffic in stream classes not yet processed, and with overflights, are permitted to occur. This process is repeated for all other airports in the Center, where the order of airports is determined by their rank based on traffic demand. At each scheduling epoch, the last step is to resolve the non-arrival conflicts. The conflicts resolved in the last step include the original set of non-arrival conflicts as well as new secondary conflicts between arrivals and non-arrivals that had been created in the process of sequencing and deconfliction of the arrival traffic.

The Arrival Manager has been implemented in software and integrated into the Autoresolver software suite. A fast-time simulation has been used to validate the algorithm and evaluate its performance. A web-based data analysis capability is available for evaluating the results of the simulation. It includes displays of scheduling lists and time line plots of traffic crossing arrival fixes [6]. This capability is a convenient analysis tool for evaluating scheduling decisions and resolution procedures.

3. EVOLUTIONARY PATH TO DEVELOPMENT

Since changes in air traffic control operations have historically evolved gradually, often over long periods of time, it is important to consider if separation assurance can evolve toward higher levels of automation in a series of steps. The system architecture and the algorithms outlined in this paper can be viewed as the final step in the long road toward a future air traffic system that will include a high level of automation. Both the system architecture and the algorithms for conflict detection and resolution outlined in this paper lend themselves to operational implementation in evolutionary steps. The two main options for stepwise implementation are short-range conflict resolution and strategic conflict resolution.

As described in Ref. 4, the first option, which is referred to as TSAFE, would be a paradigm-shifting step in that it would largely remove the controller from responsibility for detecting and resolving short-range conflicts. The two supporting technologies required for implementing this option are the data link built into Mode S and the onboard systems required for TCAS level 2. These technologies are already in operational use and could be adapted for this application with relatively minor modifications to systems onboard aircraft. In addition, the short-range detection and resolution algorithm would also have to be implemented in the ground system. Alternatively, it may also be possible to implement TSAFE or similar technologies as an airborne separation assurance system that is independent of systems on the ground. Airborne separation assurance is the subject of research at institutes throughout the world.

The second option would be to implement strategic conflict resolution using an algorithm such as the Autoresolver described in this paper and in references [2-4]. The Autoresolver would have to be integrated into the ground system where it would be used by controllers initially as a decision support tool. Controllers would issue the automatically generated resolution trajectories to equipped aircraft primarily via data link. However, in the absence of TSAFE, they would retain responsibility for short-range conflicts. This option is critically dependent on the installation of a ground-air data link in a large proportion of aircraft. Such a data link is under development but is still years away from deployment in the U.S. airspace. Once a data link becomes widely operational in aircraft and ground systems, this option could be implemented first in high-altitude enroute airspace and then extended into lower altitude transition airspace at a later time. The Arrival Manager described in this paper would have to be deployed to handle arrival flows conflict-free into terminal area airspace.

After both the short-range and strategic resolution functions have been in operation for a period of time, the final evolutionary step would consist of integrating these functions, thereby achieving the level of automated separation assurance envisioned for NextGen.

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