NASA Technical Memorandum 108790

IN-03
207558
19P

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January 1994

(NASA-TM-108790) CONFLICT-FREE TRAJECTORY PLANNING FOR AIR TRAFFIC CONTROL AUTOMATION (NASA) 19 p

N94-25272

Unclas

G3/03 0207558

National Aeronautics and Space Administration

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Conflict-Free Trajectory Planning for Air Traffic Control Automation

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Summary

As the traffic demand continues to grow within the National Airspace System (NAS), the need for long-range planning (30 minutes plus) of arrival traffic increases greatly. Research into air traffic control (ATC) automation at Ames Research Center has led to the development of the Center–TRACON Automation System (CTAS). CTAS determines optimum landing schedules for arrival traffic and assists controllers in meeting those schedules safely and efficiently.

One crucial element in the development of CTAS is the capability to perform long-range (20 minutes) and short-range (5 minutes) conflict prediction and resolution once landing schedules are determined. The determination of conflict-free trajectories within the Center airspace is particularly difficult because of large variations in speed and altitude. This paper describes the current design and implementation of the conflict prediction and resolution tools used to generate CTAS advisories in Center airspace. Conflict criteria (separation requirements) are defined and the process of separation prediction is described. The major portion of the paper will describe the current implementation of CTAS conflict resolution algorithms in terms of the degrees of freedom for resolutions as well as resolution search techniques. The tools described in this paper have been implemented in a research system designed to rapidly develop and evaluate prototype concepts and will form the basis for an operational ATC automation system.

Introduction

As the traffic demand continues to grow within the National Airspace System (NAS), the need for long-range planning (30 minutes plus) of arrival traffic increases greatly. Airspace and airport or runway capacity limits create bottlenecks within the extended terminal area (approximately 250-nautical mile (n. mi.) range) when the demand is high. These bottlenecks result in air traffic delays, increased workload for the controller, and less than optimum efficiency (fuel burn).

Several terminal areas, such as Denver and Dallas–Fort Worth, meter en route arrivals to coordinate the flow of arrival traffic and objectively distribute the delays over the extended terminal area when the demand is high. In these cases, the Air Route Traffic Control Center (ARTCC or Center) will meter traffic to the Terminal Radar Approach Control (TRACON) feeder gates to expedite the flow without exceeding the TRACON capacity. A description of this process may be found in references 1–3, and is summarized in the next section. Other facilities employ in-trail spacing strategies to allow room for the merging of arrival flows in the TRACON. Although both methods have been proven effective in meeting capacity limits, the challenge is to gain maximum air traffic efficiency (minimum operating cost in terms of time and fuel), while maintaining safety (aircraft separation), and reducing workload for a given airport or airspace capacity.

Research into air traffic control (ATC) automation at Ames Research Center has led to the development of the Center–TRACON Automation System (CTAS) (ref. 4). CTAS is designed to assist both Center and TRACON controllers with the management of traffic within the extended terminal area. CTAS determines optimum conflict-free schedules for arrival traffic and assists controllers in meeting those schedules safely and efficiently. The laboratory implementation of CTAS is based on a distributed network of Sun SPARC workstations with standard keyboard input and a three-button mouse (or trackball). Field evaluations of CTAS, in a joint program with the Federal Aviation Administration (FAA), have begun at the Denver and Dallas–Fort Worth areas.

Although an aircraft's arrival schedule may be conflict free at the scheduling reference point (e.g., runway or metering fix), the actual aircraft's trajectory leading up to the reference point may be in conflict with another aircraft. One crucial element in the development of CTAS is the capability to perform long-range (strategic) conflict prediction and resolution once schedules are determined. The determination of conflict-free paths within the Center airspace is particularly difficult. The process of merging arrival traffic from en route cruise conditions into terminal area arrival streams is highly complex because of the large altitude transitions (on the order of 10,000 to 20,000 feet), large indicated airspeed changes (up to

50+ knots), and the wide variety of aircraft performance characteristics. The altitude transitions are further complicated because of the variation of atmospheric characteristics (e.g., wind) which occur as a function of altitude. The variations in altitude, airspeed, and wind combine to result in tremendous changes in ground speed (up to 200+ knots) within the en route descent area. By comparison, the merging problem within TRACON airspace tends to be more two dimensional (horizontal) with significantly less variation in altitude and speed. The large variation in altitude and speed within Center airspace renders manual prediction and control of aircraft difficult and inefficient.

The purpose of this paper is to describe the current design and implementation of the conflict detection and resolution tools used to generate CTAS advisories. In particular, this paper will focus on the problems uniquely associated with Center airspace. The paper will begin with a background description of CTAS emphasizing the elements most closely associated with Center automation. A brief description of the conflict prediction process will follow. The majority of the paper will describe the current implementation of CTAS conflict resolution algorithms as well as related issues. The paper will conclude with a summary section including a discussion of topics for future research.

Background

ATC

Figure 1 shows the Denver Center, with its four TRACON feeder gates (Center metering fixes)—KEANN, DRAKO, KIOWA, and BYSON. The center is divided into numbered regions, called sectors. Each sector is handled by one controller normally and by two controllers during a rush. Sectors are divided by altitude into two or three layers. The high sectors handle high-altitude traffic arriving at the airport and crossing over the airport. The low sectors handle low-altitude traffic, merging it with traffic that was sequenced by the high sectors. The TRACON is the area shown by the shaded region.

Due to the large amount of traffic, arrivals and departures are segregated by airspace to prevent conflicts. The arrival traffic is channeled through a gate to enter the TRACON, while the departure traffic passes between the gates. In some Centers, when there is a large amount of arrival traffic, aircraft are metered. Metering is done by setting a flow rate, limiting the number of aircraft which are allowed to cross the metering fix per hour. Each aircraft is assigned a time slot, based on its ETA, at which to cross the metering fix. These times are shown to the controller. In Denver Center the metering is done only to the metering fixes, but in Dallas–Fort Worth Center there is both metering to the gate and outer metering, where aircraft farther out are given times to cross a radius from the gate.

Some centers, such as Chicago, use in-trail spacing instead of metering. In-trail spacing methods do not schedule aircraft to a metering fix or gate. Aircraft may cross the gate at any time as long as they are separated by 5 miles horizontally or 1,000 feet vertically. This may lead to all gates sending through an aircraft at the same time, to be dealt with in the TRACON.

CTAS

CTAS is composed of three major automation tools: the Traffic Management Advisor (TMA); the Center Descent Advisor (DA); and the TRACON Final Approach Spacing Tool (FAST). The TMA is designed to minimize delay and optimize traffic flow efficiency by determining optimum sequences and calculating arrival schedules at the runways and TRACON feeder gates (refs. 5–7). Although arrival time scheduling at the runway is considered to be more desirable than metering (ref. 1), and is the preferred mode of operation of TMA, the TMA parameters may be modified to degrade the system to emulate a flow rate metering operation. The DA and FAST tools are designed to assist the Center and TRACON controller, respectively, in meeting TMA scheduled times of arrival (STAs) in an efficient manner while maintaining minimum separation (refs. 4 and 8). Both DA and FAST provide the controller with advisories to meet control objectives (e.g., TMA schedules, altitude and speed restrictions, and separation) as well as feedback on progress toward meeting those objectives. Additional information describing the design and evaluation of FAST may be found in reference 8. A functional description of TMA and its scheduling algorithm may be found in references 6 and 7. Additional material on the design and evaluation of DA beyond the scope of that presented here (including integration with datalink and airborne FMS automation) may be found in references 9–11.

Each of the CTAS tools is highly adaptive to controller and pilot action and allows for sector controller feedback into the sequencing and scheduling process. Each sector (through DA in Center, FAST in TRACON) provides the TMA with real-time updates of each aircraft's estimated time of arrival (ETA) as well as other sector constraints on the traffic flow (e.g., relative sequence constraints). The TMA processes the real-time data from each sector to determine the best overall sequence and schedule under the current conditions and provides schedule updates to all affected sectors. CTAS dynamically adapts to changes in the traffic flow and airspace constraints such as runway configuration changes, closed gates, airspace blockages (e.g., thunderstorms), pop-ups, and missed approaches. As a whole, CTAS is an integrated system which coordinates actions across sector and facility boundaries through TMA scheduling objectives.

Although the focus of this paper will be narrowed to functions and algorithms developed specifically within the DA for application to Center airspace problems, much of the discussion will apply to FAST on the conceptual level.

Descent Advisor

The objective of DA is the determination of efficient trajectories that are conflict free at all points and that meet the TMA schedules. The DA is composed of several parts. The parts that are discussed in this paper are the display, user inputs, trajectory analysis algorithms, conflict detection algorithms, and conflict resolution algorithms. The display presents the results of the calculations to the controller and shows the results of inputs from the controller. The trajectory generation process is used to find trajectories which meet the scheduled times and is described in the next section.

The overriding consideration of all ATC is the need to keep aircraft apart. This is the primary concern of controllers. To meet this requirement the DA contains conflict detection and conflict resolution algorithms. Conflict detection algorithms check to see if aircraft will remain separated by the required amount for specific trajectories. Conflict resolution algorithms vary the trajectories of aircraft to attempt to remove conflicts. Both of these algorithms were designed to include the controller's wishes as much as possible. It is important to note that the conflict resolution algorithms described in this paper are part of a research system designed to rapidly develop and evaluate prototype concepts, and are not intended to represent an operational ATC automation system. However, the features described are in the process of evaluation via real-time ATC simulation. Results from these evaluations will lead to the specification and design of conflict prediction and resolution algorithms and procedures for the operational CTAS system.

Trajectory Generation

The analytical foundation of DA is the Trajectory Synthesis (TS) algorithm (referred to as DA in past publications: refs. 12 and 13). The TS generates precise four-dimensional (4D) trajectories which accurately account for aircraft performance, pilot procedures, and atmospheric characteristics. The TS trajectories are based on the aircraft's initial state, planned routing, and any vertical profile constraints (e.g., speed and/or altitude restrictions). The trajectories are fuel conservative in that the algorithm attempts to minimize fuel burn for a fixed time trajectory by minimizing level flight at lower altitude in high drag configurations. In addition, the DA attempts to reduce aircraft speed toward best endurance to minimize fuel burn during delay maneuvers.

In general, the DA applies expert rules to determine the combination of trajectory degrees of freedom such as path, altitude, and speed profile which may meet the constraints. An iterative process is then used to determine a solution, based on those degrees of freedom, which meets all the ATC requirements such as schedule and separation. For each step within the iteration process, the DA defines a set of horizontal and vertical profile constraints and passes them to the TS. The TS then synthesizes a precise 4D trajectory solution within those constraints and returns the result to the DA. Then the DA analyzes the trajectory to determine its value in meeting ATC requirements. If a controller (or pilot) wishes to constrain the process (e.g., limit the planned descent speed, descent path, or cruise altitude), the controller simply enters a flight plan amendment and the DA constrains its solution search to adhere to the additional constraints.

Conflict Detection

There are two different types of conflict detection algorithms in the DA—strategic and short term. Strategic conflict detection is based on the 4D trajectory generated by the TS and is discussed in reference 14. The discussion here will include a short summary of the previous work and will emphasize the new points. Short-term conflict alert in CTAS is functionally similar to the conflict alert installed in the current Center software. This function is based on simple approximations to the trajectories of all aircraft and is used to predict conflicts less than 5 minutes in the future.

Strategic Conflict Detection

For strategic conflict detection, the entire trajectories (x, y, and altitude) of all aircraft taken two at a time are compared to see if they violate the separation requirements of the airspace, which are discussed later. The trajectories are calculated assuming the aircraft will follow the cruise and descent advisories calculated by the TS. Each aircraft's trajectory is compared to the trajectories of all other aircraft arriving at the same feeder gate with STAs within some parameter (e.g., 5 minutes) of the aircraft's STA. The conflict is produced because the procedures used to calculate the values of the cruise and descent speed only considered meeting the scheduled time. It is generally predicted far enough in advance so that even without a computer search of alternative trajectories, the controller can change the speed, altitude, or path of the aircraft so as to avoid the predicted loss of separation while meeting the STA. The trajectory is also compared to predicted trajectories for all aircraft not landing at the airport (overflights). The update rate of the conflict detection algorithm and the number of aircraft that are compared (STA difference) can be varied to trade off computer calculation time and quickness of response.

Short-Term Conflict Alert

The DA also contains a short-term conflict alert function designed to imitate the conflict alert available to controllers in the current ATC system. A time is set by the researcher (in the real ATC system this time is 2 minutes). The DA projects the current paths of all the aircraft ahead by this time assuming constant altitude, heading, and speed. The projections of all aircraft are compared at the current time, one-half time (1 minute), and final time (2 minutes) to see if any will violate separation during this time. This function compares all aircraft no matter what their STA. It is therefore useful for situations such as holding where aircraft with highly different STAs all occupy the same airspace.

Conflict Display

A picture of the sector controller display of the DA is shown in figure 2. The screen shows the airspace corresponding to several sectors of traffic arriving through the KEANN gate. The Denver Airport is in the lower left. At the left side of the screen is a timeline, which has the current Greenwich Mean Time at the bottom and shows a tic mark every minute. Each 5-minute interval is labeled with the number of minutes past the hour. The ETA is shown in yellow on the right side of the timeline, and the STA is shown in blue on the left side. The trajectory profile box at the top center of the screen shows the entire proposed vertical trajectory, which will meet the scheduled time, for each aircraft. UAL123 is planned to slow to 250 knots in cruise and start its descent at 75 n. mi. from the Denver Airport, descend at 250 knots, crossing the metering fix KEANN at 17,000 feet and 250 knots at 31 minutes 36 seconds past the hour. EAL158 will slow to 240 knots, descend at 280 knots starting 75 n. mi. from Denver, and arrive at 30 minutes 22 seconds past the hour.

Each aircraft that is being controlled by the controller is shown as a diamond-shaped target connected to a data block with a line. The data block has four lines of text. The first line shows the aircraft call sign or identification. The second line shows the aircraft's current altitude. The third line shows the unique computer identifier number on the left and the current MACH or CAS on the right. This line alternates to show the type of aircraft on the left and the ground speed on the right (fig. 5). The fourth line shows the DA advisory. When a trajectory that meets the STA is found, the controller is shown the commands necessary for the aircraft to follow the trajectory in the fourth line. Overflights, like AAL220, are shown with two-line data blocks in white. The first line is the call sign and the second is the altitude on the left and ground speed on the right.

Strategic conflict display– If a strategic conflict is found, the advisory line turns red, a red triangular conflict marker appears on the display at the location where the loss of separation first occurs and at the end of the aircraft call sign, and a conflict warning box appears in blue on the upper right corner of the screen. The conflict warning box contains three fields, shown in figure 2. The first two are the call signs of the two aircraft that are in conflict and the last is the time remaining until the separation criteria are first violated.

In figure 2, the aircraft UAL123 and EAL158 have a strategic conflict detected in 20 minutes and will lose separation at the point marked by the red marker near the PONNY intersection.

Short-term conflict display– If a short-term conflict alert is predicted, the first line of the data tags, containing the aircraft call signs for the two aircraft predicted to lose legal separation, will turn red.

In figure 2, the two aircraft USA389 and AAL220 have a short-term conflict detected some time in the next 2 minutes. The two aircraft are shown with lines extending the heading and ground speed for 2 minutes, and it can be seen that the two lines will come within 5 n. mi. at the 2-minute mark.

Separation

A conflict occurs when both horizontal and vertical separation rules are simultaneously violated. Current instrument flight rules (IFR) require a horizontal separation of 5 n. mi. above 18,000 feet altitude and 3 n. mi. below 18,000 feet. The required (IFR) vertical separation is 2,000 feet above 29,000-foot altitude and 1,000 feet below. For any altitude, if an aircraft is either more than 5 n. mi. apart horizontally or 2,000 feet apart vertically, it is separated. A conflict occurs at any altitude if the aircraft are separated by less than 1,000 feet vertically, and less than 3 n. mi. horizontally. These rules are not applied when the two aircraft are in visual flight rules (VFR) where it is the responsibility of the pilots to see and avoid each other.

Besides the legal separation requirements, there are buffers that increase the legal minimum separation under certain circumstances. These buffers can be set automatically within the code or specifically by the controller or researcher. Currently, internal to the DA, there are buffers based on the acceleration of the aircraft and the rate of change in the altitude. It is also possible to increase the size of the buffers at a single sector to adapt to controller preferences. Future research is planned to make buffers dependent on the aircraft's navigational capabilities.

Conflict Classification

When a conflict is found, it is classified to be either a cruise or descent conflict. Since the STAs are chosen to maintain separation at the metering fix, a conflict must end somewhere before the metering fix. If a conflict is predicted to end while both aircraft are still in cruise at level flight, it is classified as a cruise conflict. If a conflict is predicted to end while either aircraft is in descent, it is classified as a descent conflict. The search region for a conflict resolution is handled differently for the two types of conflict.

Resolution Algorithm

A conflict predicted between two trial trajectories is resolved by varying the degrees of freedom of the aircraft while still meeting the STA. The degrees of freedom that are considered by the DA are speed (constrained by the aircraft performance), altitude (which provides a wider speed range that still meets the time), and routing (which moves the aircraft apart). The automatic resolution currently considers one aircraft at a time, but work is in progress in the area of simultaneous multiple aircraft resolutions. The algorithm describing the order of the variations is shown graphically in figure 3.

Descent Speed Search

First, the direction (increasing or decreasing) of the descent speed search is chosen based on the type of conflict. Conflicts in cruise arise because the aircraft that is farther away from the gate is going faster than the aircraft closer to the gate, and the faster aircraft is scheduled first. The faster aircraft must pass the slower aircraft which requires altitude separation. The search direction is chosen to reduce the cruise speed of the faster aircraft or increase the cruise speed of the slower aircraft. Since time is constant, the cruise and descent speeds are dependent; a decrease in cruise speed requires a compensatory increase in descent speed.

Descent conflicts arise because the aircraft with the faster descent speed is scheduled first. Since the aircraft will be separated at the gate, the first aircraft must have a faster descent speed to pull away from the conflict. Thus, the direction is chosen to reduce the descent speed of the first aircraft or to increase the descent speed of the second aircraft.

Increasing or decreasing descent speeds from the aircraft's current descent speed are searched using even increments (in the current system, increments of 5 knots are used). The descent speed search continues until the maximum or minimum descent speed possible for the aircraft is reached, further descent speed changes will be unable to meet the time, or the trajectory is conflict free. If the trajectory is conflict free the search ends. Note that even though the search is for speeds, the altitude profile is also affected.

Altitude Search

When the speed is outside the range for the aircraft or the STA cannot be met with the speed, the algorithm reduces the altitude by an increment of 1,000 feet below 29,000-foot altitude and 2,000 feet above. The aircraft's altitude is rounded to the nearest 1,000 feet to avoid giving an advisory for an altitude that the controller would not issue. In the present implementation, if the altitude reaches a defined minimum altitude, the search stops and a message is sent to the controller stating that a resolution cannot be found. If the search altitude is above the minimum altitude and the proposed trajectory is still in conflict, the descent CAS is set to the airline preferred CAS and the algorithm returns to the descent CAS iteration at the new altitude.

Matching the descent speeds of an aircraft pair will remove any descent conflict. So altitude changes are required when one aircraft cannot meet its STA if the descent speeds are matched or for cruise conflicts. Altitude changes help cruise conflicts by adding immediate altitude separation between the two aircraft. They help descent conflicts because the increase in air density at lower altitudes changes the amount of time the cruise portion of the trajectory will take. This means that the descent speed can be increased and still meet the scheduled time, giving the algorithm a better chance of matching descent speeds.

In figure 4, trajectories are shown for the maximum and minimum cruise speeds with the cruise at the initial altitude of 33,000 feet and the same cruise speeds with an altitude change to 27,000 feet. All four trajectories have a time duration of 1,140 seconds. The horizontal changes are exaggerated for clarity. The minimum cruise speed (V_c = 250 knots) trajectories are shown in the light gray and the maximum cruise speed (M = 0.82) trajectories in the dark gray. The altitude change trajectory with the minimum cruise speed, which meets the same time, requires 55 knots more descent speed. Therefore, the altitude change trajectory results in a larger speed range and a greater chance of matching descent speeds between the two aircraft.

Route Search

An experimental version of the software exists which, after reaching the minimum altitude without resolving the conflict, will try to turn the aircraft off route to resolve the conflict. This logic is shown in the dashed lines in figure 3. The route change is done only for the current altitude and the airline preferred descent speed. What angle to turn to, how far to travel, and where to rejoin the route are still being studied. Varying route, speed, and altitude is also an area for future research. Before all these cases can be studied, research needs to be done to increase the efficiency of the search, either by increasing the computer power or by further logical rules to limit the search matrix. The current software is near the limit of the computing power of the Sun SPARC 2 workstations being used.

Controller Interface with the Conflict Resolution Logic

The variations of the degrees of freedom to resolve conflicts can be done completely by the controller using trial and error with feedback from the DA, automatically by the DA after being requested by the controller, or completely automatically, invisible to the controller.

Controller Resolution

In the manual mode, if a conflict is presented to the controller (see fig. 2), he decides how to resolve it. The controller can input either cruise speed, descent speed, or altitude, and the TS will use these added constraints to calculate the trajectory. The new trajectory is checked for conflicts and new conflict information is presented to the controller. If the aircraft trajectory does not contain any conflicts, the conflict warning signs will disappear. If the aircraft is vectored off the route, it is presumed that the aircraft will rejoin the route so the conflict warning remains active until the aircraft can be turned back without a conflict. The conflict shown in figure 2 can be resolved by the controller typing in an altitude and a descent speed for one of the aircraft.

Controller Requested Automatic Resolution

In this mode, the controller is presented with the conflict warning signs and must decide which aircraft or which set of aircraft to attempt to resolve. An aircraft is selected by the controller and an input initiates the resolution algorithm. The software performs the conflict resolution algorithm and either produces a new conflict-free advisory or a failure message. If a resolution is found, the software will automatically try to maintain a resolution unless the controller makes a further input to remove the resolution.

The resolution algorithm can either be applied only to a single aircraft or to several aircraft sequentially depending on the input that is used and the parameters which are set. If the algorithm is applied to multiple aircraft, a single command will apply the resolution algorithm to aircraft in STA order, starting at the indicated aircraft and searching either forward or backward, depending on the input.

The controller can remove the suggested resolution advisory at any time and try to find a resolution for another aircraft in the conflict.

Automatic Resolution

When automatic resolution is chosen and a conflict is predicted, the DA automatically tries to resolve the aircraft within the conflict that is scheduled latest. Unless the controller creates a conflict by issuing a bad speed or altitude, conflicts should appear when the second aircraft appears. It is assumed that the first aircraft will have already been included in the controller's plan, so only the second aircraft is automatically resolved. The software will try to maintain the resolution. If the resolution fails, the controller can try to resolve the first aircraft within the conflict using a keyboard input or use other methods to remove the conflict. If there are multiple conflicts present when the automatic resolution function is turned on, the resolution attempts will resolve all conflicts starting with the earliest conflict.

Automatic Recalculation of Solutions

When a solution is found, the trajectory calculation used for conflict detection assumes that the aircraft will follow the given advisory starting at its current position. For example, if an altitude and cruise speed change are given, the calculated aircraft trajectory will start at the current position, perform an altitude and speed change, and continue until the new top of descent. If the aircraft is not issued these altitude or speed changes, and continues flying its original path, at some time the advised altitude and speed will no longer be conflict free. Then the system will automatically try to resolve the new conflict using the resolution algorithm on the same aircraft starting with the advised altitude and speed.

Resolution Display

If a conflict-free trajectory is found for the aircraft, the resolution is presented to the controller as a new speed and/or altitude advisory. In figure 5, the resolution advisory is a descent speed of 265 knots and an altitude change to 29,000 feet for UAL123. This altitude and descent speed requires a cruise speed change from Mach 0.76 to 250 knots. Since there is only one conflict, the other aircraft's advisory remains the same. The advisory shown was produced by the automation after a keyboard input by the controller, but the same result would come from the automatic resolution. The conflict would also be resolved if the controller input this descent speed and altitude. If the resolution fails, the normal conflict information is still displayed.

Controller Keyboard Inputs for Resolution

A forward resolution sweep is initiated by dwelling on an aircraft and hitting the "f" key. Starting at the indicated aircraft, the DA tries to find a resolution to all conflicts involving the current aircraft by sequentially performing the resolution algorithm on aircraft with earlier scheduled times. For example, aircraft LEFT and RIGHT, aircraft LEAD and TRAIL, and aircraft LEAD3 and TRAIL3 in figure 6 are in conflict, with LEAD scheduled to arrive first, TRAIL second, LEFT third, RIGHT fourth, LEAD3 fifth, and TRAIL3 sixth. If LEAD is selected and a forward resolution is requested, the DA will try to resolve LEAD, then stop. If RIGHT is selected the DA will try to resolve RIGHT. If it fails to find a resolution it will try LEFT, then TRAIL. If it finds a resolution for TRAIL, then LEAD will no longer be in conflict so no further calculations will be needed. If not, it will try to find a resolution for LEAD. In figure 7 an "f" was input on aircraft RIGHT which found a resolution advisory of 35,000-foot altitude and 245-knot descent speed, then TRAIL was resolved with a 31,000-foot altitude and 265-knot descent speed advisory.

A backward resolution is initiated by dwelling on the aircraft and hitting the "b" key. Starting at the indicated aircraft, the DA tries to find a resolution to the indicated aircraft's conflicts by sequentially performing the single aircraft resolution algorithm on aircraft with later scheduled times. For the example from figure 6, if TRAIL3 is selected a resolution will be attempted only for TRAIL3. If LEAD3 is selected, either a resolution will be successfully completed and the calculations will stop or a resolution will be tried for TRAIL3. In figure 7, a "b" was input on aircraft LEAD3 finding a descent speed resolution advisory of 265 knots.

A forward or backward sweep always stops when it reaches an aircraft that is not in conflict with any other aircraft. If the multiple aircraft ability is disabled, both "b" and "f" will result in the same resolution attempt.

Automatic Recalculation of Solutions

In figure 8, we see the same aircraft as in figure 7 about 2 minutes later. The advisories calculated for figure 7 were not issued; they became trajectories with conflicts and the computer had to recalculate new conflict advisories. Looking at aircraft RIGHT, the new advisory is simply a descent speed of 255 knots while the aircraft TRAIL could not resolve the conflict only using descent speed and found a solution with a lower altitude. The aircraft LEAD3 changed its descent speed advisory from 265 knots (with conflict) to 240 knots (without conflict).

Automatic Resolution Method

In figure 9, the same situation shown in figure 6 was created with the automatic resolution function on. Since the automatic resolution function applies only to the second aircraft in each conflict, TRAIL, RIGHT, and TRAIL3 have resolution advisories. The conflicts were resolved in order of the conflict time, so LEAD and TRAIL with 18 minutes until the conflict were resolved first, followed by LEAD3 and TRAIL3 with 19, followed by LEFT and RIGHT with 24.

Research Options

The conflict resolution software has a variety of research options to study controller preferences and methods to investigate reduction of the number of required advisories.

Resolution Within a Group

The resolution can be limited to the aircraft within a single conflict group. A conflict group is a group of aircraft that are in conflict with each other. Every aircraft does not need to be in conflict with every other aircraft (although this will always be true for a group of two), but any two aircraft with consecutive STAs within the group must be in conflict.

The six conflict aircraft in figure 6 make up three conflict groups: LEAD and TRAIL, LEAD3 and TRAIL3, and LEFT and RIGHT. When the resolution within a group mode is on, a forward or backward resolution sweep will stop when it reaches the end of a conflict group. Thus if LEFT is indicated as the first aircraft for a forward resolution, a resolution will only be attempted for LEFT. If resolution within a group is off, a resolution will be tried for LEFT, TRAIL, and LEAD, as needed, in that order. TRAIL3, LEAD3, and RIGHT are scheduled later than LEFT, so a forward resolution will not consider them. Since the resolution sweep stops when it reaches an aircraft that is not in conflict, if TRAIL and LEFT were separated by an aircraft that was not in conflict, a forward or backward resolution would only continue within the group.

Number of Aircraft Resolved

The maximum number of aircraft that the computer will try to resolve can be prescribed by the controller to prevent large numbers of trajectory calculations if the computer is overloaded. If this is set to one, it is the same as turning off the multiple aircraft function. If the number of aircraft that are in conflict is greater than the maximum prescribed number of resolution aircraft, the algorithm will stop after trying to resolve the prescribed number.

Separation Multiplier

A resolution multiplying factor is used to enlarge the horizontal and vertical separations in the operation of the conflict detection algorithm during a resolution attempt. The conflict detection algorithm is performed for each trajectory calculated during the resolution algorithm's search to decide whether or not to end the resolution. During these conflict checks, a separation multiplying factor increases the other buffers discussed in the separation section. Resolution trajectories are compared to all other trajectories, searching for a minimum separation equal to the regular separation multiplied by the resolution factor, which is between one and two. This extra buffer is used to increase the time for which a conflict resolution advisory will work. If the resolution buffer is set to one, the same distances will be used for separation during the original conflict detection and during a resolution. A small change in position due to the advisory not being issued immediately will cause a conflict to be detected which the software will try to resolve. For the cases shown in figures 7 and 8, a multiplying factor of 1.1 was used and all three conflicts reappeared within 2 minutes. With a larger multiplying factor, the controller could wait a longer time without new advisories which will reduce workload.

Concluding Remarks

The conflict detection and resolution algorithms in CTAS are designed to provide a series of building blocks for development of intelligent algorithms that will perform more and more of the planning to determine conflict-free trajectories. The requirements for reliable conflict-free planning are accurate prediction of trajectories, responsiveness to constraints, and adaptability to controller preferences. The longer the time before a conflict is predicted to occur, the smaller the amount of change necessary to remove the conflict leading to more options, fewer advisories, and a more fuel efficient solution. However, the trajectory must be flown more accurately to remain conflict free.

The conflict resolution software has multiple options which can be studied for human factors issues, controller preferences, and efficiency of the system. These options range from letting the system automatically attempt a resolution, to resolving a single aircraft with a keystroke, to using completely manual methods.

Future research in conflict detection will examine the definition of separation to take into account aircraft capabilities. For example, if an aircraft's speed is only accurate to 1 knot, a 1-knot error could be projected over the course of the aircraft's trajectory, causing larger separation requirements near the end of the trajectory than at the beginning.

In the conflict resolution area, there are three types of research efforts which are being considered. First, more efficient or intelligent algorithms are required to cut down on computer time. Second, human factor issues such as presentation of the conflict and resolution advisories to the controller or providing for controller preferences in degrees of freedom should be studied. Third, different degrees of freedom and different combinations should be considered. This includes simultaneous resolution of multiple aircraft, incorporation of path distance into the search algorithm, and adding extra criteria to the search algorithm to choose the direction (such as fuel optimal).

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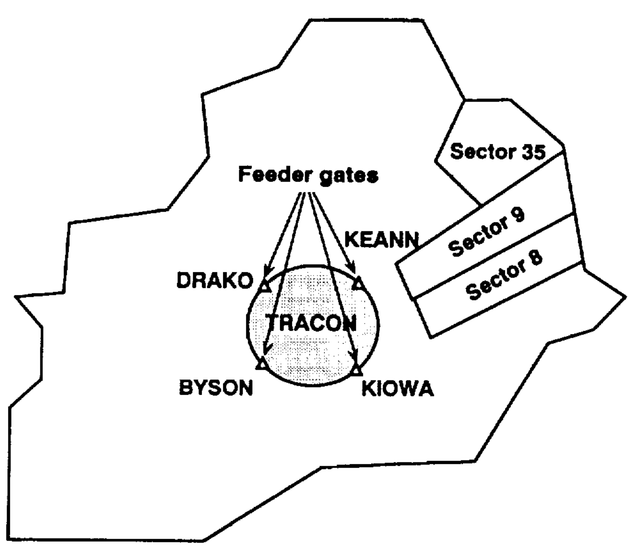

Figure 1. Denver ARTCC airspace.

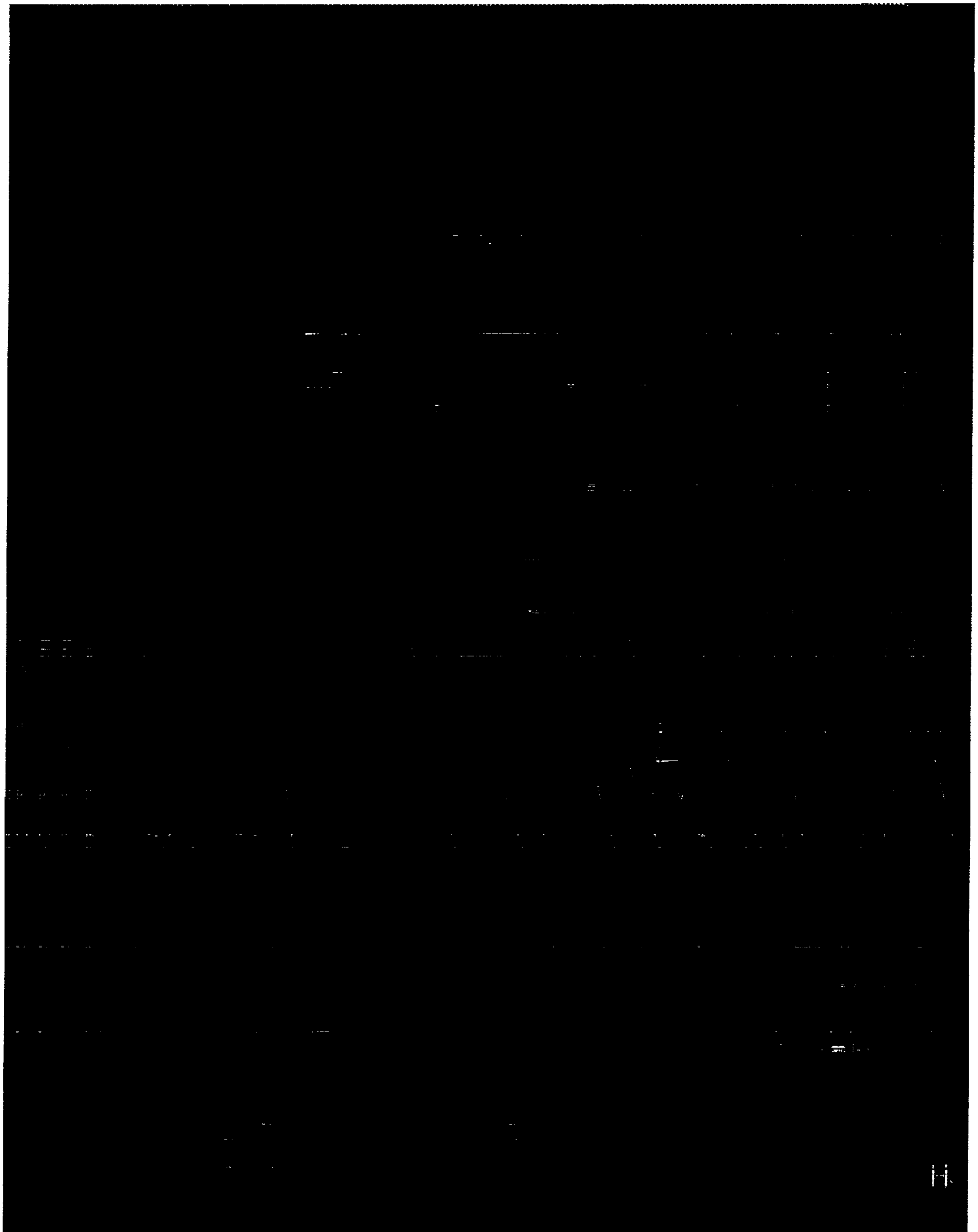

Figure 2. Short- and long-term conflict displays.

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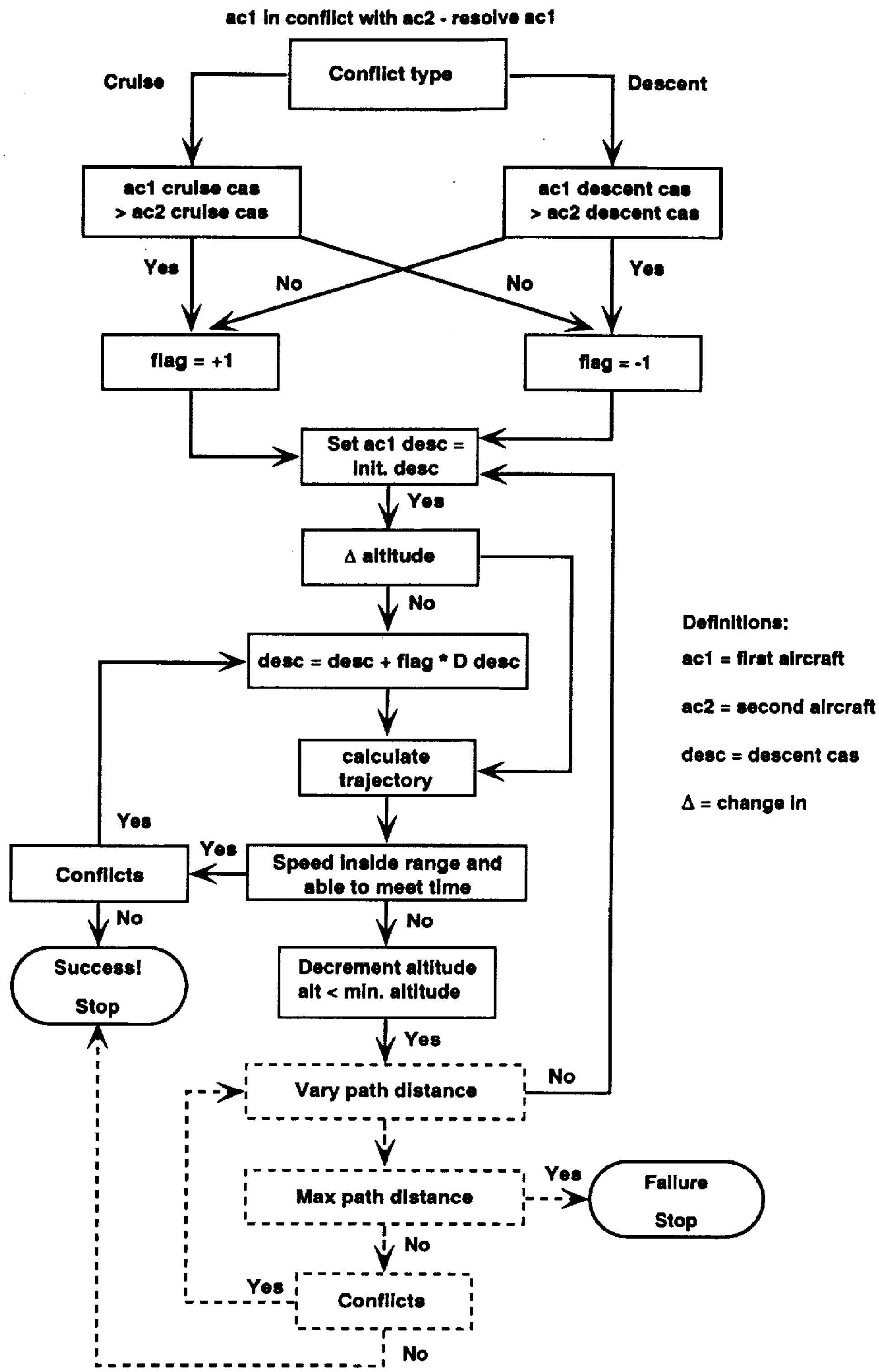

Figure 3. Conflict resolution algorithm.

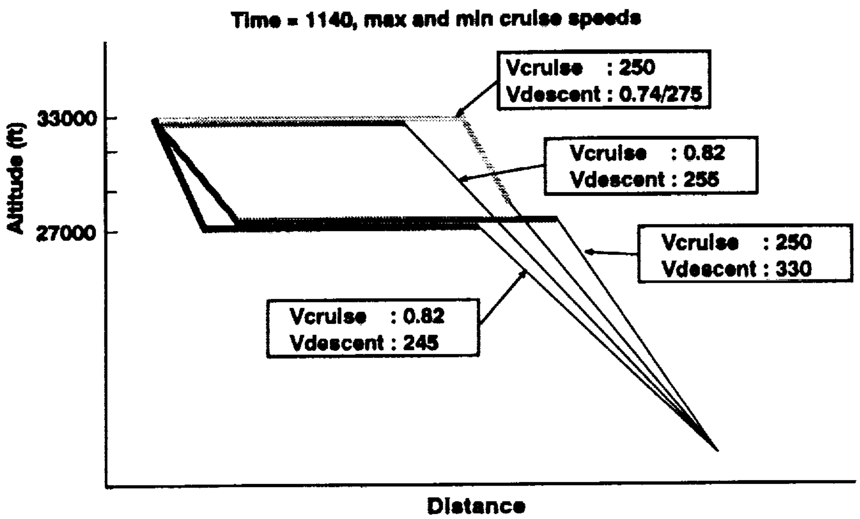

Figure 4. Conflict resolution trajectories.

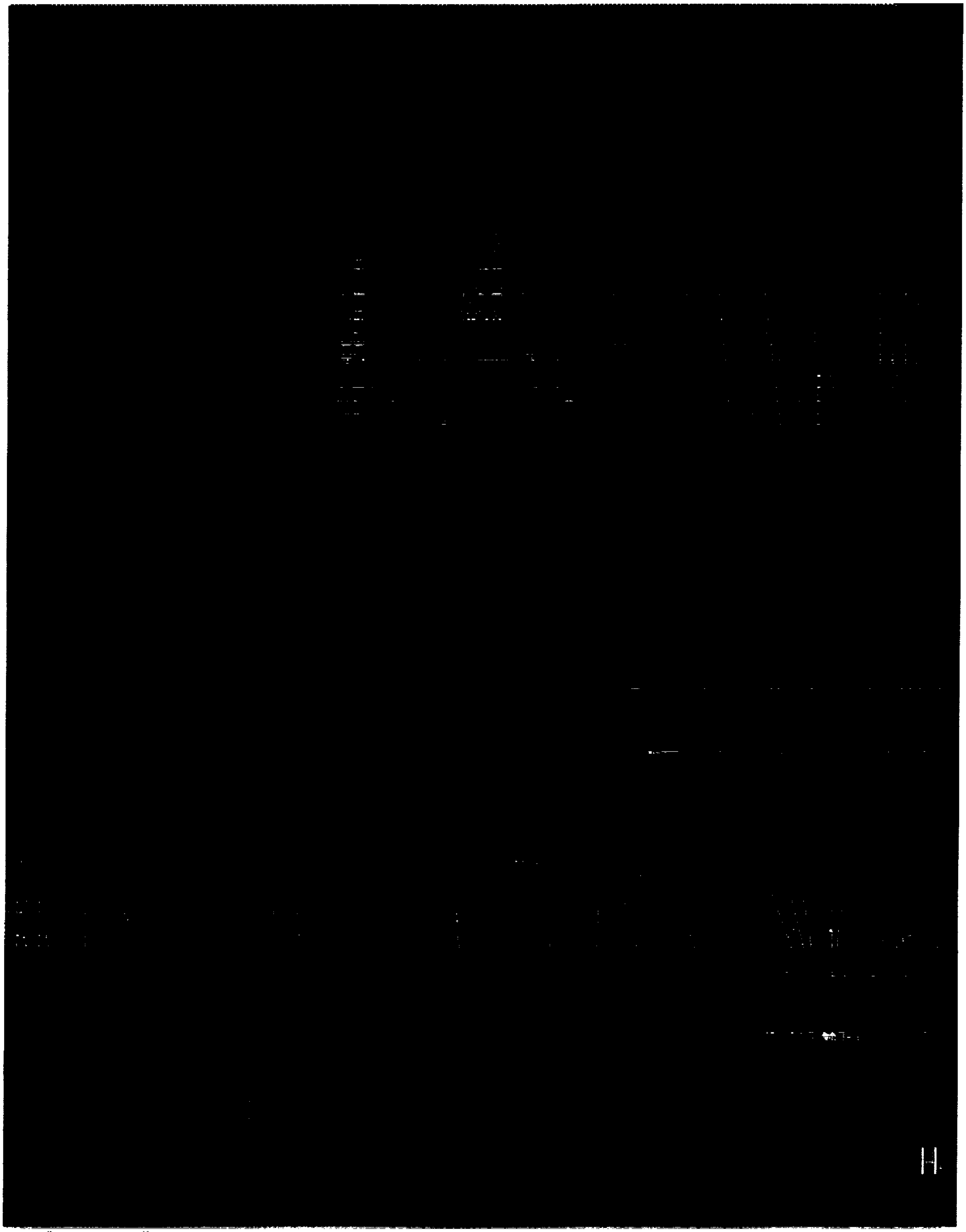

Figure 5. Conflict resolution advisory display.

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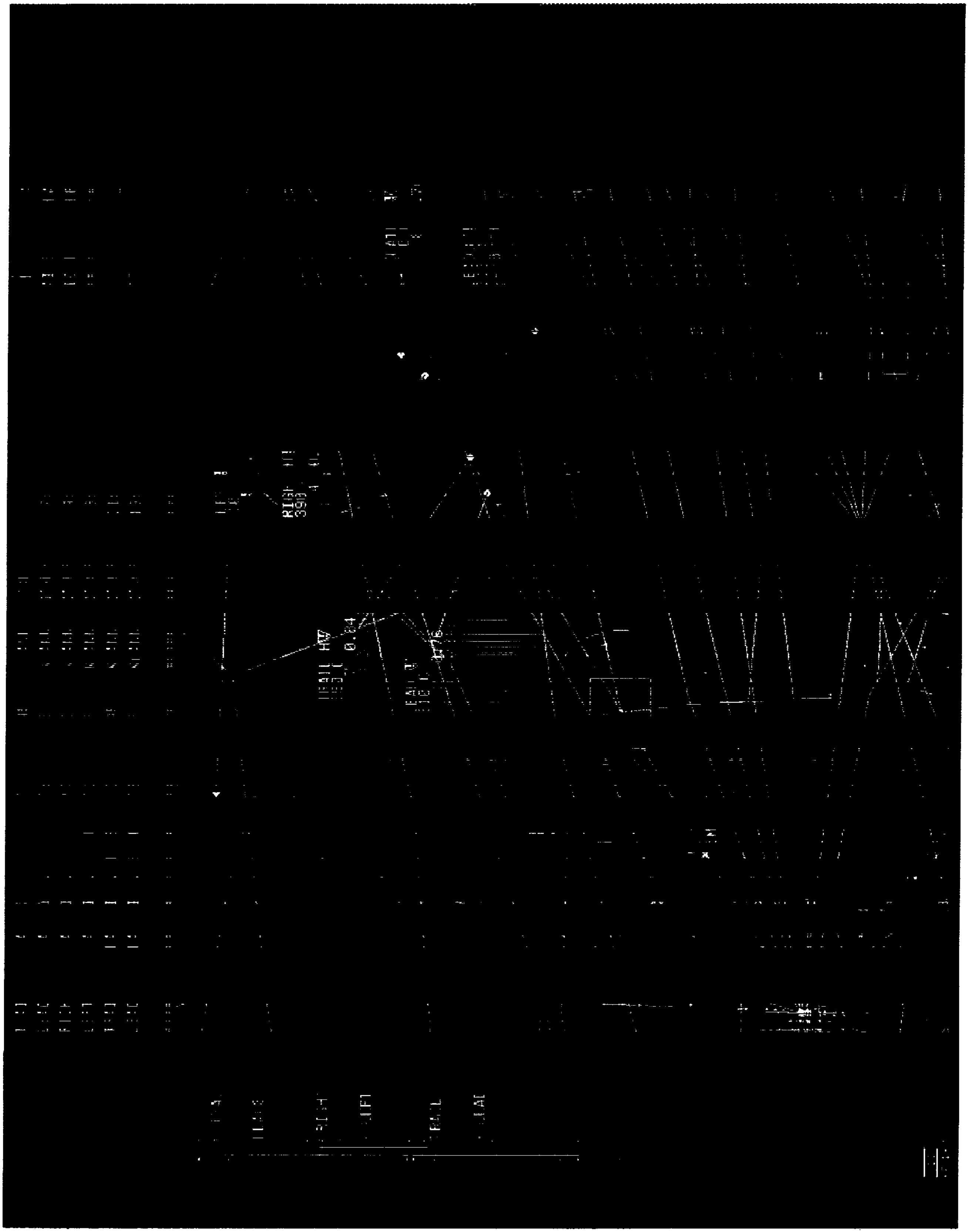

Figure 6. Multiple aircraft conflicts.

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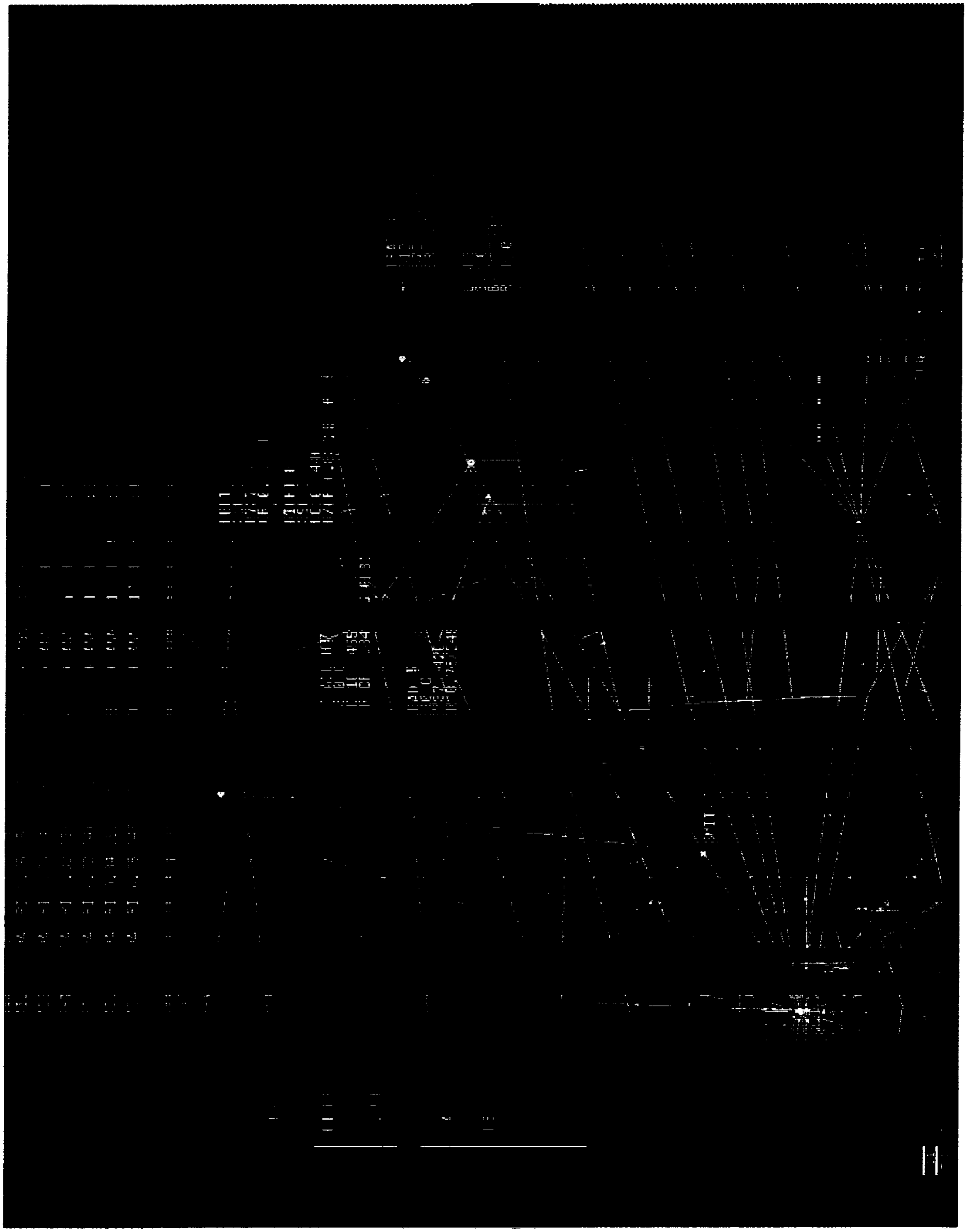

Figure 7. Individual conflict resolutions—forward resolution for aircraft RIGHT and TRAIL, backward resolution for LEAD3.

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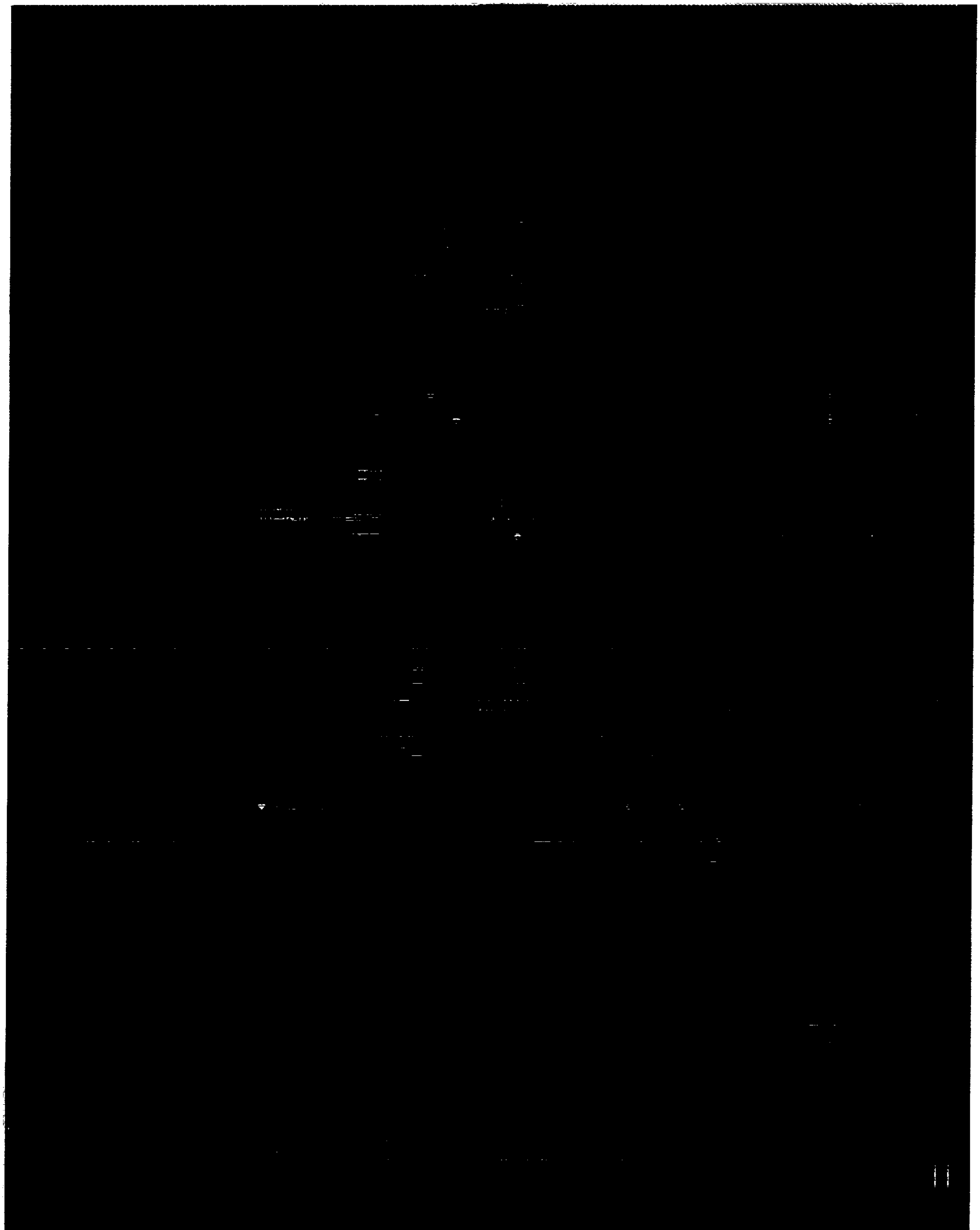

Figure 8. Automatic recalculation of conflict resolution advisories.

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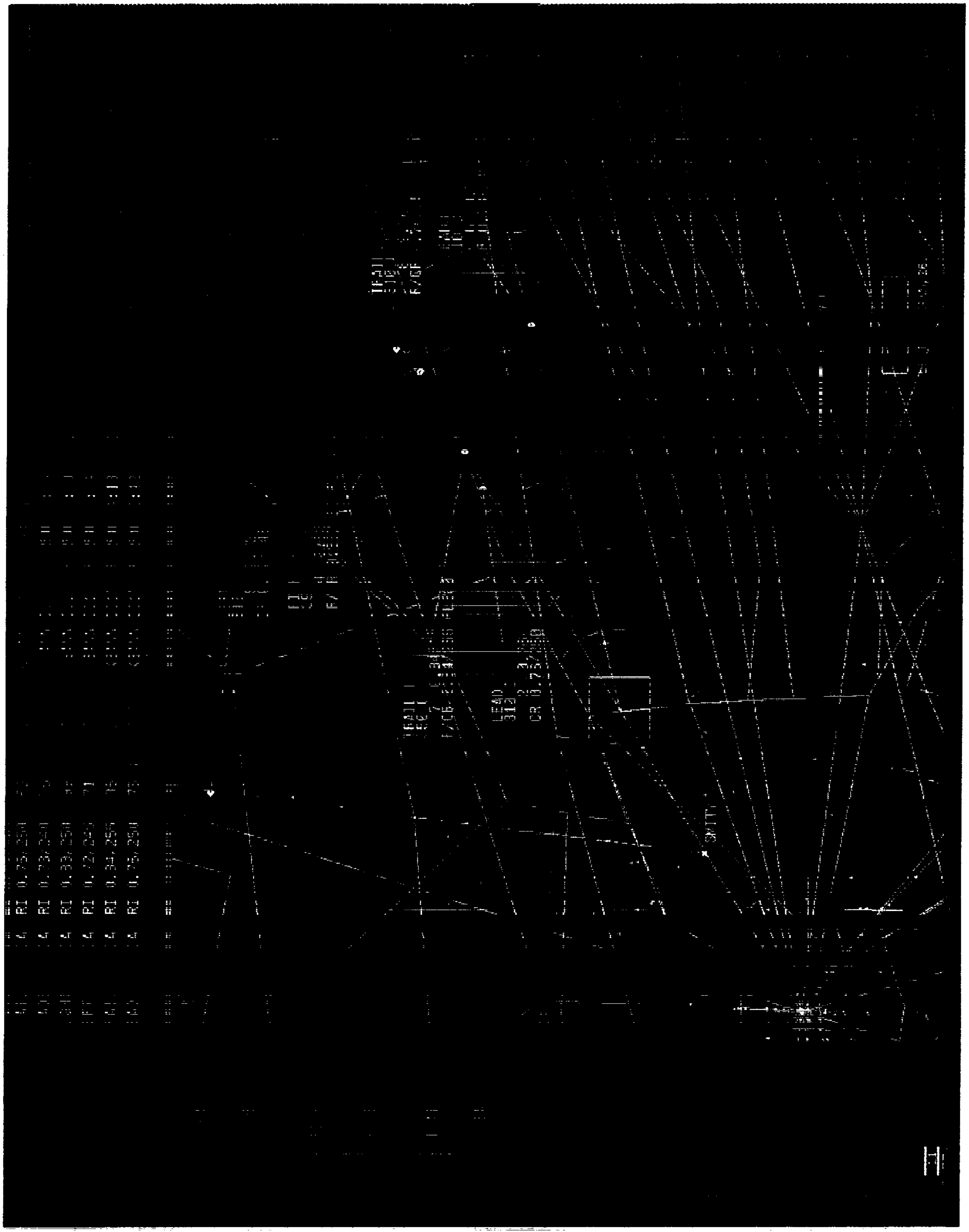

Figure 9. Automatic conflict resolution.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1994	Technical Memorandum

4. TITLE AND SUBTITLE
Conflict-Free Trajectory Planning for Air Traffic Control Automation

5. FUNDING NUMBERS
505-64-13

6. AUTHOR(S)
Rhonda Slattery and Steve Green

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Ames Research Center
Moffett Field, CA 94035-1000

8. PERFORMING ORGANIZATION REPORT NUMBER
A-93132

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-108790

11. SUPPLEMENTARY NOTES
Point of Contact: Rhonda Slattery, Ames Research Center, MS 210-9, Moffett Field, CA 94035-1000; (415) 604-5435

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified — Unlimited
Subject Category 03

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

As the traffic demand continues to grow within the National Airspace System (NAS), the need for long-range planning (30 minutes plus) of arrival traffic increases greatly. Research into air traffic control (ATC) automation at Ames Research Center has led to the development of the Center–TRACON Automation System (CTAS). CTAS determines optimum landing schedules for arrival traffic and assists controllers in meeting those schedules safely and efficiently. One crucial element in the development of CTAS is the capability to perform long-range (20 minutes) and short-range (5 minutes) conflict prediction and resolution once landing schedules are determined. The determination of conflict-free trajectories within the Center airspace is particularly difficult because of large variations in speed and altitude. The paper describes the current design and implementation of the conflict prediction and resolution tools used to generate CTAS advisories in Center airspace. Conflict criteria (separation requirements) are defined and the process of separation prediction is described. The major portion of the paper will describe the current implementation of CTAS conflict resolution algorithms in terms of the degrees of freedom for resolutions as well as resolution search techniques. The tools described in this paper have been implemented in a research system designed to rapidly develop and evaluate prototype concepts and will form the basis for an operational ATC automation system.

14. SUBJECT TERMS
Air traffic control, Conflict-free planning, Conflict resolution

15. NUMBER OF PAGES
20

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102