En route Spacing Tool:
Efficient Conflict-free Spacing to Flow-Restricted Airspace

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Abstract

En route miles-in-trail (MIT) spacing restrictions are often used to distribute arrival delays upstream of destination airports and to mitigate local areas of en route airspace congestion. National statistics for the U.S. indicate that en route spacing restrictions are applied by Centers for approximately 5000 hours per month. These restrictions impact approximately 45,000 flights per month. Current-day practices for MIT-spacing increase controller workload, concentrate traffic unnecessarily, and degrade the performance of conflict-probe decision support. Today's procedures also result in inefficient conformance actions that directly impact the airspace user. It is estimated that the fuel penalty alone approaches $45 million per year. A concept-exploration spacing tool has been developed to help en route controllers efficiently conform to miles-in-trail (MIT) spacing restrictions. Integration with conflict probe will reduce the probe's false-alarm and missed-alert rates due to better knowledge of the controller's intended actions for spacing conformance. Integration will further reduce workload and fuel consumption by reducing the number of corrective clearances needed to achieve flow-rate conformance while avoiding conflicts. This paper analyzes the impact of MIT-spacing restrictions on the National Airspace System and describes a near-term decision support tool solution that is based on current conflict-probe technology.

Introduction

A fundamental goal for en route decision support tool (DST) automation is to assist the controller in providing better Air Traffic Control (ATC) service while increasing safety and productivity. The economic benefits to airspace users may come in the form of increased capacity/throughput, reduced restrictions and deviations (time and fuel consumption), and increased flexibility to plan and fly their aircraft.

There are many factors that impact air traffic operations, but primary factors include conflicts and Traffic Flow Management (TFM) flow-rate restrictions. Conflicts relate directly to safety while flow-rate restrictions relate directly to the efficient management of capacity-constrained resources (e.g., runways and sectors). Certainly the safety considerations alone warrant the community's past emphasis on conflict probe technology. However, in terms of mitigating user deviations, particularly in light of the projected rate of traffic growth, it is the flow-rate restriction that is at the core of unlocking user benefits. Although flow restrictions only impact a percentage of flights, the resulting deviations are significant compared to those required for maintaining basic radar separation.

It is particularly interesting to consider en route airspace that is subject to dynamic flow-rate restrictions related to local en route bottlenecks (e.g., sector overload) or the transition to/from high-density terminal-areas. NASA has been active in the development and evaluation of tools and techniques for efficient conflict-free planning in the presence of such constraints. The research is based on Center-TRACON Automation System (CTAS) technology [1].

In general, two types of flow-rate restrictions must be considered. These include time-based arrival metering[1] and en route miles-in-trail (MIT) spacing. Where operational, arrival metering is generally performed in en route airspace within the last 20 min of flight prior to entering terminal airspace. Even with arrival metering operations, many flights will still be subject to MIT-spacing restrictions. MIT-spacing procedures can be expected to play a predominant role for several reasons. The first is the occasional need to merge departures with en route traffic. Second, the limited number of arrival-metering sites leaves the remaining airports to depend on MIT-spacing procedures. Third there is a need to occasionally propagate delays upstream of terminal airspace prior to the arrival-metering horizon. As traffic growth outpaces capacity, more flights will be affected by dynamic flow-rate initiatives including MIT-spacing restrictions.

Much of the en route decision support tool effort within the U.S. and Europe has focussed on near-term implementations of conflict probe and arrival metering capabilities. There has been some long-term progress towards the development of advanced advisory tools that integrate capabilities for conflict detection/resolution and flow-rate conformance for arrival metering [2-5]. However, there has been little effort on near-term controller tools to assist with flow-rate conformance, let alone integration with conflict

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[1] Arrival metering tools for operations within the U.S. and Europe include the CTAS Traffic Management Advisor (TMA), COMPASS, and MAESTRO with future developments including Multi-Center TMA (U.S.) and Arrival Manager (Eurocontrol).

detection/resolution. Furthermore, there has been little emphasis, if any, on the en route spacing problem.

In the near term, there are many opportunities to enhance current and emerging technologies such as those being deployed in the U.S. under the FAA's Free Flight Phase 1 (FFP1) program. For the purposes of this paper, Conflict Probe (CP) refers to a basic en route conflict-probe capability. CP assists the controller by predicting problems based on flight plans and radar-track data (e.g., loss of minimum-required separation between two flights) and providing trial-planning support to formulate and coordinate resolution actions.

Two near-term enhancements to CP technology may go far in reducing user deviations from their preferred trajectories. First, a tool is needed to help en route controllers efficiently conform to flow-rate restrictions. This will enable controllers to strategically plan conformance actions resulting in reduced workload, flight deviations and fuel consumption. The second enhancement to CP involves the integration of conflict detection and resolution capability with flow-rate conformance. Integration will further reduce fuel consumption and workload by reducing the conflict-probe false-alarm and missed-alert rates. This improved accuracy, due to better knowledge of the controller's intended conformance actions, will reduce the number of corrective clearances needed to achieve flow-rate conformance while avoiding conflicts.

As a first operational step, there may be a relatively large return on investment in applying CP technology (conflict detection and trial planning) to flow-rate conformance. Although the manual trial-planning approach is too cumbersome for arrival metering[2], it may very well lend itself to en route spacing operations.

This paper analyzes the impact of current-day MIT-spacing operations, presents a conceptual solution, describes a near-term Spacing Tool implementation (based on current conflict-probe technology), and illustrates the tool's application through an example traffic scenario.

En route Miles-In-Trail Spacing

In the U.S., traffic management coordinators (TMCs) within each ATC facility are responsible for coordinating MIT-spacing initiatives within their facility when needed. Dynamic initiatives are either generated within the facility (e.g., local arrival spacing to a non-metered airport), received from neighboring facilities, or coordinated through the ATC System Command Center (ATCSCC).

MIT-spacing restrictions are defined in terms of a stream of flights, spacing-reference fix, active period, and a spacing requirement (e.g., 20 nm in trail). Restrictions may also segregate streams by altitude stratum and/or arrival routing.

Once a MIT-spacing restriction is initiated, local TMCs identify the flights within their facility that are affected by the restriction. TMCs then coordinate re-routes to form "freeways in the sky" that allow sector controllers to visualize the stream and determine the maneuvers necessary for conformance. Controllers primarily use vectors to establish and maintain the desired spacing. The "path-dependent" nature of this process makes MIT-spacing restrictions operationally feasible to implement, monitor, and control across sector boundaries, with little or no automation assistance.

TMCs assess each MIT-spacing situation and determine the appropriate sectors, upstream of the spacing-reference fix, to begin coordinating controller actions for conformance. This effective range (or time horizon) for controller conformance depends on the available airspace and the magnitude of delays. Traffic streams nominally have a natural spacing: the greater the difference between the nominal and required spacing, the greater the delay resulting from conformance. Depending on the magnitude of the delays and available airspace, it may be necessary to propagate MIT-spacing restrictions to upstream facilities (with coordination facilitated by the ATCSCC).

Figure 1 illustrates an example scenario for Chicago's O'Hare Airport where it is not uncommon for delays to propagate upwards of 1000 nm upstream. The "delayability" of a flight (i.e., the operationally acceptable amount of delay that can be absorbed) grows with the range-to-go and airspace capacity. As terminal-area delays grow, Chicago Center must throttle the arrival flow. Even with airborne holding, the back up of arrival traffic can saturate the airspace. Chicago Center then coordinates a restriction with Minneapolis Center to space incoming arrivals (e.g., 10 MIT by Fort Dodge (FOD)). Depending on the situation, Minneapolis may in turn need to slow the rate of incoming traffic from Denver Center (e.g., 20 MIT by Oneil (ONL)).

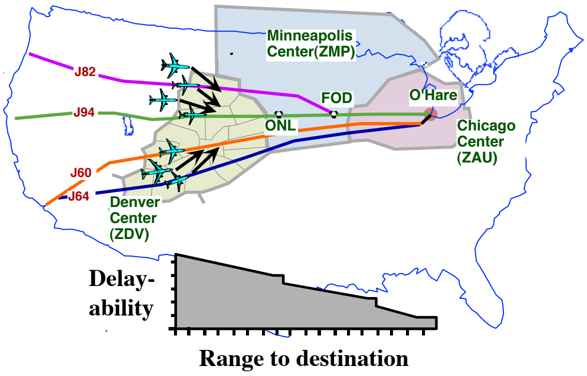

Figure 1. En route coordination of spacing delays.

Even if high-density terminal areas (such as Chicago) convert to time-based arrival metering, MIT-spacing initiatives still provide TMCs with an effective means

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[2] Arrival metering involves complex trajectory-planning challenges with high densities due to traffic compression and merging near the terminal area.

for dynamically distributing excess delay upstream. MIT initiatives have a significant operational advantage in that they are relatively straightforward to delegate (within and between ATC facilities), implement, and monitor. When flights are formed into in-trail streams, controllers are able to visualize and control spacing at the sector without automation assistance.

Impact of MIT-Spacing Restrictions in the U.S.

The frequency, source, and impact of MIT initiatives vary widely from day to day as dynamic changes in traffic load exceed airspace capacity (primarily due to weather). National statistics for 1998 [6] indicate that the number of restriction hours averaged approximately 5000 hours per month (±15%).

A detailed study of Denver Center operations was conducted to estimate the number of flights impacted by MIT restrictions within that facility. The objective was to estimate the frequency with which MIT-spacing restrictions were imposed and the number of flights affected. The study focused primarily on traffic to the top four destination airports that resulted in restrictions on Denver Center: Los Angeles (LAX), Chicago (ORD), Dallas/Ft. Worth (DFW), and Las Vegas (LAS). Data was collected for June 1996. These data included the Traffic Management Unit (TMU) logs (noting the duration and nature of MIT restrictions), and recordings of the hourly sector traffic count as a function of destination.

Figure 2 presents the results from the study in terms of a three-dimensional pie chart to illustrate the average daily volume of impacted flights. The cross section of each column indicates the percentage of days for which MIT initiatives were active. The radius indicates the average number of flights per hour affected by restrictions for that airport. The column height represents the average duration of initiatives on an active day. Some active days involve multiple initiatives (e.g., Chicago may call for restrictions for 60 min in the morning and 90 minutes in the afternoon).

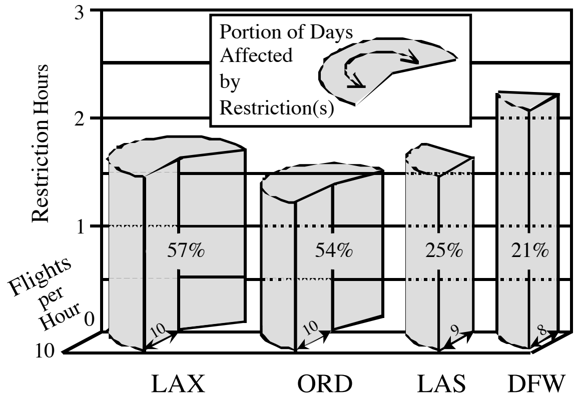

Figure 2. Denver Center MIT restrictions (June 1996).

On a weekly basis, the figure indicates that 163 flights within Denver Center are affected by MIT-spacing restrictions for the top four destination airports. The number of flights per hour affected by restrictions averaged 10 for LAX, 10 for ORD, 9 for LAS, and 8 for DFW. The combined data for the four destinations indicate that approximately 9 flights per restriction hour were affected by spacing initiatives. Although restrictions tend to be relatively heavy for the month of June (due to thunderstorm impact on sector capacity), these results were relatively light and considered to be representative of the annual average for Denver.

An additional study [7], commissioned by the author, performed a nation-wide analysis of the frequency of, number of flights impacted by, and reasons for MIT restrictions. The data set included ATCSCC logs of imposed MIT restrictions as well as flight plan and track data archived from the En route Traffic Management System (ETMS). The study analyzed 54 days of traffic, sampled between November 1998 and October 1999, representing the gamut of operations (peak holiday traffic, severe weather, and routine operations). The number of restrictions implemented per day ranged from 69 to 346 with an average of 186. These restrictions impacted an average of 13.5 aircraft per restriction with an average rate of 8.5 flights per restriction hour.

Table 1 presents the top four categories of restrictions noted in the traffic management logs. These account for 85% of the restrictions studied. Approximately two thirds of the restrictions were attributed to traffic volume and weather. Whereas the weather category captures situations involving reduce airspace capacity due to weather, the volume category captures situations involving excess volume. The next largest categories, traffic demand and reduced airport acceptance rate (AAR) contributed to 21% of all restrictions. The AAR category captures situations involving delays due to a reduction in airport capacity. A clear definition of the demand category was never found. In total, these top four categories impacted approximately 2.4% of all flights within the national airspace system (NAS).

Table 1. Top four categories for MIT restrictions.

Reason	Number of restrictions	% Total	Number of Flights	%NAS Total*
Volume	388	33%	2621	0.9%
Weather	362	31%	2097	0.7%
Demand	158	13%	1703	0.6%
AAR	91	8%	702	0.2%
Total	999	85%	7123	2.4%

* % of all flights within the national airspace system.

Table 2 categorizes the same data set by destination. Traffic streams are often defined by destination even though many restrictions are not directly related to the destination itself. This enables traffic managers to quickly identify flight groups that, if restricted, will solve the problem with one restriction. This "least common denominator" also simplifies the communication of the restriction to other traffic managers and individual sectors. Although this technique may not result in an equitable distribution of delay, it is a practical approach that has evolved from operational necessity.

Table 2. Number of MIT-impacted flights by destination.

Airport	Number of restrictions	% Total	Number of Flights
Chicago	164	14%	2621
Cincinnati	126	11%	982
Atlanta	119	10%	2119
Detroit	78	7%	856
Dulles	70	6%	1341
Total	557	47%	7919

Chicago and Atlanta arrivals account for nearly one fourth of all MIT restricted flights. This is not surprising given their status as two of the busiest hub airports: airport delays impact a large number of flight arrivals; and for en route delays, changes to their arrival streams can effect a significant change to the traffic environment.

Disadvantages of Current-day MIT Procedures

Although today's "manual" MIT-spacing techniques are straightforward to implement, there are several disadvantages related to their path-dependent nature. From the airspace-user's point of view, deviations from their preferred trajectory come in three forms:

- TMC-initiated re-routes to establish a stream;
- controller vectors to establish spacing; and
- controller vectors for conflict resolution.

Figures 3 and 4 illustrate the problem. Three flights are initially on user-preferred eastbound routes. The circles indicate the relative sequence of the un-delayed flights when the first flight crosses the boundary. The natural order of arrival at the boundary is B, C, and A. Consider the situation where the downstream center (ARTCC 2) imposes an MIT-spacing restriction at the boundary. Without automation assistance, it would be difficult for sector controllers to visualize and space their flights relative to flights in other sectors that are orthogonal to the flow. Referring to figure 3, the controller in sector 2 would have difficulty in spacing B relative to A or C. To overcome this problem, TMCs coordinate the re-routing of A and C (figure 4) to form a stream that can be visualized and controlled by sectors 2 and 5. Depending on the natural distribution of flight paths, these re-route actions add a significant penalty.

Once streams are formed, spacing adjustments typically involve vectors. Although speed control can help fine-tune spacing under current procedures, it is often too little to establish spacing because of performance mismatches and limited range within a sector (for speed changes to take effect). In-trail flows also reduce the opportunity for faster aircraft to pass slower ones when the faster aircraft would naturally arrive first at the spacing-reference fix. Once spacing is established within a stream, additional deviations may result from conflicts with crossing traffic.

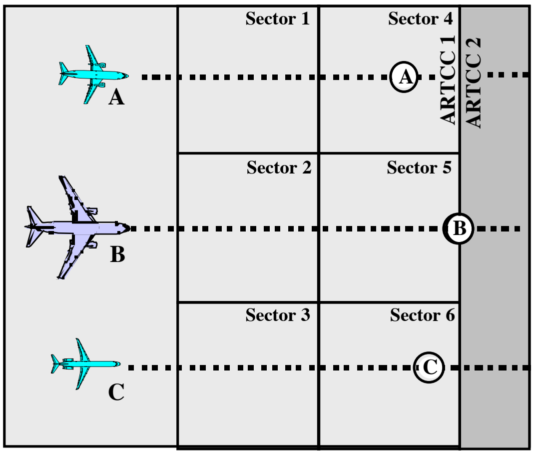

Figure 3. User-preferred routes.

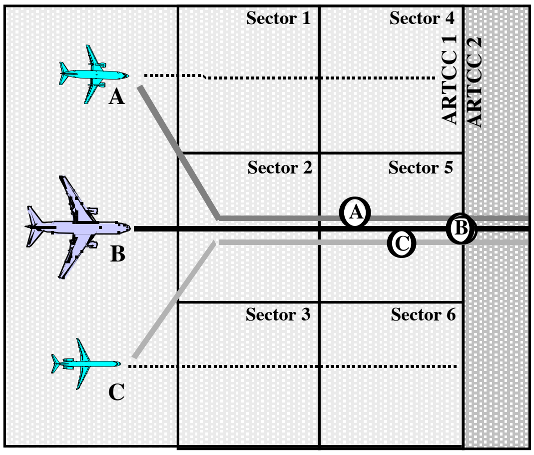

Figure 4. Re-routes to form spacing trail.

From the ATM point of view, current-day spacing procedures present several disadvantages. First is the workload required to establish the stream. Second, controllers must rely on tactical techniques to establish spacing based on experience and trial and error. Third, in-trail techniques force flights into streams that concentrate traffic density and workload in the "spacing" sectors as opposed to distributing flights across sectors. Finally, the spacing sectors are impacted in terms of conflict detection and resolution because the tactical nature of current-day spacing techniques negatively impacts the operational use of CP tools.

Regarding conflict detection, consider the situation illustrated in figure 5. The two eastbound flights are subject to a spacing restriction while the other two flights represent crossing traffic. The solid lines indicate the path used by CP. The spacing-conformance path for the first eastbound flight is also shown in a dashed line. CP has no knowledge of the controller's plan for spacing conformance until the conformance maneuvers are completed. More often than not, such plans are not updated or reflected in the ATC Host computer. This is due to several factors including the controller workload associated with flight plan amendments and the difficulty controllers would have in reflecting today's relatively tactical spacing techniques in a flight-plan amendment. As a result, CP may experience a greater rate of false alarms (due to the lack of spacing-conformance intent) and missed alerts (if the controller's conformance actions result in a new conflict.

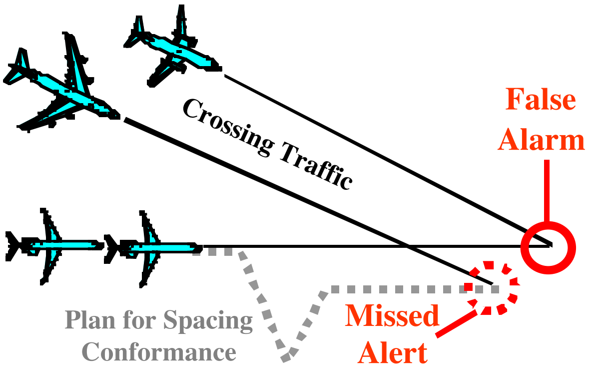

Figure 5. Spacing impacts on CP accuracy.

Spacing Tool Concept

The disadvantages of today's MIT-spacing procedures may be overcome by a simple application of the 4D trajectory-prediction and trial-planning capability associated with CP technology. Figure 6 illustrates the desired situation, assuming that the downstream "receiving" facility will still require an in-trail stream at the hand off. As long as the tools and procedures result in conformance prior to the spacing-reference fix, each of the cross-stream sectors may work their flights independently and thus delay the merge until the spacing-reference fix.

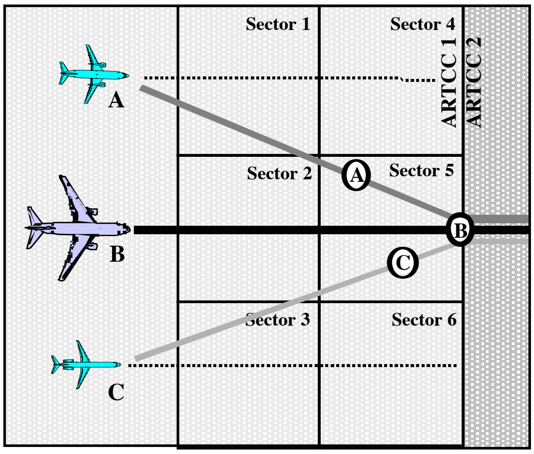

Figure 6. Spacing with minimum deviation.

Additional benefit could be achieved if the downstream "receiving" facility relaxed the requirement for an in-trail flow at the hand off. At the theoretical extreme, the automation could help controllers deliver an "equivalent" spacing across a "wide" stream of flights (figure 7) with the absolute minimum deviation from each user's preferred route. Of course, depending on the amount of delay required (i.e., relative to the aircraft's performance and speed envelope), a certain amount of vectoring may be necessary to space each flight. Figure 7 approaches the user-desired concept of "free routing" where flow-restrictions are implemented, as needed, with required time-of-arrival (RTA) assignments. In fact, spacing solutions could be used to determine RTA assignments for equipped aircraft.

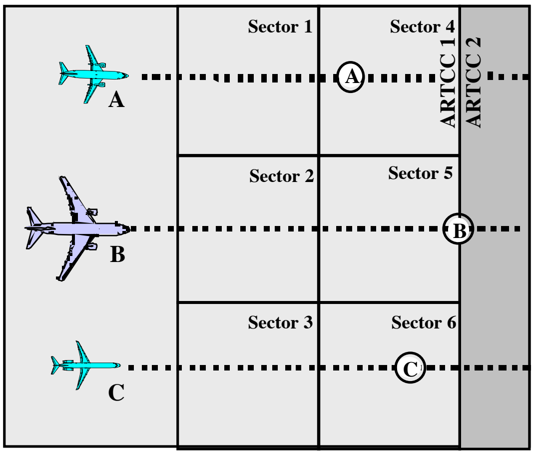

Figure 7. Path-independent spacing.

Figures 6 and 7 illustrate several of the advantages to the spacing tool approach. First, the degree of route deviations required for spacing conformance is minimized. Second, the traffic density and spacing workload is distributed across more sectors. This distribution of flights reduces the impact of dissimilar speeds among sequential flights, in a stream, thus allowing more opportunity for natural overtakes. It also provides for a more equitable distribution of delays based on the nominal performance of the aircraft. In addition, the integration of CP and spacing-conformance tools will result in more efficient trajectories with fewer false alarms and missed alerts.

Potential Fuel Benefits

One of the benefits of applying CP technology to the conflict-free planning of MIT-spacing conformance is the reduction of path deviations for both stream formation and spacing adjustment. By allowing flights to remain on independent paths (delaying any merge until the spacing-reference fix), speed control may be exercised more effectively and to an economic advantage. A detailed study of this particular benefit mechanism, on a national or even regional level, is beyond the scope of this paper. However, this benefit was estimated by the following approach.

Consider a typical flight impacted by a spacing restriction on a standard-atmosphere day with no wind. The analysis will assume a medium-sized commercial jet with a nominal cruise speed of Mach 0.82 (approximately 475 knots true airspeed at flight level 350) and a fuel burn of approximately 7000 lb/hr (at a cost of $0.10/lb of fuel). Additional assumptions include an average spacing delay of 3 min per flight, and a conformance horizon of 200 nm (i.e., the range between the start of spacing maneuvers and the spacing-reference fix). This range corresponds to a nominal time-to-fly of 25.3 minutes.

If speed control were to be used instead of vectors, the aircraft could absorb all of the delay with a speed reduction to 250 knots indicated (approximately 424 knots true airspeed). This speed reduction would reduce the rate of fuel consumption by approximately 25% resulting in a fuel savings of 825 pounds. These results are based on a computer simulation of aircraft performance for a typical medium-sized jet transport. Considering an average national rate of 5000 restriction hours per month, impacting an average of nine flights per restriction hour, a spacing tool implementation could save $44.6 million per year in fuel alone.

This estimate only represents one benefit mechanism of value. Additional fuel savings (not counted here) would be gained by a reduction in the major re-routings required for some "off route" flights to join in-trail streams. Other fuel and workload savings would be realized when traffic streams must be merged. For example, consider figure 8 which illustrates two west bound streams. In anticipation of a later merge with a net spacing of 10 nm, each stream is restricted to a 20 nm spacing. If the streams happen to be synchronized (coincidentally), there will be little downstream effort needed to achieve a single flow with 10 nm spacing. However, if the flows are not synchronized, controllers will be forced to delay flights to merge the streams. Since the Spacing Tool provides guidance for spacing conformance independent of routing, it enables the controllers to synchronize the 10 nm spacing up front.

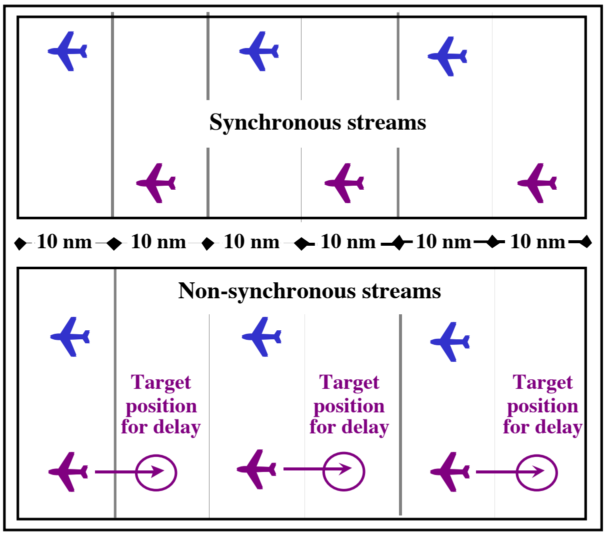

Figure 8. Convergence of synchronous streams.

Aside from direct fuel savings, the tool will reduce the uncertainty associated with today's methods for monitoring and control of critical traffic streams. Improvements to the ability to monitor and control flow rates may provide TMCs with the confidence to reduce the frequency and extent of MIT-spacing restrictions. Although difficult to measure, there is additional value associated with the tool's ability to increase the conflict-probe performance and lower traffic densities across sectors.

Early Spacing Tool Implementation via CP Technology

Initially, CP technology is being deployed as a "D-side" tool. Each en route sector has two primary controller positions/roles: the R-side and D-side. The R-side monitors the plan view radar display and issues all clearances to the aircraft in the sector. In general, the D-side complements the R-side by analyzing the flight plans of incoming traffic, coordinating upstream changes to protect the sector (R-side) from high workload situations, and other duties to allow the R-side to focus on the tactical situation. During light traffic periods, one controller performs both positions, during heavy periods, additional controllers may help the sector team to handle the workload.

Initial CP problem-resolution capability is based on a "manual" trial-planning process. The controller uses a graphical user interface to trial plan changes in route, altitude, and speed. Problems include the predicted loss of separation between two flights (i.e., a conflict) and penetration of special use airspace. Compared to the manual process that D-side controllers perform with flight plans, CP represents a significant improvement to the operational system. However, the time consuming nature of the trial-planning process may preclude its use during high-workload situations.

For applications to arrival metering, it is probably not feasible to apply the trial planning process to metering conformance. The arrival-metering horizon is relatively close to terminal airspace (generally within 20 minutes) resulting in a high concentration of arrivals (per sector) to plan. In addition, the arrival phase of flight is far more complicated to plan accurately than the cruise phase. Finally, compression of traffic through fixed arrival gates results in tighter inter-stream spacing near the terminal area than farther upstream. In order to feed the runway capacity, the target spacing at the terminal boundary can easily approach the minimum standard for en route separation (5 nm), leaving little room for uncertainty in the trajectory plan. Recent controller simulations and field tests have confirmed the difficulties associated with trial planning for arrival metering.[8]

There may be a niche however for applying CP technology to the en route spacing problem. Compared to arrival metering, en route spacing is often initiated farther upstream where traffic is distributed across a larger airspace resulting in fewer aircraft to delay per sector. The development of a spacing tool could reduce sector densities further as flights are left on their routes longer. Furthermore, en route spacing requirements are generally much larger than the minimum standard for radar separation: 5 nm. The compression of traffic for arrival metering, on the other hand, typically approaches this minimum-separation standard. As a result, en route spacing often demands less precision (for any individual flight) than arrival metering. Controllers have greater flexibility in achieving en route spacing conformance as long as they deliver the overall flow rate. For example, consider a stream of flights subject to a 10 nm spacing restriction. If the first two flights are spaced by 8 nm, and the third is spaced by another 12 nm, the controller has still conformed to the general flow rate without violating the minimum-separation standard. The combination of a relatively simple phase of flight (i.e., cruise), fewer flights to plan, and the relatively large amount of "wiggle" room for flow-rate conformance greatly increases the feasibility of applying CP technology to the MIT-spacing problem as opposed to arrival metering.

Spacing Tool Description

An en route spacing function was developed within the CTAS baseline in 1994 in preparation for field tests of the Descent Advisor (DA).[2] This function allows a controller to identify a stream of traffic and a spacing-reference fix within or beyond the boundaries of their sector. The reference fix may be an arbitrary position, defined by the controller, independent of any one flight's airway or routing. Streams may be defined to include flights on independent paths (i.e., paths that are not constrained to any one airway, routing, or common fix). The algorithm allows for a stream to be comprised of aircraft in the climb, cruise, and/or descent phase of flight. This enables the same tool to be applied to problems involving en route spacing, arrival spacing, and the merging of departures into an en route stream. The subtle variations in along-path predictions may be accounted for within the supporting trajectory-prediction functions (i.e., variations in ground speed due to winds and lateral path, true airspeed profile, and aircraft performance in the case of climb/descent segments).

Figure 9 illustrates the spacing computation based on a reference fix. A spacing prediction is made for each flight in the stream when the first flight (or next flight) is predicted to cross abeam the spacing-reference fix. A corresponding spacing marker shows the predicted-spacing position of each flight when the first flight in the stream passes abeam the reference fix. If a controller vectors or assigns a new speed/altitude to a flight, this predicted spacing position is updated to reflect the changes to that flight's predicted trajectory. The "equivalent" in-trail spacing is computed for each flight based on the along-track distance from its predicted spacing position to its future position abeam the control fix. In this case, the figure illustrates a spacing merge of a departure (flight C) into an en route stream comprised of flights A, B, and D.

Alternatively, the spacing computation may be based on any one of several reference geometries: an airspace/sector boundary, a fixed line, or a fixed arc from a reference fix/airport. Figure 10 illustrates an algorithmic implementation for a reference-arc based computation.

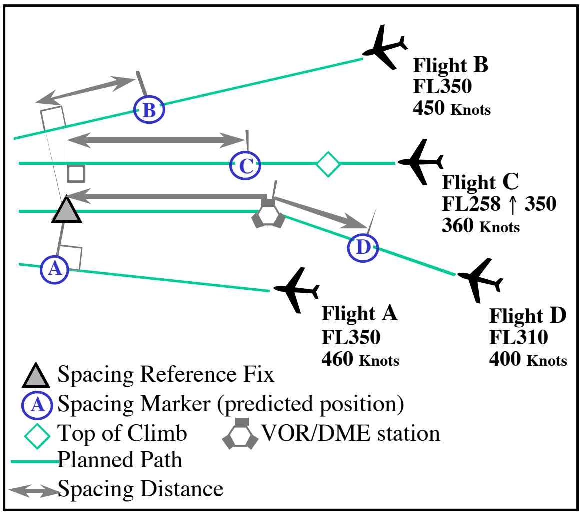

Figure 9. Generalized spacing-fix algorithm.

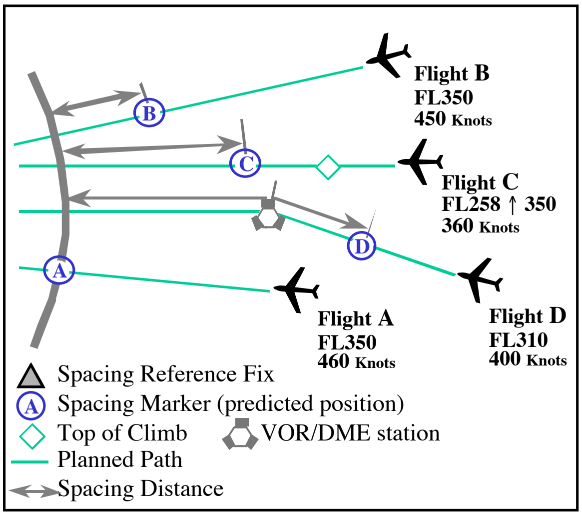

Figure 10. Generalized spacing-arc algorithm.

For delay planning, the tool interface included "quick" keyboard inputs for speed and altitude changes, and a graphical interface for route changes. Quick inputs allow the controller to enter speed/altitude changes with a minimum of keyboard entries and head-down time. The speed changes could be entered as a function of phase of flight (climb, cruise, and/or descent), and speed, route, and altitude changes can be combined in one plan. The trajectory-prediction accuracy, associated with speed/altitude/route changes in cruise and descent, was validated in a field test [2].

The graphical display automatically updates the predicted spacing while simultaneously displaying any conflicts predicted by the conflict-probe function. The controller may then use the CTAS trial-planning capability to plan actions for spacing conformance while simultaneously resolving any predicted conflicts. This integration allows the controller to create and implement a conflict-free plan for spacing conformance. This capability also provides the controller with a flexible tool for managing complex merge problems even if MIT-spacing restrictions are not in effect.

An advanced "automatic" version of the Spacing Tool[3] was also developed within CTAS to provide arrival-spacing support for high-density airports that are not served by the CTAS Traffic Management Advisor (TMA). However, due to the FAA's near-term focus on initial conflict probe and TMA capabilities, development of the CTAS-spacing applications was put on hold. In the mean time, the basic DA tool (now referred to as the En route/Descent Advisor (EDA)) has undergone many refinements to its controller interface, trajectory planning, and conflict-probe capability [8-10]. The current plan is to re-implement the Spacing Tool capability within the CTAS baseline and conduct research activities in support of Free Flight Phase 2.

Spacing Tool Scenario

The following example scenario is presented to illustrate the integration of MIT-spacing conformance with conflict detection and resolution (figures 11-13). The figures represent a simplified depiction of the tool's graphical interface from a 1996 version of CTAS. The example involves the northern portion of the Denver Center airspace centered on sector 33, a sort of cross roads for transcontinental traffic. The scenario focuses on a simulated traffic problem involving the five flights depicted in figure 10. Four of the flights are destined for the Northern California Bay Area (San Francisco, San Jose, and Oakland airports). A fifth flight, DAL 357, is destined for Seattle along a route that crosses the paths of the westbound traffic.

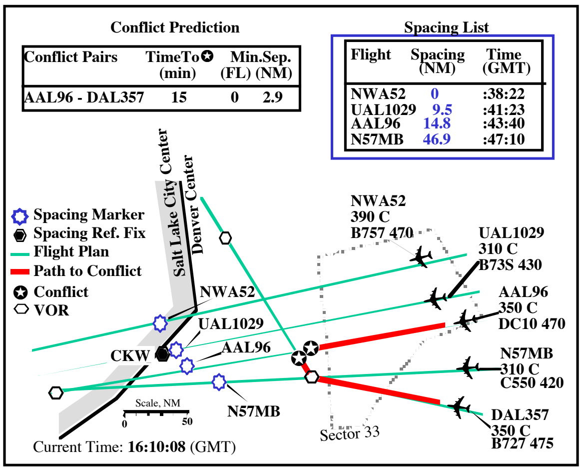

Figure 11. En route spacing example: conflict probe without spacing conformance.

DAL 357 is a conventionally-equipped B-727 that is navigating with ground-based navigational aids along jet airways (hence the slight zig-zag in its routing). NWA52 (B-757) and UAL1029 (B-737-300) are equipped with flight management systems (FMS) and are navigating along NRP flight plans comprised of a series of direct segments along a "best-wind" path. AAL96 is a DC10, with area navigation (RNAV) capability, flying direct on a NRP flight plan. N57MB is a conventionally-equipped Citation Jet. The data block for each flight indicates the flight's call sign, flight level (line 2), and ground speed in knots (line 3). The following scenario is based on standard atmosphere and zero-wind conditions.

The scenario begins with all five flights progressing along their flight-plan routes. Figure 11 depicts a conflict probe of the situation. The conflict-probe list indicates that the separation between AAL96 and DAL357 is predicted to fall below minimums in 15 min. The minimum-separation distance is predicted to be 2.9 nm. This conflict-probe alert is based on the current flight plan and track data for each flight.

However, the scenario is far more interesting when a MIT-spacing initiative is considered for the Bay-Area arrivals. For the purposes of this illustration, it is assumed that terminal-area delays (due to fog) have propagated upstream and forced Salt Lake City Center to place a restriction on Denver Center. The restriction requires that a spacing of 20 MIT be established on all Bay-Area landing traffic before the hand off at the Salt Lake boundary.

For this situation, the spacing function is invoked for the four westbound flights. The Cherokee navigational aid (CKW), just inside Denver airspace, is selected as the spacing-reference fix by the TMC. Results from the spacing analysis are depicted graphically (figure 11) with spacing markers. The markers indicate the predicted position of each restricted flight when the lead flight is predicted to pass abeam the reference fix. As the lead flight crosses the reference fix, the next flight in the sequence becomes the lead.

A precise representation of the spacing analysis is also presented in the flow-restriction list (upper right corner of the figure). The list displays each flight in the order of its arrival time, abeam the reference fix, along with a prediction of its equivalent "in-trail" spacing and arrival time. The spacing is displayed here in terms of the "total" spacing for each flight relative to the lead flight. The total spacing represents the predicted along-track range to go to the reference fix when the lead flight is predicted to cross the reference fix. An alternative approach is to display the relative spacing between each succeeding flight based on the difference between the "total" spacing of each succeeding flight. An additional option (not shown here) is to display the spacing error in terms of the difference between the predicted and desired spacing values for each flight.

The flow-restriction list indicates that the first flight, NWA52, is predicted to cross CKW at 38 min and 22 sec after the hour. The following flights are all predicted to arrive early relative to the 20 nm spacing restriction. UAL1029 is predicted to have an equivalent in-trail spacing of 9.5 nm with the lead flight and is therefore 10.5 nm "early." AAL96 is predicted to be 25.2 nm early, based on a total spacing of 14.8 nm (5.3

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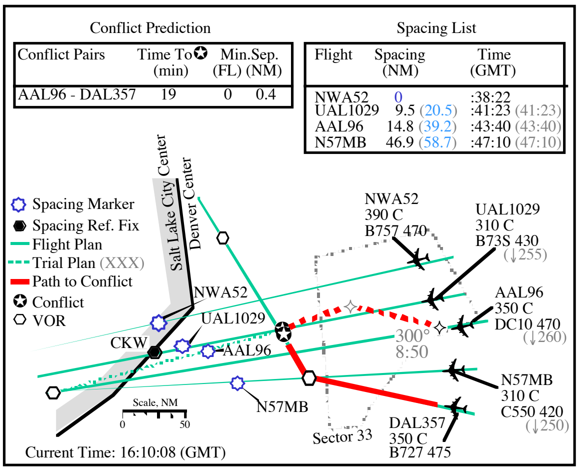
[3] The spacing algorithm was integrated with DA functions for automatic generation of clearance advisories (cruise speed, descent speed, top of descent, and vectors) for arrival spacing.

nm behind UAL1029), while N57MB is predicted to be 13.1 nm early, based on a total spacing of 46.9 nm (22.1 nm behind AAL96). Clearly, the flight plans used for the conflict probe do not reflect the future actions necessary to bring UAL1029, AAL96, and N57MB into MIT-spacing conformance.

Figure 12 shows the same traffic situation after initial trial planning for spacing conformance. The trial plan calls for UAL1029 to reduce speed to 255 knots indicated airspeed (KIAS). This action, if implemented, would reduce UAL1029's ground speed by 21 knots (resulting in a 20.5 nm spacing without deviating from the user's preferred path). The tool also indicates that a speed reduction to 250 KIAS (400 knots ground speed) would bring N57MB into MIT-spacing conformance. That action would result in a total spacing of 58.7 nm also while keeping N57MB on its preferred path.


Conflict Prediction

Conflict Pairs	Time To ✪ (min)	Min.Sep. (FL)	(NM)
AAL96 - DAL357	19	0	0.4

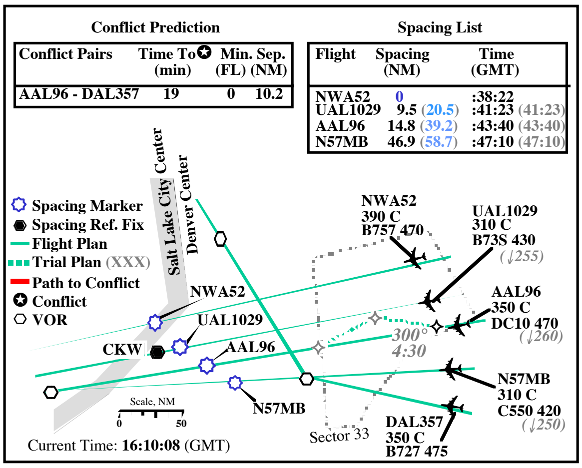
Spacing List

Flight	Spacing (NM)	Time (GMT)
NWA52	0	:38:22
UAL1029	9.5 (20.5)	:41:23 (41:23)
AAL96	14.8 (39.2)	:43:40 (43:40)
N57MB	46.9 (58.7)	:47:10 (47:10)

Figure 12. En route spacing example: conflict probe with spacing conformance.

For AAL96 however, only part of the delay will be absorbed by a speed reduction. For the purposes of this example, the speed reduction will be limited to 260 KIAS (443 knots ground speed) to illustrate the use of vectors. Such a speed reduction would result in a total spacing of 27.5 nm or 12.5 nm early for AAL96. For the remainder of the spacing, the controller would use the graphical user interface to generate a combined vector and speed solution. As the controller "stretches" the path graphically, the spacing feedback helps the controller zero in on a conformance solution. The resulting plan for AAL96 calls for a turn to a heading of 300 degrees (for 8 min and 50 sec), followed by a turn to 254 degrees to rejoin the user's preferred route.

With the tool-based spacing-conformance plans generated, the conflict probe will have an accurate model of intent upon which to base any conflict predictions. In this case (figure 12), the automation still predicts a conflict between AAL96 and DAL357, albeit at a later time (19 min). For a complete solution, the controller could use the trial planner while combining the feedback from the spacing and separation predictions.


Conflict Prediction

Conflict Pairs	**Time To ✪ (min)**	**Min. Sep. (FL)**	**(NM)**
AAL96 - DAL357	**19**	**0**	**10.2**

Spacing List

Flight	**Spacing (NM)**	**Time (GMT)**
NWA52	**0**	**:38:22**
UAL1029	**9.5 (20.5)**	**:41:23 (41:23)**
AAL96	**14.8 (39.2)**	**:43:40 (43:40)**
N57MB	**46.9 (58.7)**	**:47:10 (47:10)**

Figure 13. En route spacing example: conflict-free spacing conformance.

Figure 13 illustrates the controller's final solution. AAL96's path-stretch vector was adjusted to achieve separation with DAL357. This plan calls for AAL96 fly a heading of 300 degrees (for 4 min 30 sec), followed by a turn to 240 degrees to rejoin the user's preferred route. The final plan achieves spacing conformance while resolving the conflict between AAL96 and DAL357 with a minimum separation of 10.2 nm. The automation feedback helps the controller minimize the extent of the deviations to get the job done.

Concluding Remarks

Approximately 45,000 flights per month are impacted by dynamic MIT-spacing restrictions throughout U.S. airspace. Significant potential exists for reducing user deviations, fuel burn, and the controller workload associated with today's procedures for spacing conformance. The Spacing Tool concept was introduced and described in terms of its operational impact and potential benefits. A prototype of the tool was implemented within the CTAS baseline. The spacing algorithm was presented and the tool's operation was described through an operational scenario. Analysis indicates potential airspace-user benefits of at least $45 million per year in fuel savings alone. Furthermore, the integration of the Spacing Tool with conflict probe will significantly reduce the probe's false-alarm and missed-alert rates during spacing operations. These potential benefits are of particular value because they are achieved during flow-rate constrained operations, precisely the time when airspace users are impacted by deviations from their preferred trajectories.

Future plans call for the re-implementation of the Spacing Tool capability within the CTAS baseline to facilitate research activities in support of Free Flight Phase 2.

Biography

Mr. Green joined NASA Ames Research Center in 1985 as a research engineer for Air Traffic Management automation. One of the four CTAS "founders," he lead the development and field testing of the CTAS Descent Advisor (DA), and was the principle investigator for the development/evaluation of air-ground integration concepts including CTAS-FMS integration, en-route trajectory negotiation, and data exchange to enable UPTs. He manages NASA's en route ATM research and co-leads NASA's Distributed Air-Ground research and RTCA SC-194/WG-2 on FMS-ATM-AOC Integration. Steven M. Green received a B.S. (Aeronautical and Mechanical Engineering) from the University of California at Davis in 1985, a M.S. degree in Aeronautics & Astronautics from Stanford University in 1988, and is an instrument-rated pilot.

References

1. Erzberger, H., Davis, T.J., and Green, S.M., "Design of Center-TRACON Automation System," AGARD Guidance and Control Symposium on Machine Intelligence in Air Traffic Management, Berlin, Germany, May, 1993.

2. Green, S.M., Vivona, R., Grace, M.P., and Fang, T.C., "Field Evaluation of Descent Advisor Trajectory Prediction Accuracy for En route Clearance Advisories," AIAA-98-4479, AIAA Guidance, Navigation, and Control Conference, Boston MA, August, 1998.

3. Slattery, R. and Green, S.M., "Conflict-Free Trajectory Planning for Air Traffic Control Automation," NASA TM-108790, January, 1994.

4. Green, S.M., and Vivona, R., En route Descent Advisor (EDA) Concept," Advanced Air Transportation Technologies Project Milestone 5.10 Report, September 1999, M/S 262-4, NASA Ames Research Center, Moffett Field, CA, U.S.A., 94035.

5. Swenson, H.N. et al, "Design & Operational Evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center," 1st USA / Europe Air Traffic Management R&D Seminar, Saclay, France, June 1997.

6. "Quarterly Restriction Report, Third Quarter 1998,"Federal Aviation Administration David J. Hurley Air Traffic Control System Command Center (ATO-200), Reston, VA

7. Klopfenstein, M., et. al., "En route User Deviation Assessment," RTO-37 Final Report, Contract # NAS2-98005, NASA AATT Project Office, NASA Ames Research Center, Moffett Field, CA 94035, November, 1999.

8. McNally, B. D., Erzberger, H., Bach, R., and Chan, W., "Controller Tools for Transition Airspace," AIAA-99-4298, AIAA Guidance, Navigation, and Control Conference, Portland OR, August, 1999.

9. Erzberger, H., Paielli, R.A., Isaacson, D.R., and Eshow, M., "Conflict Detection and Resolution In the Presence of Prediction Error," 1st USA / Europe Air Traffic Management R&D Seminar, Saclay, France, June 1997.

10. Laudeman, I.V., Brasil, C.L., and Stassart, P., "An Evaluation and Redesign of the Conflict Prediction and Trial Planning Graphical User Interface," NASA TM-112227, April, 1998.