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A Brief History of Airborne Self-Spacing Concepts

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Table of Contents

Acronyms and Nomenclature

4D:	4 dimensional
ADS-B:	Automatic Dependence Surveillance Broadcast
ATC:	Air Traffic Control
CDA:	Continuous Descent Arrival
FANS:	Future Air Navigation System
FMS:	Flight Management System
IMC:	Instrument Meteorological Conditions
KCAS:	Knots, Calibrated Airspeed
kt:	Knots
nmi:	Nautical Miles
Ownship:	From a flight crew's perspective, the aircraft that they are flying
RNAV:	Area Navigation
RTA:	Required Time of Arrival
TCAS:	Traffic Alert and Collision Avoidance System
TTG:	Time-To-Go

Abstract

This paper presents a history of seven of the more significant airborne and airborne-assisted aircraft spacing concepts that have been developed and evaluated during the past 40 years. The primary focus of the earlier concepts was on enhancing airport terminal area productivity and reducing air traffic controller workload. The more recent efforts were designed to increase runway throughput through improved aircraft spacing precision at landing. The latest concepts are aimed at supporting more fuel efficient and lower community noise operations while maintaining or increasing runway throughput efficiency.

Introduction

Airborne self-spacing is an operational concept in which the management of the aircraft's speed is delegated by ATC to the flight crew in order to precisely achieve some operational goal. The development of electronically-enabled, self-spacing concepts for aircraft began in the 1960's with the testing of military station-keeping equipment (ref. 1). Within the next two decades, civil aviation concepts began to emerge that were focused on enhancing airport terminal area productivity while maintaining or reducing air traffic controller workload (refs. 1-12). By the mid 1990's, the focus in airborne spacing research in the U.S. was primarily on reducing arrival delay at high-demand airports. In the past several years, interest in reducing airport community noise and the increased cost of aviation fuel has led to the development of continuous descent arrival (CDA) procedures, with CDAs providing lower noise and lower fuel usage than more traditional arrival and approach procedures (ref. 13). However, because aircraft typically have different descent profiles and CDAs are generally "hands off" from an air traffic control (ATC) perspective, increased spacing is required in CDA operations to preserve separation minima. To bring the arrival rates back toward non-CDA rates, self-spacing and required-time-of-arrival (RTA) concepts are now being developed to support CDA procedures.

The self-spacing concepts that are examined in this paper span a continuum of operational goals and techniques for civil aviation applications. On the left end (fig. 1), pure, state-based concepts are shown, with station-keeping probably being the simplest and purest form of airborne self-spacing. On the other end of the scale are concepts that include the aircraft's planned trajectory, such as RTAs. While the use of RTAs is not actually self-spacing, RTAs are of interest in this paper in that they may be used by ATC as a form of airborne-assisted spacing. Each of the concepts shown in figure 1 will be presented in this paper.

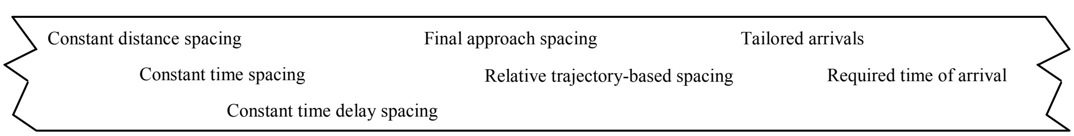

Figure 1. Spacing concepts continuum.

The early concepts, i.e., those explored in the 1970's and 1980's, included constant distance spacing (a.k.a. station-keeping), constant time spacing, and constant time delay spacing. These concepts were focused on immediately obtaining the spacing goal, be it an ATC provided distance or time. In this regard, these concepts are considered short-term control techniques. The primary objective for these concepts was to reduce ATC workload for terminal arrival operations. The newer concepts (refs. 14-40), which are largely trajectory based, are designed such that the spacing goal is typically obtained at the runway threshold. In this regard, these concepts are considered long-term control techniques. The primary objective for these latter concepts was to increase runway utilization through a reduction in the dispersion error of aircraft interarrival landing times at a systems level, i.e., the interarrival performance of an individual aircraft may be reduced to obtain better overall system performance for all of the landing aircraft.

The reduction in the uncertainty of aircraft interarrival landing times is important for airports with a high arrival demand as reduced uncertainty can reduce arrival delays. The relationship of airport demand, potential throughput increase, and arrival delay reduction may be described through the following example. Figure 2 portrays what could be a typical distribution of the error in the runway threshold crossing times between aircraft pairs landing to a runway. For a well managed ATC facility, this distribution would be approximately ±15-20 seconds for operations under instrument meteorological conditions (IMC) (ref. 41). Of interest to this paper is that to maintain an acceptably small number of go around operations caused by inadequate separation or runway occupancy problems, a spacing buffer must be added to the nominal spacing interval. This buffer is the time interval between the go-around boundary and the nominal, no error point on the distribution. The use of airborne spacing techniques allows for the reduction in the error dispersion (fig. 3) through precision spacing at the runway. By reducing the distribution of the error, the spacing buffer may then be reduced while maintaining the same acceptable number of go-around operations and the same separation standards. Advanced ATC tools have also been developed that address the reduction of this spacing buffer though a reduction of the interarrival spacing error (ref. 42).

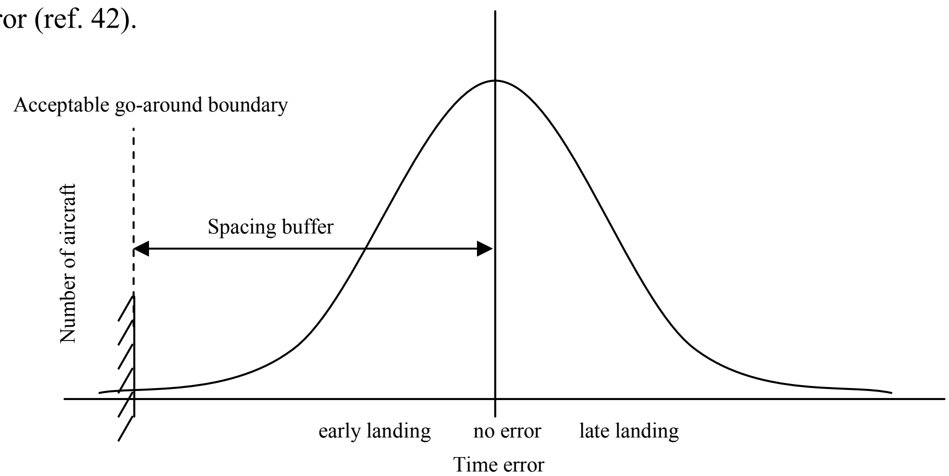

Figure 2. Distribution of landing time error.

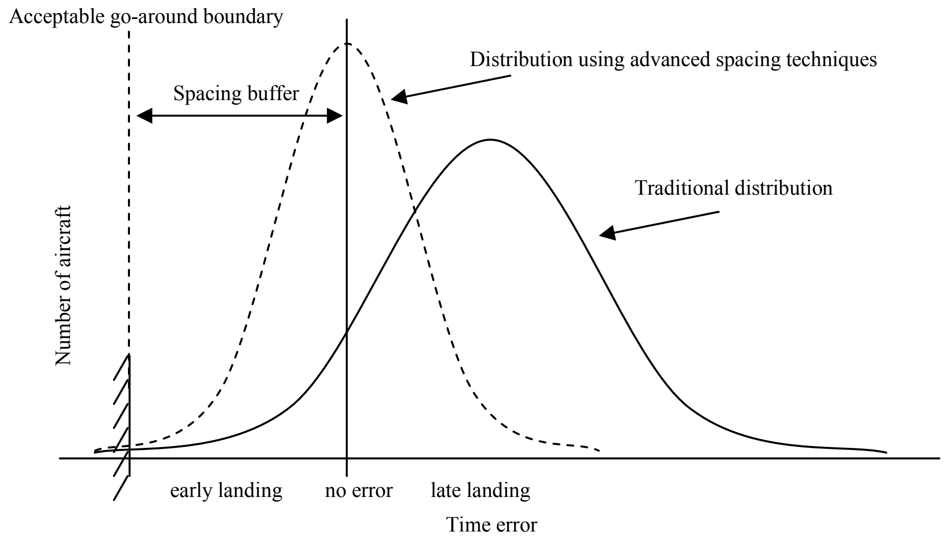

Figure 3. Reduced distribution of landing time error.

While a small reduction in this spacing buffer may seem insignificant, from an airport capacity and arrival delay standpoint this small improvement can result in a large, system-wide benefit. Recent tests have shown that a 5% increase in runway throughput is operationally attainable using airborne-spacing techniques (refs. 13-18). At an airport with an 85% arrival demand (the ratio of the number of arrivals relative to the airport's arrival capacity), which is not unusual for a major hub airport during its peak arrival period, the demand graph (ref. 42) of figure 4 shows that this 5% increase in throughput yields a 29% reduction in arrival delays. So, small increases in runway throughput obtained by small reductions in the arrival spacing buffer can lead to large reductions in airport arrival delays. This reduction of the spacing buffer can also be translated into an increase in the number of aircraft that could be landed over a given period of time, i.e., an increase of the landing rate.

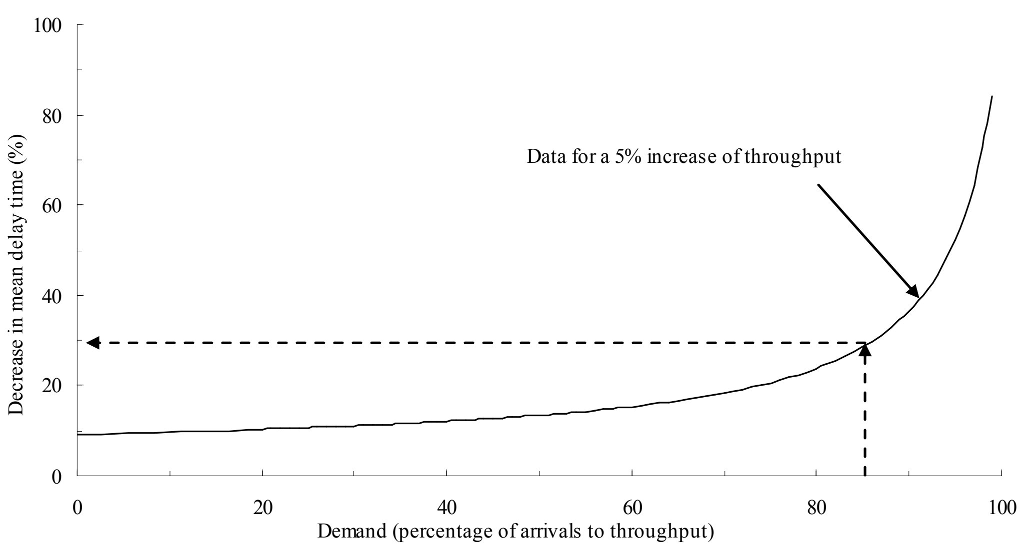

Figure 4. Demand graph.

It is important to note that the applications discussed in this paper are spacing applications and not separation applications as defined by the FAA/EUROCONTROL Co-operative Research and Development Committee, Action Plan 1. They define spacing applications as "requiring the flight crews to achieve and maintain a given spacing with designated aircraft, as specified in a new

ATC instruction. Although the flight crews are given new tasks, separation provision is still the controller's responsibility and applicable separation minima are unchanged."

This document examines each of these concepts that have been conceived over the past 40 years along with their distinct implementation and operational characteristics. The goal of this paper is to provide a brief, historical overview of several of these concepts along with the benefits and constraints inherent to each.

Spacing Concepts

Constant Distance Spacing

Constant distance spacing, which is also known as station-keeping, is probably the purest and most basic form of airborne self-spacing. Using this technique, the aircraft simply keep a fixed distance interval between themselves and their leading aircraft. This technique is fundamentally electronically-assisted formation flying. One example of a flight deck display for constant distance spacing is shown in figure 5 (refs. 1 and 3). In this moving-map example, the pilot would set the range arc to the spacing distance specified by ATC. The speed of the ownship would then be adjusted to overlay the range arc on the symbol for the leading aircraft. For example, if the range arc was behind the leading aircraft's symbol, then the ownship is behind where it needs to be and needs to fly faster than the leading aircraft to reduce this error. The advantages of this concept are that it is relatively simple to implement and for the flight crews to understand.

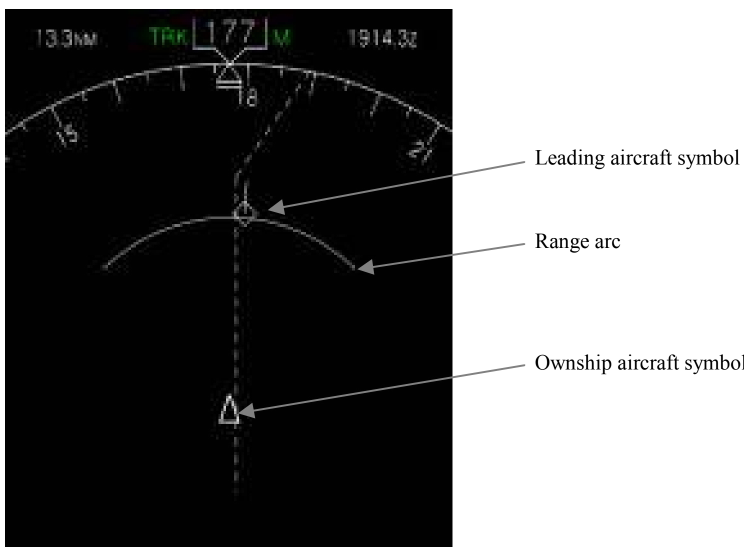

Figure 5. Example constant distance spacing display format.

Several disadvantages to this concept have also been observed. First, because the display presents distance but the flight crew is controlling speed, there is a tendency to slightly undershoot and then overshoot the spacing objective. This particular deficiency can be greatly minimized with the additional of closure rate information on the display. A second problem is that if the leading aircraft turns, the closure rate between the two aircraft increases because the relative range between the two aircraft decreases. A third problem with this implementation is that the spacing accuracy is dependent on the symbology resolution on this display. That is, at larger map scales, a set physical distance on the display represents greater distances such that a 0.25 inch distance measured on the display at a small map scale may represent 0.25 nmi while at a larger map scale that same display distance may represent 2 nmi. Thus the spacing accuracy becomes dependent on how well the pilot can resolve the difference in distance between the range arc and the leading aircraft's symbol (ref. 3). From a systems operational standpoint, there are two major problems with this concept. Because the aircraft are flying at a fixed distance, as soon as the leading aircraft changes speed, the following aircraft must make exactly the same speed change. While this may be acceptable for en route operations, when aircraft are flying miles-in-trail, this technique quickly becomes unacceptable for terminal operations. Consider three aircraft in-trail on an ILS approach with the first aircraft following a nominal approach speed schedule (e.g., 210 kts then slowing to 170 kts) (fig. 6). As soon as the leading aircraft changes speed, all of the other aircraft must also change speed, with each successively matching the speed of its leading aircraft (fig. 6). The last aircraft is then flying very slowly while still far from landing, with an increase of both fuel use and community noise. The other operational problem relates to an issue termed "unbounded speeds," which may best be described by an example. If each spacing aircraft is behind its required spacing interval, then each aircraft must fly faster than its leading aircraft to correct this spacing error (fig. 7). The problem with this successively increased speed is that even with a small number of spacing aircraft, the speed quickly becomes operationally unacceptable for terminal area operations.

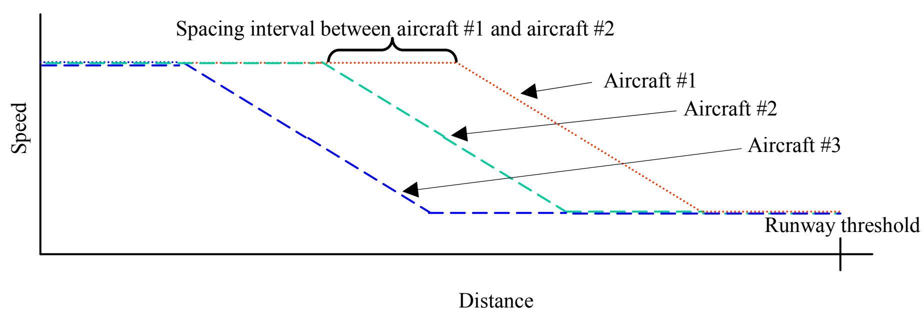

Figure 6. Example of nominal speed profiles for constant distance spacing aircraft.

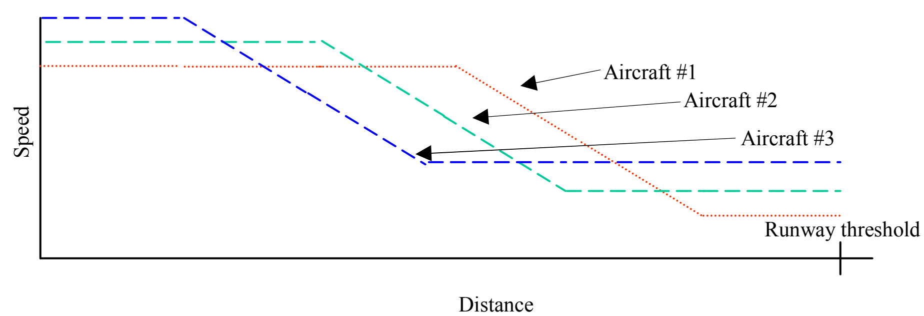

Figure 7. Example of successively faster speed profiles.

In summary, the constant distance spacing concept is relatively easy to implement and understand. The spacing accuracy is related to the display size and the map-scale value. Constant distance spacing has three very undesirable operational characteristics: closure rate increases if the leading aircraft turns, all of the aircraft change speed, proportionately, at the same time, and there is no speed bound.

Constant Time Spacing

Constant time spacing is also a very basic form of airborne self-spacing (refs. 4-9). Using this technique, the aircraft simply keep a fixed time interval between aircraft where the displayed interval is proportional to the spacing time interval and the current ground speed of the self-spacing aircraft. One example of a flight deck display for constant time spacing is shown in figure 8 (ref. 1). In this moving-map example, the pilot would set the trend vector to the spacing interval specified by ATC. The speed of the ownship would then be adjusted such that the end of the trend vector and the symbol for the leading aircraft were approximately on the same arc. For example, if the trend vector was behind the leading aircraft's symbol, then the ownship is behind where it needs to be and needs to fly faster than the leading aircraft to reduce this error. Similar to constant distance spacing, the advantages of this concept are that it is relatively simple to implement and for the flight crews to understand.

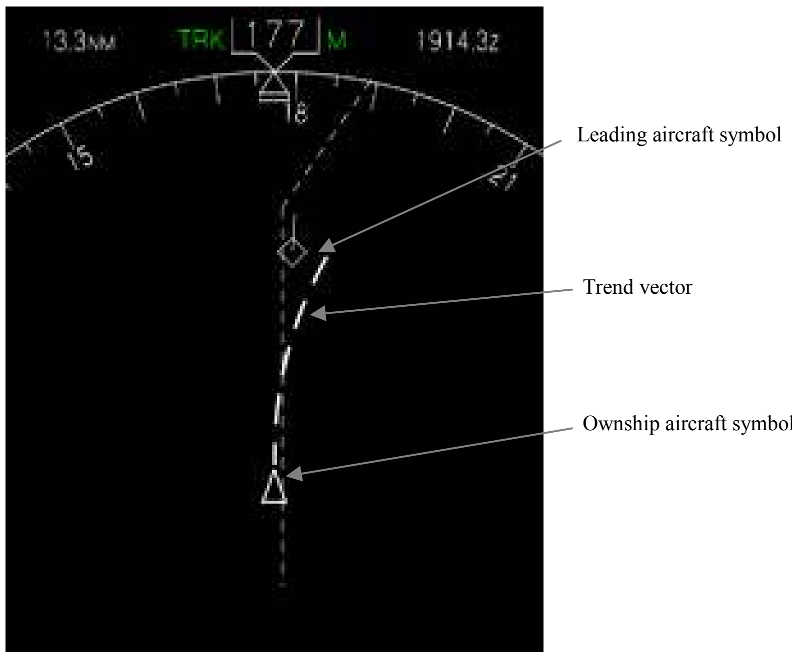

Figure 8. Example constant time spacing display format.

The disadvantages to this concept are similar to those of the constant distance concept. Again, the spacing accuracy is dependent on the symbology resolution of this display as well as the pilot's estimation of whether the trend vector and the leading aircraft's symbol are on the same arc. From a systems operational standpoint, there are again two major problems with this concept. Because the aircraft are flying at a fixed time interval with the displayed length on the trend vector dependent on this interval and the current ground speed, as soon as the leading aircraft changes speed, the following aircraft must also change speed. While this may be acceptable for en route operations, this technique quickly becomes unacceptable for terminal operations, although not as quickly as the constant distance spacing technique. Consider three aircraft in-trail on an approach. As soon as the leading aircraft changes speed, all of the other aircraft must also begin changing speed (fig. 9). The last aircraft is then flying slower while farther from the runway, with an increase of both fuel use and community noise. Unlike the constant distant concept, however, the speed profile for a speed change also becomes flatter for successive aircraft. The other operational problem is that this concept also suffers from unbounded speeds.

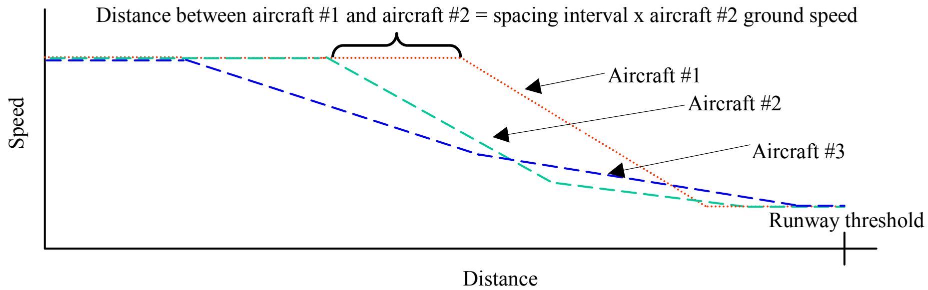

Figure 9. Example of nominal speed profiles for constant time spacing.

In summary, the constant time spacing is similar to constant distance spacing. Constant time spacing has three undesirable operational characteristics that are similar to the constant distance spacing problems: closure rate increases if the leading aircraft turns, successive speed changes begin farther from the runway for each successive aircraft, and this technique also exhibits unbounded speed behavior.

Constant Time Delay Spacing

Constant time delay spacing was developed to overcome the problem of early slowdown of successive aircraft in terminal operations. In this concept, which is also know as time-history spacing, each successive aircraft attempts to fly the speed profile of the aircraft it is following (refs. 7, 10, and 11). To do this, the previous time-correlated position data for the leading aircraft are retained by the ownship. Then, if the spacing goal were to maintain a 120 second spacing, then the ownship would attempt to be at a speed and position where its leading aircraft was 120 seconds earlier. Again, this generic concept was developed and evaluated in the mid-1980's by NASA. One example of a flight deck display for constant time delay is shown in figure 10 (ref. 1). In this moving-map example, the pilot would set the ownship symbol over the history dot that corresponds to the spacing interval specified by ATC. While not as simple as the constant distance spacing or constant time spacing techniques, this concept is still relatively simple to implement and for the flight crews to understand. Also, because the leading aircraft's ground track information is displayed via the history dots, an ATC instruction to "follow" the leading aircraft is relative easy to do by simply flying along the ground path created by the history dots. Because the ownship is nominally flying the same speed profile, with the speed changing at the same ground position as its leading aircraft, the early slowdown by successive aircraft is eliminated (fig. 11). Also, because the ownship is following the ground speed profile of its leader, this technique is extremely robust in situations where large wind shifts occur, even if these shifts are unexpected.

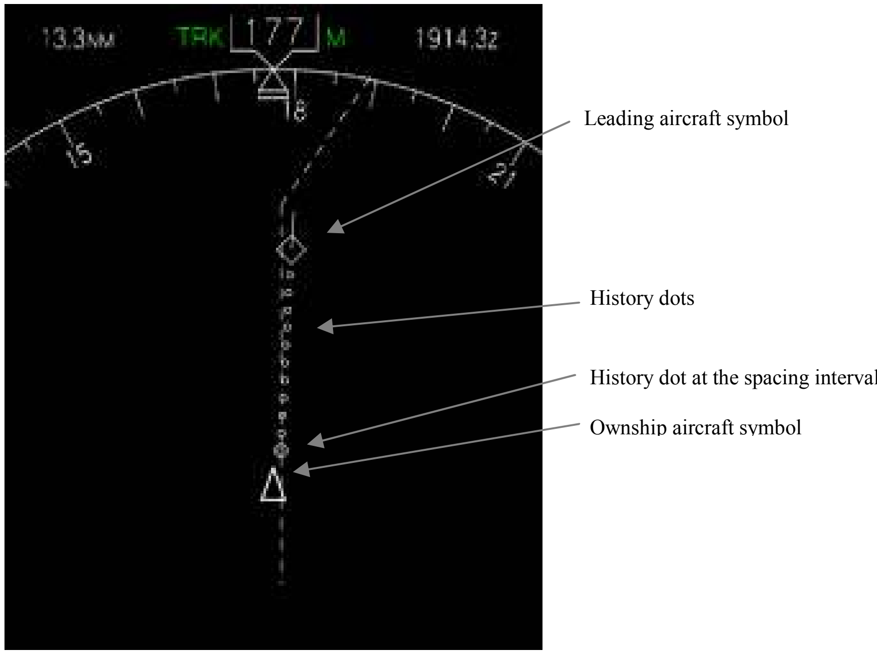

Figure 10. Example constant time delay spacing display format.

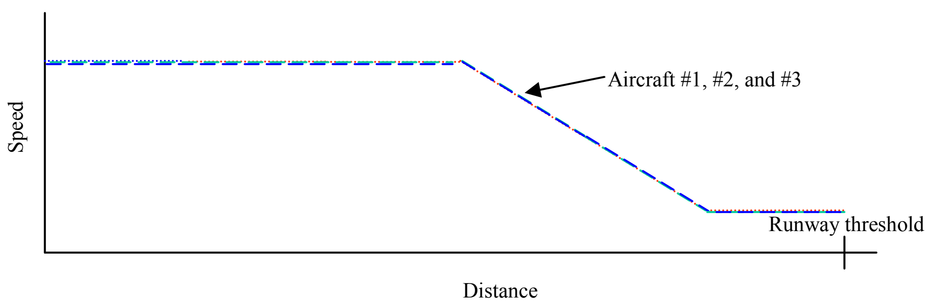

Figure 11. Example of nominal speed profiles for constant time delay spacing.

The disadvantages to this concept are common to those of the constant distance concept. Again, the spacing accuracy is dependent on the symbology resolution of this display (ref. 3). From a systems operational standpoint, the major problem with this concept is that it also suffers from unbounded speeds.

A later adaptation of this concept was investigated during the FAA SafeFlight 21 OpEval-2 flight trials (ref. 43) as a final approach spacing tool. To reduce pilot workload and to eliminate the spacing accuracy dependence on the display resolution, this implementation provided the pilot with a speed command that was based on the spacing error (fig. 12) and the ground speed history (fig. 13) of the leading aircraft. While the presentation of a speed command did appear to reduce pilot workload and head-down time, i.e., the amount of time the pilot needed to monitor the display to perform the task, numerous observations of the unbounded speed problem led to the conclusion that this technique was not viable for further development.

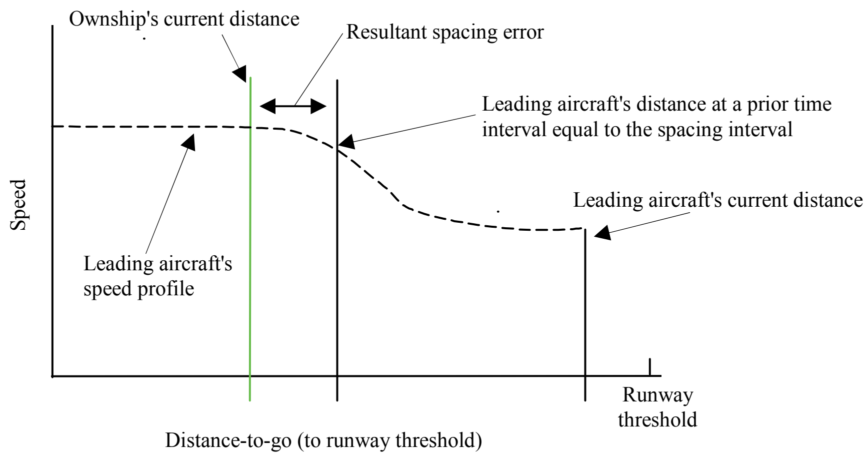

Figure 12. Constant time delay spacing error.

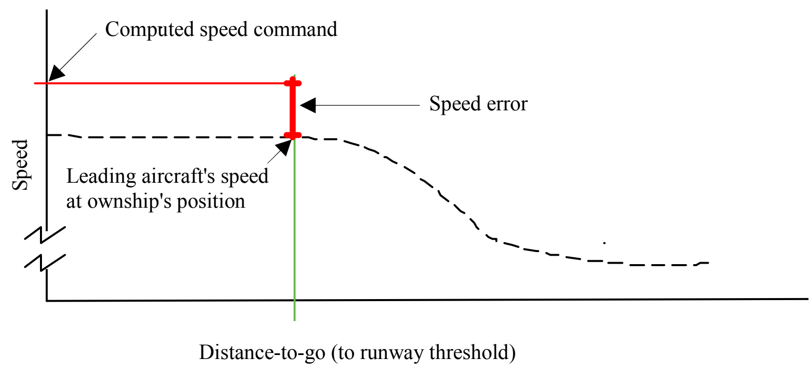

Figure 13. Constant time delay speed command.

Final Approach Spacing

Due to the unbounded speed problem observed during the FAA SafeFlight 21 OpEval-2 flight trials, both MITRE and NASA began pursuing a concept for final approach spacing that included a simple trajectory that would define the nominal approach speeds. The concept that NASA developed was a blend of constant time delay spacing coupled with a simple trajectory that provided the nominal speeds (refs. 14-19). As with the constant time delay concept, this technique is fairly robust in changing and unforecast wind fields. In this concept, the spacing error is computed in the same manner as in the constant time delay technique. The nominal speed, however, is taken from a simple speed-distance schedule (fig. 14) that would match the arrival speeds that would typically be assigned by ATC for this runway. The distance to the runway would be computed from the position data of the aircraft and a simple database containing the runway threshold data. To calculate the speed command, a speed error value would be computed based on the spacing range error. This speed error would then be converted from a ground speed reference to airspeed, then limited if necessary to ± 10% of the profile speed, and this term would be added to the nominal speed schedule value for the computed speed command value (ref. 13).

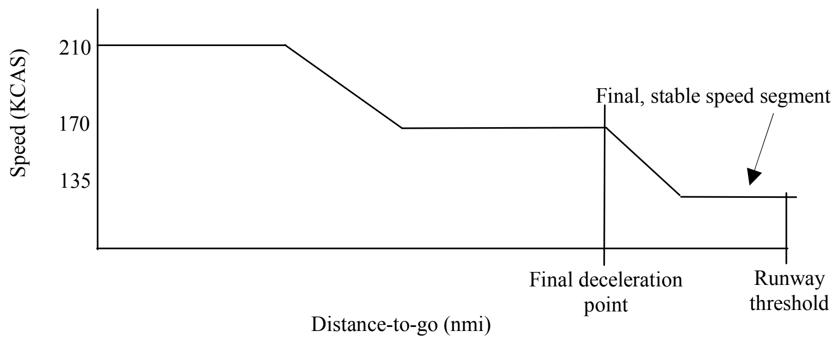

Figure 14. Typical nominal speed schedule.

Since this algorithm was designed to be operationally acceptable while still minimizing the variation of the spacing error at the runway threshold, a provision to support a stable, constant speed segment prior to the threshold (i.e., a stabilized approach capability), was designed into the concept. In this regard, the speed command would transition from actively tracking the aircraft spacing to providing speed guidance to the ownship's planned, corrected final approach speed with the speed change occurring along a planned deceleration schedule. This transition would be initiated at a specified distance, i.e., the final deceleration point from the threshold. But to minimize the spacing error at the runway when the ownship and the traffic have different final approach speeds, the algorithm would compensate for these dissimilar final approach speeds prior to the final deceleration point and adjust the spacing interval accordingly. For example, assume the following: the final deceleration point is 5 nmi from the runway, speed at the final deceleration point of 170 kts, ownship's final approach speed of 135 kts, leading aircraft's final approach speed of 120 kts, a final deceleration schedule of 0.75 kts / sec, and a planned spacing interval of 180 seconds. In this scenario, the ownship would close on the leading aircraft by almost 10 seconds during the last part of the approach. To compensate for this 10 second difference, this difference would be used to adjust the ownship's spacing interval to 190 seconds.

While no certified airborne equipment currently exists to support this concept, this could be relatively easy to implement, assuming that ADS-B information were available. This concept is further described in a standards document that defines a final approach spacing system (ref. 20).

Required Time of Arrival

At the other end of the aircraft spacing spectrum from constant distance spacing is required time of arrival (RTA). While not technically airborne spacing, the use of RTA is a means of airborne-assisted, aircraft spacing. Using this technique, ATC would schedule aircraft such that this scheduled time to cross a metering fix or the runway threshold would provide appropriate aircraft separation at that point, with this scheduled time becoming the RTA. Research of this concept has been ongoing for several decades (refs. 44-47) and has reached a level of maturity such that flight operations to further develop the concept are underway (refs. 30-32). To implement this concept, the aircraft requires a flight management computer (FMS) that has the ability to provide speed guidance to meet this assigned RTA. To do this, the FMS must compute a precise 4D trajectory, determine the current time error relative to the RTA, and then adjust the speed profile to eliminate this computed time error.

Probably the greatest advantage to using a RTA to achieve aircraft spacing is that the flight crew would simply be flying a FMS arrival procedure, albeit with a RTA. (fig. 15). The RTA function of the FMS would make the necessary speed adjustments to achieve the desired crossing time and the flight crew would simply follow the provided guidance. Also, because the solution is trajectory-based, aircraft do not need to arrive along a common path, which is the case for all of the previously presented concepts. Other advantages are that the aircraft could fly a near-optimum descent, since the vertical guidance is from the FMS, and the profile that the FMS is using could itself be a CDA profile.

Figure 15. Example of RTA data from FMS.

There are several problems, however, that must be addressed prior to using a RTA for aircraft spacing. The first problem is that the ATC ground system must be able to provide a reasonably accurate arrival schedule for the landing aircraft. This scheduling solution is not trivial in that uncertainties in individual aircraft performance and wind forecast errors can have a significant, detrimental effect on the arrival time estimation. If the schedule is not achievable, the aircraft will subsequently need to be given an updated arrival time or its RTA clearance cancelled. If the schedule is not accurate, then the potential for loss of separation exists since the aircraft are operating independently of each other.

The second potential problem with using RTA for spacing is that the design of a specific FMS will obviously determine how it would compute a speed profile to meet waypoint crossing restrictions, to include a RTA. Figure 16 shows the speed schedules for an extreme example on how two different techniques could be used to meet exactly the same crossing restrictions, to include time. In this example, both aircraft start at exactly the same position, at the same speed (240 kt), and at the same time. Both aircraft will finish at the same position, again at the same speed (170 kt) and at the same time. At the start, one aircraft begins a linear deceleration such that it will cross the next waypoint just as it reaches 170 kt. At the same time, the second aircraft maintains 240 kt until it is almost midway between the two waypoints and then decelerates at 1 kt/sec to 170 kt, remaining at that speed while crossing the next waypoint. What is of interest to aircraft spacing is that at a time halfway between the two waypoints, the second aircraft has flown approximately 1.5 nmi farther than the first aircraft (figs. 17-18). If these same speed schedules were used for the case when the second aircraft was following the first, the second aircraft would have closed 1.5 nmi during this segment of the arrival. The real issue, from an operational standpoint, is that differences in aircraft and FMS performance could easily create a separation problem when the arrival route is composed of numerous segments, especially if some of them are unconstrained in speed. Even if the intermediate waypoint speed and altitude crossing restrictions are constructed to minimize this problem, assuring that a RTA schedule is met at the waypoint or the runway threshold may not guarantee separation throughout the procedure.

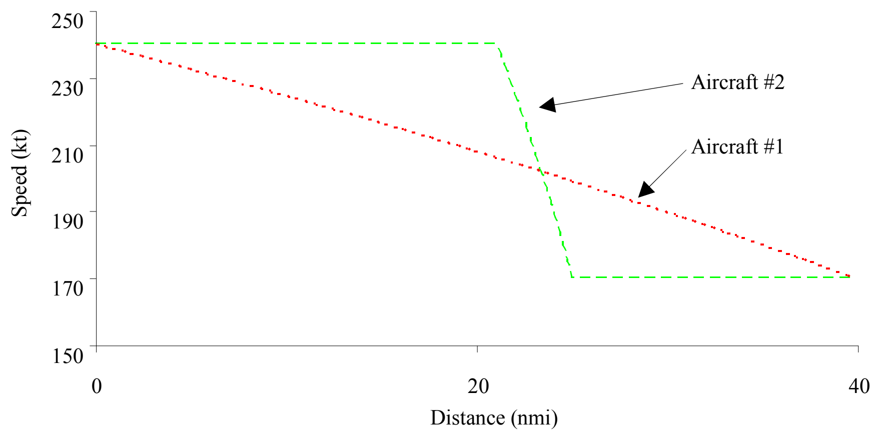

Figure 16. Example of speed – distance profiles.

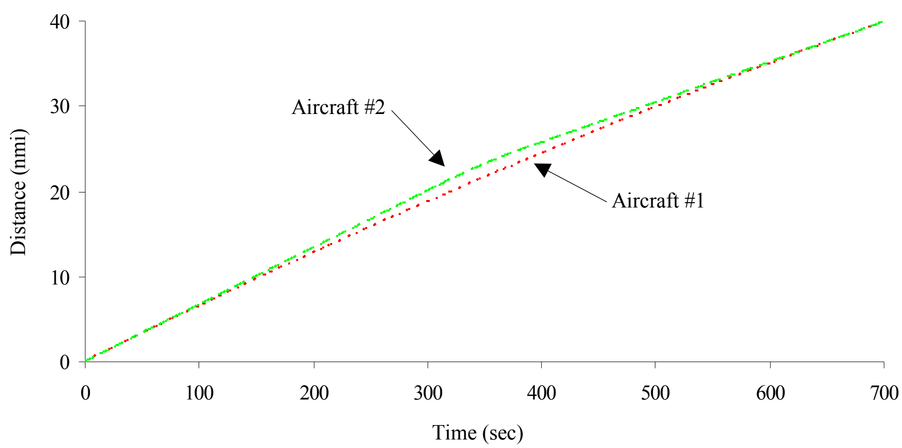

Figure 17. Distance – time results from the example of figure 16.

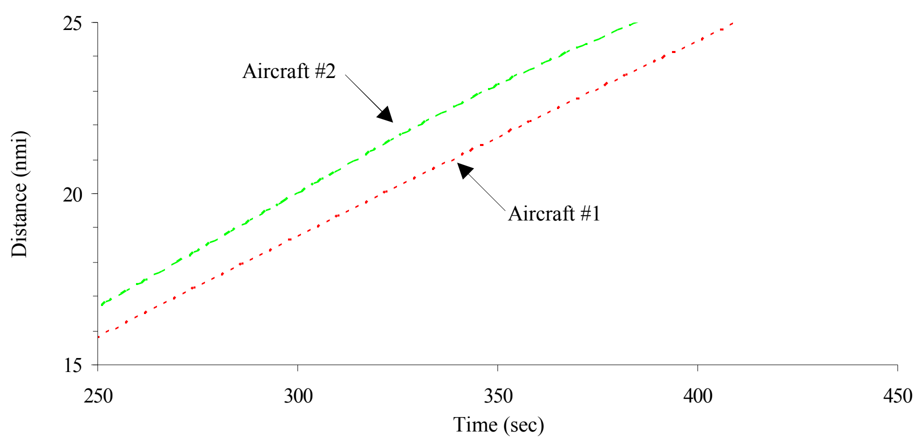

Figure 18. Partially expanded view of figure 17.

One means to overcome the potential loss of separation during RTA operations is currently being developed and flight tested in Europe (ref. 33). This technique uses the latest generation GE Avionics FMS installed on Boeing 737NG aircraft to downlink to ATC the aircraft's full 4D trajectory, based on the aircraft's nominal landing time. A newly-developed ATC system then evaluates this 4D trajectory with respect to the downlinked trajectories of all surrounding aircraft to determine if the trajectory is conflict-free. If the trajectory is conflict-free, then ATC may issue a RTA to the aircraft based on its nominal landing time. If the trajectory is not conflict-free, ATC may issue an alternative RTA and the process is then repeated. While research and flight experimentation into this trajectory exchange and negotiation process to enable fuel efficient descent has been ongoing since 1994 (ref. 48), the current work is nearing regular operational use.

The third issue relates not just to the RTA concept, but to any spacing concept when spacing is not actively performed relative to another aircraft. In determining the landing rate for a runway, the nominal runway threshold arrival rate and the arrival rate error must be considered. For aircraft that are independently arriving at the runway, as with a RTA, the arrival rate error for both the leading and the following aircraft must be considered in determining the landing rate. For aircraft that are spacing relative to their leader, the arrival rate error for only the following aircraft needs to be considered in determining the landing rate.

The final issue is also not limited to just the RTA but for all of the trajectory-based solutions, i.e., RTA, tailored arrivals, and relative trajectory-based spacing. The issue is that since aircraft can arrive from different directions in these concepts, an inaccurate wind forecast can have a much larger, detrimental impact on pre-merge spacing operations than on post-merge, in-trail operations. This is because the wind forecast error can have a doubling effect in opposite-direction, pre-merge situations, even in the presence of the same wind environment. That is, with a wind forecast error, one aircraft could have a headwind error that would exceed its speed control authority to correct and arrive late at waypoints along its route, while the other aircraft has tailwind error causing an early arrival. If the headwind aircraft was scheduled to arrive just before the tailwind aircraft, these aircraft could experience a loss of spacing at the waypoint where their routes merge. Several techniques have been considered that could minimize this problem, with the continuous updating of the arrival schedule being the first and most obvious technique. This technique, however, introduces its own issues, the most significant being that if an aircraft's arrival schedule is changed at or after the top of descent, the aircraft may not be able to continue on a CDA. Another obvious alternative would be to provide very frequent updates to the forecast data via a data link from the ground to the aircraft. These and other techniques are currently being explored to minimize this problem.

In the near term, probably the greatest limitation to using RTA for arrival spacing is that very few aircraft have the ability to perform this operation. In addition, the ATC ground system must be able to provide a reasonably accurate, conflict-free RTA schedule for this to be a viable concept.

Tailored Arrivals

Similar to the RTA, tailored arrivals (refs. 35-40) aren't technically airborne spacing, but are a means of airborne-assisted, aircraft spacing. The concept is similar to RTA in many other aspects except that it doesn't require a RTA-capable aircraft. Like the RTA, ATC would schedule aircraft such that adhering to this scheduled time to cross a metering fix or the runway threshold would provide appropriate aircraft separation at that point. Unlike the RTA, however, the ATC ground system would compute even the initial trajectory (ref. 34). This trajectory, which includes the basic route data, wind information, and crossing restrictions, is then data linked to the aircraft.

These data, once inserted into the aircraft's FMS via a Future Air Navigation System (FANS) -1/A data link, provide a pseudo-RTA capability to the aircraft. A special ATC software program would generate an RNAV arrival route for each aircraft, with this route based on a performance model for that aircraft type; hence the route is "tailored" for that aircraft. This tailored route, which includes real-time wind updates obtained via data link from arriving and departing aircraft that are processed by the ground system, provides a high degree of assurance that the route will be as near optimum as possible for the aircraft while maintaining a conflict free path.

This concept is very similar to the RTA with respect to benefits and limitations (see the previous section, *Required Time of Arrival*). The major difference in airborne equipment is that the RTA concept requires a RTA-capable FMS while the tailored arrivals require FANS capability. The ATC ground system for the tailored arrivals requires performance models for each aircraft type so that it can deliver near-optimum arrival routes for each aircraft. Because the route data are uplinked from the ground, the tailored arrival concept is not limited to preloaded waypoint data. While the RTA requires a ground system that can supply a reasonably achievable arrival time for the aircraft, the tailored arrivals concept requires a supporting ground system that includes specific aircraft model performance data.

Field trials are currently underway for this concept using a ground-based, support system developed by NASA to provide the trajectory solutions and FANS equipped, Boeing 777ER and 747-400 aircraft operated by United Airlines (ref. 40).

Relative Trajectory-Based Spacing

Relative, trajectory-based spacing can be thought of as a blending of the final approach spacing concept with RTA. A fairly simple implementation of this concept has been developed by EUROCONTROL (ref. 49). Another implementation (ref. 50) of this general spacing concept is under development by NASA and is part of the future work planned for the FAA Flight Deck-based Merging and Spacing (FDMS) activity. Like the RTA concept, this latter implementation employs a full 4D trajectory from each aircraft's position to the runway. With aircraft arriving in sequence to the same runway, the controller can assign each following aircraft in the stream to arrive at the runway threshold at a specific interval, either time or distance, behind an assigned lead aircraft. Because this spacing operation is pair-wise, two aircraft arriving via different routes will merge onto the common route without the need for any additional flight crew intervention or change in the spacing guidance. Numerous arriving aircraft can be sequenced and spaced in this fashion. By combining airborne spacing with CDAs, the environmental benefits of CDAs can be realized while maintaining or increasing capacity relative to current-day levels.

In this concept, the ownship would use both its and the leading aircraft's arrival route information to generate a 4D trajectory for each aircraft. It is expected that the name of each aircraft's arrival route will be broadcast by that aircraft via ADS-B. An alternative technique that has been proposed is to have each aircraft compute just its own trajectory and broadcast its calculated time-to-go (TTG) to the runway. The nominal spacing time is then computed by adding the leading aircraft's calculated TTG to the runway, based on its current position on the trajectory, to the spacing interval. The difference between this nominal spacing time and the calculated TTG to the runway for the ownship is the spacing error (fig. 19).

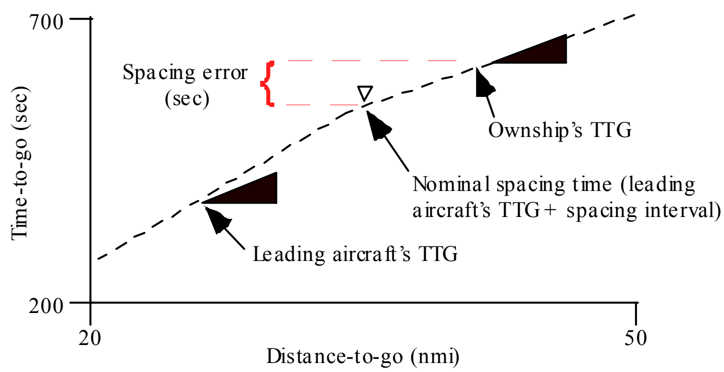

Figure 19. Example of relative trajectory-based spacing error.

Since the goal of this self-spacing system is to deliver the aircraft properly spaced at the runway threshold while maintaining arrival stream stability, gains are applied to the spacing error so that the resulting speed commands are less aggressive far from the runway and become more aggressive as the aircraft approaches the runway. This technique has been shown to aid in providing stability to the arrival stream. The computed speed command that would be provided to the flight crew is a speed error value that is added to the published arrival route speed associated with the position of the ownship on this route. The speed error value is initially based on the spacing error and is then limited to a percentage of the profile speed. This method of using the published speed as the nominal speed command also enhances arrival stream stability and eliminates excessive excursions from the published arrival speeds, where these excursions can otherwise become operationally problematic when successive spacing aircraft are attempting to overcome large spacing errors.

For an initial airborne implementation of this FDMS concept, this technology was not planned to be integrated into the existing aircraft systems, especially the autoflight system, but was planned to be an independent add-on implemented in an Electronic Flight Bag (EFB). Because of this, a large effort was undertaken to minimize pilot workload during the self-spacing operation. As part of this workload reduction, speed changes were limited to 10 knot increments. Also, gain scheduling was used to reduce the magnitude of the speed commands at increasing distances from the runway and a spacing error notch filter, also based on the distance to the runway, is employed. The spacing error gain and notch values were set to 0.25 and 1 nmi, respectively, for distances greater that 130 nmi from the runway and 1.0 and 0 nmi, respectively, for distances less than 30 nmi. These values were changed linearly between these two distances. Examples of the resulting, adjusted spacing error are shown below for distances to the runway of 30 and 130 nmi (fig. 20).

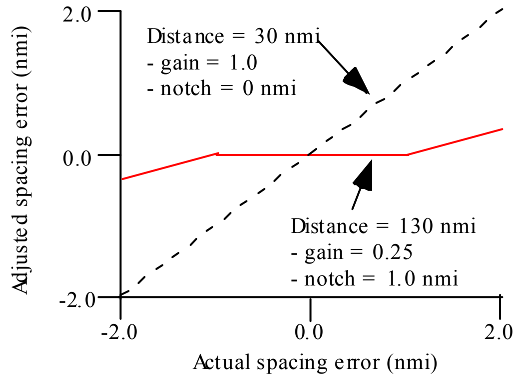

Figure 20. Gain and notch filtering for the relative trajectory-based spacing concept.

As with the RTA and Tailored Arrivals concepts, the ATC ground system must be able to provide a reasonably accurate arrival schedule for the landing aircraft. However, the ATC landing schedule for relative, trajectory-based spacing does not need to be as exact as for the other concepts since the aircraft will be continuously adjusting their spacing relative to their leading aircraft. Thus small disturbances and scheduling inaccuracies would be compensated for because of the relative spacing design.

While inaccurate wind forecasts are probably the greatest issue for all of the trajectory-based solutions, forecast errors can have a compound, detrimental effect on this concept. For example, during pre-merge spacing operations, with the aircraft approaching from opposite directions, the spacing system could erroneously predict that the leading aircraft would arrive sooner than actual to some waypoint due to an invalid tailwind forecast. The opposite could also be true for the ownship, which could be predicted to arrive later than actual to the same waypoint due to an invalid headwind forecast. The doubling problem with this relative spacing concept is that the spacing system will attempt to compensate for both of these prediction errors. Several techniques have been considered that could minimize this problem, with the continuous updating of the wind forecast either from the ground to the aircraft or via aircraft-to-aircraft wind information exchange. These and other techniques are currently being explored to minimize this problem.

Summary

The concepts presented in this paper evolved to provide either additional operational benefits or to overcome deficiencies in previous designs. The short-term control concepts included constant distance spacing, constant time spacing, and constant time delay spacing. These concepts were focused on immediately obtaining the spacing goal and are relatively easy to understand and implement. In fact, both constant distance spacing and constant time spacing concepts could be implemented with existing aircraft systems, i.e., TCAS and the navigation display, although TCAS is not certified for this use. However, because of the immediate slowdown effect of these two concepts, they are not suitable for terminal area operations, especially if long strings of aircraft are involved. While the constant time delay concept was designed to overcome this slowdown problem, operational trials have shown that the unbounded problem make this concept unsuitable for final approach operations. The final approach spacing concept was a derivation of the constant time delay concept that included a simple approach trajectory with this trajectory used as a means to overcome the unbounded problem. These four concepts, while relatively simple, required the participating aircraft to be in-trail, i.e., one behind the other. The three 4D trajectory concepts, while relatively complex, allow the aircraft to operate in a more efficient manner, to include supporting CDA operations. These three trajectory concepts also allow for spacing operations to be conducted prior to the aircraft becoming in-trail, i.e., they allow merging operations. A synopsis of the relative merits and requirements for the presented concepts is provided in Table 1. As can be seen from this table, as the operational capability is expanded, the complexity of the supporting system increases as well.

Table 1. Synopsis of the spacing concepts.

Concept	Supports merging	Supports aircraft optimized arrivals	Supports runway arrival precision	System complexity	
				Aircraft[1]	Ground – ATC[2]
Constant distance				very simple	none
Constant time				very simple	none
Constant time delay				simple	none
Final approach			*	simple	none
Relative trajectory-based	*	*	*	complex	complex[3]
Tailored arrivals	*	*	*	complex[4]	very complex[5]
Required time of arrival	*	*	*	complex[6]	complex[3]

[1] Assumes traffic data, e.g., ADS-B and basic display of traffic.
[2] All concepts may require some form of performance monitoring capability for ATC.
[3] Requires a reasonably accurate scheduling capability.
[4] Certified equipment, i.e., FANS, currently exists on a limited number of aircraft.
[5] Requires a reasonably accurate scheduling capability with aircraft specific performance models.
[6] Certified equipment, i.e., RTA-capable FMS, currently exists on a limited number of aircraft.

While the focus of this paper has been on the history of airborne spacing concepts, the future is that one or more of these 4D spacing concepts will probably be operational within the next decade. However, accurate wind forecast data are critical to the operational success of these concepts. With large starting distances from the airport and multiple routes, even relatively small wind forecast errors can result in significant disruptions to the efficient and effective use of these concepts in supporting increased growth and reduced costs for operating within a national airspace system. The greatest technical challenge in fielding one of these concepts will not be the spacing equipment *per se*, but will be the ability to provide accurate wind forecast data to the airborne and ground systems that are supporting these operations.

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14. ABSTRACT

This paper presents a history of seven of the more significant airborne and airborne-assisted aircraft spacing concepts that have been developed and evaluated during the past 40 years. The primary focus of the earlier concepts was on enhancing airport terminal area productivity and reducing air traffic controller workload. The more recent efforts were designed to increase runway throughput through improved aircraft spacing precision at landing. The latest concepts are aimed at supporting more fuel efficient and lower community noise operations while maintaining or increasing runway throughput efficiency.

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