

Controlled Time-of-Arrival Flight Trials

Results and Analysis

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Abstract—The CASSIS project has been tasked with developing a Concept of Operations for use of Time-of-Arrival Control in the terminal area. Reducing or replacing low level vectors and holding with enroute delay through the use of time constraints is a key component in both NextGen and SESAR. A set of revenue service flights using airborne time control to the Initial Approach Fix and the runway threshold was conducted in September 2008 as part of the CASSIS project. These flight trials facilitated an examination of the factors affecting time control behavior and the potential for use of airborne time control in the terminal area in near- and mid-term time frames. The impact of airborne control to a single time constraint on separation between aircraft is also examined. This analysis shows that the use of current generation avionics to meet a time constraint at a point in the approach is possible with accuracies of less than 5 seconds, and can achieve 2 minute landing spacing at the runway threshold with no loss of intermediate separations. Recommendations for future developments and considerations for larger scale implementation are also discussed.

Keywords - Required Time-of-Arrival; Trajectory Based Operations; Controlled Time-of-Arrival; Flight Management System; 4D Trajectory

I. INTRODUCTION

Two major obstacles confronting the growth of air traffic in North America and Europe over the next twenty years are environmental impact – including noise and greenhouse gas emissions – and capacity constraints in terminal airspace. The FAA forecasts that the current levels of air traffic will more than double by 2025, and acknowledges that the current air traffic control system will not be able to manage this growth [1]. This issue is clearly recognized by both the USA’s NextGen and Europe’s Single European Sky ATM Research (SESAR) programs, which aim to *reduce* the environmental impact of aviation while *increasing* capacity and safety. A key transformation to achieve these goals is the use of Trajectory Based Operations (TBO), including the use of airborne Required Time-of-Arrival (RTA) functionality.

The NextGen Avionics Roadmap has identified three mid-term (2012 – 2018) capabilities needed to improve traffic management with RTA:

- Route Clearance with RTA

- Route Clearance with RTA and Downlink of Expected Trajectory
- Trajectory Clearance with RTA and Downlink of Expected Trajectory [2]

However, a significant amount of ambiguity remains regarding TBO and what it means from an aircraft’s perspective. Additionally, [2] has identified that of all the dimensions in a 4 Dimensional Trajectory (4DT), time is currently the least constrained. Moreover, the FAA’s NextGen Implementation Plan 2008 identifies a key change required to implement 4D TBO will be “[d]efined constraints on vertical and time-along-path performance and the ability to communicate these constraints over a robust data link (in addition to the trajectory itself)” [3].

Launched in November 2007, the CTA-ATM System Integration Studies (CASSIS) Eurocontrol Partnership Project involves stakeholders from industry, research and operations. The project is investigating the use of airborne functionality to fly to a Controlled Time-of-Arrival in medium and high density traffic situations [4]. The potential to improve predictability and sequence traffic at an earlier state than is currently done, as well as an expansion of the ATM planning horizon to replace terminal low-level holding by en-route delay is being examined. In addition, the project is looking at the increased use of trajectory-based and time-coordinated operations to enable more flight-efficient, airborne-managed-operations. This paper describes the results of a series of time controlled flights, presenting an initial investigation into the current state-of-the-art of the time-along-path performance relative to a reported trajectory and the factors that impact this performance. Moreover, the impact of CTA use on multi-aircraft separation and recommendations for future use are presented.

II. TRAJECTORY BASED OPERATIONS

A primary goal of Trajectory Based Operations is to reduce the uncertainty associated with the prediction of an aircraft’s future location through use of an accurate trajectory in all 4 dimensions (latitude, longitude, altitude, time). The NextGen Concept of Operations states that the “use of precise 4DTs dramatically reduces the uncertainty of an aircraft’s future flight path, in terms of predicted spatial position (latitude,

longitude, and altitude) and time along points in its path” [5]. This represents a significant change from the present ‘clearance-based control’ (depending on observation of the aircraft’s current state) to trajectory-based control, with the goal of allowing the aircraft to fly along the user-preferred trajectory. A critical enabler for TBO is the availability of the full planned optimal profile, providing the controller with valuable information to allow more effective use of the airspace.

The defined trajectory may include one or more time constraints. These constraints are referred to as Required Time-of-Arrival (RTA) or Controlled Time-of-Arrival (CTA). In the remainder of this paper, these constraints will be referred to as CTAs. Current Time-of-Arrival control functionality adjusts and regulates the aircraft’s speed along the trajectory in order to arrive at a specified waypoint (potentially the arrival runway) at a specified time, thus improving the predictability of the arriving aircraft. This in turn may be used to improve runway throughput, by more precisely organizing movements into arrival slots using the time control capability of the aircraft. Also controller efficiency may be improved by providing automated support functions to enable this up-front coordination. Other ‘time related’ optimizations are also possible, such as collaborative decision making on best use of assets (gate assignments, supporting equipment and personnel).

Another proposed use of airborne CTA functionality is for metering of aircraft in terminal operations to facilitate efficient arrival and departure flows. One of the key NextGen mid-term Operational Improvements is the introduction of Time-Based Metering Using RNP and RNAV Route Assignments. It is recognized that replacing miles in trail restrictions with the use of time-based metering at designated metering fixes will allow the increased implementation of Optimized Profile Descent (OPD) operations and more efficient use of runways and airspace. In the mid-term, these meter fix crossing times will be issued to the FMS in the form of single time constraints [6].

Airborne time control has also been identified as a key component of SESAR. Datalink supporting airborne CTA navigation functionality is called a key airborne enabler for the 2015 ECAC airspace concept [7]. Moreover, [8] states that the use of CTA to meter aircraft into the terminal airspace will improve both flight efficiency and capacity, and the combination of CTA with advanced RNP capability is called a step towards the SESAR 4D Trajectory Management concept.

It is clear that the use of airborne time control functionality to meet a time constraint at a metering fix will be a key enabler to the time-based metering concept proposed in both NextGen and SESAR. However, one concern expressed regarding this concept is the impact on intermediate separation between two consecutive aircraft flying the same lateral profile. Although two aircraft assigned unique time constraints at a metering fix to achieve a desired time spacing at the fix will be separated at the beginning and end of that operation, concerns have been raised about possible intermediate losses of separation while the respective aircraft are maneuvering to meet that time

constraint. There are several reasons why this might occur. One reason is intermediate speed changes that may be made to compensate for wind errors while controlling to the necessary time-of-arrival. Another potential cause could be significantly different speeds used by the two aircraft, possibly due to different FMS algorithms.

Ref. [9] examined this issue assuming two different CTA algorithms which would compute very different cruise and descent target speeds to meet their time constraints. This study determined that a loss of minimum separation was possible during the descent even if both aircraft exactly met their assigned metering times. However, [10] and [11] presented a simulation analysis showing that although separation losses were possible in cases of extreme wind modeling errors, the results were the same or better than when a ground issued speed target was used for the operation.

There are varying degrees of CTA functionality implemented in modern commercial aircraft FMSs, and some of these are described in [12]. Although airborne time-of-arrival control was originally designed for use in the enroute portion of a flight, it is now recognized that this functionality can also be very beneficial in the descent and arrival flight area by providing increased predictability to the Air Navigation Service Provider (ANSP), thereby reducing the amount of vectoring needed to ensure the appropriate spacing between aircraft.

Although CTA functionality has been available in modern commercial jet transport Flight Management Systems (FMS) for many years, the use of the functionality to improve traffic management and efficiency has been investigated only recently. Simulation analysis has been used to demonstrate the potential ATM improvements using airborne time control functionality [10], [11], [13]. Flight trials have also demonstrated this potential. In 2001, a series of flight trials with Scandinavian Airlines System (SAS) evaluating the use of their Boeing 737 FMS and its CTA function for a future Air Traffic Management (ATM) environment was performed, indicating that aircraft equipped with the current generation avionics can reliably ‘predict’ and maintain a 4D trajectory over an entire flight in real-world fleet operations [14], [15]. Subsequent flight trials in 2006 [16] and 2007 [17] evaluated improvements to the CTA algorithm, showing increased time control accuracy. These flight trials showed the accuracy of modern FMS CTA functionality in descent in the presence of wind modeling error. The accuracy and stability of the FMS-generated 4DT as well as the trajectory file size and dynamics were evaluated, demonstrating the role TBO may have in contributing to the SESAR and NextGen goals of increased capacity and safety with a reduction in environmental impact.

III. CASSIS FLIGHT TRIALS

As part of the larger set of flight trials within the CASSIS project defined in [18], a subset of 32 revenue-service 4D Trajectory data-gathering CTA flights was conducted with SAS from September 22 to 25, 2008. The data collected in these flight trials has allowed an investigation on the suitability of the

FMS 4D trajectory and time-control behavior for Trajectory Based Operations.

A. Objectives

The 2008 flight trials aimed to build on the previous trials by collecting additional data to evaluate the time-control accuracy and the factors impacting the behavior. The Quick Access Recorder (QAR) data was collected from each flight, and multiple instantiations of the full ARINC 702A defined 4D trajectory for each flight were down linked, allowing a more detailed and thorough examination of the accuracy and stability of the intervening 4D trajectory. Finally, a comparison of the full 4D trajectory is performed between flights to evaluate how this affects separation between flights.

To evaluate what role TBO may have in contributing to the SESAR and NextGen goals of increased capacity and safety with a reduction in environmental impact, the key objectives of this experiment have been:

- 1) Analyze factors affecting CTA behavior
- 2) Analyze the impact of CTA use on separation

B. Experiment Setup

The experiment was conducted from September 22 to 25, 2008 using SAS Boeing 737-600 and 737-800 aircraft. The FMS onboard these aircraft were the GE Aviation Systems FMS Update 10.7. This FMS includes an implementation of the ARINC 702A-1 Trajectory Bus, allowing the FMS' constructed trajectory to be shared in networks, using aircraft data link. The ARINC 702A-1 Trajectory bus outputs the current aircraft state as well as the latitude, longitude, altitude, and estimated time-of-arrival at every trajectory change point (TCP) between the aircraft and the destination. The 4D location of various TCPs (such as Top-of-Climb, Top-of-Descent, crossover altitude, or the start of a deceleration) is also provided. In addition, the FMS update U10.7 includes CTA and predictions capabilities improvements to support further TBO evaluations.

To keep aircraft wiring changes to a minimum for this experiment, network access to the Swedish Air Navigation Service Provider (Luffartsverket – LFV) was performed using an existing data link. The data link used was the SAS ACARS networks via the airline operational communications (AOC) functions, including the SAS/Rockwell Collins Hermes data link application portal, to form the necessary interface with LFV's application infrastructure. To make the trajectory data available to ACARS, the FMS software "copies" the Intent bus data content to a number of words on the ACARS bus, facilitating network access with almost no change to any of the currently operational functions.

The infrastructure at LFV comprises the Collaborative Information Exchange System (CIES), which collects the aircraft trajectory data, performs the coordination functions and generates any applicable constraints required to preserve proper conflict free operation. In the experiment, freedom of conflicts was enabled by constraining the lateral flight path to a standard arrival routing (STAR), while assigning a time slot to the flight under analysis in the form of a CTA constraint at the runway landing threshold.

A jump-seat observer (JSO) was present in the cockpit during each trial flight to instruct and assist the crew regarding the goals of the trial. This was extremely important to maintain consistency between the flights, given the variability of pilot actions and preferences during normal flights. All cockpit actions were recorded using a digital audio-video camera, allowing evaluation of conformance with test goals, identification of anomalous behavior (such as flight plan changes, ATC intervention, etc), actual and entered winds, FMS prediction update events, cockpit communications, and other events that might affect the trajectory computation and/or stability.

The flights were designated as "Trial Flights", so the ANSP issued only time constraints once the crew was notified of the planned arrival runway and STAR, refraining from issuing speed constraints, altitude constraints or vectoring to the extent possible. This ensured not only the desired data quality by allowing the FMS to conduct the entire flight with both lateral and vertical navigation engaged, but also avoided invalidating earlier instantiations of the trajectory prediction by subsequent tactical interventions.

IV. RESULTS AND ANALYSIS

Following the flight trials, the cockpit videos were reviewed to determine any anomalies that may have impacted the trial, such as a change of cruise altitude, a Direct-To clearance, or vectors. This allowed the flights which were unaffected by ATC to be isolated, and any remaining anomalies to be correlated to cockpit actions. Using the 4DT downlinks and QAR data for these flights, the time control accuracy could be examined relative to factors such as wind modeling error and flap/slat extensions. Because the 4DTs contained time predictions in seconds, and the QAR data was recorded every second, the predicted and actual trajectories could be 'time-shifted' to simulate one aircraft following another. This facilitated an examination of the potential use of time constraints on intermediate separation.

A. Factors Affecting CTA Performance

Because the use of Controlled Time-of-Arrival in revenue service operations has been very limited, the influence of different factors on the dynamic behavior in real-world scenarios has not been explored in significant detail. One of the primary goals of this set of trials was to isolate various factors to determine their impact on the time control performance.

For these trials, several different types of time constraints were used. On half of the flights into Stockholm-Arlanda (ARN), the time constraint was placed at the runway threshold, while on the other half of the inbound flights the time constraint was placed on the Initial Approach Fix (IAF), which also has a 5000 foot altitude constraint. Moreover, on some of the flights the original Estimated Time-of-Arrival (ETA) was simply converted to a time constraint, while on other flights the time constraint was set earlier or later than the original ETA by 2 minutes.

The overall accuracy is summarized in Table I. The relative mean and standard deviation were computed using the

CTA Error as defined in (1), where an early error is negative, and a late error is positive. The absolute values, on the other hand, use the magnitude of the right-hand side of the equation, as defined in (2).

$$\text{CTA Error} = \text{Actual TOA} - \text{Required TOA}. \quad (1)$$

$$\text{CTA Error} = |\text{Actual TOA} - \text{Required TOA}|. \quad (2)$$

	CTA Accuracies				
	IAF	Threshold (All)	Threshold (ETA)	Threshold (ETA+2)	Threshold (ETA-2)
<i>Rel. Mean</i>	-0.4 sec	3.3 sec	7.6 sec	-6.6 sec	3.1 sec
<i>Rel. σ</i>	5.9 sec	17.3 sec	10.9 sec	19.7 sec	23.6 sec
<i>Abs. Mean</i>	4.0 sec	14.7 sec	10.9 sec	17.0 sec	19.4 sec
<i>Abs. σ</i>	3.9 sec	9.4 sec	7.1 sec	9.1 sec	11.4 sec

TABLE I. COMPARISON OF CTA ACCURACIES

The magnitude of the time error at the IAF is very small at only 4 seconds, with a 3.9 second standard deviation. Moreover, the relative mean is on -0.4 seconds. However, as expected, the time error at the runway threshold itself was significantly larger than at the IAF. Although the relative time error at the runway threshold was also small, at only 3.3 seconds, the average magnitude of the error was almost 15 seconds. This is still very good time precision for runway operations, but it is much less precise than what was observed for time control at the IAF, which was approximately 19 nautical miles before the threshold. This error is also significantly larger than the 7.8 second mean error magnitude observed during similar trials in 2007 [17].

Although the error at the threshold was larger than expected, it allows some very useful comparisons to isolate the factors that contributed to the behavior. The last three columns in Table I show the error at the threshold broken up by whether the CTA was set equal to the original ETA, 2 minutes later, or 2 minutes earlier. This shows that the error is much larger when the time constraint is set farther from the optimal time. Thus, one factor influencing the CTA behavior is the magnitude of the difference in the time constraint from the original (optimal) time-of-arrival.

The difference in CTA performance from the previous trials also provides insight into factors that may have caused these differences by examining discrepancies between the two sets of trials. One significant difference between the trials was the

runway and approach procedure that was used for CTA flights inbound to ARN. In 2007, all CTA flights to ARN arrived at runway 26; however, during the 2008 trials the arrival runway was 01L. The speed profiles for these two STARs are shown in Fig. 1.

Fig. 1 clearly shows how the speed control authority was lost much earlier in the approach during the 2008 trials at approximately 40 NM from the runway, as opposed to only 16 NM away during the 2007 trials. The speed and altitude constraints on the Green Approach STAR to runway 01L require a deceleration along a steep descent gradient. As a result, the deceleration to the final approach speed (V_{ref}) begins much earlier in the approach than it does on the Green Approach STAR to runway 26. Because the speed control authority is lost so much earlier, disturbances such as wind modeling errors and delayed level clearances have a much more significant impact on the CTA accuracy.

Another factor significantly affecting the CTA behavior is the accuracy of the forecast wind used by the FMS to predict the ETA. This is illustrated in Figs. 2 and 3, which show both the predicted CTA error and the cumulative time error resulting from the wind modeling error for two different flights.

Fig. 2 shows the wind error and predicted CTA error as a function of Time-to-Go for flight 24. The forecast wind model for this flight was quite accurate, resulting in very stable CTA behavior. Conversely, Fig. 3 shows the dynamics for flight 2, where the forecast wind model was significantly different than the actual wind encountered, resulting in a significant CTA error in the same direction (positive, or late) as the wind error. A similar pattern was observed in the majority of these flights, highlighting the importance an accurate forecast wind model has on time-based metering, especially when the ability to adjust speed to compensate for errors is significantly reduced, as it was for these flights.

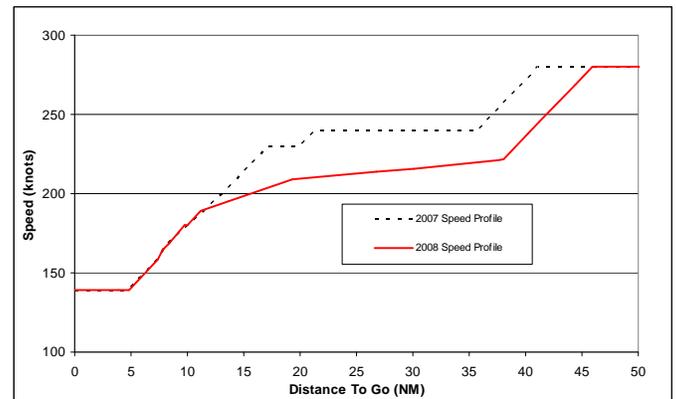


Figure 1. Speed Profiles for STARs to Runways 01L and 26.

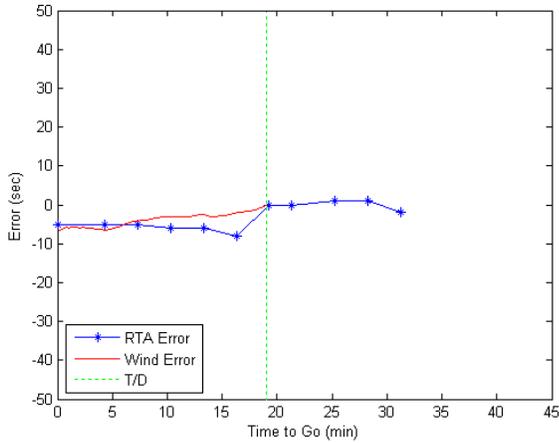


Figure 2. CTA and Wind Dynamics, Flight 24.

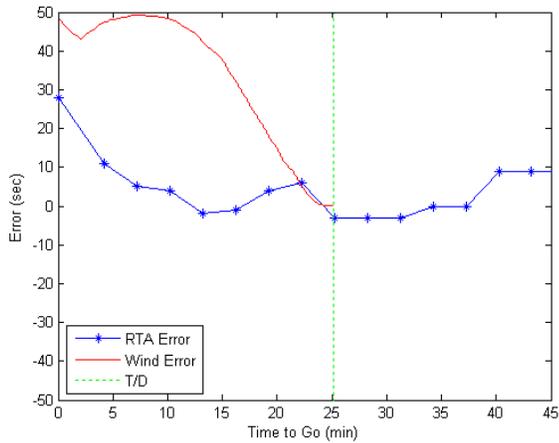


Figure 3. CTA and Wind Dynamics, Flight 2.

Although the wind error plays a significant role in time-control accuracy for the entire descent portion of the flight, it is particularly important in the later stages of the descent where the potential to adjust speeds to compensate for errors is greatly reduced or even eliminated. Fig. 4 shows a scatter plot of the CTA error vs. the wind error for the entire descent, as well as a linear and quadratic curve fit to the data. Fig. 5 shows the same information, but the wind error was accumulated only below FL100.

These plots show the correlation between the CTA error and the wind error. Although there is certainly a correlation when looking at the winds for the full descent, the majority of the wind errors are clustered on the left side of the graph. However, looking at the wind errors only below FL100, the correlation appears to be much stronger. The wind errors are distributed more evenly throughout the graph, and the largest CTA errors in the positive and negative direction are associated with the largest wind errors in the same direction. This reiterates the importance of accurate wind forecasts, especially in the portion of the flight during which the speed adjustment authority is reduced or eliminated.

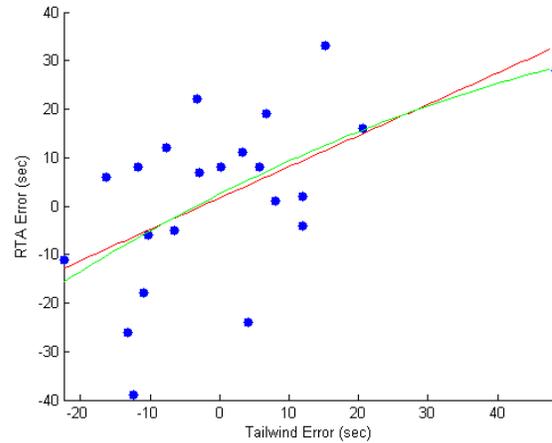


Figure 4. CTA Error vs. Tailwind Error, Full Descent.

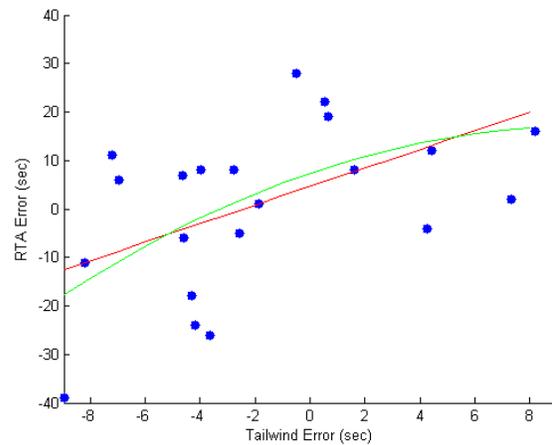


Figure 5. CTA Error vs. Tailwind Error, Below FL100.

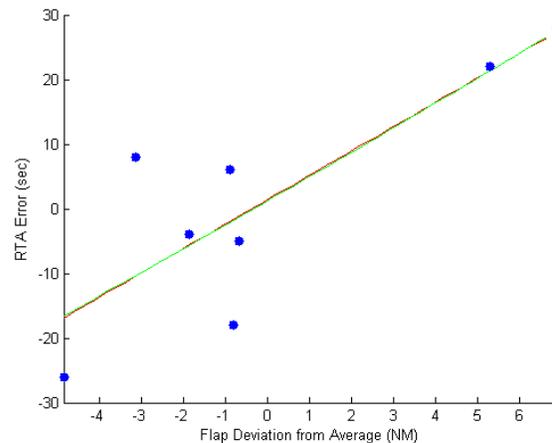


Figure 6. CTA Error and Flap Deployment.

As illustrated by the differences in CTA accuracy at the IAF versus at the runway threshold, the use of time control to a constraint at the runway threshold presents unique challenges due to the loss of speed maneuverability prior to the constraint location. Once the speed control authority has been lost, the automated CTA algorithms can no longer close the loop to null out time errors. When this automated speed control can no longer be performed, pilot behavior has a significant impact on time control accuracy.

Although no special actions were requested of the crew during these flights, the point at which the aircraft was initially configured with flaps and slats extension was examined to determine its impact on the time error. The FMS provides a queue to indicate when the deceleration towards the final approach speed is assumed to take place; however, the crews were accustomed to following ATC-issued speed commands rather than FMS-generated queues in the final stages of the approach. As a result, there was significant variation in the location of this deceleration start and beginning of the landing flap extensions.

Fig. 6 shows the correlation between variations in initial configuration and CTA error at the threshold. The horizontal axis represents the deviation from the mean initial flap deployment on all approaches into Runway 01L. The vertical axis represents the CTA error that was seen for that flight. From this plot it is clear that the location of initial flap deployment plays a significant role in the CTA accuracy.

As can be seen in Fig. 6, the earlier flap extensions (represented by the positive values on the horizontal axis) are correlated to late CTA errors. Conversely, the later extensions (negative values on the horizontal axis) coincide with early CTA errors. This is logical, since later flap extension results in a faster airspeed closer to the runway, causing the aircraft to arrive earlier than if the flap extension occurred farther from the runway. Fig. 6 also shows that the large spread for where the aircraft was initially configured – up to a 10 NM difference between flights. This area of high uncertainty must be addressed to achieve accurate arrival times at the runway threshold.

The use of airborne time control to a point in the terminal area is a key part of NextGen and SESAR concepts for trajectory based operations. These trials showed the use of existing avionics to meet a time constraint late in the approach, at 5000 feet, with better than 5 second accuracy is possible.

These trials also demonstrated that use of a CTA at the threshold is possible, but with lower accuracy. Key factors affecting the use of time control at the threshold are wind accuracy, speed and altitude constraints, and configuration for landing. Because the FMS will not adjust speed beyond the initial configuration point, these factors must be addressed to facilitate the robust use of time control to the threshold, which will be key to maintaining or increasing capacity in high-density airspace.

B. CTA Impact on Separation

Another goal of these flight trials was to evaluate the impact of CTA operations on intermediate separation. This is

one of the key research questions affecting time-based metering operations for NextGen and SESAR. Early work by [9] showed that when significantly different speed adjustment algorithms are used to meet a time-of-arrival constraint an intermediate loss of separation may occur even if the target separation is achieved at the metering fix.

Although these flight trials used the same FMS – and therefore the same time control algorithms – it is possible to examine the impact significantly different speed schedules will have on the separation. This was accomplished by using the same initial cost index for all flights and varying the time constraint either 2 minutes earlier or 2 minutes later than the original ETA. This resulted in some aircraft with much faster cruise and descent speeds than other aircraft, and facilitated an examination of the potential for one aircraft to ‘catch up’ to another.

To analyze the separation impacts of Time-of-Arrival Control, the QAR data providing latitude, longitude, and altitude at one second intervals was used. Only flights which had the same arrival and STAR were valid for a comparison, as different arrival procedures may have different altitude and speed restrictions which could skew any separation analysis. Each combination of flights for which a comparison was valid could be compared in both arrival orders – Flight B following Flight A and Flight A following Flight B. This yielded a total of 33 valid flight pairs, and 66 valid comparisons. Only flights which had a time constraint at the threshold were used for the comparison, as this represents the worst case scenario for separation.

Because the flights took place over four days the actual QAR time was ignored. Instead, the absolute time was converted to a relative time before the assigned time constraint. Given a delta time between time constraints, representing a target time spacing at the runway threshold, the distance, time and altitude between the two flights was computed every second for the last 50 nautical miles of the flight profile. A loss of separation was assumed to occur if the two flights were closer than a minimum separation of 3 nautical miles and 1000 feet at any point.

The analysis was performed for target landing spacings between 60 seconds and 120 seconds. The number of separation violations for each case is summarized in Table II. Using a target separation of less than 90 seconds is obviously not feasible. It is interesting to note that when a target separation of 60 seconds or 75 seconds was used, the separation violation always occurred at the threshold itself (although there may have been other losses of separation as well). Thus, it is obvious that with current flight methods a landing separation of 75 seconds or less will frequently result in separations of less than 3 NM. In fact, with no wind and a 130 knot landing speed, 75 seconds translates to only about 2.8 NM at the threshold itself.

When a the target separation is increased to 90 seconds, the number of separation violations decreases dramatically to only nine losses of separation of the 66 flights, or 13.6%. If a target separation of 120 seconds or larger is used, there are no losses of separation at all.

TABLE II. COMPARISON OF SEPARATION VIOLATIONS

Target Landing Separation	Separation Violations	
	Number	Percent
60 sec	64	97.0%
75 sec	57	86.4%
90 sec	9	13.6%
105 sec	1	1.5%
120 sec	0	0.0%

It is worth examining in more detail the nine flight pairs for which a loss of separation would have occurred with a target landing spacing of 90 seconds. These flights are summarized in Table III. This table shows each of the flight pairs for which a theoretical loss of separation was detected, as well as the distance from the runway of the leading flight when the separation loss would have occurred. For each flight, the CTA error and the difference in CTA from the original ETA is shown. The last column indicates where along the flight the separation loss occurred – if there was a separation violation at 0 NM from the destination, then the flights would not have been adequately separated at landing.

Noteworthy from this table is that in two of the cases the loss of separation was present at the threshold itself, indicating that the only way separation could have been achieved would be through a larger offset between time constraints at the threshold. This indicates that in some cases even a 90 second offset in landing times may be too close to ensure separation regardless of whether or not time-based metering is used at the threshold.

One notable trend from Table III is that eight of the nine cases where separation was lost involve at least one of the six largest errors from the trials. This suggests that the likelihood of a separation violation increases significantly with decreasing CTA accuracy. It is also worth noting that of the nine combinations of 18 flights in Table III, there are only 12 unique flights listed due to the same flights either leading or trailing in multiple cases. This suggests something unique to that flight may have contributed to the loss of separation.

Another interesting factor to note regarding these cases is that in six of the nine instances the leading aircraft arrived early while the trailing aircraft arrived late. This may not seem intuitive, as one would expect additional separation between an aircraft arriving earlier than scheduled, followed by one arriving later than scheduled. However, examining the dynamics of the individual flights reveals the reasons for this behavior.

Focusing on the flights that are listed in more than one case is useful to focus on some underlying factors contributing to the theoretical losses of separation. The first two cases in Table III involve the same leading flight. In this flight, a stronger than modeled headwind resulted in an ETA that was several seconds later than the time constraint. To compensate for this error, the pilot added thrust manually to speed up and get back on time. However, too much thrust was added resulting in a 24 second early arrival. This switch from late to early caused the hypothetical loss of separation. This can be seen more clearly in Fig. 7, which shows the theoretical separation in distance, time, and altitude between flights 29 and 27. The lines are highlighted where a violation of the minimum separation would have occurred. This parabolic shape of the time separation is due to the slowing effect of the headwind followed by the increasing speed due to added thrust.

TABLE III. DETAILS OF SEPARATION VIOLATIONS, 90 SEC TARGET

Leading Flight			Trailing Flight			Separation Violation Distance From Destination
ID	CTA Error	Δ CTA	ID	CTA Error	Δ CTA	
29	24 sec EARLY	+2 min	27	7 sec LATE	0 min	8 – 25 NM
29	24 sec EARLY	+2 min	23	12 sec LATE	0 min	10 – 50 NM
22	18 sec EARLY	-2 min	20	22 sec LATE	+2 min	0 – 2 NM
21	19 sec LATE	-2 min	17	33 sec LATE	+2 min	22 – 50 NM
5	39 sec EARLY	-2 min	25	8 sec LATE	-2 min	5 – 8 NM
4	4 sec EARLY	0 min	30	8 sec LATE	-2 min	8 – 9 NM; 15 – 31 NM
4	4 sec EARLY	0 min	20	22 sec LATE	+2 min	12.5 – 22.5 NM
2	28 sec LATE	0 min	30	8 sec LATE	-2 min	3 – 5NM; 7 – 10NM
2	28 sec LATE	0 min	20	22 sec LATE	+2 min	0 – 4 NM; 8 – 9 NM

Another set of cases involving repeated flights are the last four cases in Table III. These four cases involve the same two leading flights and the same two trailing flights. The two leading flights occurred on the first day of the trials, when the wind was from the south, resulting in 15 to 25 knot headwinds during the descent. The two trailing flights, on the other hand, both occurred later in the week when the winds were from the north and the descent winds were 20 to 40 knot tailwinds. Although the wind magnitudes were not particularly strong, the difference in directions resulted in 35 to 50 knot differences in effective wind experienced by the leading and trailing flights, which directly affects the ground speed of the aircraft. Fig. 8 shows the wind profiles for flights 2 and 20.

Because the leading flights experienced a headwind and the trailing flights experienced a tailwind a compression would have occurred, resulting in the loss of separation. This magnitude of wind differences would not be encountered by two aircraft several minutes apart on the same day, so these four cases of separation violation are likely not realistic cases. However, this does illustrate the effect of wind modeling errors on such a scenario.

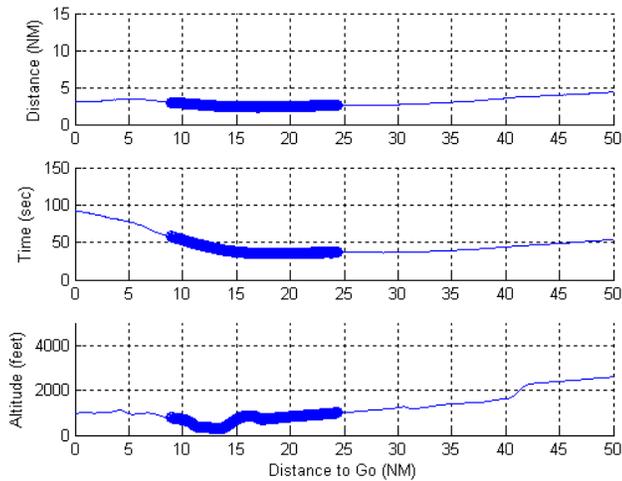


Figure 7. Theoretical Separation Between Flights 29 and 27.

The separation in distance and altitude for all valid combinations of flights for a target spacing of 120 seconds at the threshold is shown in Figs. 9 and 10, respectively. The minimum separations of 3 NM and 1000 feet are superimposed in dashed lines on the graphs. As can be seen in this figure, there several combinations dip below the minimum distance separation line between 5 and 7 NM from the destination. One combination also goes below this threshold when over 43 NM away. However, in each of these cases there is a greater than 1000 foot vertical separation between these flights. Similarly, when several of the flight pairs lose their minimum vertical separation there is an adequate lateral separation between them.

This analysis has examined the effects of airborne time-control on in-trail separation using real-world flight data time-shifted to simulate a target separation at the runway threshold. The analysis indicates that using current generation avionics, a target separation of 120 seconds or more at the threshold resulted in no intermediate losses of separation, and reducing the target separation to 105 seconds resulted in a loss of separation less than 2% of the time. Moreover, using a 90 second target resulted in separation losses of less than 14%, and less than 8% if the comparison excludes the unrealistic comparison of the flights from different days with 50 knot wind differences.

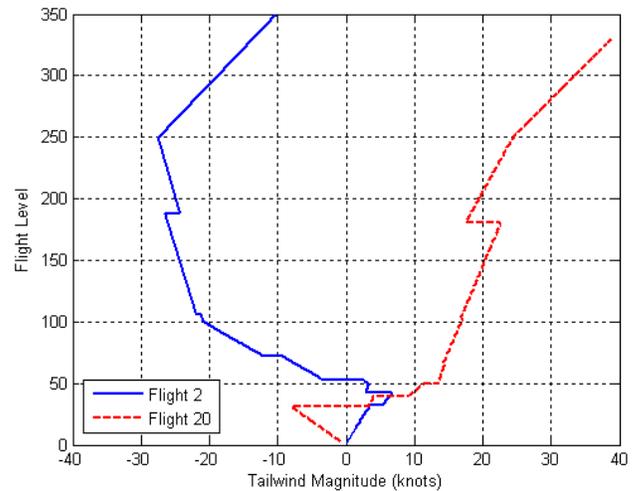


Figure 8. Actual Tailwinds for Flights 2 and 20.

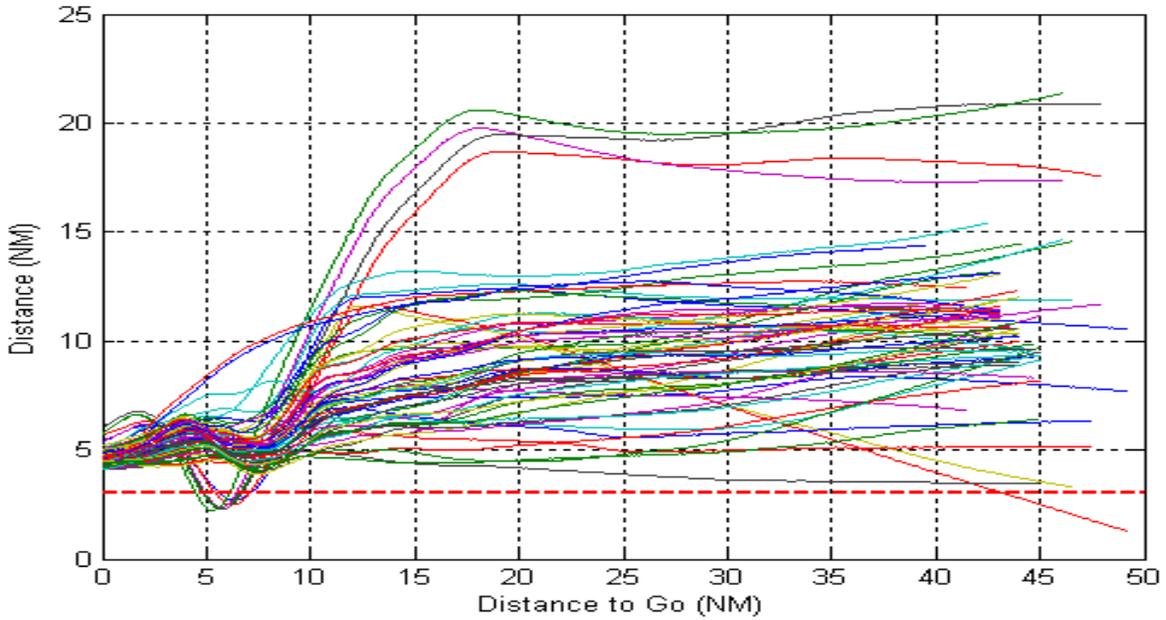


Figure 9. Lateral Separation Results for All Flights, 120 Second Target

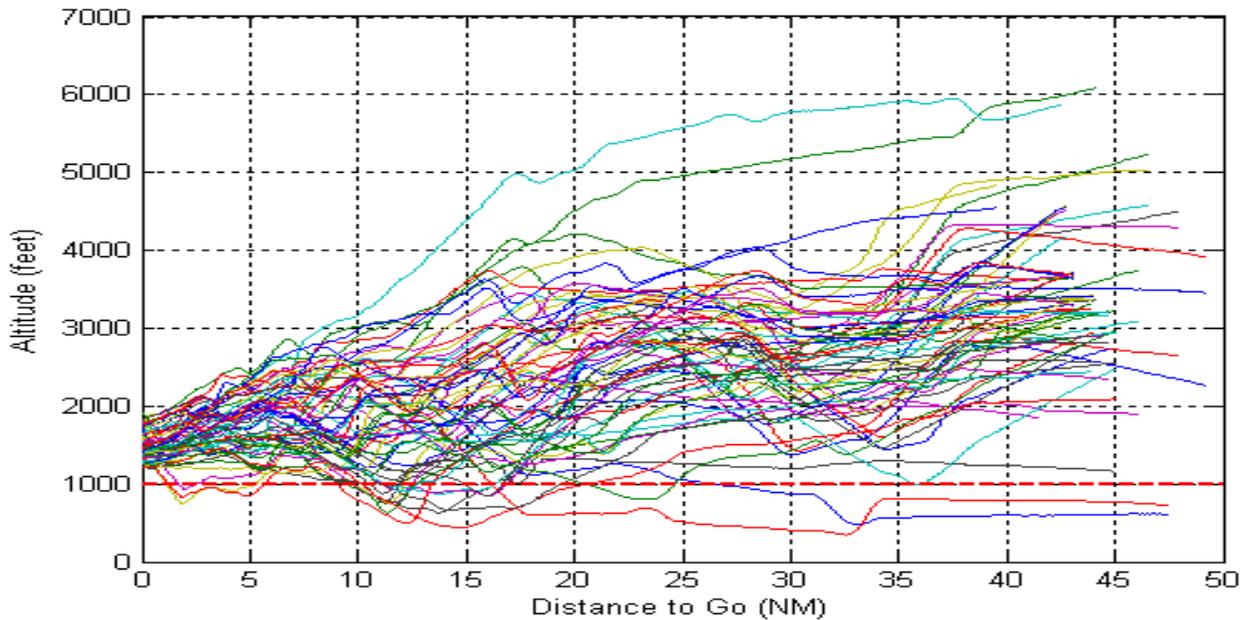


Figure 10. Vertical Separation Results for All Flights, 120 Second Target

V. RECOMMENDATIONS AND NEXT STEPS

In section IV an analysis of the CASSIS CTA flight trials was presented. This analysis has shown that the use of airborne Controlled Time of Arrival to a point late in the arrival is feasible with a mean accuracy of less than 5 seconds. However, the accuracy decreased significantly when the time constraint was placed at the runway threshold. Thus, the increased use of airborne time control to facilitate time-based

metering at a point in the arrival is highly encouraged as existing avionics are capable of meeting these time constraints. However, there are several lessons that were learned during these trials that should be taken into account in any time-based metering scenario, whether the time control is implemented by airborne automation or via ATC issued constraints.

A primary consideration in time-based metering is the combination of speed and altitude constraints used. If these constraints combine to cause a steep path prior to the time

constraint location any perturbations such as wind errors will cause problems in the time control. Because the aircraft cannot decelerate quickly on steep gradients errors can accumulate quickly, degrading the performance.

The accuracy of the actual winds, particularly during the speed constrained portion of the flight, have a considerable impact on the accuracy of the CTA operation. A higher wind modeling accuracy and a quantification of the wind accuracy may considerably improve the accuracy of the CTA operation.

Another obvious consideration is the predictability of flap extensions for landing. Because the aircraft speed will vary significantly depending on where it is configured, a significant variation in this location can also degrade the time metering performance. Thus, it is recommended that unless a higher predictability in the location of the flap extensions is available, the location of the metering fix should be prior to the initial configuration of the aircraft.

This analysis has also raised several additional research questions. One issue is the data that should be coordinated between the aircrew and the controller to facilitate these operations. During these trials it was noted that the controllers frequently asked the crews for the planned airspeeds to enable downstream conflict detections. Thus, it seems that current and future speeds would be useful data to share between the air and ground. There is likely additional data that should be coordinated such as the earliest and latest achievable times at downstream points.

Another research topic is the Human Machine Interface (HMI). Current numeric display of the CTA and error could be improved with more intuitive, graphical displays. This will be essential for monitoring and communication when very high precision time control is needed in high density airspace.

These and other research questions will be addressed in the second phase of the CASSIS program. In this phase additional information will be shared and potential modifications to ground-based decision support tools will be examined, and the use of CTAs will be expanded to additional aircraft types.

VI. CONCLUSION

Trajectory Based Operations and the use of time-based metering to allow efficient use of the airspace and runway is proposed as a key operational improvement by both NextGen and SESAR. In September 2008 the CASSIS project conducted a set of Controlled Time-of-Arrival trial flights to examine the potential of airborne time control in the near and mid-term as well as the issues associated with it. These trials demonstrated that current generation avionics can achieve time control with 4 second accuracy at the initial approach fix, and less than 15 seconds at the runway threshold.

Factors affecting the accuracy of the time control were shown to be the speed and altitude restrictions in the arrival procedure, wind modeling accuracy, and the location of the landing configuration extension. In addition, the actual flight data was used to perform a theoretical separation analysis where the CTA was used to space subsequent aircraft at the threshold. This showed that using a spacing of 105 seconds or

greater should not cause separation problems. Additional research questions based on this analysis were identified to be examined during the next phase of the project.

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