HOW TO COMPUTE A SLOT MARKER – CALCULATION OF CONTROLLER-MANAGED SPACING TOOLS FOR EFFICIENT DESCENTS WITH PRECISION SCHEDULING

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Abstract

This paper describes the underlying principles and algorithms for computing the primary Controller-Managed Spacing (CMS) tools developed at NASA for precisely spacing aircraft along efficient descent paths. The trajectory-based CMS tools include slot markers, delay indications and speed advisories. These tools are one of three core NASA technologies integrated in NASA's ATM Technology Demonstration-1 (ATD-1) that will operationally demonstrate the feasibility of fuel-efficient, high throughput arrival operations using Automatic Dependent Surveillance-Broadcast (ADS-B) and ground-based and airborne NASA technologies for precision scheduling and spacing.

Introduction

The FAA forecasts commercial aviation will annually grow on average 2.4% at en-route centers and 1.8% in terminal areas over the next twenty years, and reach one billion passengers by 2024 [1]. Arrivals into high-density airports, especially during peak periods and inclement weather, experience significant inefficiencies resulting from use of miles-in-trail procedures and step-down descents. Use of these current procedures contributes to reducing airport capacity, increasing controller workload, increasing arrival delay, as well as increasing aircraft fuel burn, emissions and noise.

In today's operations, an aircraft landing at a high-density airport generally executes a series of step-down descents starting at its cruise altitude along a published airway, transitions to a Standard Terminal Arrival Route (STAR), and enters terminal airspace at a metering fix or corner-post. At this point the aircraft is handed off from en-route controllers in the Air Route Traffic Control Center (ARTCC) to approach controllers in the Terminal Radar Approach Control (TRACON). The aircraft will continue to fly the STAR; however, since most STARS do not connect to the runway, approach controllers usually issue radar vectors to the final approach course.

During periods of light to moderate traffic, aircraft may be able to conduct a fuel-efficient descent from cruise to the runway called an Optimized Profile Descent (OPD). Typically, these operations are not feasible during periods of heavy traffic due to the variability and unpredictability of the aircraft trajectories. Uncertainties in the aircrafts' descent profiles and landing times can be accommodated if there is enough extra spacing between aircraft; this is usually the case in light traffic (for example late at night). Imposing larger spacing at the runway to enable OPDs during congested periods would lead to a significant reduction in runway throughput, thus increasing delays, and reducing efficiency.

In order to maintain throughput during periods of heavy traffic, significant research has been conducted both in the United States and Europe to develop trajectory management tools enabling aircraft to simultaneously execute efficient descents while maintaining separation with other aircraft and high throughput. This research has added controller advisory tools to work in concert with current arrival scheduling tools like the FAA's Traffic Management Advisor (TMA) [2] or the European Arrival Manager (AMAN) [3]. However, these research systems are usually limited to either only en-route [4] or only terminal airspace [5, 6] -application.

In addition to research on controller aids, flight-deck-based technologies for precise spacing are enabled through the introduction of ADS-B In and Out. Research, simulation and field trials on airborne precision spacing have been conducted in the US and Europe, [7, 8]. While some of this research has included scheduling and air traffic control aspects for simple arrival flows [8, 9], to our knowledge, little to no research has looked at fully integrated arrival operations with advanced scheduling systems, controller tools, and airborne spacing for complex arrival flows into congested airports.

Since the efficient scheduling and control of aircraft from cruise to touchdown during congested periods is a highly complex problem, current procedures and arrival scheduling tools do not yet allow use of advanced arrival procedures such as Area Navigation (RNAV) OPDs during periods of peak traffic [10]. The following section describes a NASA initiative intended to enable fuel-efficient, high-throughput arrival operations for complex arrival flows in busy terminal areas.

NASA's ATM Technology Demonstration-1 (ATD-1)

NASA initiated the ATM Technology Demonstration (ATD) sub-project within the Airspace Systems Programs System Analysis Integration and Evaluation Project in 2011 to focus on operational demonstrations of innovative NASA technologies that have attained a sufficient level of maturity in the foundational stage and merit more in-depth research at the system level in relevant environments. ATD-1 will operationally demonstrate the feasibility of fuel-efficient, high-throughput arrival operations [11].

ATD-1 integrates three research efforts that were conducted in the simulation laboratories at NASA's Ames and Langley Research Centers in parallel for many years leading to an operational demonstration at a major US airport targeted for 2015.

The three NASA technologies are

- TMA-TM: Traffic Management Advisor with Terminal Metering (TMA-TM) for generating precise time-based schedules to the en-route meter fixes, the runways and intermediate control points within the terminal area [12]

- CMS: "Controller-Managed Spacing" (CMS) decision support tools for controllers to manage aircraft schedule and spacing conformance along efficient descent profiles [5, 13]

- FIM: "Flight deck Interval Management" (FIM) aircraft avionics and flight crew procedures to conduct efficient airborne spacing operations [7, 14]

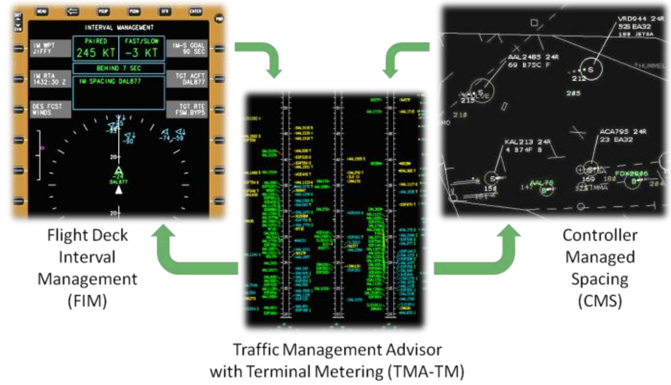

Figure 1: Technologies for ATD-1

ATD-1 is described in detail in [15] and [16]. This paper focusses on the Controller-Managed Spacing (CMS) tools including the slot markers that are an important component within ATD-1. Since the CMS tools were designed to support a specific concept of operations, this concept is briefly described next.

ATD-1 Concept of Operations

In order to introduce the concept of operations, we use the operational scenario depicted in Figure 2.

The concept focuses on the arrival phase of flight, beginning prior to the aircraft's top-of-descent. Aircraft are navigating along RNAV OPDs that include runway transitions connected to instrument approach procedures. These advanced arrival procedures allow flight crews to use their onboard FMS capabilities to fly from cruise to landing without controllers providing radar vectors to the final approach course.

At approximately 100 to 200 NM from entry into terminal airspace, arriving aircraft are assigned runways and fix crossing times. TMA-TM generates an arrival schedule that in addition to fix crossing times for en-route meter points, also includes terminal meter points. The terminal meter points are arrival procedure-specific adapted control points; including merge points where traffic flows converge. These additional control points are necessary to ensure that (1) the arrival schedule considers separation constraints at important merge points between the arrival meter fix and runway threshold, and (2) all aircraft maintain the arrival schedule from top of descent to the runway. This allows for seamless merging of aircraft spaced by controllers

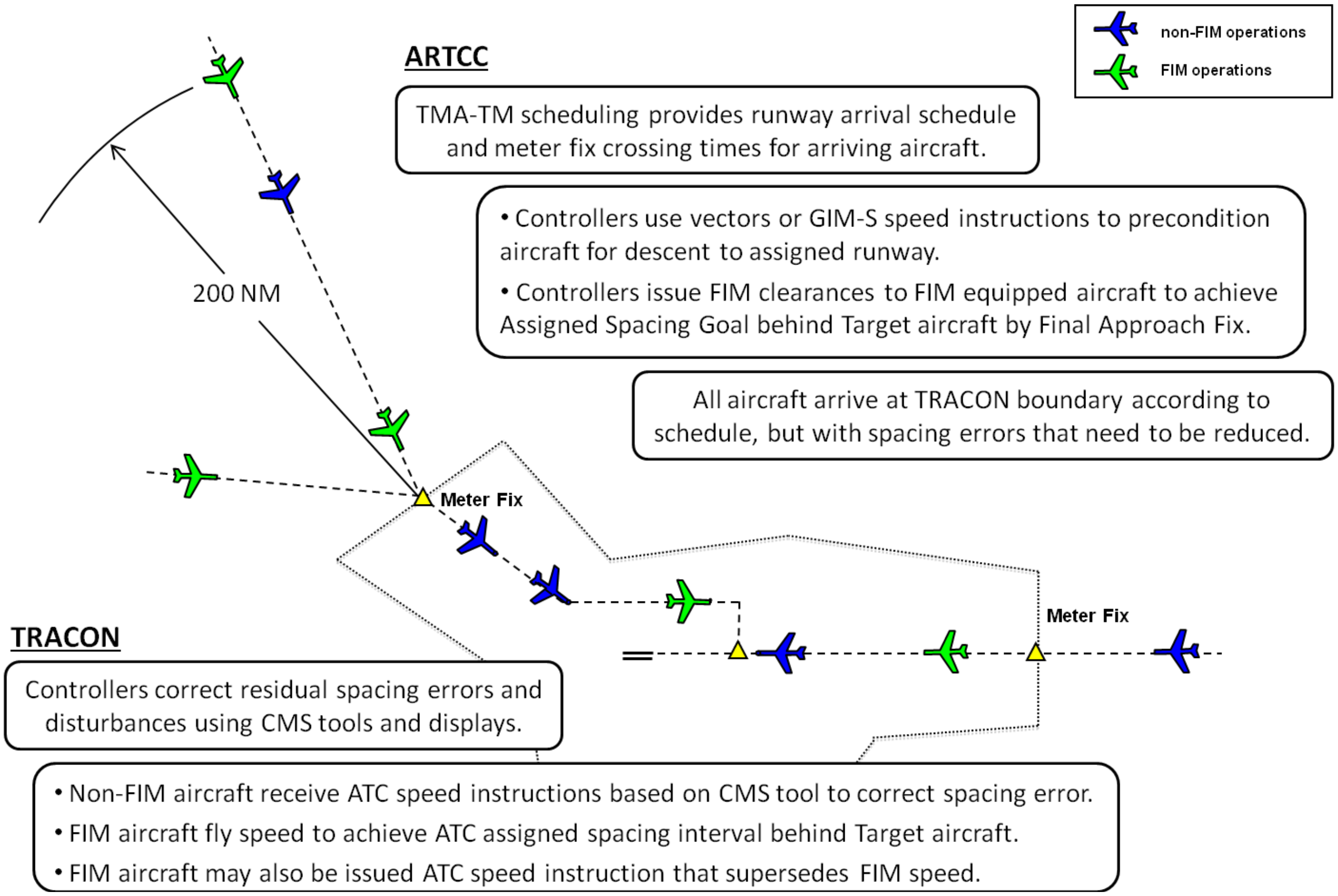

Figure 2: Operational scenario for the ATD-1 concept of operations

using CMS technologies and aircraft spaced by flight crews using FIM technologies.

At each control point, scheduled times-of-arrival are calculated that meet the required aircraft separation and successively condition the traffic flow with the necessary amount of delay. In order to ensure speed control alone is sufficient to maintain aircraft separation, the amount of delay absorbed between each control point is carefully distributed. Delay that exceeds the amount afforded by speed control alone is successively passed back to upstream control points. As a result, aircraft absorb more of their required delay at higher altitudes which is generally more fuel-efficient.

The initial delay is absorbed using ground-based interval management tools for spacing (GIM-S) such that the subsequent arrival plan can be implemented with speed control alone. Once appropriately preconditioned conventional aircraft receive speed instructions from en-route and terminal-area controllers to meet the scheduled times of arrival at the associated control points, FIM aircraft receive instructions to initiate FIM operations for precise spacing behind the designated lead aircraft.

The FIM spacing operation is initiated near the top of descent when the flight crew receives a clearance from the controller to begin interval spacing. The clearance includes the target aircraft's identifier, the spacing goal (e.g., spacing interval and achieve-by point) and -in cases where the target aircraft is not yet within ADS-B range or there is no ADS-B equipped target aircraft- an RTA at the achieve-by point. In addition, the spacing tool uses the arrival procedure of the target aircraft and its planned final approach speed (if the achieve-by point is the runway threshold).

With the proper setup in the en route airspace, FIM and non-FIM aircraft arrive at the intermediate control points with residual spacing errors that can be corrected by small speed adjustments by the flight crews of FIM aircraft and by the controllers for the other aircraft.

In the TRACON controllers use CMS tools to monitor the status and conformance of all aircraft with respect to their spacing goals. Non-FIM aircraft receive control instructions to meet the TMA-TM generated scheduled arrival times. FIM aircraft are monitored for compliance and potential separation problems. The CMS toolset is described next.

CMS Tools

CMS tools are designed to help controllers manage aircraft arriving on RNAV routes through the terminal area according to a schedule. Under nominal conditions, control is accomplished by adjusting the speeds of aircraft so that they can remain on efficient descent profiles along the RNAV route. This is done by the controllers for conventional aircraft and by the pilots for aircraft conducting FIM operations. CMS tools include schedule timelines, data block early/late indicators, slot marker circles, and speed advisories. An overview over the entire suite of CMS tools integrated into the experimental air traffic controller station at NASA Ames is given in Figure 3.

They are:

- Timeline display (on the lower left)
- Slot markers (shown as circles in various locations on the map display)
- Early/late indications (shown in the third line of the data tags)
- Speed advisories (sometimes shown in the third line of the data tags instead of early/late indications)

The initial CMS research was conducted in the Airspace Operations Lab at NASA Ames Research Center using the Multi-Aircraft Control System (MACS). MACS was used for computing and displaying all CMS information. Since MACS is intended for simulations only and ATD-1 aims to demonstrate the capabilities at a field site, the CMS graphics are currently integrated into a Standard Terminal Area Replacement System (STARS) prototype and the algorithms are being re-implemented into TMA-TM.

Figure 3 Experimental air traffic control station at NASA Ames with CMS controller tools

CMS graphics

The primary CMS graphics are shown in Figure 4, which is an excerpt of a (MACS) feeder controller display during a recent simulation within the Dallas Ft. Worth (DFW) airspace that shows all primary CMS elements. A timeline showing all arrivals to DFW 17C is shown on the right. The slot markers are shown as gold circles with the nominal indicated airspeed in a position opposite the data tag leader line. Speed advisories are shown in the third line of the data tag whenever a new speed instruction would improve the on-time performance. Early/late indications are used in the third line when the aircraft is estimated to be off by a second or more and no speed advisory is available or needed. The intent is to provide situation awareness for the controllers in a way that allows them to formulate appropriate instructions; elements that appear unnecessary can be removed from the display upon controller request/input.

In order to discuss the behavior of the CMS tools in more detail, consider the four easternmost aircraft depicted in Figure 4: AAL2040, AAL1847, ASQ4150 and AAL1705. All aircraft are scheduled to land on runway 17C. The timeline indicates the estimated times of arrival for the final approach fix on the left side and the scheduled time of arrival on the right side. Figure 5 represents a zoomed in view of Figure 4 for the four aircraft of interest.

The ***timeline*** indicates that AAL2040 is currently estimated to arrive slightly earlier than scheduled, because the ETA on the left hand side is smaller than (below) the STA on the right hand side. ASQ4150 and AAL1847 are also predicted to arrive early. AAL1705 is currently estimated to arrive after its scheduled time. The timeline provides temporal information in a graphical format adequate for schedule monitoring and general situation awareness. Timelines have been part of the fielded Traffic Management Advisor and have been used by traffic

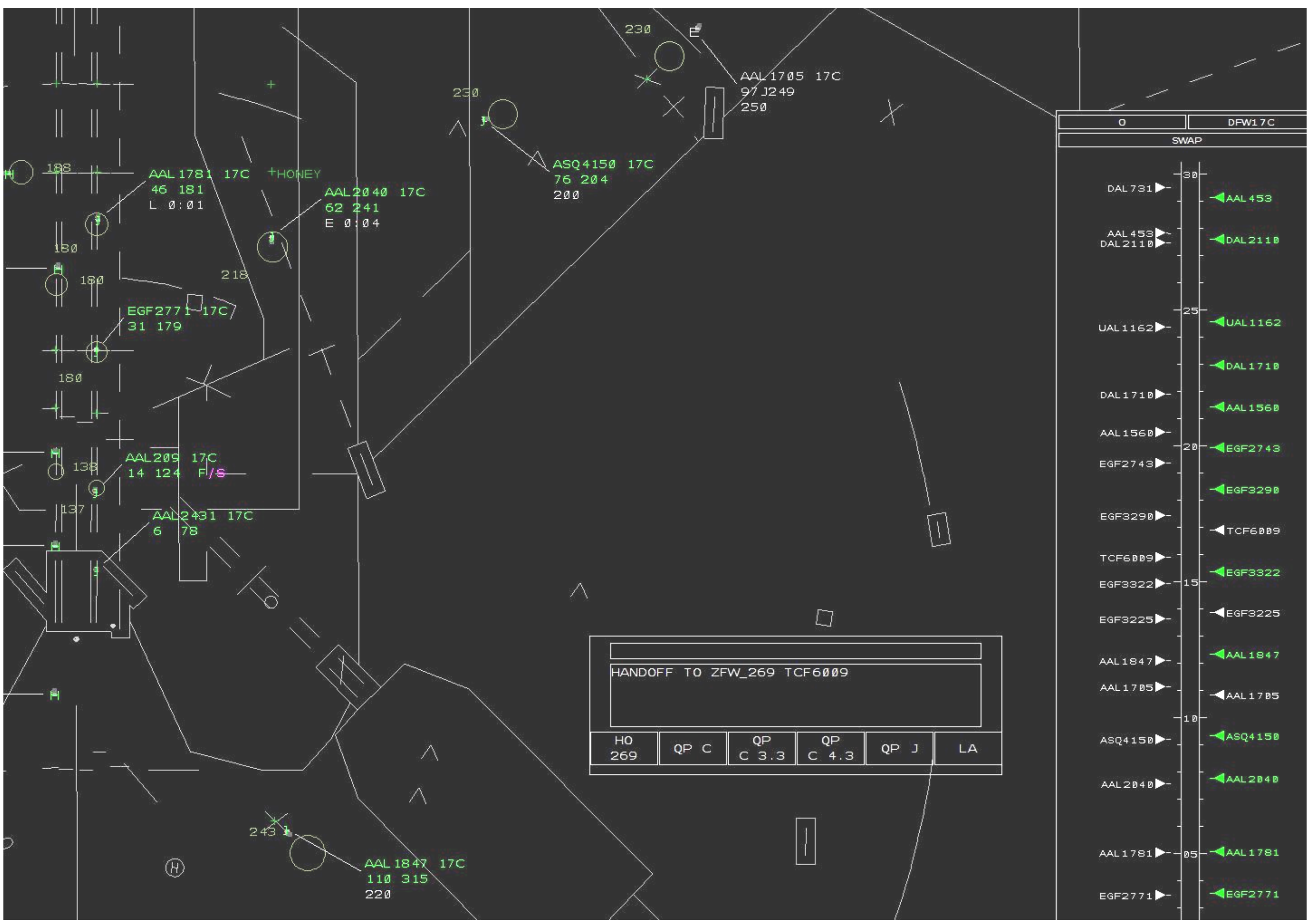

Figure 4: Experimental Feeder controller display with CMS tools during recent simulation

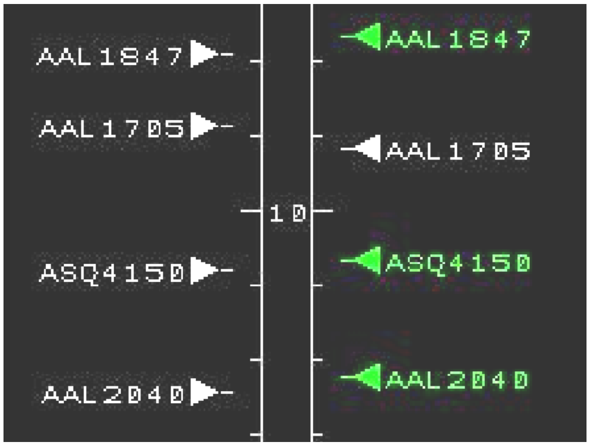

Figure 5: Timeline on control position

managers for many years. Studies indicate that timelines can be useful on the control positions as well, but additional information and calculations are required to integrate timeline information adequately into a controller's workstation.

One problem with timelines located at the control position is that the location is outside the controller's scan area. Therefore controllers have to look away from the traffic and find the respective aircraft to get the temporal information. This process can be simplified if aircraft are highlighted in both places when dwelled or by adding the temporal information to the data tag. ***Early/late indicators*** provide that capability (see Figure 6).

The "E 0:04" in the data tag indicates to the controller that AAL2040 is currently predicted to arrive 4 seconds earlier than scheduled at the next control point. This information is more precise than the timeline information and can be gathered without taking the scan away from the traffic situation. However, it provides information only for one aircraft and not the context that the timeline provides.

Figure 6: Early/late indication

The temporal information can be used by controllers to develop control instructions. ATD-1 is designed to use speed control along fixed paths, so speed instructions are the primary means of control under normal circumstances. CMS computes ***speed advisories*** to provide on-time performance for aircraft at the next control point. If such speeds are available they are depicted in the data tag instead of early/late indicators. An example speed advisory of 200 knots is shown in Figure 7.

Figure 7: Speed advisory

These speeds are intended as additional information for the controllers. If issued, the displayed speed will put the aircraft on time at the next control point. Controllers can use this information as a point of reference in developing their own strategies and are not expected to issue each suggested speed exactly.

The arguably most powerful CMS tool is the ***slot marker***. Slot markers (circles in Figs. 4, 6 and 7) translate the temporal information available in the timeline into the spatial domain. Slot markers are indicated as circles on the controllers plan view display and depict where the aircraft should be right now, if it arrived at all control points exactly on time while flying the nominal speed profile. The nominal speed is also indicated at the slot marker. An aircraft that is early is ahead of its circle (e.g. ASQ4150 or AAL2040), an aircraft that is late is behind its slot marker (e.g. AAL1705). In well-conditioned flows slot markers will be fairly close to the aircraft position symbol and are easy to interpret. The aircraft location relative to its slot (e.g. nominal position) and the aircraft speed relative to its nominal speed are easily understood and can be used to formulate the appropriate control actions. The control task can be simplified and consists of getting the aircraft into its slot marker at the appropriate control points, so that separation is provided and the problem for the downstream controller is adequately preconditioned.

Slot marker locations are computed based on the individual aircrafts nominal trajectory taking into account its performance characteristic and the current environmental conditions.

This trajectory-based approach distinguishes slot markers and the CMS tools in general from other tools suggested for terminal area operations (e.g. [6]). The underlying computations will be discussed in detail next.

Arrival Time Computations for CMS

Timelines and early/late indications

CMS timelines and early late indications are derived from the STAs and ETAs at relevant control points. Timelines display the Aircraft Id, aircraft type, weight class, STA and ETA. Early late indications indicate the difference between STA and ETA.

Scheduled Times of Arrival (STA):

Scheduling is performed by TMA-TM. CMS assumes to receive scheduled times of arrival at all control points that TMA-TM has been adapted to enforce. These STAs are used for timeline displays, delay computations, slot markers and speed advisories.

Estimated Times of Arrival:

Estimated Times of Arrival at all control points are used for timelines and early/late indications. In the current simulation system the controller displays can be set up to display either the ETAs computed by TMA-TM or those computed by the CMS embedded trajectory predictor. Slot markers and speed advisories require access to a trajectory predictor capable of computing additional ETAs.

Slot Marker Computations

Slot markers are a graphical depiction of the nominal flight state (latitude, longitude, altitude, speed, etc.) at which an aircraft should be in order to meet the scheduled time of arrival at the next control point when flying the nominal arrival profile.

The following steps are performed to compute the slot markers:

1. Retrieve and store the control point schedules
2. Compute the Nominal Trajectory
3. Time-shift the nominal trajectory to meet the control point STAs
4. Compute the nominal flight state for the current time along track the time-shifted nominal trajectory
5. Publish the nominal flight state to enable displaying the slot marker and associated values (e.g. ground speed, indicated air speed)

Following are detailed descriptions of each step:

1. Retrieve and store the control point schedules

The control points are adapted in TMA-TM for the airspace organization and route topology and include en- route meter fixes, terminal merge points and other relevant control points such as the final approach fixes, the runways and potentially handoff points between control positions. STAs for these control points are generated by and transmitted from the scheduler. For each such control point a schedule is maintained that contains STAs and ETAs for all scheduled aircraft. The schedules are updated every-time new scheduling information is received.

2. Compute the Nominal Trajectory

The nominal trajectory is the trajectory that the aircraft would fly if it met all control point time constraints and all speed and altitude restrictions that are specified in the nominal arrival procedure. Nominal arrival procedures are specified as ATC procedures in an ‘atc_procedures’ file. The next section describes the ATC procedures that serve as the basis for the nominal trajectories.

Figure 8 and Table 1 below show example ATC procedures designed for simulation purposes into the Los Angeles International airport (LAX). The two procedures shown in Table 1 were used during a recent human-in-the-loop simulation for jet aircraft flying to LAX24R via the SADDE7 and RIIVR2 arrivals on the HEC and AVE transition.

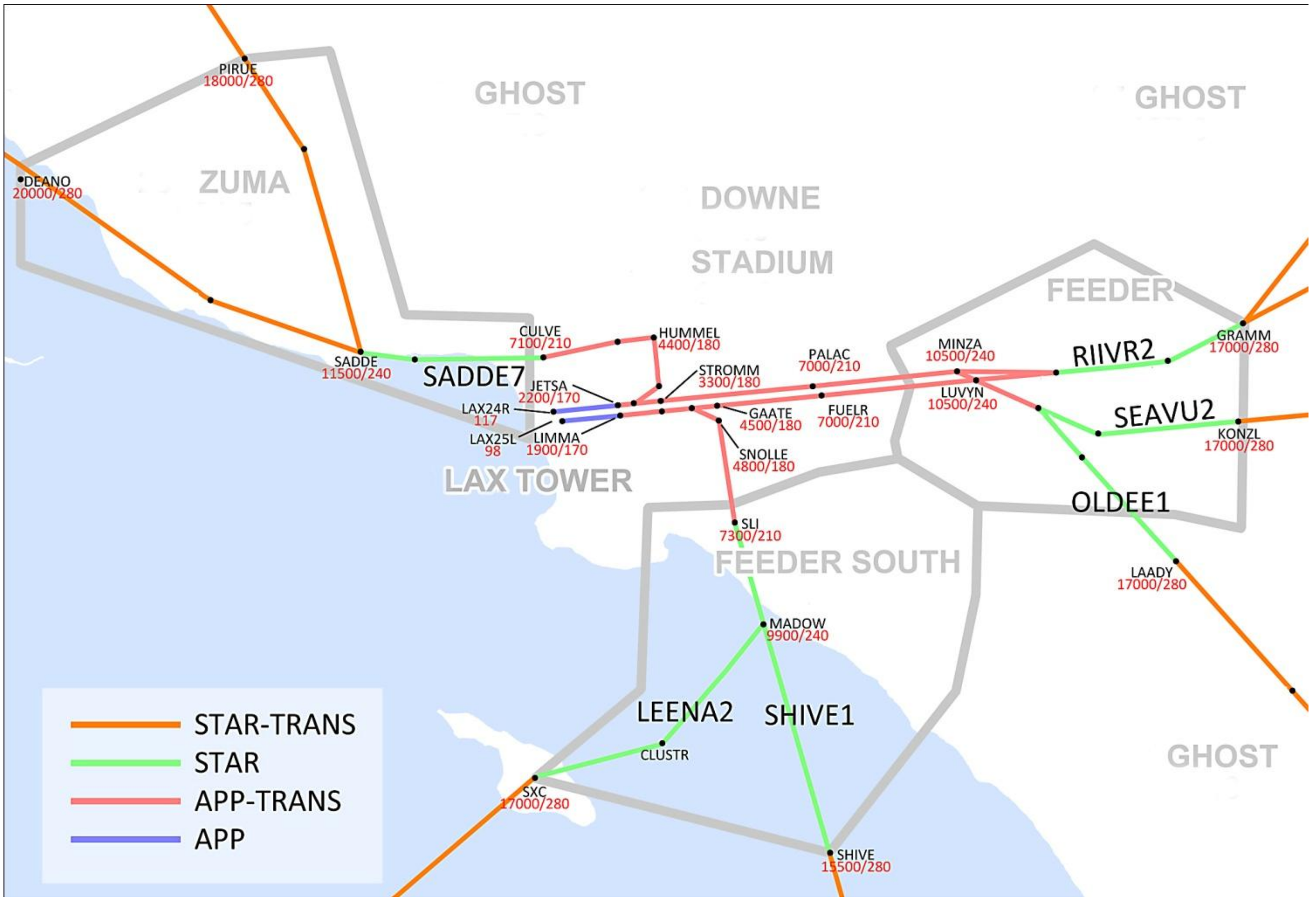

Figure 8: Example ATC procedure

The ATC procedure description first contains the type of procedure, e.g. ARRIVAL, DEPARTURE or GO_AROUND. Then it includes identifying information describing the airport, runway, entry fix, engine type and name of the procedure. The name of the procedure is intended to be used in the flight plan route to uniquely specify the ATC procedure. Using this procedure name controllers can also enter the desired procedure into the ground system with a route amendment. Since the En Route Automation Modernization (ERAM) system, which is being installed in all en-route facilities in the NAS includes the capability to predefine route amendments, all valid ATC procedures at a given sector position can be predefined to provide Center controllers an easy means to enter the appropriate assignment.

The Descent CAS field includes the calibrated

Table 1: ATC procedures text description

Type	Airport	Runway	Entry Fix	Eng. Type	Name	Des. Cas	Range	Routing
ARRIVAL	LAX	LAX24R	HEC	JET	HEC.RIIVR2.LAX24R	280	200	HEC,GRAMM:AT17000:S280,RUSTT,RIIVR,MINZA:AT10500:S240,PALAC:AT7000,S210,ROYAL,STROMM:AT3300:S180,JETSA:AT2200:S170,LAX24R:AT117
ARRIVAL	LAX	LAX24R	AVE	JET	AVE.SADDE7.LAX24R	280	200	AVE,DERBB,REYES,PIRUE:AT20000:S280,FIM:AT15800:S280,SADDE:AT11500:S240,BAYST,CULVE:AT7100, S210,CONDOR,HUMMEL:AT4400:S180,BEEVOU,SPARKX:AT2600:S180,JETSA:AT2200:S170,LAX24R:AT117

airspeed (CAS) at which the aircraft is expected to descend unless otherwise instructed by air traffic control. The range field defines how far from the airport the computation of the nominal ATC procedure is to commence, which will also be the first position at which the slot marker can be displayed.

Finally, the routing field contains all waypoints, altitude and speed restrictions along the nominal procedure. A simple annotation is used to append restrictions directly after waypoints. These can also be altitude windows, slow and fast speeds, and specific leg types, such as RF legs.

Building the nominal trajectory

To build a nominal trajectory from an ATC procedure, the trajectory generator computes a trajectory from the initial nominal flight state to the runway using the restrictions defined in the ATC procedure. It is important that the trajectory generator uses the correct aircraft type and the best current wind predictions for the nominal trajectory. The initial nominal flight state is the flight state of an aircraft when it reaches the defined range for the ATC procedure. The range is selected such that the initial nominal flight state will be placed prior to the aircraft's top of descent, such that a full nominal trajectory can be computed from cruise to touchdown.

The initial nominal flight state becomes the starting position for the slot marker and the origin position for computing the nominal trajectory.

Figures 9 and 10 show two examples for the relationship between the initial nominal flight state, the ATC procedure and the current flight state of an aircraft. The difference between the situations depicted in the two figures is that the aircraft in Fig. 9 was not tracked when reaching the range that was specified in the ATC procedure, while the aircraft in Fig. 10 was tracked when reaching this range.

In the situation in Fig. 9 a virtual initial nominal flight state is computed at the position at which a straight line from the runway to the entry fix reaches the length specified as range. This process can be used if, for example only a terminal area radar tracking is available and the aircraft is first tracked well within its descent, but the slot marker may be behind the aircraft, because the aircraft is early.

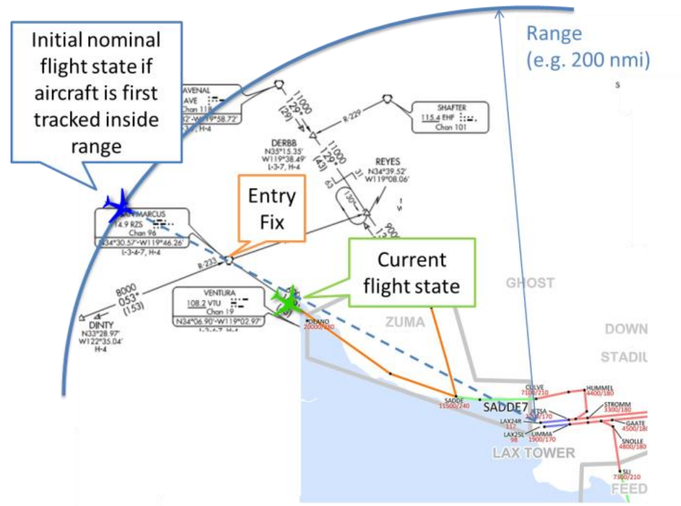

Figure 9: ATC procedure, initial nominal flight state and current flight state when aircraft first tracked inside range

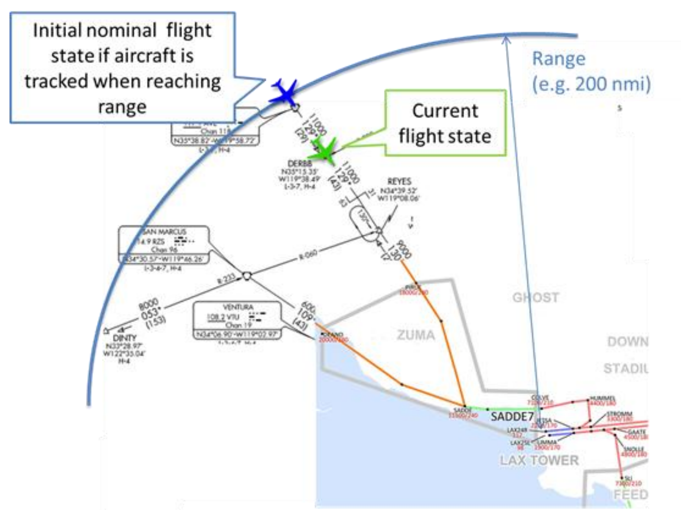

Figure 10: ATC procedure, initial nominal flight state and current flight state aircraft first tracked outside range

In its current implementation, the timestamp at the initial nominal flight state is set to the current time to allow a trajectory computation into the future, even if the aircraft has long passed this position.

Once the initial nominal flight state is set, the nominal trajectory is generated. All defined speed and altitude restrictions as well as modeled approach and landing speed are used as constraints for the trajectory generator, which generates a full trajectory from the initial nominal flight state to the runway.

Figure 11 shows a schematic of the simplified nominal speed profile for the AVE.SADDE7.LAX24R ATC procedure:

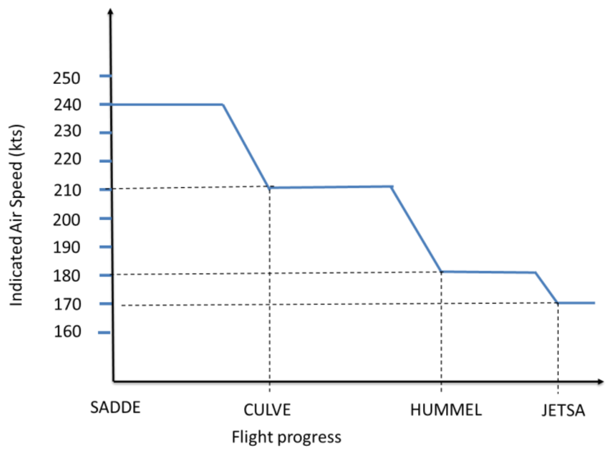

Figure 11: Nominal speed profile for AVE.SADDE7.LAX24R ATC procedure

This speed profile represents the nominal speed profile as specified in the ATC procedure and is used to compute the nominal flight times for each segment and the associated ETAs. A later section in this paper describes how this speed profile is modified to compute speed advisories.

A virtual ETA is computed for all points along the nominal trajectory and can be interpreted as the ETA at which an aircraft would be at that point if it were presently at the initial nominal flight state. For example if the current time was 10:00 UTC and the flight time to the runway was 35 minutes, the virtual runway ETA in the nominal trajectory would be recorded as 10:35 UTC. However, this time is not displayed to any controller since usually aircraft are not at their initial nominal flight state. Instead the nominal trajectory is time-shifted to meet the control point STAs. The purpose of this time-shift is to generate the nominal trajectory such that it meets all STAs at the control points.

3. Time-shift the nominal trajectory to meet the control point STAs

In order to identify the arrival times for the nominal trajectory, the term nominal time of arrival (NTA) is used subsequently. A nominal time of arrival is the time at which an aircraft would have to be at a waypoint along the route to meet the STA at the next scheduled point. Therefore (NTAs) equal STAs whenever STAs exist. Algorithmically they are inserted as follows:

Starting at the runway and working backwards for all trajectory points:

Check whether the trajectory point is a control point for which an STA exists.

If an STA exists,

NTA = STA

compute the time difference (delta T) between STA and the (virtual) ETA

deltaT = STA-ETA

If no STA exists

NTA = ETA +deltaT

After this computation each trajectory point will have a NTA that represents the time at which an aircraft would arrive at this waypoint if it flew the nominal trajectory and arrived at the STA at the next control point. Figure 12 depicts a nominal trajectory.

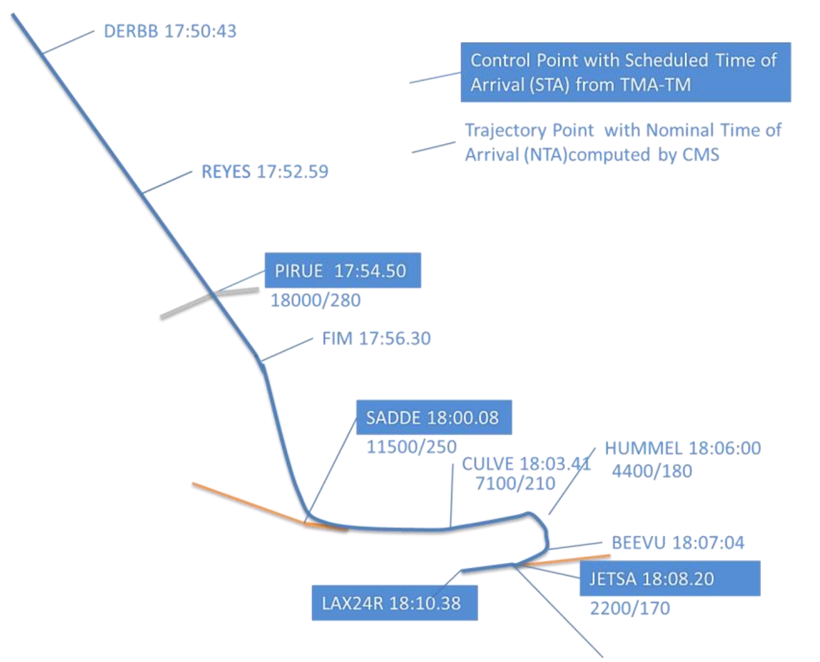

Figure 12: Nominal Trajectory example AVE.SADDE7.LAX24R (see Fig.8)

In the example in Fig. 12 TMA-TM has been adapted to generate STAs along the AVE.SADDE7.LAX24R at the following control points: PIRUE: en-route meter fix and the entry fix into the terminal area. SADDE: merge point between two STAR transitions. JETSA: Final Approach Fix and LAX24R: runway. The nominal trajectory was computed to meet those STAs including the NTAs shown next to the trajectory points DERBB, REYES, FIM, CULVE, HUMMEL, and BEEVU.

It should be noted that generating and time-shifting the nominal trajectory to meet the TMA-TM STAs at the control points is only necessary if TMA-TM does not generate and publish its internal nominal scheduling trajectory that meets all scheduled times of arrival at the control points. Otherwise the external computation of the nominal trajectory is not necessary and the TMA-TM generated trajectory can be used directly as the nominal trajectory.

The relationship between the NTA as derived from the nominal trajectory and the ETA that is derived from the current trajectory prediction can be used to display delay information at all trajectory points. The nominal trajectory is further used to compute the nominal flight state which determines the location of the slot marker.

4. Compute the nominal flight state

Using the nominal trajectory and the nominal times of arrival, now the flight state is computed that matches the point along the trajectory at which an aircraft would be at the current time. This is done using a trajectory-based interpolation algorithm applied to the nominal times of arrival.

Once this point is identified the remaining nominal values, such as air speed, altitude, heading, and ground track are extracted from the trajectory and comprise the nominal flight state. Figure 13 shows example nominal flight states along the nominal trajectory that was depicted in Fig.12. For example, in order to meet the STA of 17:54:50 at PIRUE, the aircraft is expected to be just past DERBB at time 17:51.00. At 17:54.00 it should nominally be coming up on PIRUE and be at 19550 feet and 300 knots.

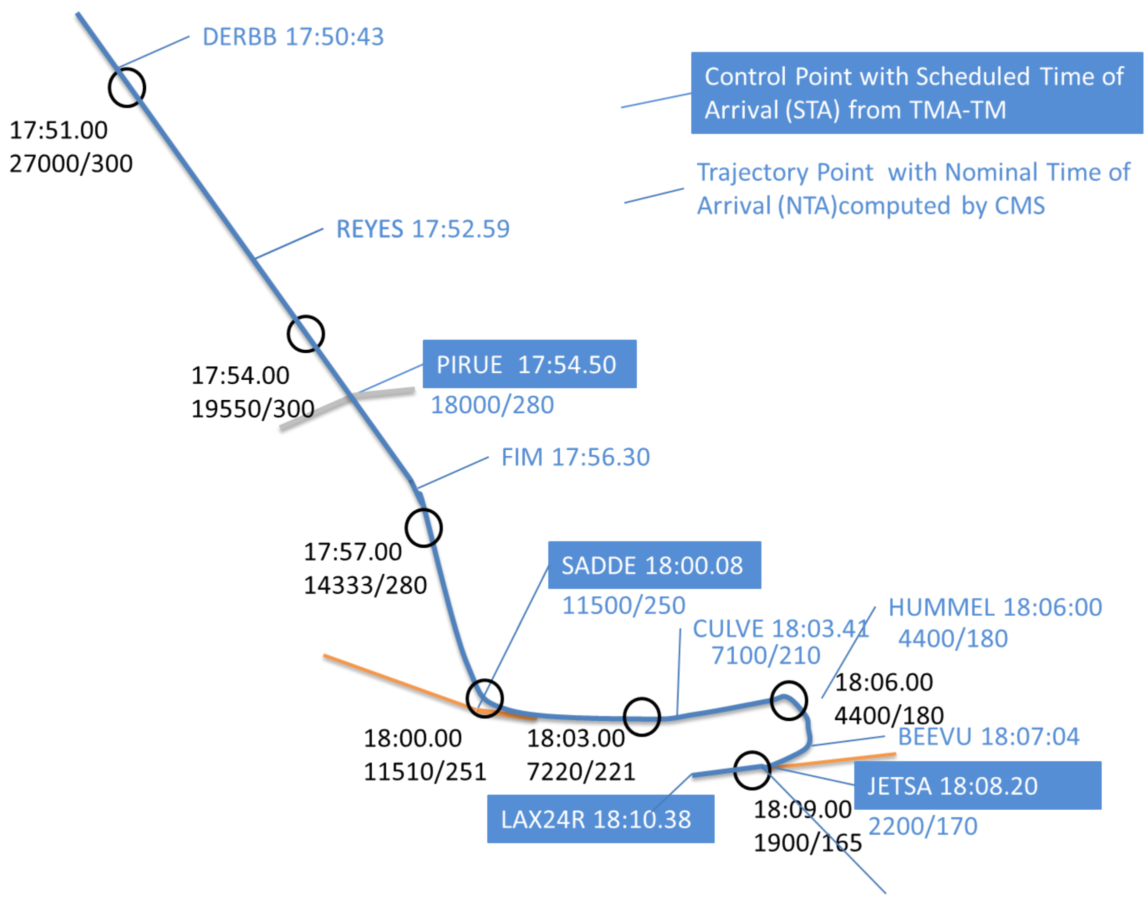

Figure 13: nominal trajectory and example nominal flight states (slot markers) at different times

At 18:06.00 the nominal flight state of the aircraft will be within the base turn at 4400 feet and 180 knots passing HUMMEL.

Note that the computation of the nominal flight state does not use the actual aircraft position. It solely depends on the schedule and the nominal trajectory that meets the schedule.

5. Publish the nominal flight state to enable displaying the slot marker and associated values

Lastly, the relevant values of the nominal flight state need to be published and made accessible to the display. While the nominal flight state can contain many more values, the following have been used in the past: timestamp, latitude, longitude, indicated airspeed, groundspeed.

The timestamp is needed to determine the validity of the data and enable smoothing and extrapolation if necessary. The latitude and longitude describe the center of the slot marker for the given timestamp. The indicated airspeed or the groundspeed can be shown in combination with the slot marker to provide an additional reference to the controller as shown with the slot marker in Figure 7.

Speed Advisories

CMS to date has used two different speed advisory logics. The first type of speed advisories used in all CMS simulations until 2011 consists of a single speed and a waypoint at which the charted speed will be re-captured. The goal is to have one speed advisory issued that if followed gets the aircraft on time at the advised waypoint. The second advisory type used in some simulations in 2012 is designed for multiple, sequential but smaller speed changes. Both types are illustrated below

Speed Advisory Logic-1: Single speed advisory and capture waypoint

Figures 14 and 15 show the underlying logic for the first type speed advisory for the cases at which an aircraft is early and needs to be delayed, i.e. slowed down (Fig.14) and when an aircraft is late and needs to be sped up (Fig.15) to reduce flight time.

The blue line is the charted speed profile depicted in Figure 11. In this example it starts with a segment at 240 knots, then a slowdown to 210 to

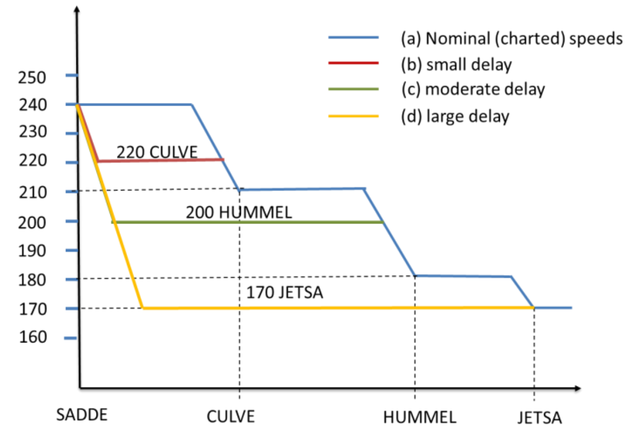

Figure 14: Absorbing delay with single speed advisory (logic-1)

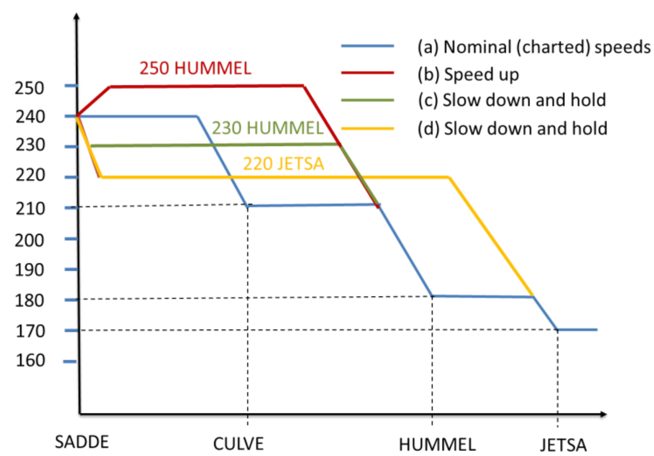

Figure 15: Reducing flight time with single speed advisory (logic-1)

cross waypoint CULVE at 210, another slowdown to cross HUMMEL at 180, and another slowdown to cross JETSA at 170. After JETSA there will be another speed reduction to the approach speed and the final slowdown to the landing speed (not shown in Figures 11, 14-17).

The speed advisory logic -1 tries to find a speed profile that allows the aircraft to increase or reduce to a given speed now, then initiate the slow down to meet the speed restriction at a downstream waypoint. This way the advised speed and the waypoint at which the nominal speed should be recaptured can be communicated in one clearance. Figure 14 shows three potential slow downs, to absorb increasingly larger delays from top to bottom. For example speed advisory (c) would usually be implemented via a "maintain 200 knots until HUMMEL" air traffic control instruction. This assumes that at HUMMEL charted speeds are resumed. This early slowdown will cause the aircraft to arrive at HUMMEL later than the charted profile. Speed advisory (d) in Fig.14 is likely not possible in a clean configuration and may be rejected by the pilots.

Figure 15 indicates how this speed advisory logic deals with speed ups and reducing flight time when the aircraft is late.

Speed profile (b) reflects an increase to 250 knots and an assumed resume to charted speeds at HUMMEL. This will increase the aircraft speed, reduce the flying time and cause the aircraft to arrive earlier at HUMMEL. Profile (c) indicates an immediate slowdown to 230 knots be maintained until the HUMMEL waypoint and profile (d) indicates maintaining a speed of 220 knots to waypoint JETSA.

The advantage of logic-1 is that it allows controllers and pilots to implement a single speed adjustment and know when it is to be terminated. The disadvantage is that the advised speeds can sometimes be less intuitive. Consider case (c) (and (d)) in Figure 15. The aircraft is late and the flight time needs to be reduced. However, in order to achieve the required average speed up in one instruction, the advisory is to slow the aircraft to 230 (220) knots now, but hold it throughout the 190 knots (and 180 knots) segment. This achieves a shorter flight time. However, the controller would see a recommended slow down for an aircraft that is late, which is counter-intuitive. The other disadvantage of this logic is that it is fairly aggressive and may cause an aircraft that was early to get behind, only to require a speed up later. To address the shortcomings of this advisory logic speed advisory logic-2 has been implemented and an early prototype tested in a recent simulation.

Speed Advisory Logic-2: Sequential speed advisories

Speed Advisory Logic-2 does not absorb the required delay in one advisory. Instead it modifies the entire speed profile, requiring multiple, sequential instructions to be implemented. Figures 16 and 17 show slowdowns and speed-ups for speed advisory logic-2. This logic adjusts the speed profile by a certain percentage and modifies each segment up to 15% of its nominal speed profile. While the internal computations use a finer resolution, logic-2 always rounds the speed up to the next 10-knot increment. As with speed advisory logic-1, logic 2 also uses procedural limits in determining its bounds. For example the speed ups in Figure 17 are all limited to 250 knots, because of the air traffic control restriction to not exceed 250 knots below 10, 000 ft.

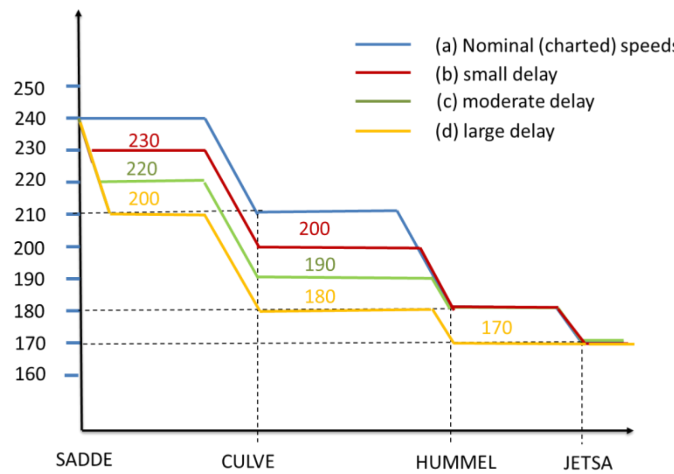

Figure 16: Absorbing delay with sequential speed advisories (logic-2)

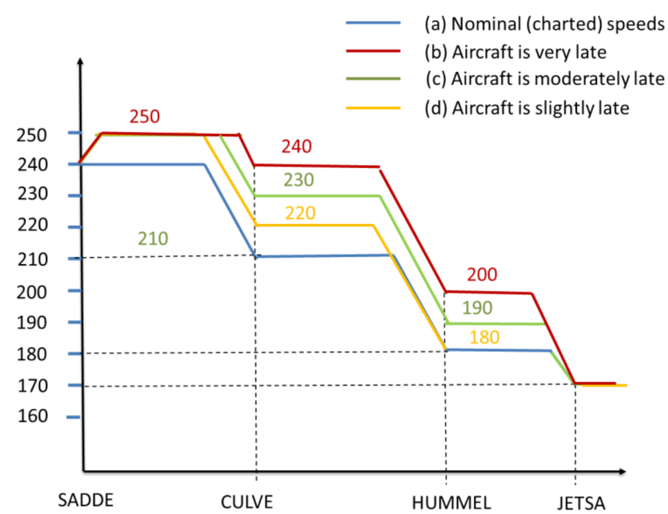

Figure 17: Reducing flight time with sequential speed advisories (logic-2)

Speed advisory logic-2 is designed to be issued in multiple instructions. For example, case (c) in Figure 16 advises the controller to issue a reduction to 220 knots first. Then shortly before the aircraft approaches CULVE, it advises the controller to issue a slowdown to 190 knots, followed by a slowdown to 180 knots when approaching HUMMEL. Charted speeds will be resumed at JETSA. The advantage of sequential advisories is that adjustments are distributed over the profile. Therefore the changes are not as aggressive as a single speed. Additionally, this logic will also always show a correction in the intuitively correct direction. This means that an aircraft that is late will get an advisory faster than the nominal speed, an aircraft that is early will get an advisory for a speed slower than the nominal speed. The primary disadvantage of this logic is that it requires multiple instructions and potentially more work to issue them.

Discussion

The preceding sections have described the computations for the CMS tools that were used in various simulations. CMS research has been conducted in a series of HITL studies and included analyzing the effectiveness of these tools, the associated controller workload, and the tool usage and acceptability.

One of these simulations investigated how well controllers could control aircraft to land them as close to their STA as possible using speed control alone. Controllers were assigned one of three levels of tools: (1) *Timeline:* timelines and early/late indicators, (2) *Slot marker:* timelines, early/late indicators and slot markers, (3) *Advisory:* timelines, slot markers and speed advisories. These speed advisories were the single speed advisories described as logic-1. Controllers also had to compensate for errors in the forecasted winds that had not been taken into account by the scheduler. Results show that speed clearances were sufficient under all conditions to maneuver aircraft closer to their STAs. From participant reports, this form of control incurred acceptable workload and two of the three levels of tools were deemed easy to use [5][13].

That study found that controllers reported they used the slot markers 93% of the time in the advisory condition and 90% of the time in the slot marker condition. Controllers also reported they used the speed advisories 30% of the time. Controllers' commented that they preferred the slot markers over the speed advisories and the timelines as their "tool of choice." Controllers used the early/late indicators about the same amount in the timeline and slot marker conditions but more than they reported using the speed advisories that replaced them in the advisory condition. Fig.18 illustrates these results. Details and additional findings are available in [5,13].

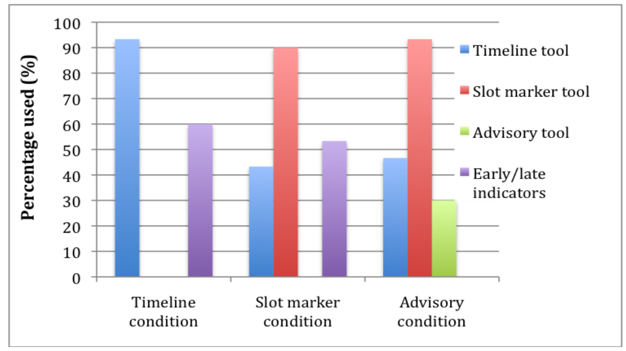

Figure 18: Amount participants "used" the tools in each toolset condition. [5]

In a recent CMS/ATD-1 study [17] the tools shown in Figures 4-7 were used by Final and Feeder controllers with an early prototype of the sequential speed advisories. Figure 19 depicts TRACON controllers' ratings of how helpful these tools were plotted against their confidence in the information.

Slot markers were rated highest among the CMS tools in line with prior research. The timelines were also highly rated. Again in this study, speed advisories received the lowest ratings. Controllers generally thought winds could affect the usability of the tools, particularly very strong winds.

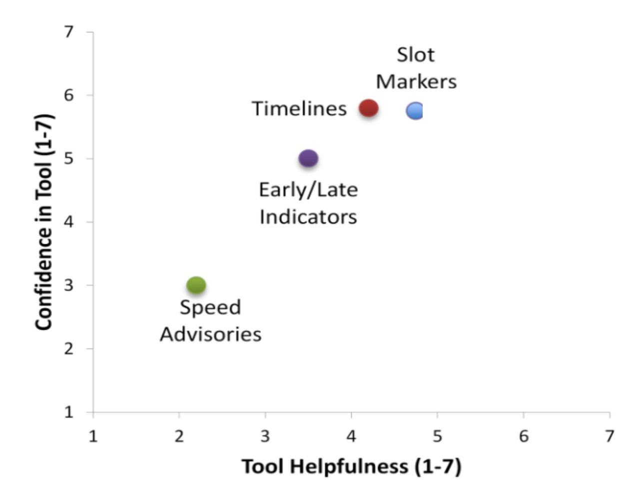

Figure 19: TRACON controllers' ratings of CMS tools in CMS/ATD-1 study [17]

It should be noted that the sequential speed advisories used in this study were an early prototype and work is underway to improve their stability and correctness to provide more confidence for the controllers. However, all CMS research to date has consistently indicated that the slot markers are the most useful and used tools for spacing and controlling aircraft towards their scheduled time and that timelines and early/late indicators provide very helpful information on the overall schedule situation.

Next Steps

In order to realize the objective of ATD-1, a field demonstration, the CMS tools are re-hosted into an operational prototype. The algorithms are implemented into TMA-TM and the graphical user interfaces into a STARS prototype. The speed advisory logic is undergoing additional refinements to increase its usability. More studies are underway to further refine the interoperability of flight deck interval management and controller tools.

Concluding Remarks

Prior publications discussed the benefits of the controller managed spacing tools. In this paper the actual computations underlying the CMS tools are discussed in detail. The CMS tools will be integrated into an operational prototype for further evaluation within NASA's ATM Technology Demonstration-1.

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