

TRAJECTORY-ORIENTED TIME-BASED ARRIVAL OPERATIONS: RESULTS AND RECOMMENDATIONS

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Abstract

Research projects on enabling trajectory-based 4D operations have had limited success in the past causing tendencies to abandon the idea of “absolute” time-based operations in favor of “relative” aircraft-to-aircraft based operations. Over the past five years researchers at NASA Ames Research Center have matured a concept of trajectory-oriented time-based arrival management in a number of human-in-the-loop simulation studies. Data gathered in recent experiments reflect the potential benefits envisioned for the concept. Inter-arrival time variability has been significantly reduced. More aircraft were able to conduct energy-efficient descents during a reduced flight time. Controller workload at the busiest sector was reduced; with some workload shifted to less busy sectors. Objective and subjective data were analyzed to provide recommendations for ground-based automation that enables trajectory-oriented operations with its associated benefits. These operations can facilitate and be complemented with relative operations to circumvent the problems of 4D operations and increase the potential benefits even further. This paper presents data excerpts, recommendations and a concept for combining airborne self-spacing and merging functions with trajectory-oriented time-based arrival operations. Funding for this work was provided by the Advanced Air Transportation Technologies (AATT) Project of NASA's Airspace Systems Program.

Introduction

Current research trends indicate a shift towards “relative” aircraft-to-aircraft operations supported by airborne separation assistance systems (ASAS) to solve some of the bottlenecks of the current ATC system. This shift can partially be attributed to the lack of success of previous air traffic management

research on trajectory-based 4D operations. Graham, Hoffman, Pusch and Zeghal [1] recommend that 4D operations should be limited to the outer traffic flow control loop with time estimate accuracy in the order of minutes rather than seconds, while “relative” operations provide for the separation control loop. With reference to research results from the Programme for Harmonized ATM Research in Europe (PHARE), Graham et al. state that 4D operations most likely require new avionics, and additional buffers. They conclude "In short, full 4D with tubes in space for aircraft separation enables tactical flow management, empowers the flight planning function at the cost of a loss of tactical level reactivity and increased workload management for the executive controller" (page 6).

Researchers at NASA Ames Research Center pursued an approach to 4D operations that used three-dimensional trajectories and a single time constraint along the trajectory, typically at the metering fix [2-3]. This concept differs from the 4D tubes concept in that it relies on flight crews configuring their conventional Flight Management System (FMS) with climb, cruise, and descent speeds issued by controllers or computed by the FMS to meet the time constraint along a given route. The resulting trajectories are then either transmitted to the ground via data link, or recreated by a ground based trajectory synthesizer to enable visual inspection by the controllers, conflict probing, and compliance feedback. The controllers can modify the speeds as well as the routes to resolve conflicts, or re-adjust the aircraft arrival time, if necessary. This flexibility, made possible by a mature set of ground automation tools, can be considered one of the key differences to the PHARE concept in which 4D tubes are contracted and then are difficult to adjust to changes in the environment. A series of experiments showed increasing improvements in the management of arrival flows while the procedures and ground automation tools underwent continuous refinements.

At the current time it is fair to say that a flexible 4D concept with appropriate ground automation can provide improvements over current day operations.

The first part of this paper provides excerpts of results from a recent high-fidelity experiment conducted at NASA Ames to demonstrate the benefits. The second part of the paper will detail recommendations that in the authors' opinion are critical for making this concept work, and indicate problem areas. Addressing these problems may require additional procedures and automation that relative operations may provide. A promising complimentary use of the two concepts is the subject of the third part of the paper.

Recent Results

Earlier papers [e.g. 3] reported trends and observations from several experiments conducted in the Airspace Operations Laboratory (AOL) and the Crew Vehicle Systems Research Facility (CVSRF) at NASA Ames Research Center. Research in the framework of the Distributed Air Ground Traffic Management (DAG-TM) project [4] expanded the simulation capabilities to a higher fidelity including more piloted flight simulators and cockpit display of traffic information (CDTI) equipped aircraft [5]. The pseudo pilot interfaces underwent significant improvements by including the Multi Aircraft Control System (MACS) into the simulation [6]. These changes allowed a capability enabling realistic simulations of full mission air traffic operations [7]. This air-ground simulation facility was used in September 2002 to conduct an experiment comparing trajectory-oriented DAG-TM operations with and without separation responsibility assignment to some aircraft against a control condition. While details on this experiment including the autonomous operations are reported in [8] this paper includes only comparisons between ATC controlled 4D operations and the control condition. (DAG-TM research is being jointly conducted at NASA Ames, Langley, and Glenn research centers.)

Scenario and Conditions of Interest

The conditions of interest for the purpose of this paper are the control condition and one experimental condition labeled Concept Element 6 (CE6) "En route Trajectory Negotiation" in the DAG-TM framework [4].

The air traffic scenario was modeled after current peak arrival traffic within and adjacent to the northwestern area at Ft. Worth Center (ZFW). About 90 aircraft, half of which were arrivals and half

overflights and departures, were fed in and out of one enroute high altitude sector in Albuquerque Center (ZAB), two high altitude sectors in ZFW and one ZFW low altitude sector. Two sectors of Dallas-Ft. Worth (DFW) Terminal Radar Control TRACON operations were also simulated. Figure 1 shows the subject airspace. Whereas previous studies used data-link equipage level mixtures, this experiment assumed 100 % data link equipage for all conditions and runs.

Control Condition: "Tactical ATC"

The control condition was designed to reflect current day operations at ZFW, which has been using the Center TRACON Automation System (CTAS) [9] Traffic Management Advisor (TMA) for a number of years. These operations are characterized by tactical sector oriented actions [10]. Subject and confederate controllers fed the air traffic from peripheral Centers and sectors, sometimes with miles-in-trail restrictions, into the subject high altitude sectors. The TMA was set up for seven nautical miles in-trail at the meter fix. No additional restrictions were imposed by the airport acceptance rates. The ZFW controllers issued tactical heading, altitude and speed instructions (vectors) to aircraft to meet scheduled times of arrival (STA) for specific sector exit conditions. The exit condition for the high altitude controllers was referenced to a 60 nautical mile arc around the respective meter fix, which the aircraft had to cross at flight level 240 and 280 knots indicated air speed at the outer arc STA. Traffic permitting, the high altitude controllers could also issue pilot's discretion descents after coordinating with the low altitude controller, thus disregarding the restrictions at the outer arc.

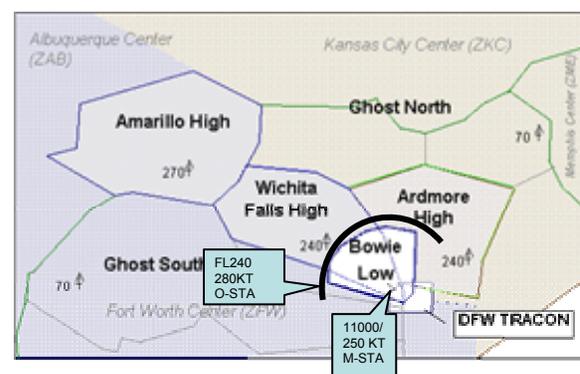


Figure 1: Subject Airspace

The STA and the required delay were shown in hours, minutes, and seconds on the controller's display. The exit condition for the low altitude controller was referenced to the assigned meter fix,

which the jet aircraft had to cross at 11000 feet and 250 Knots. The STA and delay at the meter fix were also displayed to the low altitude controller position. The low altitude controller was instructed to provide seven nautical miles in trail over the meter fix to approach control and use the displayed time information at his or her discretion. It should be noted that unlike the experimental setup described, in current day operations at ZFW controllers usually get STA and delay information rounded to the minute.

Experimental Condition: “4D Trajectory-Based”

The experimental condition discussed in this paper reflects one instance of the DAG-TM CE6 En-route Trajectory Negotiation. The CTAS TMA had a configuration identical to the control condition (seven nm in trail, no additional TRACON constraints). However, controllers were given decision support tools (DSTs) to visualize and modify the aircraft 4D trajectories in a fashion compatible with the FMS. The exit conditions at the high altitude sectors were removed and all controllers were instructed to adjust the aircraft trajectories as required to meet the STA at the metering fix. The controllers’ DSTs were CTAS-based and included a timeline display, a cruise/descent speed advisory function, a trial planning function for route modifications, and an integrated Controller-Pilot Data Link Communication (CPDLC) function. The CTAS conflict probe was monitoring active and provisional trajectories for potential separation losses. Controllers could also use a new precision descent procedure clearance that instructed flight crews to fly their descent coupled to the FMS that was configured with assigned cruise and descent speeds. The procedure required flight crews to initiate the descent at the FMS computed top of descent location and to meet the altitude and speed restriction at the metering fix. Some aircraft were additionally equipped with an experimental Required Time of Arrival (RTA) capability that computed the cruise/descent speed combination to meet the RTA and loaded it into the FMS. Flight crews piloting those aircraft could accept RTA clearances instead of speed clearances.

Participants

The controller participants were Full Performance Level (FPL) controllers from different facilities in the United States not including ZFW. Only the low altitude controller had some operational time-based metering experience. The controllers were only moderately familiar with the subject airspace. They were trained for at least one and a half weeks and were involved at several stages in the DAG-TM project, giving them a good understanding of the

operational concept used in the experimental condition. Comparisons of their performance in the control condition to earlier experiments with FPL ZFW arrival controllers working similar scenarios indicate an equivalent level in terms of workload and performance, e.g., arrival sequencing and spacing in the simulation environment for the control condition.

The pilot participants flying the full mission simulator and the desktop-based single pilot stations were all airline pilots with glass cockpit experience. They were trained for about one week on tools, procedures, and simulator handling.

The pilots of the multi aircraft control stations were private pilots who have participated in a number of experiments and simulations and were well trained to handle the remaining traffic.

Data Collection

Data collection consisted of three variations of the same basic scenario per condition. The conditions were alternated. Each scenario lasted for about 75 minutes with traffic density and complexity peaking between 30 and 50 minutes. The comprehensive data collection included all controller and pilot inputs to the automation, frequent state information, workload recordings during and after the runs, observations at each subject position, and questionnaires. Most performance measures were analyzed to reflect the measures suggested and used by the Free Flight Office [11]. The reader is referred to [8] for more information and the majority of the measures.

Results

The number of data runs and participants is insufficient to draw generalized conclusions on their own merit. However the data analysis confirms and intensifies the trends that were noticed in a number of related experiments over the course of five years. Given that a comprehensive air traffic control study with a sufficient number of participants and data collection runs is difficult to conduct due to time and resource constraints, it therefore appears appropriate, in the authors’ opinion, to present some result excerpts of this recent experiment indicating the potential of a trajectory-oriented time-based metering concept.

Three individual results are presented as examples for the potential capacity, efficiency, and workload impact. The inter-arrival spacing at the meter fix is presented as an example for reduced excess spacing and higher throughput at the metering fix. One goal of the concept is to allow aircraft to stay at their cruise altitude longer and perform uninterrupted idle descents, thus increasing efficiency and reducing noise. The mean altitude of the arriving

aircraft is shown to illustrate how the trajectory oriented approach can facilitate this goal. Finally, sector workload is analyzed showing a reduction at the busiest low altitude sector and unchanged levels at the feeding high altitude sectors, where the controllers performed additional tasks, solving downstream problems. As with all operational concepts there are problems that accompany the associated benefits, some of which are addressed and discussed at the end of this section.

Inter-Arrival Spacing at the Meter Fix

The CTAS TMA was configured to schedule aircraft seven nm in trail at the meter fix creating delays that averaged about two minutes, going up to five minutes. Given the winds used and a crossing restriction of 11000 feet and 250 Knots, the in-trail restriction computes to 82 seconds spacing. Fifteen seconds tolerance was assumed to be adequate for traffic management purposes in the TRACON. Aircraft less than 58 seconds apart had less than five NM lateral separation and were therefore delivered at different altitudes to avoid the separation loss. The samples used for figures 2 and 3 were created using all metered jet aircraft pairs from the three control condition runs and the three CE6 experimental runs.

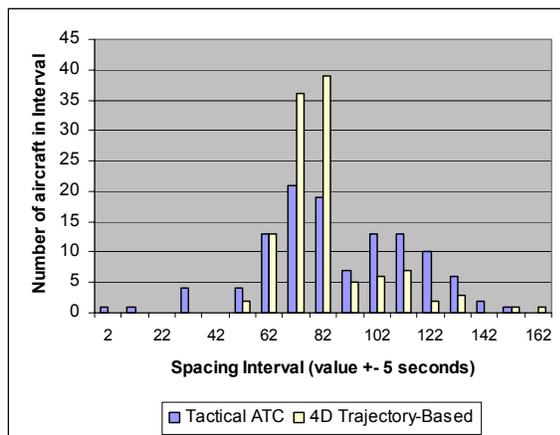


Figure 2: Inter-Arrival Spacing Histogram

The 4D trajectory-based operations resulted in a significant reduction of the variance of the inter-arrival spacing at the metering fix, meaning that aircraft were delivered more consistently.

Table 1: Summary of the data samples for meter fix inter-arrival spacing

Sample	Count	Mean spacing	Variance	Std. Error	Std. Dev.
Tactical ATC	115	88.44	772.69	2.59	27.80
4DTrajectory-Based	115	83.43	351.67	1.75	18.75

There was also a marginal reduction of the inter-arrival spacing itself, bringing the mean within 1.5 seconds of the target spacing of 82 seconds. In the control condition 10 aircraft were delivered vertically spaced with less than five nm lateral spacing, as opposed to only two aircraft in the experimental condition. Overall, the trajectory-based approach promises improvements for the consistency of the traffic flow with a good potential for improving throughput at traffic bottlenecks like a metering fix.

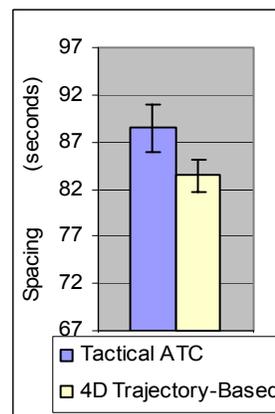


Figure 3: Inter-Arrival Spacing Mean and Standard Error

Mean Altitude of Arriving Aircraft

Figure 4 shows the mean altitude of the arriving aircraft at different ranges from the meter fix. Means and standard errors are shown for 115 aircraft in each condition that started between flight level 290 and 370 averaging flight level 350. In the experimental condition aircraft stayed longer at higher altitudes. Controllers in the current day condition started descending aircraft from their cruise altitude before the top of descent point, indicated by the lower altitude at the 120 nm range. They also felt more comfortable issuing precision descent clearances in

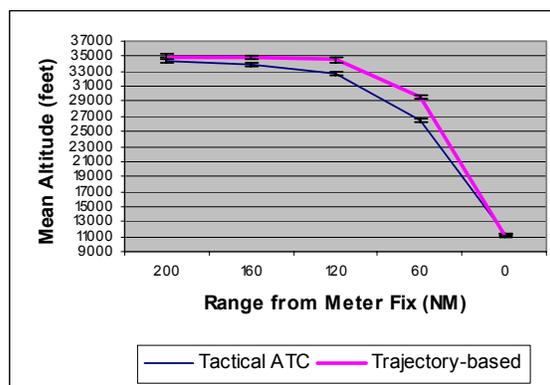


Figure 4 : Mean Altitude for the Arrivals

the trajectory-based condition than pilot's discretion clearances in the control condition, thus letting more aircraft fly their FMS computed idle descent path.

Controller Workload

Figure 5 represents subjective workload ratings on a modified NASA TLX scale that were obtained

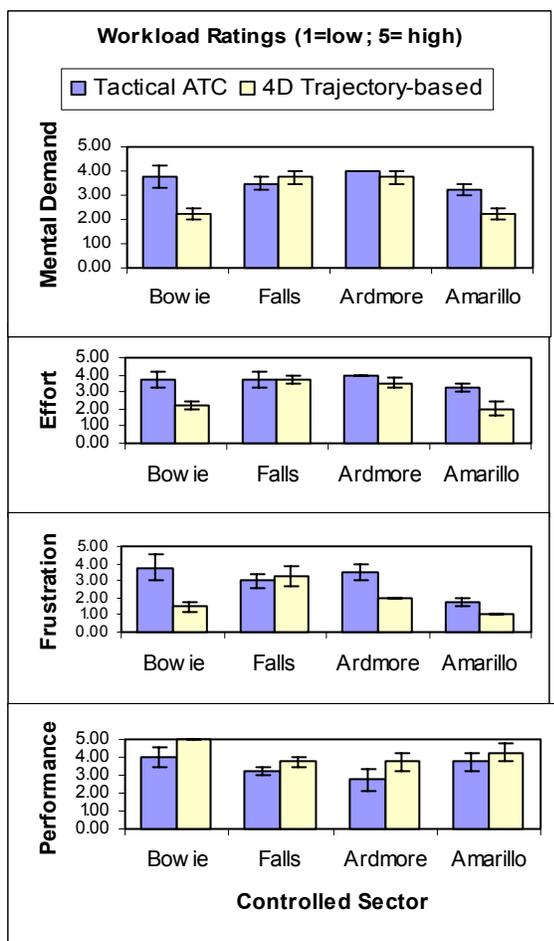


Figure 5: Subjective Workload Ratings

from the controllers after each run. Workload ratings were also obtained during the runs using Workload Assessment Keyboards (WAK) that prompt the operators periodically to assess their workload on a scale from 1 to 7. These ratings were consistent with the post-run ratings and are not presented here. The sectors can be located on the airspace map in Figure 1. The main workload impact can be seen at the low altitude sector (Bowie) that benefits most from the trajectory-based approach, because the feeding high altitude sectors set up the trajectories for the downstream sector. The controller reported less mental demand, effort, and frustration required to achieve a higher level of performance. At the same time, workload for the feeding sectors was not increased, while the controllers felt that they were performing better than in the tactical ATC condition.

Problem Areas

Some of the problems encountered early in the research project have been addressed through

conceptual adjustments, tool modifications, or procedural changes. Two remaining fundamental problems with the concept of 4D trajectories with a single time constraint are the neglect of spatial constraints in the scheduling process and the usability of the toolset provided to the operators.

Spatial vs. Time Constraints

One of the fundamental problems with the concept and tools used in this experiment was the trajectory de-confliction. By controlling toward a single time constraint at the metering fix, separation at this point can be assured. However, the scheduler did not take into account local spatial constraints along the way to the metering fix. Even if all aircraft meet their STA precisely, there may still be separation losses at intermediate merge points. This fundamental problem of interacting spatial and time constraints is not always obvious to the controllers who may only try to modify aircraft trajectories to absorb a given amount of delay while acting under the misconception that the trajectory-based speed advisories will automatically de-conflict the aircraft pairs along the route.

Tool Usability

The second problem frequently encountered is the usability of the automation tools. If the tools require a significant amount of attention to complete a task, controllers may be distracted long enough that they can get behind in controlling the traffic in their airspace. Observers in the experiments noted frequent problems for controllers interacting with the route trial planning tool in its current implementation. The tool required the controller to pick and drag a point along the route and wait for the trajectory to re-compute and be conflict-probed, which took approximately one second. In addition the tools did not provide sufficient support for absorbing large delays (> six minutes) inside the ZFW airspace. A holding function was not available and “S” turn creation with the route trial planner was cumbersome. This is consistent with prior simulations and field tests [12, 13].

Discussion

The promising results above indicate some of the potential benefits of a 4D trajectory-based approach. Throughput and efficiency can be increased and controller workload at the busiest sectors can be reduced. The tools provided to the controllers need to be well designed to provide the flexibility and usability to facilitate these benefits.

The next section gives a set of recommendations for the DSTs, controller displays,

and level of automation that reflects one possible way to achieve measurable benefits when applying the trajectory-oriented time-based concept.

The issue of solving local separation problems while adhering to the given schedule needs to be addressed further. Possible trajectory-oriented solutions range from improved conflict feedback for the controllers to DSTs that generate conflict free trajectories and transmit those to the aircraft automatically [13, 14]. A different approach that combines 4-D trajectory operations with airborne separation assurance logic will be proposed in the third part of this paper.

Recommendations for Ground-Based Automation Facilitating 4D Trajectory Operations

The following list of recommendations is based on the “do’s and don’t’s” encountered in evaluating the concept described above. It needs to be noted that several critical decisions, e.g., about the level of automation, were made early in the research process based on initial controller feedback and discussions among the researchers. A particular recommendation here does not imply that other options may not be as viable or even better. A recommendation here means that a particular tool or way of interacting with the tool has been tested in a reasonably realistic environment and was found useful, useless, acceptable, or unacceptable, and why it appears this way.

Recommended Toolset

Table 2, Table 3 and Figure 6 summarize some results gathered in a series of three experiments conducted in 2002, including the DAG experiments described above. Thirteen controllers used minor variations of the same toolset to control arrival traffic in a trajectory-oriented fashion for several days. After each simulation series controllers completed a questionnaire including the questions quoted in the captions of Tables 2 and 3. The question about the conflict list was added to the questionnaire after the first group. The toolset is described in [3]. The most important DST capacities are discussed after the results on ease of use (usability) and importance (usefulness) are presented.

The results are consistent with results from previous studies [3]. The timeline was ranked the most useful and usable tool of the provided toolset. The color coding also plays an important role as do

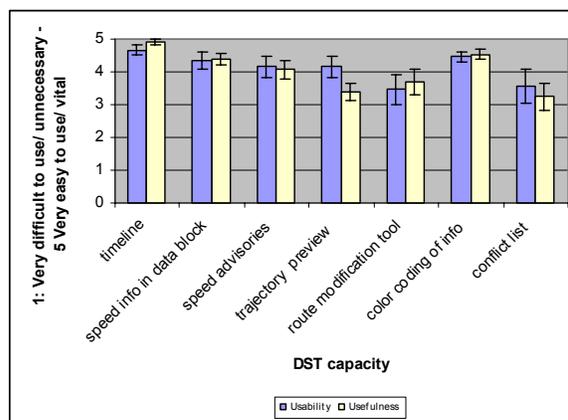


Figure 6: Mean and standard error of usability and usefulness

the speed indication in the data block and the speed advisories. The trajectory preview, which allows controllers to “dial out” the predicted position of all aircraft into the future, was considered usable, but only marginally useful. Opinions on the route modification tool were spread across the full range, which is likely a result of its somewhat complicated usage. The conflict list was also considered only marginally useful and usable. Comments indicated that it was not well enough integrated with the rest of the information and therefore disregarded once the traffic got very busy.

Table 2 : Data Summary “Please rate the usability of each of the following: *Very easy to use (5) Very difficult to use (1)*”

DST capacity	Mean	Std. Err.	Med.	Std. Dev	Count
Timeline	4.7	0.14	5	0.49	12
Speed info in data tag	4.3	0.26	4.5	0.89	12
Speed advisories	4.2	0.32	4	1.14	13
Trajectory preview	4.2	0.32	4	1.14	13
Route mod. tool	3.5	0.45	4	1.61	13
Color coding	4.5	0.14	4	0.52	13
Conflict list	3.6	0.53	3	1.40	7

Table 3 : Data Summary “Please rate the usefulness of each of the following: *Vital (5) Unnecessary (1)*”

DST capacity	Mean	Std. Err.	Med.	Std. Dev	Count
Timeline	4.9	0.09	5	0.30	12
Speed info in data tag	4.4	0.18	4	0.65	12
Speed advisories	4.1	0.29	4	1.04	13
Trajectory preview	3.4	0.27	3	0.96	13
Route mod. tool	3.7	0.40	4	1.44	13
Color coding	4.5	0.14	5	0.52	13
Conflict list	3.3	0.41	4	1.16	8

Timeline

The timeline provides a graphical representation of the time dimension. Some controllers had initial problems getting used to the format, but once trained reported it to be the most desirable tool. The example in Figure 7 shows an excerpt of the timeline on one of the high altitude controller's display.

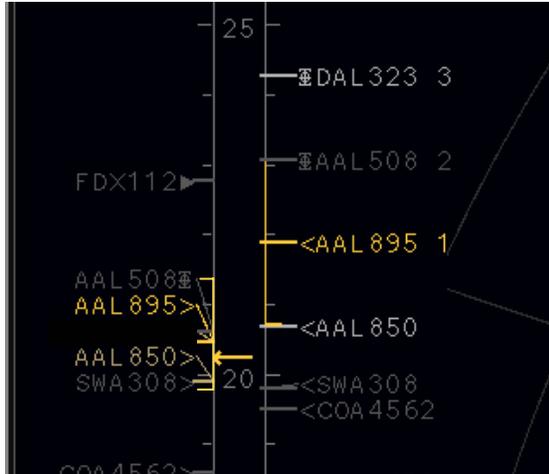


Figure 7: Timeline Display

The four aircraft with the bright labels (DAL323, AAL895, AAL850, UAL1472) are controlled by one controller; a different controller controls the remaining aircraft. The right side indicates the STA, the left side the estimated time of arrival (ETA). The numbers next to the STA labels depict delay to be absorbed. AAL895 is currently highlighted and is approximately 85 seconds ahead of schedule. The bracket on the left side indicates, how much earlier, or later the aircraft could arrive by modifying its speed without changing the route or its cruise altitude. Since the upper line of the bracket (latest time) is still below its scheduled time the aircraft needs an additional delay vector or an altitude change to achieve its STA. The bracket on the STA side indicates the minimum time separation required to meet the miles in-trail restriction used by the CTAS TMA in this example.

Color Coding and Expandable data tags

Discussion with the controllers, observations, as well as further data analysis revealed that the positive feedback on the color coding and the speed indication is mainly due to some simple display characteristics.

1. Arrivals into the DFW metroplex including Dallas-Love Field were displayed in a different color than overflights and departures, making them easy to distinguish.
2. Whenever an aircraft is highlighted on any part of the display it is highlighted everywhere it

appears and additional information is provided. This simplifies the scan for the controllers.

3. Expandable data blocks provide additional information if an aircraft is dwelled on or selected. This reduces clutter on the screen while still providing the necessary information.

Speed Display and Speed Advisories

A dwelled upon aircraft is highlighted in the timeline and the speed and scheduling brackets appear. The data block is expanded and the current and planned speeds appear in the fourth line. The controllers could ask for speed advisories with a mouse click on the speed field or the ETA in the timeline. The speed the aircraft should fly to meet its STA is displayed and the controller can modify, data link, accept, or reject the advisory.

Route Modification and Holding Function

A number of different comments were made with regard to the route modification tool, which is reflected in the large variance in controller ratings of this capacity. Several controllers thought that route changes created with this tool provided more efficient and precise routings than vectoring. However, the tool needs to be easier to use and provide faster feedback to be usable for those controllers who thought it was problematic. When the controllers moved a waypoint to a test location the conflict probed route was drawn with a one second time delay. One idea that might resolve this problem would be a semi-automatic tool that provides a path stretch advisory on controller's request [13]. The controllers could avoid several trial and error cycles, but could ask for a path stretch that absorbs the required amount of delay and modify or execute it. This could greatly improve tool usability especially for integration into the radar controller's display.

A second frequently mentioned problem was that the route modification tool was considered inappropriate for absorbing large delays (> six minutes). Since these delays are typically dealt with by sending aircraft into holding patterns, a holding function should be integrated that allows controllers to assign and include holdings into the trajectory planning process.

Discussion: Guidelines on Level of Automation and Automation Behavior

Controllers accept automation support if they are in command

Good controller acceptance was achieved, when the automation support was available on request only. Examples are the interactively generated speed

advisories and the expandable data blocks. Advisories appearing on the screen automatically were less well received. For example, an upcoming top of descent point was automatically shown on the screen as long as the controller had not issued a descent clearance. This was found to be annoying rather than helpful. The controllers preferred to have a quick way of displaying the aircraft's route including its top of descent point.

The automation should provide instantaneous feedback

Automation that provides delayed feedback can have a negative impact on the controller's scan/action pattern as well as trigger erroneous actions.

Air traffic controllers are used to working very efficiently under time pressure. This is due to a combination of scanning the traffic, identifying the need for an action, and issuing a proactive instruction that assures a clear path for the aircraft at least until the controller scans the aircraft again. If dealing with the automation interrupts the regular scan, controllers can get behind in handling other aircraft. This can result in a chain reaction of late and reactive rather than proactive instructions that increase the workload and decrease the traffic flow efficiency. A typical example during the conducted experiments was the latency of the route trial planning function.

Latency between a controller's request for a DST advisory and its response occasionally led to issuing an instruction prematurely to the aircraft. The DST implementation used especially for the earlier series of experiments resulted in some of these problems. It sometimes took a few hundred milliseconds to compute the requested advisory or provide feedback on whether the solution would cause other conflicts. When a controller issued the first advisory immediately he or she occasionally corrected the instruction or gave a second clearance because the advisory had not been completed when the instruction was issued.

The trajectory computations must be highly reliable and clearly indicate failure

By definition, the 4D trajectory-based concept relies heavily on trajectory computations performed in the aircraft and on the ground. These trajectory computations need to be highly reliable for conflict detection purposes, ETA predictions, and to provide the appropriate situation awareness for the operators. In a few instances during the simulations the trajectory predictions were not updated by the DST for a significant time period. The available "no-trajectory" indication supplied by CTAS was disabled by the experimenters. The last valid

prediction was maintained in the system when the trajectory computation failed. As the aircraft progressed, the controller did not notice that the estimated time of arrival for this aircraft did not reflect its current state. This misleading information led to excessive delay routes that eventually caused the aircraft to miss its scheduled time of arrival by several minutes, thus disrupting the overall arrival flow. If these failures occur frequently, controllers lose trust in the automation and the tools do not provide adequate support for the task. However, when these failures occur, the trajectory derived data need to be clearly marked as old and unreliable.

The active trajectories should always be available, "What if" planning should be done on provisional trajectories

Good acceptance was achieved with the concept of leaving active trajectories unmodified until a new instruction was implemented. Controllers wanted to be sure that the computed times and trajectories actually reflected what the aircraft would be doing if it followed its current route. When generating an advisory provisional routes should be generated and modified to enable independent evaluation for conflicts and compliance with time constraints.

Complimenting 4D trajectory based operations with aircraft-to-aircraft based operations

A Problem with Absolute Operations

One identified problem area, discussed earlier, is the interaction of time and spatial constraints. Aircraft trajectories that provide separation at a common time-constraint waypoint may not provide separation along the way, especially at intermediate merge points. Secondly, the overall traffic flow is very vulnerable to individual aircraft not meeting the scheduled time within very narrow tolerances. The following example that was used in earlier studies illustrates the problem: A schedule has been generated to provide six nautical miles separation at the meter fix. In the test environment described above this schedules aircraft 70 seconds apart at the metering fix. Aircraft arriving within less than or at 58 seconds lose lateral separation at the meter fix. So, the tolerance for meeting the absolute time would have to be set to +/- five seconds to avoid having to deliver aircraft separated by altitude. As studies indicate some FMS equipped aircraft and controllers supplied with the toolset described above may be able to meet RTAs within these tolerances.

Operationally, such a precision may be impractical and hard to achieve for the majority of aircraft.

A Problem with Relative Operations

One of the problems with relative operations like self-merging and self-spacing is the available range and the preconditioning of the aircraft. ASAS tools are limited by the range that the technologies like traffic collision avoidance systems (TCAS), automatic dependent surveillance broadcast systems (ADS-B), or traffic information services broadcast systems (TIS-B) provide. Flight crews use much smaller navigation displays for dealing with other aircraft than controllers. In order to merge behind or follow another aircraft, flight crews need to be able to identify the traffic and they need to be in a position close to the time or distance interval target.

A Possible Combination

One way of taking advantage of the strengths of both, absolute and relative operations is to use trajectory-based operations for the global scheduling and route planning. ASAS type clearances can be issued for solving local spatial constraints and fine-tuning the merge and spacing. This combination is similar to the proposal made in [1], except that it is not the authors' opinion that the accuracy of time estimates along the trajectories should be limited to minutes rather than seconds. The full benefits of the 4D trajectory-based operations can only be achieved if only minor adjustments are required to solve local spacing problems with ASAS guidance. If for example +/- 30 seconds time-error tolerances were acceptable for trajectory-based operations the relative aircraft-to-aircraft guidance would have to be able to handle a 60 second deviation, unless the controller issued additional vectors to prepare the limited delegation. This would likely negate the positive impact the trajectory-based operations have on the controllers' workload. If FMS fall short of the required precision, external cruise/descent speed calculations embedded in the ground automation or a different cockpit device (like a CDTI) can be used to compute the parameters required to program or load into the FMS.

Example Application

The combination suggested above was briefly tested during a few demonstrations in the AOL at NASA Ames Research Center to get an initial feasibility check. The lab organization and scenarios were the same as described in the results section of

this paper. The TMA restriction at the meter fix was reduced to six miles-in-trail. All pseudo aircraft were equipped with a simple experimental self-merge/self-space capability similar to the one described in [15] that uses speed changes alone to achieve its target. The high altitude controllers used the trajectory tools as described for the experimental condition. The low altitude controller evaluated the sequence of the incoming aircraft and their trajectories and issued "merge behind" or "follow" clearances to all eligible pairs. Because of the precise time-based preconditioning of the aircraft, usually the on-board automation could immediately take control and the aircraft could stay on their trajectories using the lateral navigation function of the FMS. By the time the aircraft reached the meter fix or an intermediate merge point they were spaced almost precisely at the desired spacing interval while reducing the controllers' workload.

Concluding Remarks

Trajectory-oriented, time-based arrival operations have shown potential benefits for throughput, efficiency, and controller workload. In order to achieve these benefits a well-designed set of ground automation tools and procedures is required. The operational concept described in this paper and similar approaches provide the necessary flexibility for being applied in high-density air traffic control sectors. The trajectory-oriented approach can be complimented with aircraft-to-aircraft based operations to increase the potential benefits even further while at the same time solving some of the problems with 4D trajectory-based operations.

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Air ground integration, distributed air ground traffic management, human factors, simulation

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