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Simulation of CTAS/FMS Air Traffic Management

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Abstract

A simulation of integrated air and ground operations was conducted to demonstrate procedures, flight management automation, data link technology, and air traffic control decision support tools for improving Air Traffic Management (ATM) efficiency. Air traffic controllers managed simulated arrival traffic using Center-TRACON Automation System (CTAS) tools. Flight crews in Flight Management System (FMS) and data link-equipped simulators were included in the arrival flows. Controller observations help understand CTAS tool use and arrival flow planning issues. Flight crew results indicate procedures developed for FMS and data link operations can work in concert with CTAS.

Introduction

Current ATM relies primarily on voice communications and tactical vectoring for separation and traffic flow management during the arrival and approach phases of flight. If operations remain unchanged, increasing demands will exacerbate delays and may compromise safety. Proposed solutions entail a range of operational and technological changes: FMS procedures for coordination and more precise flight trajectories, greater freedom for airlines in scheduling and selecting preferred traffic routes, improved air-ground communications via digital data link, modified airspace structure, and new tools for air traffic controllers. Some ‘free flight’ concepts go further, shifting responsibility for separation to flight crews and thereby altering the role of air traffic control (ATC).

This paper presents an operational concept that integrates selected features of new technologies, in order to manage arrival traffic more efficiently and safely. The approach focuses on first planning an efficient arrival flow in accordance with the constraints and preferences of all the participants in the ATM system. A special-purpose controller, called the ‘arrival planner,’ preconditions the arrival flow by generating a schedule and sequence that—to the extent possible—puts arriving aircraft on conflict-free flight paths. To execute the plan, controllers use data link to ‘uplink’ these flight paths to flight crews, who are responsible for precisely flying them. Sector controllers are responsible for maintaining aircraft separation and adapting the arrival plan as necessary.

A simulation was conducted at NASA Ames and Langley research centers to demonstrate how automation can be integrated in an operational ATM environment in which pilots and controllers can effectively perform. As the final phase of NASA’s Terminal Area Productivity (TAP) program, the simulation is targeted to the 2010 time frame, at which time the simulated technologies could be operational (Prevôt, Crane, Palmer, and Smith, 2000).

Advanced Technologies

Four advanced capabilities anchor the concept: FMS-equipped aircraft, CTAS tools, data link, and FMS arrival procedures.

FMS-equipped Aircraft

Flight Management Systems (FMS) enable an aircraft to compute an efficient 3D/4D flight path and follow it precisely to execute the arrival plan. Because commercial aircraft operating in the target time frame are likely to be predominantly

FMS-equipped, so are the pseudo-aircraft and flight simulators participating in the simulation.

Center-TRACON Automation System (CTAS) Tools

The CTAS ground automation can compute, integrate, evaluate, and display flight path information, to aid traffic management and provide capacity and flow control benefits (Erzberger, 1995). CTAS tools include:

- Traffic Management Advisor (TMA), which helps optimize the arrival traffic flow and create the arrival plan;
- Descent Advisor (DA), which simultaneously provides air traffic visualization support and advisories to carry out the arrival plan;
- a conflict probe that assists in detecting and resolving potential separation violations;
- Final Approach Spacing Tool (FAST), which assists approach controllers in assigning aircraft to runways and sequencing and spacing aircraft on final approach;
- Planview Graphical User Interface (PGUI), which, in the present implementation, integrates aircraft display with the capability to monitor and modify the TMA schedule, uplink DA advisories and FMS approach transitions, resolve conflicts detected by the conflict probe, and coordinate ‘trajectory clearances’ or ‘arrival plans’ with other controllers.

Data link

Data link enables data exchange between the FMS and ground-based CTAS automation to support coordination and synchronization. In the simulation, wind, route, and speed information are data linked from CTAS to the FMS, while state, intent, and preference information are data linked from the FMS to CTAS. This ‘downlinked’ data includes FMS route information that controllers can display on their PGUIs to assess important air-ground coordination information, such as the FMS- and CTAS-computed top-of-descent locations. This use of data link simulates Automatic Dependent Surveillance (ADS)-type data exchange—another technology due for widespread implementation in the target time frame. The simulation environment assumes a mix of data link-equipped and unequipped aircraft.

FMS Arrival Procedures

FMS arrival procedures specify speed and altitude restrictions to guide aircraft from cruise flight to final approach intercept. Air traffic controllers can assign cruise and descent speeds to modify the flight path according to scheduling and spacing requirements. Aircraft should fly the FMS trajectory computed according to the FMS arrival procedure. Controllers can monitor, evaluate, and modify this trajectory with accurate CTAS trajectory predictions. ADS-B-type data further improve the quality of trajectory information. Procedural coordination of FMS and CTAS trajectory computation functions enables operational use of the concept in a voice-communication environment (Crane, Prevôt, and Palmer, 1999).

Arrival Planner

The arrival planner controller position is designed to help ‘downstream’ sector controllers—and other participants in the air traffic system—get the most out of the above technologies. The arrival planner is responsible for developing a plan for arriving aircraft in multiple sectors, all converging to meter fixes at the Terminal Radar Approach Control (TRACON) boundary. The planning task entails iteratively monitoring and adjusting the TMA-generated schedule of arrival times at the meter fix. The planner also evaluates the 4D trajectories of arriving aircraft for predicted conflicts, or discrepancies between the current estimated time of arrival (ETA) and scheduled time of arrival (STA) at the meter fix. Because the planner is not responsible for aircraft separation, only for deriving suitable arrival routes, the planner must coordinate with other controllers to adapt the schedule/sequence.

Distributed Simulation Architecture

Figure 1 is a simplified depiction of the distributed simulation architecture. CTAS systems and their associated PGUIs used by Center and TRACON controllers are linked through a simulation hub to multiple simulated FMS-equipped aircraft. Operators using graphical pilot-stations control most aircraft that comprise the traffic; each controls several at a time. The Airspace Operations Laboratory at NASA Ames Research Center houses this portion of the simulation. The simulation includes two high-fidelity flight simulators, one at NASA Ames Research Center, and one at NASA Langley Research Center.

This paper presents flight crew data and controller observations gathered from simulations implementing the proposed operational concept. The paper begins by describing the simulation scenarios, from both flight deck and ATC perspectives. It continues with a description of important flight deck procedures and interfaces, followed by a description of key ATC components. The paper then discusses, in turn,

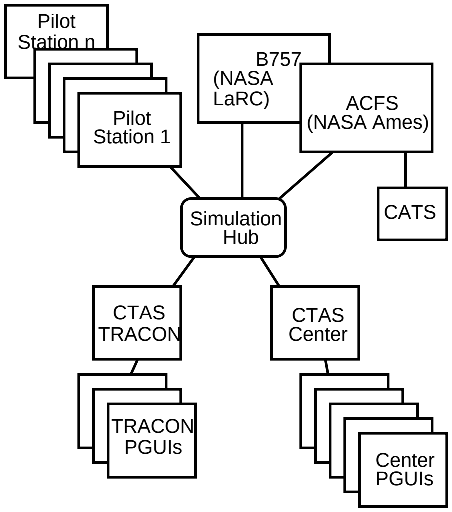

Figure 1. Simplified distributed simulation architecture.

results and observations from integrated flight deck and ATC simulation trials. Overall, the simulation provides evidence that the proposed operational concept allows flight deck procedures and interfaces to work in concert with CTAS tools to the benefit of the future air traffic system.

Simulation Scenarios

We used Fort Worth Center (designated 'ZFW')—specifically the northwest and southwest ZFW arrival quadrants—for developing and simulating the concept. This airspace currently experiences at least two major arrival rushes every day. The base scenario uses recorded traffic and weather data from a day in 1999 with IFR conditions. It is modified to create various scenarios with traffic loads ranging from moderate to more than current peak rush demand, and different mixes of data link-equipped aircraft.

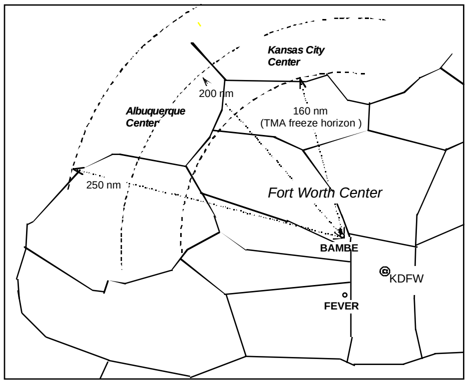

Figure 2. Airspace, including northwest arrival-planning region.

The arrival planner works aircraft bound for Dallas-Fort Worth airport (DFW) that arrive from the northwest on converging paths from a radial arc roughly 200 miles away from the meter fix ('BAMBE') (Figure 2). Thus, aircraft do not all enter the region in-trail, but instead on 'preferred,' free-flight-type routes (Figure 6 below depicts a typical arrival rush). The planner's airspace includes portions of five sectors within ZFW (four high altitude sectors and one low altitude sector), as well as portions of Albuquerque Center and Kansas City Center airspace. Thus, the arrival planner works northwest arrival traffic first (while still owned by a 'ghost' controller representing an Albuquerque or Kansas City Center controller), then the high and low altitude sector controllers in the ZFW airspace, and finally the DFW TRACON and tower controllers.

Aircraft arriving from the southwest enter the simulation scenarios close to the TRACON boundary, and are therefore not subject to the arrival planning process; these aircraft land on a different runway from the planned, northwest arrivals. The southwest arrivals are included to add complexity to the TRACON traffic flows (because of approach transition pattern crossings), and more specifically, to continue investigations of data linked, 'auto-loadable' FMS route modifications in the TRACON (Romahn, Callantine, and Palmer, 1999; Crane, Prevot, Palmer, 1999). Two flight simulator scenarios 'fit' within one ATC scenario such that the flight simulators fly the first scenario, land, and then reinitialize and fly the second scenario—all during one ATC arrival rush scenario.

Flight Deck Perspective

Figure 3 depicts the two flight simulator scenarios used in the simulation. The first scenario (termed the 'Center scenario') begins with a simulator at cruise altitude outside the Center airspace on a 'preferred' direct routing to an initial fix that marks the beginning of the FMS Arrival procedure. The crew establishes data link communication, receives forecast winds via data link, and reviews and auto-loads the winds into their FMS. The crew may also select a preferred descent speed to be used in CTAS predictions. Next the crew may receive a data link clearance to modify the cruise and descent according to a CTAS advisory; the clearance may also be communicated by voice. The crew may also receive a lateral route modification via data link, which they can auto-load into their FMS. Next the

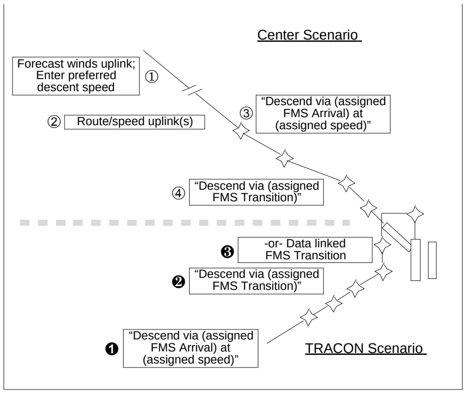

Figure 3. Flight scenarios.

crew receives an FMS descent clearance (described below). Another speed and/or route adjustment may occur in the low altitude sector by voice or data link. In the TRACON the crew receives a clearance to fly an FMS Approach Transition (described below) to a given runway. The crew receives an approach clearance from the TRACON final controller. Thus, the flight path traverses the high and low altitude Center sectors, and the TRACON feeder and final sectors, before the tower controller issues the landing clearance.

A second scenario (termed the 'TRACON scenario') begins in level flight outside the TRACON on direct routing to a fix that begins a second FMS arrival. The crew first establishes data link communications. After the crew is handed off to the TRACON feeder controller, they receive a clearance for the FMS Approach Transition to the assigned runway (described below). The aircraft is handed off from the feeder to the final controller, who may issue a CTAS-generated route modification clearance via data link. The final controller then clears the aircraft for the approach, and hands it off to the tower controller, who issues a clearance to land. Thus, the TRACON scenario flight path traverses the Center low altitude sector, and the TRACON feeder and final sectors, before the crew receives a landing clearance from the tower controller.

Air Traffic Control Perspective

From an ATC perspective, the arrival scenario develops as follows. Aircraft arrive at the center's airspace on direct routes or in-trail, and the CTAS automation estimates their meter fix arrival times. The TMA automatically creates an initial aircraft sequence, taking all airport flow control constraints into consideration. The arrival planner evaluates this sequence and interacts with the TMA and conflict probe to adjust the flow for spacing and scheduling. This task is supported by the DA, which assists the controller in creating flight paths (route and/or speed modifications) that meet the STA at the feeder fix. If the delay to be absorbed is not significant (i.e., approximately five minutes or less), an early modification to the aircraft's cruise speed, and perhaps its descent speed, is usually sufficient. The arrival planner coordinates with sector controllers, who communicate the flight path modification to the flight crew (by voice or data link); the crew sets up their FMS accordingly. After a controller issues an arrival clearance to fly the FMS-computed path, pilots and controllers both know when the aircraft will start to descend and where it will be at any given time. Data link-equipped aircraft automatically transmit the FMS flight path to the CTAS ground as part of the ADS downlink, so controllers can inspect it for any significant differences from the CTAS-predicted trajectory.

After crossing the meter fix and entering the TRACON, feeder controllers monitor the progress of aircraft on FMS arrivals. The feeder controller hands the aircraft off to the final controller, who may issue a standard FMS approach transition. The final controller may also issue a FAST-generated auto-loadable FMS approach transition via data link. Such a 'custom' FMS approach transition yields a downwind flight segment calculated to properly space the aircraft at the runway threshold.

Flight Deck Procedures and Interfaces

This paper considers flight crew factors encountered by crews flying the NASA Ames Advanced Concepts Flight Simulator (ACFS), a 'generic' full-motion, visual-equipped glass cockpit flight simulator similar to the Boeing 757. The ACFS incorporates 777-style glareshield-mounted data link message response buttons, a 747-400-like VNAV ALT autoflight mode, and a data link interface similar to that used by the Future Air Navigation System (FANS) on the FMS Control and Display Units (CDUs). The ACFS also has side-stick controllers similar to those found on Airbus aircraft. As shown in Figure 1, the ACFS is linked to the Crew Activity Tracking System (CATS), which allows crew activities to be assessed in real time, and replayed to support analyses (Callantine, 2000). This section provides details of the charted FMS Arrival and Transition procedures, and the data link interfaces and procedures.

FMS Arrivals and Transitions

FMS procedures specify the lateral and vertical flight path to localizer and glideslope capture. They are charted and contained in the FMS database. Flight crews should remain coupled to autopilot lateral navigation (LNAV) mode and, insofar as possible, vertical navigation (VNAV) mode, until cleared for the approach. The baseline FMS routing may require edits to comply with clearances generated from CTAS advisories.

Figure 4 depicts a generic FMS Arrival and Transition chart. The FMS arrival routing and crossing restrictions are on the left. The dashed lines represent 'preferred' (usually direct) routing to the FMS arrival's initial fix. The right side of the chart specifies FMS Transitions from the arrival to each runway. Notes on the chart specify clearance limits, different crossing restrictions depending on the assigned transition, and whether the database version will suffice as loaded or requires minor modifications.

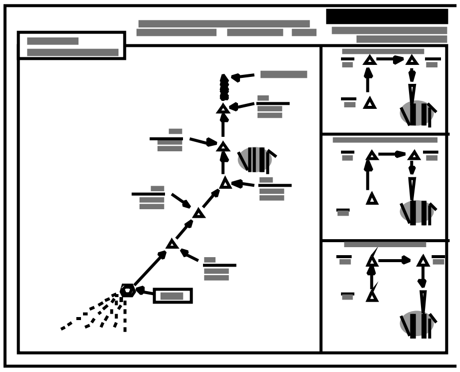

Figure 4. Generic FMS Arrival and Transition chart.

Controllers use the phraseology "descend via (the assigned FMS Arrival) at (the assigned speed)" to indicate that crews should use VNAV mode to begin the descent at the FMS-computed top-of-descent point. Transition clearances are similarly issued as "descend via (the assigned FMS Transition)." These clearances, or an FMS Transition that is data linked to the aircraft, require the crew to reference the chart to determine the altitude limit or other specifics.

Data Link

The ACFS is equipped with data link. A chime sounds and the text of an arriving message appears on the lower portion of the cockpit alerting ('EICAS') display. The text ATC MESSAGE appears on the upper EICAS and FMS Control and Display Unit (CDU). The CDU is outfitted with an 'ATC' page, which also displays the message text (Figure 5). Route and/or speed modification messages are loaded into the FMS automatically, causing the CDU 'EXEC' button light to illuminate; all messages cause the 777-style data link response buttons to activate. The general procedure for handling a data link message is to detect the incoming message, review it, and finally, to accept it and execute the resulting route and/or speed modifications.

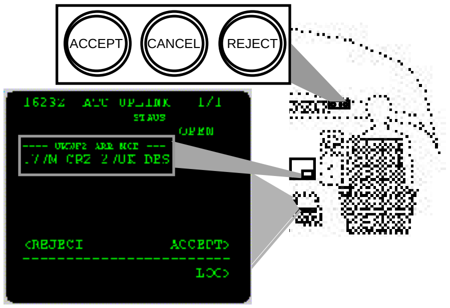

Figure 5. Data link message interfaces, showing a cruise and descent speed uplink.

ATC Procedures and Interfaces

Center

All Center controller positions, including the arrival planning position, are equipped with PGUIs that include (see Figure 6):

- the CTAS TMA timeline, which presents the current meter-fix arrival schedule. The planner compares an aircraft's scheduled time of arrival (STA) on the right side of the timeline with its current estimated time of arrival (ETA) on the left. The planner can manipulate the TMA-generated schedule by using the mouse to change the STA assignments for individual aircraft.
- a conflict prediction list, which indicates the time until a predicted conflict, and the specific nature of the conflict. Controllers may preset how the CTAS conflict probe functions.
- access to CTAS DA advisories—controllers can use the mouse to generate a DA cruise/descent speed advisory that, when flown, causes the aircraft to meet its STA.
- a trajectory preview tool, which allows controllers to use the mouse to quickly "dial out" the predicted traffic situation to a future

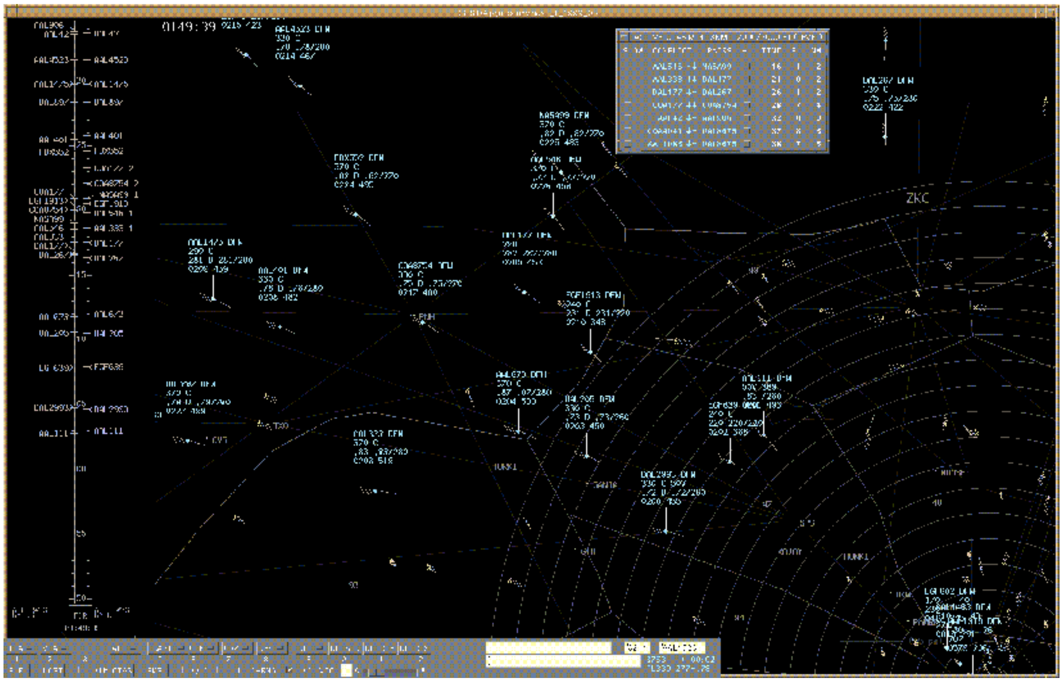

Figure 6. Arrival planner's PGUI, depicting northwest arrival traffic.

time. Controllers can use the 'dial-out' tool to examine, for example, how traffic will merge when approaching the meter fix on currently cleared routes.

The planning controller uses these tools in an iterative fashion. The planner may resolve an 'overtake' conflict, for example, by adjusting the schedule, but this may result in other conflicts that require additional adjustments. The planner coordinates with the sector controller that 'owns' the target aircraft, using the mouse to send a speed or route clearance that the planner would like the controller to issue to the aircraft These 'clearance requests' appear on the owning controller's PGUI. The sector controller can display and inspect the proposed clearance, and either uplink it to the aircraft, issue it by voice, or reject it. Again note that, in this operational concept, the planning controller is not responsible for separation; other Center controllers can similarly use these tools via their PGUIs to generate clearances required to maintain separation and adjust the arrival flow.

TRACON

TRACON controllers are also equipped with PGUIs (Figure 7) but their PGUIs are configured differently, and allow access to runway sequencing and spacing advisories generated by CTAS FAST. TRACON controllers generate modifications to the FMS transitions based on FAST calculations and uplink them in the form of 'custom' auto-loadable FMS approach transition clearances. Figure 8 illustrates an aircraft arriving from the southwest receiving and accepting an FMS approach transition. The aircraft's PGUI data block indicates the status of the data linked clearance (Romahn, Callantine, and Palmer, 1998, 1999).

Figure 7. TRACON controller's PGUI, showing traffic on an FMS approach transition in the Center scenario.

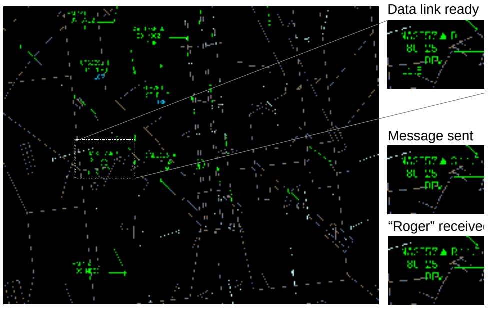

Figure 8. TRACON PGUI showing arrivals to a second runway, and data block indications for clearance uplink status.

Flight Simulation

A previous study examined the crew factors involved with the use of increasingly futuristic procedures and interfaces to support CTAS/FMS integration (Crane, Prevôt, and Palmer, 1999). Scripted clearances of the type generated by CTAS advisories were issued to the crew and responses were measured. The results showed that crews make significantly fewer automation inputs when flying FMS Arrivals than are required under current-day (vectoring) operations; however, when an FMS procedure is interrupted and resumed, crews make significantly more inputs. These results correlate with significantly lower reported workload for uninterrupted FMS operations, and a non-significant, slightly higher workload for interrupting and resuming an FMS procedure. In addition, the results revealed that crews did not uniformly use VNAV to fly the charted FMS procedures, that the CDU and glare shield-mounted data link response buttons were usable, and that speed control in VNAV was at times inadequate.

Participants

Eight flight crews with commercial Boeing glass cockpit experience were recruited to fly the ACFS in the simulation. The crews were drawn from five different airlines, and had experience on a variety of glass cockpit aircraft.

Procedure

Each crew received a short briefing (ranging from one to two hours) covering the ACFS cockpit systems, FMS Arrivals and Transitions, and data link operations. Each crew then flew six descents, alternating between Center and TRACON scenarios. Controllers in the NASA Ames Airspace Operations Laboratory used CTAS to manage the traffic, and issued clearances by voice and data link. Other personnel controlled the simulated traffic. It is important to note that unlike the previous study, in which scripted clearances were issued across specific conditions, here no such controls were in place. The simulation sought to demonstrate the operational effectiveness of the integrated system under realistic high-density traffic conditions.

Crew performance was evaluated on each descent based on crew compliance with clearances and procedures. CATS was used to analyze digital data from the ACFS; videotape was used to confirm and analyze key observations in greater detail. Crew acceptability of the proposed procedures was evaluated with a questionnaire.

Results

Data were obtained for 22 Center scenarios and 23 TRACON scenarios. Of interest to the CTAS/FMS integration problem are overall crew performance measures pertinent to the realization of efficiency and capacity gains. These measures primarily reflect the ability of crews to precisely follow a flight plan using the aircraft’s FMS, and to coordinate air and ground operations via data link.

Table 1. CTAS/FMS integration crew performance results.

LNAV mode until LOC capture	60% (27/45)
No speed violations (+/- 10 knots)	82% (37/45)
No altitude violations (+/- 250 feet)	93% (42/45)
Correct timely response to data link	96% (77/80)

Table 1 shows four such measures. First, in 60% of flights, the lateral portion of the route was flown entirely in LNAV mode; this measure also reflects positively on the success with which controllers were able to issue FMS clearances without resorting to vectors. Next, during times when the flights were cleared on FMS routing (which, at the very least, included the descent on the FMS Arrival), crews complied with 82% of speed restrictions and 93% of altitude restrictions. Of the 80 data link messages crews received, 96% were handled in a correct and timely manner. As in the previous study, however, crews did show a propensity to opt for tactical altitude control instead of VNAV whenever other tasks assumed a higher priority than monitoring the automation.

More detailed analysis identified several issues that deserve slight modification or further training. These included:

- Forecast winds data link message text: The text intended to cue the crew to enter a preferred descent speed if desired frequently confused crews, in part because the simulation was initialized with an acceptable descent speed already programmed in the FMS.
- FMS Arrival and Transition charts: Some pilots were confused about how far they were cleared on charted routing. Future efforts would likely benefit from separate charts for FMS routes to a particular runway. That way, the 'transition boxes' (right side of Figure 3) that in some cases showed information in conflict with that on the main portion of the chart would not be needed.
- Voice clearances issued while the crew was responding to a data link clearance (and vice versa): Crews had to request clarification as to which portions of each to comply with. During a handoff, pilots sometimes also found it confusing to have their check-in call simply "rogered" by a new controller who was expecting compliance with a previously issued data link clearance. The contribution of such difficulties to the observed crossing restriction violations requires further investigation. A related problem concerns controllers issuing ambiguous clearances on check-in, such as a clearance 'direct to' the same waypoint that is already active in compliance with a previous FMS Arrival clearance. Pilots were uncertain whether such a clearance should be interpreted as a cancellation of the FMS Arrival.
- 'Fly-ability' of data link clearances: One pilot in particular thought that data link clearances were guaranteed to be flyable, threatening the procedural requirement to review the clearances carefully before accepting and executing them.
- 'Furthest cleared altitude': FMS Arrivals and Transitions used in the simulation were designed to be flown in VNAV with the last charted altitude restriction set as the limiting target altitude. Pilots from airlines whose policy is to 'step down' the altitude target at times showed an unwillingness to descend to the allowable limit. VNAV mode, however, works considerably better if allowed to fly to a well-defined bottom-of-descent point.
- Over-committing to "expect" clearances: Using the FMS at low altitudes (typically, below 10,000 feet) is discouraged by some airlines; however, it is the FMS that provides the precision necessary to fly trajectories that match those computed by CTAS. Over-committing to an "expect" clearance by programming the FMS with a route that is incompatible with the one that is eventually cleared can lead to increased workload if for some reason a different clearance is issued. Crews were therefore briefed to load expected approach routing from the FMS database, but to execute it without closing any route discontinuities. Closing such discontinuities caused one crew—who had not yet received an approach clearance—to turn onto the base leg of the approach, which was not part of the cleared FMS Arrival routing to the expected approach course (see Callantine, 2001).

Pilot Questionnaire Data

The questionnaire each pilot completed following the simulation covered FMS procedures, charts, FMS clearance phraseology, automation usage, data link clearances, and data link response procedures. Questions called for scaled responses, yes/no plus explanations, or open-ended general comments.

Table 2 presents selected scaled response data. On average, pilots found workload under the CTAS/FMS integration concept to be slightly lower than in current-day operations; however, more monitoring is required. The FMS procedures as a whole were deemed acceptable, but the

Table 2. Flight crew scaled response data.

	Negative/ Low		Neutral		Positive/ High
FMS Procedures					
Workload Effect	1	5	6	4	
Required Monitoring Effect		1	7	7	1
Difficulty	4	8	1	3	
Ease versus Current Day		1		8	7
Overall Acceptability			1	8	7
Chart Clarity		2	1	9	4
Chart Organization		1	3	6	6
Chart Information Adequacy		1		8	7
Chart Overall Acceptability		1		9	6
Phraseology Acceptability			1	8	7
Mode Usage					
LNAV Acceptability-High Alt.					16
LNAV Comfort-High Alt.				1	15
LNAV Acceptability-Low Alt.				4	12
LNAV Comfort-Low Alt.				3	13
VNAV Acceptability-High Alt.		1	3	4	8
VNAV Comfort-High Alt.	1	3	1	2	9
VNAV Acceptability-Low Alt.		3	2	3	8
VNAV Comfort-Low Alt.	1	2	2	3	8
Data Link Clearances					
Acceptability-Route mods in cruise				3	13
Acceptability-Route mods in TRACON				6	10
Acceptability-Route mod phraseology			1	5	9
Acceptability-FMS edits in TRACON	1	2	1	7	5
Acceptability-Speed uplink		1		4	11
Acceptability-Speed uplink phraseology	2			4	10
Acceptability-CDU interface				4	12
Acceptability-CDU tasks				4	12

accompanying charts could benefit from some improvements, as suggested above.

Using LNAV mode to fly precise lateral routing was deemed acceptable, even at low altitudes in the TRACON airspace. On the other hand, pilots gave VNAV a wider range of generally lower acceptability and comfort ratings.

Pilots generally viewed data link usage positively. However, some pilots found the data link phraseology used for speed clearances (e.g., ".77 M CRZ 270 K DES") ambiguous. Some thought this meant flying .77 Mach in the descent until the transition to 270 knots, rather than acquiring the 270 knot descent speed immediately; in the present scheme, a clearance requiring the Mach-to-calibrated-airspeed transition to be flown would be phrased ".77 M CRZ .77/270 K DES." Performing FMS edits in the TRACON airspace also garnered a range of opinions. Pilots who made the process more complex by over-committing to "expect" clearances found edits less agreeable than those who made the process easier by leaving route discontinuities in the route until they were actually cleared on the routing.

Some explanations, although shared by a minority of participants, are notable. First, for some the charted vertical profile was less clear than the lateral track. Some also found FMS clearances that relied on charted altitudes instead of mentioning the clearance altitude specifically disconcerting. Waiting for an approach transition clearance that required FMS edits in the TRACON was disagreeable, as was VNAV behavior, if clearances required speed adjustments along VNAV trajectories. Crews who attempted to edit speeds at crossing restrictions in response to speed amendments were most prone to problems. Use of speed brakes helped crews control VNAV descent behavior.

Finally, several pilots spoke very favorably of data link communications, including one who said, "The CDU data link was easier to understand than the voice communications. Response on our part was quicker and less confusing than voice clearances." Another said it "seems like a very nice feature…—a lot less workload and frequency congestion." Overall, pilot sentiment about the CTAS/FMS integration concept and current implementation seems to be that "with training and experience it should work out to be a positive."

ATC Simulation

Previous simulations also investigated the present operational concept; an arrival planner worked aircraft in a region similar to that shown in Figure 2. Flight crew subjects participated via the Research Flight Deck at NASA Langley Research Center, which simulates a Boeing 757 aircraft with a commercial Honeywell FMS, slightly enhanced for the experiments. As in the current simulation, data link-equipped aircraft downlinked precise ADS-B-type state information that replaced simulated radar data on controller displays, and included FMS route information. Controllers could send 'auto-loadable FMS route clearances via data link. The percentage of data link equipped aircraft varied from 20% to 80% in different simulation runs. The next two sections describe participants and procedures for the current study. Subsequent sections draw upon the current simulation, as well as the previous one, for insights.

Participants

Fourteen air traffic controllers participated in the current simulation. They worked various control positions in different simulation runs depending upon their qualifications and experience as Center controllers, TRACON controllers, and/or traffic managers.

Procedure

Controllers participated in the simulation for three days, because the ATC portion of the concept was less familiar to them than the flight deck portion was to the flight crews. Training occupied one day and a half to two days, depending on observed competency. Training covered CTAS tool-use, FMS arrival procedures, and clearance phraseology for issuing FMS clearances via voice.

Overall Observations

Arrival Efficiency

After training and multiple simulation runs, participant controllers were capable of handling complex arrival rushes. In these runs, almost the maximum throughput was achieved for the one test runway, with efficient FMS descents for about 35 consecutive aircraft. An example of efficient planning and execution is shown in Figure 9. The data show the times at which aircraft cross the meter fix in two trials using the same traffic scenario. An early descent (before its VNAV top-of-descent point) by the tenth aircraft in the sequence disturbs the arrival plan in both cases. In one trial, however (denoted by squares in Figure 9), the sector controllers were able to recover and continue to execute the plan; in the other (denoted by diamonds), controllers resorted to tactical control of the traffic using vectoring. Following the plan yielded almost the minimum allowable

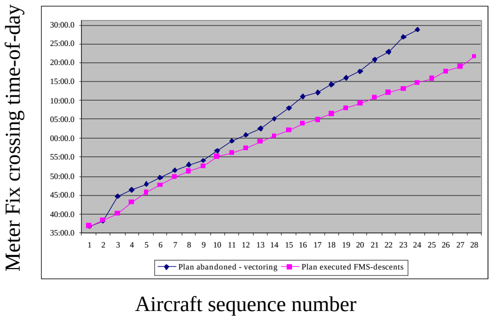

Figure 9. Meter fix-crossing times when controllers executed the arrival plan versus when they abandoned the arrival plan.

spacing, while resorting to vectoring yielded performance that is probably worse than typical current day operations. Thus, controllers must carefully monitor aircraft for non-compliance with planned FMS arrival routes, if the operational concept is to yield efficiency benefits.

Data Link

The concept does offer significant reduction in frequency congestion, as less radio communication was observed. Although the concept does not require the availability of data link, the ADS-B-like passive data exchange appeared helpful. Thus, while data link seems to be merely a nice feature for controllers, auto-loadable FMS clearances appear to have benefited flight crews considerably.

Controller Automation

Issues surrounding flight deck automation are well characterized. This operational concept requires controllers to similarly shift from controlling traffic manually, to trusting both the flight deck and ground automation. Similar problems are therefore possible, including the mode confusion, clumsy entry procedures, problems shifting between tactical and strategic control, and difficulty maintaining the ‘big picture’ as situation complexity increases. In the simulation, controller participants shifted from exclusively controlling traffic in their own sector, to planning flight paths for downstream sectors and executing plans from upstream sectors. They became comfortable using the proposed automation, procedures, and phraseology. However, attempts to revert from use of automation to manual control often caused problems. Moreover, controllers did not always detect out-of-compliance aircraft—in particular those that passed the top of descent, descended too soon, or flew at the wrong airspeed. Failure to detect non-compliance could have been due to the novelty and additional complexity of the FMS descent clearance or to increased complexity of the display itself. For example, the PGUI data block was larger than the standard DSR data block, with four lines of information and new data fields that controllers were unaccustomed to monitoring.

Feedback from Controllers

Eight participants completed and returned a mail-in questionnaire. The questionnaire assessed how the participants viewed the operational concept, automation tools, interface, procedures, workload, use of data link, and scenario realism. There were also questions about the multi-sector arrival planner position. This section presents selected controller responses.

In general, controllers found this approach to arrival flow management very promising, and seven viewed the arrival planning position as crucial to the concept. When asked to rate the relative importance of the different tools and components of the concept, they rated the arrival planner second only to the timeline display—above speed advisories, data link, FMS procedures, ADS-B, conflict probe, DA advisories, TMA, trajectory predictor, conflict probe, and the planner-controller coordination interface. Most controllers found it "completely acceptable" for the planner to prepare clearances for their aircraft; indeed, five of eight viewed coordination with the planner as unnecessary—the planner should instead issue data link clearances directly to aircraft. Some controllers did have reservations about the operational acceptability of the planner position, or were uncertain about where the planner’s responsibilities ended and the sector controller’s began. The strongest criticisms concerned the PGUI interface: the amount of information in the data block, the use of a three-button mouse, and the general complexity of some functions.

Arrival Planner Performance

Examining the arrival planner’s performance in detail is difficult, given available data and the critical role of ‘downpath’ controllers in executing the plan. This section presents the results of an analysis for two planning controllers who each worked the same two ATC scenarios. Data included time-stamped planner action records (changes to the TMA schedule, aircraft route and/or speed adjustments), associated clearance request responses (accepted or rejected, voice or data link clearance issued), and workload questionnaire data. While not conclusive, this analysis points to a ‘satisficing’ strategy as suitable for planning the arrival flow with the available tools. After summarizing the data, this

Table 3. Planner adjustments to the arrival schedule

	Planner A, Run 1	Planner A, Run 2	Planner B, Run 1	Planner B, Run 2
Number of aircraft delayed	10	15	16	22
Number of aircraft advanced	17	9	10	4
Avg. STA - ETA diff. (mm:ss)	-0:06	-0:11	0:58	1:53
STA - ETA range (mm:ss)	-4:11 to 2:48	-5:06 to 2:33	-1:41 to 6:20	-1:37 to 7:59

Table 4. Scheduled meter fix spacing between aircraft

	Planner A, Run 1	Planner A, Run 2	Planner B, Run 1	Planner B, Run 2
Average time (mm:ss)	1:37 +/- 0:55	1:28 +/- 0:35	1:37 +/- 0:26	1:34 +/- 0:15
Time range (mm:ss)	0:32 to 4:29	0:53 to 3:14	1:11 to 3:20	1:13 to 2:14

Table 5. Planner clearance requests to controllers

	Planner A, Run 1	Planner A, Run 2	Planner B, Run 1	Planner B, Run 2
Route change requests	2	1	2	15
Speed change requests	16	15	27	30
Route & speed change requests	2	1	1	13

Table 6. Workload self-ratings for planners and controllers

	Planner A, Run 1	Planner A, Run 2	Planner B, Run 1	Planner B, Run 2
Planner's effort	low	low	moderate	high
Planner's performance	high	high	high	moderate
Controllers' effort	low	low	low-moderate	moderate
Controller's performance	high	high	moderate-high	moderate

section suggests parallels with related research on multi-sector traffic management concepts.

Schedule adjustments

Table 3 shows the direction and range of manual TMA schedule adjustments made by Planner A and Planner B during the two scenarios. An adjustment is an ‘advance’ if the aircraft is scheduled to arrive earlier than its original ETA, and a ‘delay’ if the STA is later than the ETA. Table 3 also shows the range of ETA-minus-STA differences. Both planners made between 24 and 27 changes to the schedule, leaving only a few STAs untouched. As Table 3 shows, Planner A scheduled many more aircraft ahead of their initial meter fix ETA than Planner B. As a result, the average scheduled delays were one to two minutes less for Planner A than for Planner B.

Meter fix spacing

Table 4 presents the mean, standard deviation and range of scheduled aircraft separation at the meter fix for each of the four runs. 70 seconds separation translates to approximately 6 nautical miles for aircraft complying with assigned meter fix altitude and speed restrictions.

Clearance requests

Table 5 shows that Planner A made fewer clearance requests than Planner B, with a total of three route modification requests and 31 speed requests. This compares to seventeen route change requests and 57 speed change requests for Planner B. Route change requests are typically more difficult for a sector controller to assess, as the next section reflects.

Workload questionnaires

Self-reports of workload differed for the two planners (Table 6). Controllers rated their overall workload lower and their performance higher during the runs with Planner A, and Planner A rated his own effort much lower than did Planner B. These data suggest that Planner A adopted a 'satisficing' strategy that minimized delays, as well as route clearances, while occasionally sacrificing meter fix spacing between aircraft. This strategy amounts to focusing primarily 'de-clustering' arrivals—rather than attempting to resolve all conflicts—and allowing downpath controllers to make the adjustments necessary to regulate flow at the meter fix. Planner B worked harder to preserve a minimum spacing at the meter fix, which resulted in increasing delays as the scenario progressed; downpath controllers also worked harder to review the numerous FMS route-change requests.

Discussion

The simulation scenarios included traffic throughout ZFW Center. The CTAS TMA not only scheduled arrivals from the northwest and southwest, but also from the northeast and southeast. However, the arrival planner sought only to optimize the arrival flow for one meter fix and one runway, disregarding TMA constraints that accomodate traffic from the other meter fixes. Thus, the data presented here do not indicate how the planner might need to interact with the TMA in a real operational setting, or the impact of meter fix spacing on TRACON operations. Furthermore, the scenarios did not require the planner to handle requests from dispatch, or a planner working neighboring airspace. The scenarios also did not require large delays to be absorbed, or weather-related route modifications. These complexities will no doubt affect the planner's task.

Related research on multi-sector traffic management concepts affirms the viability of the concept (cf., Leiden and Green, 2000; Meckiff, Chone, Nicolaon, 1998; Willems, Sollenberger, and DellaRocco, 2001). Several 'flavors' of controller team configurations and planning task configurations are proposed. All recognize the potential benefits of longer look-ahead times along aircraft trajectories and 'conditioning' flows into dense traffic areas. At issue is the degree of conditioning that is possible and necessary. In the present research, the arrival planner could conceivably 'set up' the arrival flow such that downpath controllers need only clear aircraft on the planned FMS arrival or transition routing and hand off the aircraft. However, the data for Planner B, who attempted such 'thorough' planning, suggest this increases workload and introduces coordination problems. Planner A's subjectively more successful strategy, on the other hand, appears analogous to the Meckiff et al. concept for a tool that aids a multi-sector controller in identifying and working traffic "hotspots." Rather than attempting to de-conflict each arriving aircraft, Planner A's 'satisficing' approach can be viewed as simply addressing 'hotspots' in the TMA schedule that are clearly visible as 'clusters' on the PGUI timeline display. Such issues require further research; the next section describes plans for future NASA ATM simulations to investigate this operational concept in greater detail, as well as longer-term operational concepts.

Further Research

A follow-on simulation study has been planned to explore issues raised by the simulation presented in this paper This study will focus solely on ATC operations and include the following modifications to scenarios, controller displays and training:

- Scenarios will include scripted events designed to evaluate the impact of unanticipated disruptions to the arrival flow on arrival planner and downpath controller performance. Such events may include a reduced airport arrival rate that requires increased spacing, weather or ride problems that require tactical adjustments to the plan, and a dispatcher request or in-flight emergency that requires special handling for an individual aircraft, and out-of-compliance aircraft.
- The arrival problem will be altered to require controllers to maintain runway slots for aircraft merging from other meter fixes.
- Techniques for handling unexpected disruptions to the arrival plan will be developed, and controllers will be trained in their use.
- Normal data block information content will be reduced.

- Conformance feedback that indicates aircraft compliance with the cleared/expected trajectory will be provided.

In addition, more quantitative data will be collected to enable a more rigorous evaluation of the operational concept.

Distributed Air-Ground Arrival Planning

A second simulation will explore longer-term operational concepts as part of the NASA Advanced Air Transportation Technologies (AATT) Program's Distributed Air-Ground (DAG) project. This simulation will expand on the operational concept presented here, and explore the potential benefits of delegating some responsibility for arrival planning and separation to flight crews in Cockpit Display of Traffic Information (CDTI)-equipped aircraft. This concept includes extension of interfaces for shared situation awareness—currently available only to the planner and sector controllers—to the flight crew. Controllers may assign TMA-based required-times-of-arrival (RTAs) to self-separating aircraft, in order to merge them with other arrival traffic at the meter fix or earlier location. Flight crews may downlink clearance requests to sector controllers much like the planner in our current simulation.

Conclusion

The simulation described in this paper demonstrated a CTAS/FMS integration concept based on FMS-equipped aircraft, CTAS tools, FMS arrival procedures, and data link. Results indicate procedures developed for FMS and data link operations can work in concert with CTAS tools. In general pilots found the concept favorable, and with some modifications and additional pilot familiarity, the concept appears especially promising. Controllers appear capable of using automation tools and other advanced technologies improve efficiency as required to support anticipated air traffic demands. The role of the arrival planner deserves further examination. If this multi-sector position continues to show promise, it will be adapted to perform other strategic planning and coordination activities as part of the AATT program's DAG-ATM project.

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Nancy Smith is a Research Psychologist in the Human Factors Research and Technology Division at NASA Ames Research Center. She received her Master's degree in Human Factors Engineering from San Jose State University. Her thesis research was based on an experiment conducted in the Boeing 747-400 simulator at NASA Ames that explored the role of documentation in the operational introduction of new flight deck procedures—in particular, FMS descent procedures designed for CTAS compatibility. She has been involved in several field tests of en route CTAS tools, including Descent Advisor and En Route/Descent Advisor evaluations. Her research interest is the application of suitable methodologies for development of user-centered automation tools for aviation.

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