

Issues for Near-Term Implementation of Trajectory Based Operations

Joel Lacher, Vernol Battise, Rob Koteskey, Arik-
Quang V. Dao, Summer L. Brandt, Sarah V. Ligda,
Shu-Chieh Wu
San Jose State University
Moffett Field, USA

Walter W. Johnson
NASA Ames Research Center
Moffett Field, USA

Abstract—A primary feature of the NextGen is trajectory based operations (TBO). Under TBO aircraft flight plans are known to computer systems on the ground that aid in scheduling and separation. FANS is presently the primary flight deck system in the US supporting TBO, but relatively few aircraft are FANS-equipped. Thus any near-term implementation must provide TBO procedures for non-FANS aircraft. Previous research has looked at controller clearances, but any implementation must also provide procedures for aircraft requests. The research presented here aims to surface issues surrounding TBO communication procedures for non-FANS aircraft and for aircraft requesting deviations around weather. Procedures were developed to stringently follow TBO principles, in particular minimizing the discrepancy between flight plans stored in a ground based system and the flight plans actually flown. Three types of communication were explored: Voice, FANS, and ACARS. ACARS is a digital communication system widely used in the US for communication between aircraft and their Airline Operation Centers (AOCs); it differs from FANS primarily in that FANS allows the uplinked flight plans to be automatically loaded into the FMS, while ACARS delivers the flight plans in a text format that must then be entered manually into the FMS via the CDU. These procedures were used in a medium fidelity simulation. Sixteen pilots (eight two-person flight decks) and four retired controllers participated in 20-minute scenarios that required the flight decks to navigate through convective weather as they approached their top of descents (TODs). In this context, the rate of non-conformance across all conditions was higher than anticipated, with aircraft off path in excess of 20% of the time. Controllers did not differentiate between the ACARS and FANS datacom, and were mixed in their preference for Voice vs. datacom (ACARS and FANS). Pilots uniformly preferred Voice to FANS, liking ACARS least.

Keywords—component; Trajectory based operations, FANS, ACARS, NextGen, human-in-the-loop simulation

I. INTRODUCTION

Commercial air traffic volume has grown remarkably. In 1985 there were fewer than 6 million revenue departures in the United States (US). In 2010 there were more than 9 million [1]. Such growth shows no sign of abating. To prepare for future demand, the US federal government developed a plan to expand the capacity of the national airspace system (NAS).

This plan is referred to as NextGen, the Next Generation Air Transportation System [2].

One major change proposed in NextGen is to transform air traffic control from clearance-based to trajectory-based operations (TBO). Under TBO all aircraft fly negotiated trajectories from gate to gate. The advantage of TBO over today's clearance-based operations is that, with TBO, the future position of aircraft can be predicted with a high degree of certainty and specificity. Once the future positions of aircraft are known, ground-based trajectory automation can ensure safe and efficient separation and scheduling. However, these benefits accrue only so long as aircraft stay on trajectories.

Keeping aircraft on trajectories imposes challenges for controller-pilot communications. Unlike today's clearance-based operations where controllers typically issue vectors that take aircraft off of their flight plans, in TBO, information that maintains a complete connected trajectory needs to be exchanged between air and ground during flights. A system known as the Future Air Navigation System (FANS), which has been developed and used mainly for oceanic operations, can do this. However, because TBO is not currently used in the NAS, airlines have not felt the need to equip their aircraft with the moderately expensive FANS equipment. This has resulted in something of a chicken and egg problem where the FAA has not implemented FANS procedures for the NAS (in part) because few aircraft are equipped to use them, and airlines have not equipped their aircraft because the FAA has not implemented procedures that require such equipage.

The goal of the current research was to surface issues that may arise in a near-term implementation of TBO. One can imagine that, in a more long term future, the majority of aircraft will have FANS or even more advanced systems for exchanging trajectories between the ground and flight deck, and that weather surveillance and prediction will be such that ground based automation can specify weather-free paths [3]. However, any near term implementation of TBO must include procedures for communicating trajectories to aircraft that are not FANS equipped and procedures for pilots to request trajectory deviations, particularly for weather avoidance. Thus we developed procedures for receiving requests from and giving trajectory based clearances to aircraft with three

datacom communication equipage levels: Integrated datacom, Non-integrated datacom and Voice only. Integrated Datacom aircraft communicated using a simulation of the FANS-1/A interface currently available on some aircraft. These “FANS” aircraft were able to send downlinks directly from, and receive uplinks directly to, the Flight Management System (FMS). Non-integrated datacom aircraft communicated using a simulated ACARS Control Display Unit (CDU). These “ACARS” aircraft had text-only datacom capability with no ability to automatically load uplinks directly to the FMS. The “Voice” only aircraft had no datacom capability.

While the flight deck interfaces to ACARS and FANS are somewhat dissimilar, both are similarly capable of data communications with the ground. In contrast, the current ground infrastructure supporting these messaging platforms is quite different. FANS is used for direct communication with Air Traffic Control (ATC), which uses it to uplink routes. It is almost exclusively used in oceanic operations. ACARS is used for communications between an aircraft and flight dispatch about strategic planning issues such as delays and weather re-routing. Despite the differences between them, it may be possible to capitalize upon the ACARS infrastructure to provide a limited “FANS-lite” datacom with ATC for non-FANS equipped flight decks. This may be quite valuable since we believe there will be little change to fleet equipage in the near term. However, the FAA is in a position to act much more quickly to update its own facilities, in particular to provide an integration of ACARS datacom with ATC tools. Based upon this, we developed TBO procedures that assumed such an integration with a NextGen ATC station. A goal of this ACARS-ATC integration was to make the procedures look-and-feel as similar to that of FANS as possible, thus simplifying the ATC task.

II. PRIOR RESEARCH

Efficient and accurate controller-pilot communication is critical to safe flight operations. Not surprisingly, errors do occur and are often associated with long ATC messages sent by the controllers with the intention to reduce their own workload [4]. FANS controller-pilot data link communication (CPDLC) amends traditional radio voice communication with a written message capability and is thus better equipped to handle clearances, advisories or warning messages and provide a potential medium to directly interface with the Flight Management System (FMS). Analysis of recorded communications between en route controllers and pilots showed increased controller efficiency and reduced workload in mixed-media environments incorporating both voice and datacom communications than in voice-only environments [5].

Other research, however, has found that voice communication remains essential and the combination of voice and datacom communications outperforms individual modes [6]. Specifically, Smith, Lee, Prevot et al. [7] found that voice and CPDLC each has its own set of unique advantages. They examined route negotiations between controllers and pilots using CPDLC or voice modes. They found that requests sent via CPDLC by pilots can provide clearer intent to the controllers than voice requests whereas voice requests appear

more salient than visual (text) ones to the controllers especially when they are busy.

On the flight deck, mixed media environments (voice and datacom) have yielded mixed results: under time pressure mixing voice and datacom messages did not help capitalize on the advantage of each medium [8,9]. Closely spaced voice and datacom messages increased the number of requests for clarification for voice messages and the need to review the log for datacom messages. Others found that datacom communications also changed the nature of crew communication [10]. While the availability of datacom reduced the amount of ATC voice communications, within-crew communication regarding datacom messages increased, resulting an overall increase in communication time.

The utility of having advanced communication modes cannot be fully exploited without proper procedures that take into account their strengths and weaknesses. There has been very limited research on designing procedures for CPDLC especially in the context of TBO. Mueller [11] examined the possibility of mapping 4D strategic trajectory clearances that included metering, direct routing, and user-preferred routes to datacom messages that can be sent using a currently available datacom infrastructure. Controllers used a trial planner to design strategic trajectory clearances that, upon approval, were translated by an automated function into CPDLC messages and sent to the aircraft using a currently available datacom service (e.g., ACARS). These clearances were then loaded and executed by the flight deck crew without intervention. Mueller found that the existing air-ground communication infrastructure (FANS-1/A, CPDLC, and the prototype ground automation system) appear to be able to satisfactorily implement trajectory-based clearances from controllers.

In a follow-up study, Mueller and Lozito examined flight deck procedures for trajectory-based clearance negotiations [12]. They compared procedures for handling uplinked strategic trajectory clearances that varied the responsibility distribution between the pilot flying and the pilot monitoring (sharing versus non-sharing) in one simulation study and whether to print out datacom clearances in another. All procedures evaluated were rated to be generally suitable.

III. OBJECTIVES

The current research addresses two major challenges to near term implementation of TBO. First, previous research on designing procedures for strategic trajectory-based clearance negotiations has assumed FANS-1/A flight deck communication equipage [11,12]; however, the current fleet is simply not equipped for broad adoption of FANS procedures. Therefore, the current research looks at possible implementations of TBO using Voice procedures or, alternatively, making use of the ACARS datacom found on most transport category aircraft. Second, previous research on flight deck TBO procedures has focused on flight deck review and execution of clearances. While these issues are part of the current research, a primary focus in this study is on flight deck generated requests. Specifically, the current research looks at how aircraft could formulate requests using FANS, ACARS or Voice in a TBO environment.

To test procedures for formulating requests, a human-in-the-loop simulation was conducted. In this simulation pilots and controllers engaged in route negotiation in en route environments with three types of flight deck communication equipment: FANS, ACARS, and Voice only. The study uses weather as a way to drive communication. En route weather poses a special problem because alterations of flight plans must be done during flights. An additional complicating factor is that the air and ground have access to different information. In these cases, flight decks bear the responsibility for avoiding weather while ATC bears the responsibility for preventing conflicts. As a result, negotiation is necessary to achieve solutions that satisfy both air and ground. Further, when gaps in a storm front are sufficiently narrow, requests from the air to fly through them may be rejected due to congestion, and clearances from the ground to avoid these congested pathways may be rejected by the air because they are blocked by, or come too close to, weather.

The current research sought to uncover potential problems for near term implementation of TBO by ‘stress testing’ the system. As such we attempted to keep all planes on trajectories and to minimize radio use on datacom equipped aircraft. Therefore, except for safety of flight issues, we steered our air traffic controllers away from intermediate solutions that put aircraft on open trajectories (e.g., vectors or off-trajectory climbs and descents); and we told our pilots and controllers not to use radio for aircraft assigned to the FANS and ACARS conditions (again except for safety of flight). We recognized that relaxing these constraints may have produced better overall system performance, and operator acceptance, but it would not have served our immediate goals.

IV. CONCEPT OF OPERATION

In this simulation the controller was responsible for managing approximately 12 aircraft in a high altitude sector in Kansas City Center’s airspace (ZKC 90). The sector is on the center boundary adjacent to Indianapolis Center. The primary sector traffic in our simulation was management of normal daytime traffic flows in this sector along with UPS arrivals into UPS’s HUB at Louisville International Airport. Controllers, as in today’s operation, were responsible for aircraft separation and traffic management, while pilots were responsible for weather avoidance. Additionally, controllers were responsible for maintaining trajectory-based operations if at all possible. To accomplish this task they were instructed to minimize vectoring of aircraft by creating flight plan modifications using the trial planner [13] and delivering the modified trajectories via voice or datacom based on aircraft equipment type. In designing the datacom protocols, one of the goals of the study was to reduce the complexity and workload of managing three differently equipped aircraft types. Thus, from the controller perspective sending and receiving information from a FANS and ACARS aircraft required the same actions on the controller Display System Replacement (DSR) station. However, the controllers were briefed on the flight deck procedures for loading and executing datacom clearances on each flight deck.

There was an important difference between information available to controllers versus pilots when handling weather deviation requests sent by either datacom or voice. The

controllers constructed trial plans relative to traffic and weather on the DSR display, while pilot requests were based on flight deck weather radar. The NextRad weather (on the controller’s display) updated at 5 minute intervals. A bug in the simulation prevented updating of the (ground referenced) location of the weather on the flight deck (see Section V.D below).

Initial procedures for the flight deck were developed by the authors, one of whom is a current airline pilot, and another who is a retired air traffic controller. They were then vetted by two other retired controllers, and two pilots. The goal of all procedures was to keep an updated flight plan in a ground based “host” computer, and to make it possible for the aircraft to closely adhere to those flight plans.

It was assumed that in the near-term the ground will have an advanced interface for displaying and modifying aircraft trajectories such as that proposed by Prevot [13]. It was also assumed that all flight decks have the ability to fly a track (rather than heading). In current day operations it is typical for controllers to issue clearances for headings and monitor the aircraft to see that the heading achieves the desired track. In accordance with the general goal of NextGen to reduce controller workload we felt that such monitoring could just as easily be performed by almost all modern commercial flight decks.

For planes that are not equipped with data communications it was felt that verbal communication of arbitrary waypoints (lat-longs) was potentially too error prone. Similarly, extended clearances containing multiple waypoints were judged to be a potential source of error. As a result, our procedures for managing such aircraft called for controllers to develop multiple waypoint clearances and then monitor the aircraft’s progress, issuing multiple track or simple “direct to” clearances, as needed to keep them on route.

For planes that are FANS equipped, the crew can load clearances directly into the FMS. Thus it is feasible to create arbitrary clearances and upload them to the aircraft.

For planes that are ACARS equipped, the situation is more complicated. Flight plans can be sent to such aircraft as text messages. This reduces the opportunity for communication error. Thus, it was felt that flight plans with arbitrary waypoints such as those sent to FANS aircraft could be uploaded. However, the crew must then manually load such flight plans into the FMS, a potentially time-consuming process. To assure that the plane remained on its flight path while the waypoint was being entered into the FMS, procedures were developed that allowed pilots to keep the aircraft on its trajectory using the autopilot until the clearance was entered.

V. METHOD

A. Participants

Sixteen commercial airline pilots with glass cockpit experience (eight per week) and four retired TRACON controllers (two per week) were recruited for this simulation. Participant controllers were recruited from similar simulations and were thus familiar with modern ATC tools used in this simulation. Pilots were divided into two person crews with the more experienced chosen as the captain. They remained



Figure 1. Dual pilot station.

together for the duration of their participation. The simulation ran from August 16-27, 2010 with individual participants running in one of the two weeks. Due to unexpected events, a first officer from the second week dropped out part way through the simulation and was substituted by a captain from the first week. All pilots and controllers were compensated for their participation.

B. Equipment

Four dual-pilot stations and two controller stations were operated by study participants. In direct support of the simulation, researchers and confederates operated a simulation manager station and two pseudo-pilot stations as well as conducting training and observation of all participants

1) Dual Pilot Stations

The dual-pilot station consisted of three monitors (see Fig. 1), on which the controls and displays necessary for operating a generic Boeing transport category aircraft were simulated. The paths of participant aircraft were manipulated using the Multi-Aircraft Control System (MACS) [14] autopilot Mode Control Panel (MCP) and dual Control Display Units (CDU's). Flight path and navigation information was presented on dual Cockpit Situation Displays (CSD's) and dual Primary Flight Displays (PFD's). Controls for hand flying the aircraft (e.g., yoke) were not available.

The middle screen of the station was a shared touch screen monitor accessed by both pilots. It hosted the autopilot MCP, the two CDUs, and text display consisting of a clock and message alerting. The left and right screens of the station each contained a CSD and a PFD for the pilot on that side. Displays on the two side screens were controlled by using a mouse, one for each pilot.

The autopilot MCP, CDUs, PFDs and alerting display were driven by MACS. The autopilot MCP and PFD's operated as on most Boeing transport category aircraft, while the CDU's

operated like a Boeing/Honeywell unit and were used for datacom communications and inputting flight path modifications. The CSD was developed by NASA Ames Flight Deck Display Research Laboratory [15] and presented a 2D display of navigation information, weather radar targets and traffic out to 40 nm (similar to that displayed by the traffic collision avoidance system, TCAS).

2) Controller Stations

In addition to the pilot interface described above, MACS was implemented in a controller mode, allowing air traffic controllers to track and manage aircraft in their assigned sector. Controller tools included datacom, conflict alerting and a trial planner for route modifications.

Participant pilots and controllers also had a separate touch-screen computer used to collect workload and flight plan acceptability ratings. Participants were asked to rate on a 1-5 scale their workload once every minute throughout the trial. Following a flight plan change, participants rated the quality of the flight plan. An additional paper-and-pencil questionnaire was administered after each trial that asked about workload, safety and efficiency during the scenario. A post-simulation questionnaire administered after the final trial, asked questions about the adequacy of training, the realism of the simulation and the acceptability of the proposed procedures.

C. General Procedures

Each week began with one day devoted to training, three days scheduled for data collection and a final day for make-up trials and debriefing. Participants were informed that weather and traffic issues would be present which would necessitate negotiation between the flight deck and ATC.

Two simulation worlds were run simultaneously, each containing one participant controller and two participant dual-pilot flight decks. Also present were non-participant aircraft flown by confederate pseudo-pilots to provide a realistic traffic load of approximately 12 aircraft at any time. Confederate

“ghost controllers” managed traffic outside the experimental sector.

D. Scenarios

In each world, the dual-pilot flight decks were arrival aircraft headed for Louisville International Airport (SDF), reaching top of descent near the eastern edge of the sector. Participants flew west to east through the sector and negotiate a storm front on the eastern side of the sector.

There were four starting conditions at the beginning of the scenario as defined by the location of the weather and traffic. On the controller displays the weather for each of these four starting conditions evolved in various ways creating 16 total scenarios. Because the weather evolved differently in each case, controllers could not make assumptions about an optimal path through the weather until they watched it develop. A bug prevented movement of the weather on the flight deck. Thus the discrepancy between the location of weather seen on the flight deck and that seen on the ground was somewhat larger than intended. However, even if the weather had moved as intended most of the change in the appearance of the weather as seen from the flight deck would be due to changes in perspective that were still present. The entire simulation consisted of thirty-two 20-minute scenarios.

E. Experimental Design

The experimental design consisted of two fixed factors (Aircraft Equipage and Airspace Mixture) and three random factors (Scenario, Crew and Controller).

The Aircraft Equipage factor reflected the datacom communication capability levels of the individual participant aircraft. Three types of capabilities were modeled: FANS, ACARS and Voice.

Airspace Mixture was the number of variously equipped aircraft in the sector. There were three levels: Predominantly Voice (80% Voice, 20% FANS), Predominantly FANS (80% FANS, 20% Voice) and Predominantly ACARS (60% ACARS, 20% Voice and 20% FANS). These three conditions reflected three possible systems of managing the current majority of aircraft that are ACARS. The Predominantly Voice condition imagines that, as today, the ACARS system is not used by ATC and ACARS equipped aircraft are managed in the same manner as unequipped aircraft. The Predominantly FANS condition imagines that these aircraft are upgraded to have data communications integrated with the FMS. Finally, the Predominantly ACARS condition imagines that these aircraft are managed using special procedures. It was expected that the Airspace Mixture factor would affect the controller’s workload but have little effect on the crew.

Note that the controller managed many pseudo-piloted FANS and Voice equipped aircraft in every condition and many ACARS equipped aircraft in the Predominantly ACARS condition. These pseudo-piloted aircraft were expected to react similarly to their participant counterparts. Also note that there were no ACARS aircraft in the Predominantly Voice, or Predominantly FANS, Airspace Mixture conditions. Thus, the design was not fully crossed. Only the following seven cells were populated: Predominantly Voice/Voice, Predominantly Voice/FANS, Predominantly FANS/Voice, Predominantly

FANS/FANS, Predominantly ACARS/Voice, Predominantly ACARS/ACARS, Predominantly ACARS/FANS.

Each aircrew ran twice in each scenario, each time flying a different aircraft. Each aircraft crew ran four times in each of the six FANS and Voice equipage conditions (two times with each controller for that week) and eight times in the ACARS condition (four times with each controller for that week). Each scenario/experimental aircraft combination was used eight times (once per flight crew) once in each of the six FANS and Voice equipage conditions and twice in the ACARS equipage condition.

F. Communications Procedures

Procedures were initially developed in which proposed flight plan amendments developed by ATC included a delayed initial maneuver point (IMP) two minutes ahead of the aircraft, to allow time to negotiate, implement, and possibly reject the proposal before any modification began. However, during training and initial runs it became apparent that, for Voice aircraft, communicating this IMP increased controller workload disproportionately to any benefits in fidelity to the flight path. As a result, the procedures were modified so that, for Voice aircraft, maneuvers were off the nose and controllers amended the flight path in the host if there was a significant delay in the implementation of the maneuver or if after the maneuver the displayed position/symbology showed the aircraft to be off path. Note that, while ground automation can calculate a point directly ahead of the aircraft at which it should begin its maneuver, current day flight decks have no way to make such calculations. Also, because it is unlikely that a named waypoint happens to be right in front of the aircraft, the IMP is almost certain to need to be specified as a lat-long. Because of these issues, IMPs were not included in requests.

G. Flight Deck Procedures

1) Voice Aircraft

Procedures on the flight deck for Voice aircraft were similar to those followed today, with the exception that trajectory-based requests and clearances were required. Thus, pilots followed ATC clearances as today, however these clearances often took the form of adding a waypoint (e.g., “UPS123, direct HILLS then PRINC remainder of the route unchanged”) rather than the unconnected vectors given today (see Controller Procedures below). Pilots were to enter this new route into their FMS. Similarly, when making a request, flight decks could request a deviation for weather, but were encouraged to select a named waypoint and request a deviation direct to that waypoint and then a point at which to return to the original route. In this way, the trajectory was preserved in the host during the deviation.

2) FANS Equipped Aircraft

When an uplinked clearance was received on a FANS equipped aircraft, a message appeared on the alerting display on the center monitor. The pilot-not-flying was then to navigate to the ATC Messages page on the CDU and load the clearance into the FMS. If the clearance appeared acceptable (e.g., was clear of weather), the pilot would respond by sending an accept message via the CDU and execute the flight plan. Otherwise, the pilot would reject the clearance and follow up with a

```
AT: N3907W08710 PROCEED  
DIRECT N3945W08635 PRINC  
REST OF ROUTE UNCHANGED  
FMS CONTINGENCY: AT TIME  
02:05:15Z FLY 055 TRACK.  
WHEN ABLE DIRECT  
N3945W08635 PRINC REST OF  
ROUTE UNCHANGED
```

Figure 2. ACARS uplink.

revised request to ATC via datacom or voice. For requests, pilots developed a modified flight plan in the CDU using standard tools. This route was then downlinked to ATC using the ATC message page on the CDU. Pilots then had to monitor the status of this message to see whether it was accepted or rejected. Accepted requests could be executed. Rejected requests were typically followed up with an amended clearance.

3) *ACARS Equipped Aircraft*

Clearances uplinked to ACARS aircraft were translated into a free text format (by automation) then uplinked as a free text message that appeared on the ACARS menu in the CDU (see example, Fig. 2). As with FANS messages, these were announced on the message alerting display. The pilot-not-flying would then navigate to the ACARS messages page on the CDU. The clearance was then read and confirmed with the flying pilot before entered into the FMS on the other CDU.

Clearances were presented in two parts. The first part was the clearance itself, which contained the path the aircraft was to fly listed as a series of waypoints (possibly including lat-longs). Second, there was an “FMS contingency” part. This included a procedure to execute if the flight crew was not able to enter the clearance before arriving at the IMP, located ~2 minutes ahead of the aircraft. The FMS contingency provided the time at which automation had predicted the aircraft would reach the IMP and a track the pilots should fly to the second waypoint. In practice, the pilots often entered the second waypoint into the CDU and waited for the assigned time to execute the maneuver.

ACARS aircraft accepted clearances by free texting back WWW for Wilco, and UNA for Unable, which were interpreted appropriately by the automation. Requests made by ACARS aircraft were completed through the free text function of the ACARS ATC message page.

H. *Controller Procedures*

Datacom messages were logged and ordered on the controller DSR based on when they were received. However, the controller had discretion on when each message was handled. When a message arrived, it was also coded in the aircraft’s data tag. To reply to the message, the controller would select the portal in the data tag, which showed the route for the FANS aircraft and highlighted the ACARS aircraft in the list. For voice aircraft, controllers handled the requests immediately, or else they were required to copy/remember the requests and ask the aircraft to standby. The procedure for modifying the host flight plan using the trial planner for all

aircraft was generally the same. The current path was modified by first selecting the portal in the aircraft’s data tag. The controller then created a new waypoint on the original path and dragged that waypoint to a location that was clear of weather and traffic. The path would automatically snap to a named fix if one was close to the desired location. The controller would uplink the new trajectory to datacom equipped aircraft or deliver the new clearance via voice.

1) *Voice Aircraft*

After receiving a request to deviate for weather, the controller would create a modification to the aircraft’s current flight plan using the trial planner. This modification would be clear of weather and traffic. The controller would then communicate the route via voice to the aircraft (e.g., “UPS123, fly track 360, direct FIPEN for weather deviation, then proceed direct PRINC.”) If the new route was acceptable, clear of weather by a safe margin, pilots were to fly the assigned route (see Flight Deck Procedures above). If the new route was unacceptable, the pilots would request a further deviation via voice.

2) *FANS Equipped Aircraft*

Downlinked weather deviation requests were received, logged and displayed in the datacom request window on the DSR and in the aircraft data tag. The controller would then select the portal in the aircraft’s data tag to view the requested flight path modification. If the path was conflict free, clear of weather and fit within the traffic management plan, the controller uplinked an approval message. Upon receiving approval, the flight crew would execute the requested change. (Note that, because the request was off the nose—did not include a IMP—such approved requests generally resulted in the aircraft being off its trajectory requiring ATC to adjust the flight plan in the host.) If the controller was unable to approve the requested flight path deviation due to safety and other concerns, UNA for Unable was uplinked followed by a modified flight path clear of weather and traffic based on the downlinked request.

3) *ACARS Equipped Aircraft*

Downlinked weather deviation requests from an ACARS aircraft included a direction and distance or a named fix as a free text message in the controller’s datacom list. The controller would acknowledge the request from the aircraft and the open the trial planner to create a route for the aircraft reflecting this request. If the proposed route was acceptable, conflict free and clear of weather, the controller uplinked an approval message. For unacceptable routes, the controller could uplink a reject message or a new route created with the trial planner.

I. *Dependent Variables*

Participant pilots and controllers were provided a touch-screen computer used to collect real-time workload and acceptability ratings. Participants were asked to rate their workload, using a 1 (bored) to 5 (busy) scale, once every minute throughout the trial. Following a flight plan change, participants rated the quality of the flight plan on a 1 (best) to 5 (poor) scale in place of the workload probe. An additional paper-and-pencil workload questionnaire was administered after each trial to collect workload and acceptability ratings for

the entire trial. A post-simulation questionnaire was administered after the final trial. The post-sim questionnaire asked pilots to rate items on a 5-point Likert scale related to concept acceptability, safety and procedures, and simulation realism. Participants were provided space to add comments. In addition to the ratings variables there were three dependent performance variables: the miles added to the original trajectory by the path modification (path stretch), the number of flight path amendments, and the percent of time the aircraft was not in conformance with the host trajectory (non-conformance - aircraft were tagged as non-conforming when 1 mile off path, or on a track 15 deg discrepant from the nominal trajectory)

VI. RESULTS

A. Performance

Our initial analyses show little difference between conditions in terms of the trajectories flown. ANOVAs conducted separately for Aircraft Equipage and Airspace Mixture found no significant differences between different flight deck equipment or different airspace mixtures in terms of path stretch to avoid weather, time off path, or number of flight path amendments. The lack of effects on path stretch and amendments is not too surprising since the factors that drive flight path changes (e.g., weather, conflicting traffic, distance to top of descent) are built into the scenario and may overwhelm any influence of communication method. However, the absence of any effect on non-conformance is somewhat surprising, since it could be expected that the FANS condition should have performed best, and the Voice worst. This was not found, but a surprising overall level of non-conformance was found.

When non-conformance is examined as a function of individual controller and Aircraft Equipage, aircraft are typically non-conforming 20% of the time or more, cresting 45% in one case. These are very high numbers. The controllers also differ both in overall performance and in how Aircraft Equipage affected their ability to keep aircraft on their trajectories (Fig. 3). For two controllers Voice aircraft are off path much more often than FANS or ACARS aircraft, while for the other two, Voice aircraft are off path less often than FANS, nearly as little as ACARS. For all four controllers ACARS aircraft were off path less frequently than either Voice or FANS aircraft.

While we have not systematically categorized all instances of non-conformance, it is clear that much of the non-conformance seen in our data stems from trajectory modification requests made off-the-nose. One reason this caused problems was that we developed procedures that were superficially similar, resulting in some confusion for controllers. For example, with Voice aircraft controllers were told to verify that the request did not result in a conflict by creating an off-the-nose trial plan, entering it into the host, and then approving it verbally. For FANS requests they were told to load the downlinked trajectory and, if conflict free, approve it. For ACARS requests they were told to create a trial plan that had an IMP two minutes ahead of the aircraft and uplink that trajectory. Controllers would often combine parts of different procedures, for example, creating an off-the-nose flight plan for

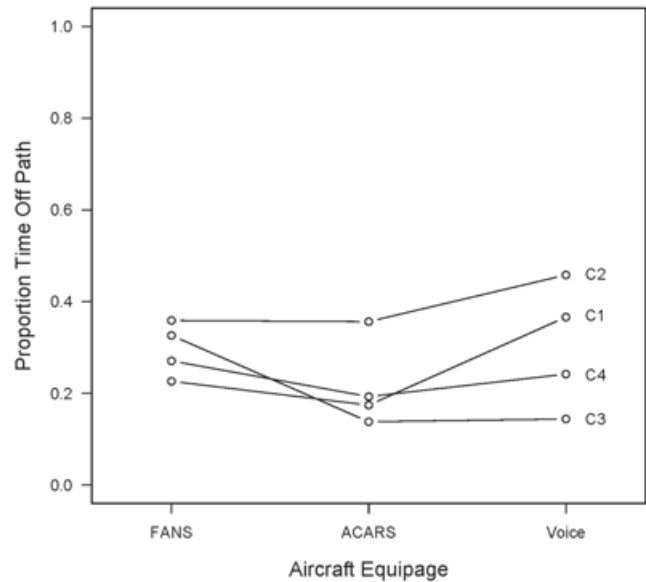


Figure 3. Proportion of time off path by controller

an ACARS aircraft. (This would result in aircraft overflying their IMP as the pilots attempted to enter and vet the new flight path.) Such confusion could probably be reduced by making the procedures more parallel (e.g., never simply approving a request; instead always inserting a maneuver point two minutes ahead of the aircraft), or by adding training that specifically compared and contrasted the differences in these procedures.

Another issue that arises when maneuvers are off-the-nose is that small differences between when the flight plan is loaded into the host on the ground and when it is loaded into the FMS on the aircraft will lead to non-conformance. For instance, if a FANS aircraft downlinks a trajectory request and the ground approves it (simultaneously loading it into the host), the host expects the aircraft to begin the maneuver immediately. If the aircraft is flying eight miles a minute and the pilots delay eight IMP by a mile and be out of conformance. Again, this issue might be remedied if controllers uplinked a new flight plan with a specified IMP to FANS aircraft, or if pilots were made more aware of the importance of executing flight plan amendments immediately after they were approved.

The incidence of non-conformance could be reduced with modified procedures and training or even using a less stringent required navigational performance (RNP) level of 2 or 3 miles. However, we are unlikely to be able to prevent aircraft from being out of conformance altogether. Recognizing this, we also gave controllers instructions to adjust the flight path on the DSR when aircraft were late in initiating a maneuver so that it matched the path the aircraft was actually flying. However, it appears that workload issues frequently prevented controllers from performing this operation.

B. Workload Ratings

At the end of each trial, all participants rated their workload (1 low to 5 high) on four criteria. Pilots were asked to rate Overall and Peak Workload associated with their flight and with weather avoidance, while controllers were asked to rate

Overall and Peak Workload associated with maintaining separation and with handling weather avoidance requests.

For controllers the four post trial workload ratings were obtained for each level of Airspace Mixture. These 12 resulting mean workload ratings clustered in a fairly restricted range (from 3.28 to 3.85). For the four measures, controllers' mean workload was highest in the Predominantly FANS condition, and was lowest for Predominantly Voice, with the exception of Overall workload associated with separation, for which Voice and ACARS were nearly identical. These trends were significant for the "Overall workload associated with separation" ($F(2,6)=13.905$, $p=.006$) and "Overall workload associated with weather avoidance requests" ($F(2,6)=5.966$, $p=.037$).

As expected, there was no effect of Airspace Mixture on any pilot workload measure, with these varying from 2.10 to 2.77. There were significant effects of Aircraft Equipage; across all four workload measures, pilots consistently rated their workload highest in the ACARS condition and lowest in the Voice condition. These differences were significant for Overall workload associated with flight, $F(2,14)=10.310$, $p=.002$; Peak workload associated with flight, $F(2,14)=4.811$, $p=.026$; and Overall workload associated with avoiding weather, $F(2,14)=5.484$, $p=.017$.

C. Ratings of Procedures

After the simulation, both pilots and controllers rated how much they agreed with 15 statements (1 - low to 5 high) about each of the different communication procedures. For example, pilots were asked to rate their agreement with "I am comfortable with the ACARS/FANS/Voice based trajectory management concept," and "Trajectory operations using ACARS/FANS/Voice are safe." Controllers were asked to rate their level of agreement with "I felt adequately aware of what the pilots of ACARS/FANS/Voice aircraft were doing," and "Trajectory operations using solely ACARS/FANS/Voice is, in principle, a workable concept."

1) Controller Ratings

The pattern in the controller data is quite clear. Controllers generally rated the two datacom procedures identically. Two of the four rated ACARS and FANS identical ratings on all 15 statements. That is, they saw no difference in the two procedures on these measures. One controller gave FANS better ratings on three criteria, and the remaining controller gave ACARS a better rating on one criterion. In addition, only one of the four controllers agreed with the statement "I was very aware of whether an aircraft I was handling was integrated datalink communication (FANS-1A) or ACARS." Thus it appears that our procedures were successful in allowing ACARS-equipped aircraft to be managed similarly to FANS aircraft from the controller's perspective.

While ACARS and FANS appeared very similar to the controllers, Voice, naturally, was quite different. Yet the four controllers differed on whether Voice was preferable to the two datacom conditions (FANS and ACARS). One controller rated the datacom conditions better than Voice on eight of the 15 criteria, while rating Voice better on none. A second controller rated the datacom better on six and Voice better on one.

However, a third controller rated Voice better on eight and datacom better on none, and the final controller rated Voice better on one and datacom better on one. Thus, it appears that controllers varied in their preferences for Voice and datacom.

2) Pilot ratings

Unlike the controllers, pilots clearly distinguished between ACARS and FANS. For the twelve statements that allowed us to infer a preference ranking among the three Equipage conditions, Voice was always rated best and ACARS always rated worst, with FANS falling in the middle (all statistically significant at the $p < .05$ level). This is not surprising since, on the flight deck, pilots were, less familiar with ACARS and FANS. In addition ACARS required significantly more work. In ACARS, flight requests had to be manually typed into the ACARS CDU page, while text copies of uplinked flight plans had to be accessed on the CDU ACARS page, and then manually input again into the CDU FMS leg page.

D. Comments and Observations

It is clear that pilots, as a whole, did not like datacom, especially ACARS. Some insight into this finding can be gleaned from comments gathered during the simulation, responses to open ended questions on the post-simulation questionnaire, and from comments made during the post-simulation debriefing. Pilots had three major concerns about the datacom procedures. The first, and perhaps expected, concern is the time and effort to create and manage messages on the CDU (mentioned by 7/16 for both FANS and ACARS). A second concern was ATC response time (mentioned by 7/16 pilots for FANS and 13/16 for ACARS). In current day operations with voice the controller responds to messages as they are received. However, in a datacom environment they seem to ascribe priorities in their responses to messages based on traffic management needs. For example, if the controller receives a request from an aircraft that will soon be handed off, the controller may respond to it before responding to a previous request by an aircraft in the middle of the sector. Meanwhile other flight decks wait without feedback that the controller has even received their message. Finally there were concerns related to message format, such as how the ACARS clearance was formatted, and how the ACARS and FANS messages came up across two pages, thereby requiring additional effort to integrate.

VII. DISCUSSION

While other studies have shown clear benefits to datacom procedures, our results show a more mixed picture. Controllers showed no clear preference for datacom, and pilots showed quite the opposite, a strong preference for Voice. Similarly, Voice procedures were not worse than datacom procedures in our preliminary examination of performance measures. Why the difference? In our study most flight path amendments came as a result of pilot requests, while previous work has looked almost entirely at clearances initiated by the controller. Datacom equipage found on current day transport category aircraft makes it difficult to formulate requests and lacks the immediate feedback of traditional voice protocols. The generally slow response time for datacom has been noted in other studies [6,7]. Groce and Boucek [16] specifically note that pilots found datacom unacceptable for weather avoidance

clearances because of the time critical nature of such clearances.

It is possible that a communication protocol that combines both datacom and voice could result in more acceptable response times while accruing many of the benefits of datacom (such as reduced transmission error, the ability to transmit more complex clearances, and a reduction in voice traffic). For example, pilots could make requests by voice and receive an acknowledgement by voice which would then be followed up by a clearance. Several pilots in our study stated during the debriefing that their concerns about datacom would be greatly ameliorated if requests were acknowledged more promptly even if there was a delay in the actual clearance. Such measures might not only increase the acceptability of FANS but also make non-integrated datacom, such as ACARS, acceptable to pilots. This combined approach could also significantly increase options for near-term implementations of TBO. ACARS is just one example of non-integrated datacom, albeit one that is currently available on the majority of transport category aircraft. One could imagine equipping the flight deck with an electronic flight bag (EFB) capable of sending and receiving flight plans. Because of the lower certification standards EFBs can be a cheaper and more flexible way of upgrading aircraft avionics. The use of EFBs for communicating flight plans might also facilitate deployment of systems with better interfaces for creating requests such as that described in [15].

The current study also highlights the difficulties with keeping aircraft on trajectories in an environment where aircraft can make requests. Because no class of aircraft can easily create flight plans that contain IMPs, controllers cannot simply approve requests but must either create a new flight plan and send it back or adjust the flight plan in the host to match what the aircraft is actually flying. Either way adds significantly to the controller workload. One way the controller can ameliorate this problem for himself is to allow planes to go off trajectory. Despite our emphasis in training that aircraft always be on host trajectories, we occasionally observed that a controller appeared unconcerned if one or two flights were not conforming. This may have been because they were allowed to hand off non-conforming aircraft to the next sector, and/or because there were no metering constraints in our study. However, it may also reflect controllers reverting to their standard operational procedures where they consider a trajectory okay so long as they can visually confirm that it contains no conflicts.

Finally, while the current study uncovered substantial difficulties with TBO procedures, it should be noted that our scenarios were designed to surface such difficulties should they exist. Pilots might prefer Voice, and controllers might not uniformly prefer datacom on a stormy day when there are many pilot requests. However, the benefits for datacom seen in other studies under conditions where it is primarily controllers issuing clearances for separation and interval management are in all likelihood real. The current study should not be taken as a reason to question the march toward TBO, only as some additional caveats on how it should be implemented.

ACKNOWLEDGMENT

We would like to thank George Lawton, Dominic Wong, Riva Canton, Tom Quinonez and John Luk for software programming support, and Patrick Cravalho for assistance in recruiting participants. We would particularly like to thank Dr. Kim Vu and Dr. Tom Strybel of California State University, Long Beach, as well as their students for their aid and support in the running of this study.

REFERENCES

- [1] United States Department of Transportation. Air carrier traffic statistics. [Online] [Cited January 18, 2011]. (http://www.bts.gov/programs/airline_information/air_carrier_traffic_statistics/airtraffic/annual/1981_present.html)
- [2] Joint Planning and Development Office: "Next Generation Transportation System: Concept of Operation V 3.0," Washington D.C: Government Printing Office, 2010.
- [3] J. Krozel, S. Penny, J. Prete, and J. Mitchell, J. "Automated route generation for avoiding deterministic weather in transition airspace," *J. of Guid., Contr. and Dynamics.*, vol. 30, 2007, pp. 144-153.
- [4] D. Morrow, A. Lee, and M. Rodvold, "Analysis of problems in routine controller-pilot communication," *Int. J. of Av. Psych.*, vol. 3, 1993, pp. 285-302.
- [5] S. Yenson and J. Rakas, "Impacts of a mixed media air traffic control communication environment on aviation efficiency," in *Proc. of the 12th Air Transport Res. Soc. Ann. World Conf.*, 2008, Athens, Greece.
- [6] K. Kerns, "Data-link communication between controllers and pilots: A review and synthesis of the simulation literature," *Int. J. of Av. Psych.*, vol. 1, 1991, pp. 181-204.
- [7] N. Smith, P. Lee, T. Prevot, J. Mercer, E. Palmer, V. Battiste, V., and W. Johnson, "A Human-in-the-loop Evaluation of Air-Ground Trajectory Negotiation," in *Proc. of the 4th Amer. Inst. of Aero. and Astro. Av. Tech., Integ., and Oper. Conf.*, 2004, Chicago, IL.
- [8] S. Lozito, L. Martin, M. Dunbar, A. McGann, and S. Verma, "The impact of voice, data link, and mixed air traffic control environments on flight deck procedures," in *Proc. of the ATM2003, the 5th USA/Eur. R&D Sem.*, 2003, Budapest, Hungary.
- [9] A. McGann, D. Morrow, M. Rodvold, and M. Mackintosh, "Mixed-media communications on the flight deck: A Comparison of voice, data link, and mixed ATC environments," *Int. J. of Av. Psych.*, vol. 8, 1998, pp. 137-156.
- [10] C. Harvey, M. Reynolds, A. Paclej, R. Koubek, and A. Rehmann, "Effects of the controller-to-pilot data link (datacom) on crew communication," in *Proc. of the Hum.Fact. and Ergo. Soc. 46th Ann. Meet.*, 2002, Baltimore, MD.
- [11] E. Mueller, "Experimental evaluation of an integrated datacom and automation-based strategic trajectory concept," in *Proc. of the 7th Amer. Inst. of Aero. and Astro. Av. Tech., Integ. and Oper. Conf.*, 2007, Belfast, Northern Ireland.
- [12] E. Mueller, and S. Lozito, "Flight deck procedural guidelines for datacom trajectory negotiation," in *Proc. of the 8th Amer. Inst. of Aero. and Astro. Av. Tech., Integ. and Oper. Conf.*, 2008, Anchorage, AK.
- [13] T. Prevot, "On the design of integrated air/ground automation," *IEEE SMC*, 2005, Waikoloa, Hawaii.
- [14] T. Prevot, "Exploring the many perspectives of distributed air traffic management: the multi Aircraft Control System MACS", in *Proc. of the . Int. Conf. on Hum.-Comp. Interaction in Aero.*, 2002, pp. 23-25.
- [15] S. Granada, A. Dao, D. Wong, W. Johnson, & V. Battiste, "Development and integration of a human-centered volumetric cockpit situation display for distributed air-ground operations," in *Proc. of the 12th Int.l Symp. on Av. Psych.*, 2005, Oklahoma City, OK.
- [16] J. Groce, and G. Boucek, "Air transport crew tasking in an ATC data link environment," *SAE Tech. Paper Series*, ISSN 0148-7191, 1987, Warrendale, PA.