Flight Deck Procedural Guidelines for Datalink Trajectory Negotiation

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This paper presents an evaluation of three different flight deck procedures for their compatibility with a Trajectory-Based Operations Concept. Particular emphasis is placed on the interoperability of trajectory-based automation concepts and technologies with modern Flight Management Systems and datalink communication to enable negotiation between air and ground. A two-way datalink connection between the trajectory-based automation resident in the Center/TRACON Automation System and the Future Air Navigation System-1 integrated Flight Management System/datalink in NASA Ames' B747-400 Level D simulator has been established. Simulation experiments investigated the use of datalink messages to communicate strategic trajectories. A strategic trajectory is defined as an aircraft deviation needed to solve a conflict or otherwise modify a flight plan route and then merge the aircraft back to its nominal preferred trajectory using a single continuous trajectory clearance. A preliminary pilot-in-the-loop simulation evaluated two candidate procedures using a variety of horizontal and vertical trajectory clearances and found each to be feasible for basic datalink trajectory exchange. The procedure most preferred by the flight crews was adapted to enable trajectory negotiation and a second piloted simulation was conducted to measure important parameters that affect safety and efficiency. This simulation established that limited information exchange during trajectory negotiation between flight deck and ground based automation systems is feasible using current aircraft equipment and modified procedures, but that a number of factors relating to flight deck procedures are important to consider when constructing datalink clearances. Guidelines for designing flight deck-compatible clearances are presented along with the effect of several conditions on the crew's message response time and the extent to which crews initiated negotiations. Among other results it was found that response times are generally shorter for vertical trajectories than horizontal, that prescribed minimum climb rates are difficult for crews to follow, and that basic negotiation using text-based messages requires little extra time than non-negotiated clearances.

I. Introduction

The concept of operations envisioned for the Next Generation Air Transportation System (NextGen) relies heavily on the exchange of 4D trajectory information to achieve higher levels of automation for conflict detection and resolution, metering and trajectory changes while operating under conditions of increased air traffic density, reduced allowable accident rates, lower controller workload, and greater accommodation of user preferences.[1] In accordance with guidance from the multi-agency Joint Planning and Development Office (JPDO) that "it's all about the users," the goal of this research is to accommodate, to the maximum extent possible, the preferences of the airspace users, and to minimize, within strict safety standards, the adverse impact of Air Traffic Control (ATC) initiatives and restrictions. The users are generically defined as any agent that makes use of ATC services and are most commonly airlines and business aviation groups. It is proposed that the preferences of these users can be better accommodated within the constraints of the ATC system by moving from today's tactical, voice-based clearances to the use of trajectory information transmitted over datalink. A crucial capability under this new

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concept is the ability to negotiate clearances in appropriate situations to maximize the efficiency and safety of each aircraft's trajectory.
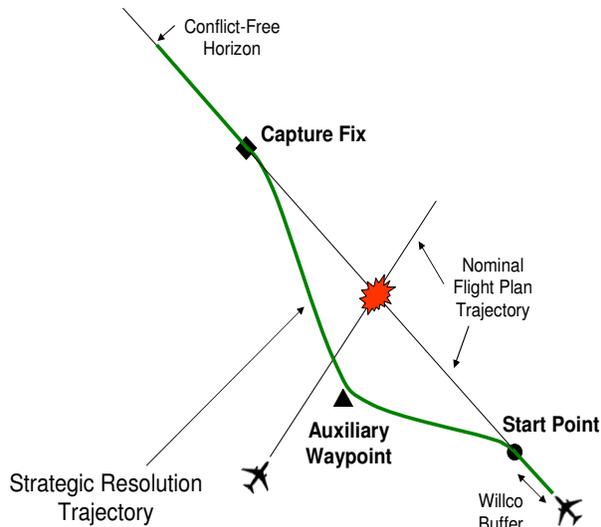
Previous research has shown the feasibility and benefit of integrating ground automation and the airborne Flight Management Systems (FMS) through datalink communication, but not all aspects of such an integration have been satisfactorily resolved. Basic exchanges so far demonstrated operationally include Transfer of Communications (TOC), altimeter calibration data, and direct-to messages.[2] Corresponding demonstrations of complex clearances with real automation systems are not complete. These complex clearances, which form the foundation of Trajectory-Based Operations (TBO), are defined as a combination of route and/or altitude changes; the amended route need not pass through named waypoints but may instead be specified with latitude and longitude coordinates. Important issues concerning the implementation of such trajectories remain to be resolved: the respective roles and responsibilities of pilots and controllers; the degree of flight deck automation required to limit workload increases; the precision with which aircraft would be able to follow 4D clearances; and the expected impact of changes, upgrades or modifications to existing aircraft equipment.[3,4] Several concepts have been developed that integrate air and ground automation with datalink to provide specific answers to these questions. Trials of Continuous Descent Approaches (CDA) into San Francisco International Airport used route clearance messages to allow aircraft to fly near-optimal fuel trajectories when the air traffic density was low, and successfully demonstrated the feasibility and benefit of datalink trajectory exchange.[5] A European experiment uploaded Required Time of Arrival (RTA) clearances to aircraft at takeoff and measured the accuracy with which the airborne FMS was able to meet that RTA at the runway threshold.[6] This example of time-based air traffic management (ATM) demonstrated one element of TBO by showing that aircraft automation is able to accurately meet an RTA over a multi-hour time horizon in real-world, low aircraft-density conditions. Further work will expose modifications to these concepts necessary to apply them under denser air traffic scenarios and, in the latter case, accommodate the trajectory uncertainty inherent to RTA clearances.

The first objective of the work described in this paper is to determine whether flight deck procedures can be compatible with trajectory-based operations and enable negotiations under those operations using current flight deck equipment. This objective extends previous work by evaluating not just the technical aspects of datalink communications, but those aspects that include both the equipment and its interaction with the flight crew. The second objective is to gather human-in-the-loop (HITL) simulation results that validate the feasibility of negotiating TBO clearances in today's environment and provide guidance about how best to enable those negotiations. These objectives are met using simulations that connect a prototype ground-based automation system, the Center/TRACON Automation System (CTAS),[7] with the most advanced airborne automation currently flying, the Future Air Navigation System-1 (FANS1) on a Boeing 747-400 (B747-400) Level D simulator at NASA Ames Research Center.[8] The simulated datalink between these systems is based on the protocols developed for Controller-Pilot Data Link Communications (CPDLC). This paper describes a strategic trajectory concept underlying TBO in detail, outlines the experimental approach used in two HITL simulations to assess the feasibility of trajectory negotiations via datalink, and presents qualitative and quantitative results characterizing the suitability of current automation systems for TBO and datalink negotiations in today's air traffic system.

II. Background

A full evaluation of an end-to-end TBO concept with all operational elements (flight deck hardware, datalink infrastructure, flight crews, etc.) has not been conducted. Researchers have proposed concepts for integrating the User Request Evaluation Tool (URET) with datalink to achieve TBO and significant benefits for airspace users;[9,10] but because this work is ongoing the fundamental barrier to trajectory-based operations, if any exists, is not yet known. Early studies of the concept have shown that aircraft trajectories may be predicted by ground based automation systems with an accuracy of tens of seconds over a 20 minute horizon if reasonable models of the wind field and aircraft dynamics are available.[11,12] Previous research has also identified some of the issues associated with TBO concepts: unmodeled wind errors; quality of surveillance data; commonality of flight crew procedures among different airlines and aircraft types; and the ability to certify datalink communications to an equivalent level of safety as voice.[13] Recent investigations have quantified the magnitude of these problems and suggested the most important are safety and procedural commonality, assuming a number of technical and cost problems are resolved.[14,15,16] In addition, high-fidelity simulations suggest the importance of pilot response time in achieving a viable datalink system.[17]

One of the most important challenges facing TBO is implementing strategic clearances on the flight deck using current FMS and datalink equipment. While the problem has not been fully investigated, it is known that integrated FMS and datalink operations cannot replace voice using current day procedures.[18] Datalink is a fundamentally

Figure 1. Single auxiliary waypoint horizontal trajectory clearance.

different means of communication with different strengths and weaknesses than voice communications and will not work well with the same flight deck procedures.[19,20] Research does exist that examines flight crew interactions with datalink technologies, and aspects of those studies helped inform this research project.[21,22]

Modeling and simulation studies also suggest that ground based automation provides significant benefit in terms of safety, capacity and efficiency and can reduce controller workload if procedures are structured correctly.[23] The challenge is to integrate ground based automation with FMS and datalink to capture all the benefits cited in literature without an unacceptable increase in pilot and controller workload or the introduction of new operator errors or safety issues to the system. For instance, 20% of the 58 operational errors analyzed in a recent study were the direct result of misunderstanding voice transmissions between the flight crew and controller, and 52% were from improperly analyzed horizontal or vertical clearances. These error types would likely be addressed by datalink communications and trajectory prediction automation. Hasan et. al. forecast up to half a billion dollars a year in savings from trajectory negotiation over datalink alone, mostly due to delays avoided by the increased capacity that datalink negotiation is predicted to afford.

The introduction of datalink into the National Airspace System (NAS) may offer a number of benefits to the users. The Controller-Pilot Data Link Communications (CPDLC) project in Miami between 2002 and 2003 represented a significant field evaluation of datalink in the US. The benefits identified in the study include reduction in voice frequency congestion, which is currently driving Europe to adopt datalink more quickly than the US, transfer of communications capability, and basic information sharing like altimeter settings.[24] Although data link research has illustrated potential capacity benefits, the use of textual messages is expected to make clearance negotiations difficult due to the inflexibility of menu structures and response selections.[25] Thus far, little research has been conducted to investigate the ability of a flight crew to negotiate via data link.

The amount of time between the transmission of a clearance and the required response is still a matter of research for TBO. Average values have been reported for simpler clearances like altitude and speed changes on the order of 30 seconds;[24,26] however, studies of operational datalink systems in Europe with more complex clearances have measured overall average response times above 60 seconds.[27] Characterizing this response time as a function of clearance type, message content and other relevant factors will be required to set the pilot response time, which in turn will have a major effect on the controller's workload and situational awareness in today's operations. A concept that results in low workload for a controller today should translate into better performance of any automated separation assurance system in the future.

III. Strategic Trajectory Operations and Clearances

This section briefly describes the concept for strategic trajectory operations as tested in simulation (see Ref. 31 for more details about the concept and the types of trajectories that have been evaluated for consistency with the CPDLC message set). Strategic trajectory clearances are delivered to an aircraft to solve a problem or honor a user request and then return the aircraft to its nominal preferred trajectory using a single datalink transmission. Examples of such horizontal and vertical strategic trajectory clearances are shown in Figure 1 and Figure 2. In all cases, problems are solved using a continuous trajectory that includes a start point, zero or more intermediate points specific to the problem being solved, and a capture point on the original flight plan.

It is expected that such trajectories: 1) will reduce both controller and pilot workload by solving problems with a single strategic clearance instead of multiple tactical clearances as in today's operations; 2) will improve overall predictability in the NAS out to a time horizon of about fifteen minutes since the complete trajectory for each aircraft is always known; 3) are well suited for FMS implementation and datalink communication; 4) are compatible with the simultaneous solution of conflict and time-based metering problems, which are common in complex, high density airspace. Laboratory research and limited simulation and operational testing suggest these characteristics

will lead to fewer restrictions, lower workload and increased airspace capacity and efficiency.[28,29,30] Important research questions about the flight deck implementation of TBO arose during laboratory testing and are being addressed in the simulations described in this paper. These questions are outlined in the following section.

A prototype trajectory based automation capability has been developed at NASA to study the impact of TBO on air and ground automation systems. The Center TRACON Automation System (CTAS) is designed to allow a controller or ground-based automation

Figure 2. Step climb clearance. Step descent clearances are functionally identical.

system to formulate conflict-free trajectories for conflict resolution, pilot requests, metering, to accommodate airspace restrictions or to deal with other ATC imperatives. Some level of automation is likely to be involved in the creation and evaluation of operational trajectory clearances, whether that is a simple conflict predictor or a fully automated conflict prediction and resolution tool, but the concept for TBO is designed to be compatible with any level of ground-based automation. Once the controller or automated system is satisfied with the trajectory designed in CTAS an automation function transmits the clearance to the appropriate aircraft. That function translates the strategic clearance into CPDLC messages and sends them to the aircraft using a currently-available datalink service (ACARS, VDL, etc.). When the flight crew has received the clearance, they review it up to the allowable WILCO buffer as seen in Figure 1, which is nominally set to two minutes in this simulation.

Some confusion can arise as to the differences in meanings of the words "trajectory," "clearance," "message," and "message element." For the purposes of this paper a trajectory is the actual path through space and time that an aircraft follows; a clearance is the full set of instructions and procedures required to cause the aircraft to follow the trajectory; a message element is one CDPLC-formatted instruction with a given CPDLC number (e.g. 79 or 20); and a message contains one or more message elements with the instructions that are a part of the clearance.

IV. Experimental Approach

Research has suggested that trajectory-based automation systems on the ground can be technically interoperable with the airborne FANS1 automation systems using an integrated FMS/datalink capability.[31] Simulations conducted in the course of that research investigated the use of the trajectory-based automation functionality and software resident in the Center-TRACON Automation System and a fully certified, Level D B747-400 simulator which is fully equipped with actual FANS1 hardware and software.[8] This integration is critical since the use of these new strategic clearance types with existing voice communications and procedures will lead to increased crew workload and errors.[19] A real-time software interface supported two-way communication between CTAS and the FANS1 hardware using CPDLC messages. The messages received by the B747 simulator from CTAS via CPDLC are identical to those that would be received in an operational setting. This experimental setup has been used in prior simulations, which suggested the best approaches for implementing each of the trajectory clearance types.[31]

The objectives of the simulations described in this paper were to answer the following research questions:

- If the ATC datalink communication procedure includes both members of a flight crew rather than just one, what is the effect on workload, efficiency and response time? Is either procedure compatible with TBO and existing flight deck equipment?
- To improve models of datalink communications, what is the effect on response time of using one or more message elements to specify a single clearance, the effect of higher or lower flight deck workload, and the difference in response times for horizontal and vertical trajectory clearances?
- Does the message response time decrease when a reason for the clearance is given or an alert is sent that a specific clearance will soon be received?
- How much longer do crews take to respond to clearances that they need to negotiate than those they accept without modification, and under what situations are crews more likely to negotiate? Will crews choose to negotiate by rejecting a message and including specific information on how the controller or ground-based automation system should modify a clearance to make it more acceptable?
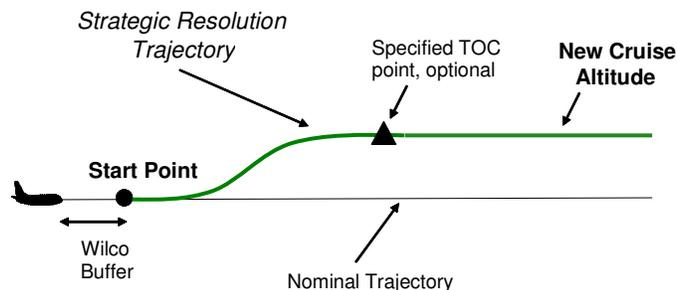
The accuracy of the CTAS trajectory predictor compared with the aircraft dynamic model contained in the simulator was measured to ensure consistency between aircraft intent and the ground system's knowledge of that intent. These measurements suggested ways to improve the design of the ground automation trajectory predictor and helped formulate requirements for accurate modeling of TBO. For example, in was recognized that in high traffic density conditions a WILCO buffer point is needed. The metrics used to evaluate the performance of the concept in this simulation are:

- Ability of aircraft to stay in its preferred performance envelope while executing clearances;
- Flight crew response times to data link trajectory clearance messages, termed "WILCO time;"
- Detection of erroneous clearance elements by the flight crew;
- Frequency with which crews abandoned datalink and contacted the controller via voice;
- Subjective data from pilot questionnaires regarding trajectory-based operations and negotiations.

A. Experiment Design for Study One – Feasibility of Procedures

The first study on procedures for TBO was conducted over two weeks in September, 2007 and evaluated two different flight deck procedures for their feasibility in handling datalink communications in departure and enroute operational conditions. The two procedures are specified in the Appendix, and differed from each other in the degree to which the pilot flying (PF) rather than the pilot monitoring (PM) interacted with the FMS. The procedure labeled "non-sharing" is adapted from the typical procedures for a large commercial air carrier, and the "shared" procedure departs from this by allowing the PF to handle some communications responsibilities. The primary goal of the September 2007 simulation was to determine whether one or both of the procedures would be suitable for TBO.

The participants in this study were five flight crews, each including a captain and first officer, who flew eight scenarios in Dallas-Fort Worth Center. Four of the scenarios began at FL150 during the departure phase of flight and four were entirely in cruise. The crews received several horizontal and vertical trajectory clearances in each scenario and responded to the clearance using the particular procedure being evaluated. Each crew was available for four hours of data collection, and several hours of briefing, training and debriefing, and each was given the chance to use both procedures. Data collected included the crews' response times to different clearances and qualitative ratings of the acceptability of each procedure for the datalink communications tasks. The results of this initial simulation are discussed in the first sub-section of the Results Section below.

B. Experiment Design for Study Two – Detailed Procedures for Negotiations

The second simulation was conducted in March, 2008 and focused on the impact of several datalink and flight deck parameters on the efficiency and acceptability of TBO. One of the variables considered was the way in which the clearance was constructed: one set of clearance types used a single message element to specify the strategic trajectory while a second set concatenated multiple message elements to specify that same trajectory. Equal numbers of messages from each set were sent to the crews, and because each crew saw the same trajectory changes, any given trajectory was specified several times using each message format. The messages themselves will be described below. Another experimental variable was the presence of additional message elements in the clearances that provided information about the cause and timing of the revised clearances. One quarter of messages contained information that traffic or an airspace restriction led to the revised trajectory, and another quarter of the clearances were accompanied by "expect" messages, which were provided to allow participants to anticipate future instructions and evaluate the re-route prior to their receipt.

Two levels of workload were present as test conditions in the simulation to determine the sensitivity of response time to activity level. A hydraulic pump overheat problem was presented in two out of four of the scenarios that each crew flew in the simulation. This problem created a warning message to the crew and required them to follow a system malfunction checklist, but did not affect the performance of the aircraft. The additional tasks required of the crews in these scenarios resulted in somewhat elevated workload levels, which were determined by the number of tasks required of the pilots, although in general clearances were not sent to the crews while they were fixing the problem to maintain consistency in experimental design. Finally, two clearances were sent to each crew that contained instructions that could not be followed ("bad" or "incorrect" clearances): one clearance was to climb to an altitude below the aircraft's current altitude, and the other attempted to reconnect the aircraft to its original flight plan using an unknown waypoint. These clearances were intended to probe the crews' error detection ability as a way to estimate the safety impact of communicating over datalink rather than voice.

The four scenarios in this second simulation used four different flight segments in Dallas-Fort Worth Air Route Traffic Control Center (ARTCC). All were in the cruise phase of flight, and each scenario lasted about 40 minutes. Ten to fourteen datalink clearances were transmitted in each scenario, a number somewhat higher than crews would experience operationally, and the pilots were asked to negotiate aspects of the clearances if they felt that there were inefficiencies or other factors that made following the instructions impossible or impractical. Three quarters of all messages included some aspect intended to be objectionable to the crews and to therefore be cause for initiating negotiations. Negotiations resulted from one of four different causes: an altitude clearance that could not be achieved due to the weight of the aircraft; an unachievable climb or descent rate; weather cells present on the route of flight or in a revised trajectory; and large heading changes the caused very inefficient flight plans. The clearances used in data collection included a mix of vertical and horizontal instructions in each of the conditions described above, plus a number of other messages not used in data collection to ensure the crews would have a variety of datalink tasks to perform; these additional messages included radio frequency changes and responses to negotiated clearances like direct-to messages.

The datalink messages used in the horizontal trajectory changes (see Figure 1) are,
- um79 CLEARED TO [capture fix] VIA [start point .. auxiliary waypoint]
- um74 PROCEED DIRECT TO [auxiliary waypoint]; um77 AT [auxiliary waypoint] PROCEED DIRECT TO [capture fix].

The datalink messages used in the vertical trajectory changes (see Figure 2) are,
- um27 CLIMB TO REACH [altitude] BY [position]
- um20 CLIMB TO AND MAINTAIN [altitude]; um171 CLIMB AT [verticalrate] MINIMUM

The first messages in each set above (#79 and #27) are the single message element clearances, where the numbers refer to the message element codes specified for CPDLC. The second sets of messages above (#74 and #20) are the multiple message element clearances. Single message element clearances may be easier and more efficient to understand and implement, while multiple message element clearances may make negotiation of a particular parameter easier for the crew. The horizontal message constructions also differ from each other in their use of a WILCO buffer point, which may only be necessary in high density airspace to make the future position of the aircraft more predictable. Both the horizontal clearances are autoloadable and executable by the FMS, while the vertical clearances are executed by the pilot on the Mode Control Panel (MCP). Details on the procedures for both of these clearance types may be found in the Appendix and Ref. 31.

C. Participants
The participants of the first study were five flight crews from commercial airlines; all of them had experience with glass cockpits. Their mean total years of experience as commercial pilots was 33, and the data collection occurred across five days with one crew (a captain and first office) participating each day. The second study used many of the same pilots and overall had the same average level of experience, but six crews over six days participated in the study. All of the participants were rated to fly the 747-400 with FANS1 equipage, and all but one had flown that aircraft recently. This last pilot was currently flying 777 aircraft but did possess a current 747 rating.

D. Experiment Protocol
At the beginning of each day in both simulations the pilots were provided a briefing about trajectory negotiation clearances and their intended use and benefits. They were then given familiarization and training in the B747-400 simulator, which included practice in receiving, reviewing, and responding to the data link trajectory clearances. This training included the use of the FMS data link menu for downlinked clearances, which enabled the pilots to respond to a message and append additional information for purposes of negotiation. For example, if the pilots elected to reject a clearance they could add a message element explaining why they were rejecting the instruction (e.g., weather, aircraft performance) and what changes, in the form of "freetext" to the instruction would make it acceptable. Freetext is the term used for a message element that includes only alphanumeric data keyed by the crew. In this experiment, "negotiations" are considered to be any response from the crew that does not accept the clearance and terminate the air-ground communication. This definition results in two levels of negotiation: a simple reject has no additional information appended to the message and represents a trivial negotiation; other responses include a reason and modifications to the uplinked instructions along with a reject message. The Results Section will consider both of these forms of negotiations.

The pilots were asked to alternate roles as pilot flying and pilot monitoring, and each handled the datalink communications tasks as specified by the different procedures discussed in the Appendix. In the second study, the negotiation procedures simulation, the crews were given the option of printing each message and reviewing it on paper, an option that all but one crew exercised. Crews in the first simulation were not given the option to print. Printing is commonly done by several airlines to avoid the possibility of missing clearance data that are on a second page of the FMS interface, an error that caused an altitude violation in oceanic airspace. Upon receipt of a CPDLC message, the crews were asked to open the message, review it, and discuss the clearance data before deciding on a response. If it was found to be unacceptable, the crew could formulate a downlink message providing feedback to the controller to begin negotiations.

Upon completion of data collection in both simulations pilots were asked to complete a questionnaire regarding CPDLC trajectory negotiations and their impact upon usability, workload, and situational awareness.

V.   Results

Three different sets of results will be presented in this section: comparisons of the acceptability of the three flight deck procedures evaluated over the two simulations in terms of qualitative responses to questionnaires and associated WILCO times; comparison of WILCO times, from the second simulation only, as a function of several factors related to the use of datalink; and general comments provided by the pilots in both studies. This last set of results will be presented along with two indicators of safety that were measured in the second simulation: the percentage of incorrect clearances detected and the frequency with which the crews reverted to voice operations. Each set of results will be presented in a separate sub-section below. Unless otherwise indicated, statistical significance is calculated using the analysis of variance method and evaluated at the 95% confidence level.

### A. Comparison of Flight Deck Procedures

Three different procedures were used in the two simulations to determine whether acceptable performance was possible using datalink and to provide data on how particular aspects of those procedures affect response time and ease of use. In the first simulation two different procedures were used: one in which the PF and PM shared review and evaluation responsibilities; and one in which the PM handled all heads-down tasks, leaving the PF to maintain situational awareness on other aspects of the aircraft's flight. It was hoped that at least one of these procedures would be satisfactory to the flight crews as measured by their responses on the post-simulation questionnaires. The results of this first simulation would then determine the broad outlines of procedures for the second simulation, and particular characteristics of datalink trajectory negotiation could then be measured in this later simulation using acceptable flight deck procedures.

The two procedural options used in the September, 2007 simulation are discussed in detail in the Appendix. Further discussion on how the pilot would execute the FMS aspects of those procedures may be found in Ref 31. The differences between these options are not large, especially given the relatively low workload that flight crews normally encounter in en route operations, and the results reflect this closeness by suggesting that either procedure would be suitable for regular operations. The procedure for the second simulation was adapted from the non-shared procedure and primarily differed in that it allowed messages to be printed out and silently reviewed by each member of the flight crew. This is a more cumbersome procedure used by some airlines to reduce the risk of a critical part of the datalink message being missed (e.g., because it is on a second page of the FMS).

The participants completed questionnaires and answered verbal questions at the conclusion of the study on the use of trajectory-based clearances, the datalink implementation used for message receipt and
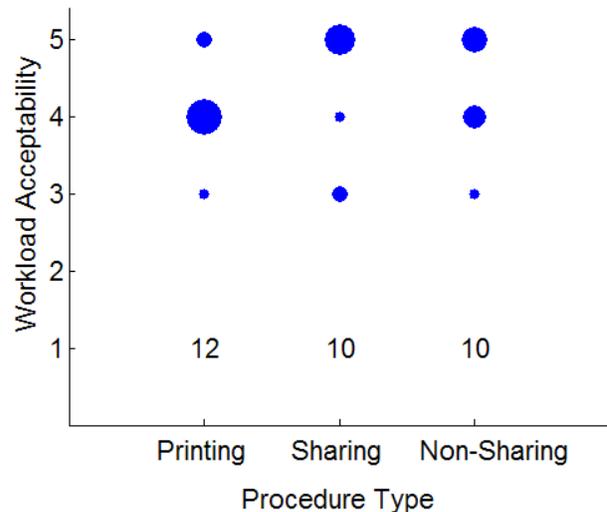
Figure 3. Acceptability of workload in responding to datalink messages. Numbers above the x-axis refer to the total number of responses received (i.e. number of pilots), and the sizes of the bubbles correspond to the number of ratings at that particular value. Medians: [4, 5, 4.5]; means: [4.1, 4.5, 4.4].
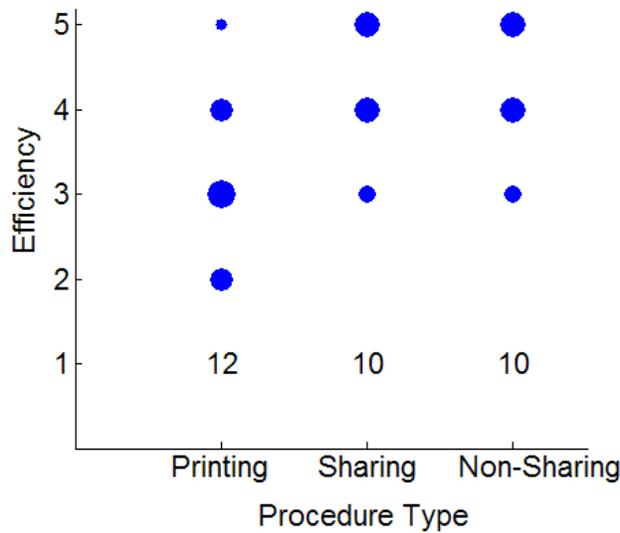
Figure 4. Efficiency of communication via datalink as a function of procedure type. Medians [3, 4, 4], means [3.17, 4.2, 4.2]
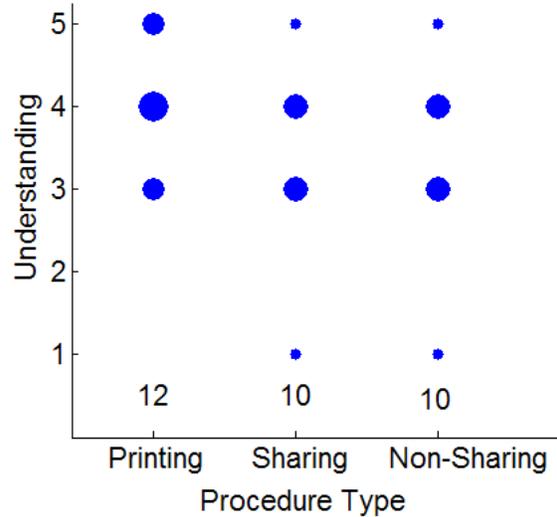
Figure 5. Ability to understand the datalink clearance as a function of procedure type. Medians: [4, 3.5, 3.5]; means: [4, 3.4, 3.4].

response, and the pilot procedures that were involved in handling the messages. The themes of the questions pertained to crew workload, understandability of the messages, and the efficiency of the interface and procedures. The questionnaires were comprised of several questions with responses in Likert scale[32] form, with responses ranging from one to five. Open-ended questions were also included to allow participant comments.

When asked about the use of data link for trajectory-based operations, the pilots indicated that the workload was acceptable and that they were comfortable with the data link procedures. The responses given by each crew member on the acceptability of the workload are shown in Figure 3, with the shared responsibility procedure receiving the best ratings, the non-shared procedure following closely behind, and the printing procedure faring the worst, but with still solidly acceptable ratings. With this and all qualitative responses it must be remembered that the shared and non-shared procedures were tested in a single simulation with the same basic datalink messages, while the printing procedure was only measured during the second simulation, during which a large number of the messages were meant to be unacceptable to the crews and so may have caused higher workload. The crews were asked, however, to rate the acceptability and efficiency of the procedures themselves, not the scenarios, so it is reasonable to conclude that poorer workload and efficiency ratings are due mainly to the printing aspect of that procedure.
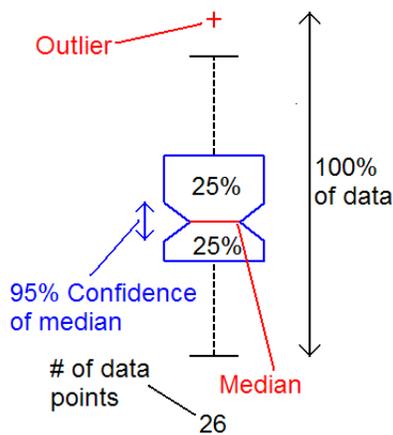

Figure 6. Key for the box and whisker plots. Red '+' symbols represent data points that lie more than twice the inter-quartile range from the nearest quartile.

Comparable results for the efficiency and understandability of datalink message exchange are shown in Figure 4 and Figure 5. The efficiency results parallel those discussed above and suggest that there is little difference between sharing responsibilities and giving all heads-down tasks to the PM, while the procedure requiring printing was judged to be slightly less efficient. The understandability of the clearances received lower ratings than did either efficiency or understanding, but in this case the printing procedure fared better than the two procedures from the first simulation. Several comments received from the participants of the first study indicated that there was confusion when dealing with a message containing both an altitude constraint and a horizontal route modification. Specifically, the pilots expressed the view that constraints associated with altitude need to be shown on the first page of the FMS ATC message so that the restriction is not missed when embedded with a horizontal route change. A single pilot gave the understandability ratings of one because of this concern with altitude restriction, however many of the pilots gave similar comments during their debriefings.
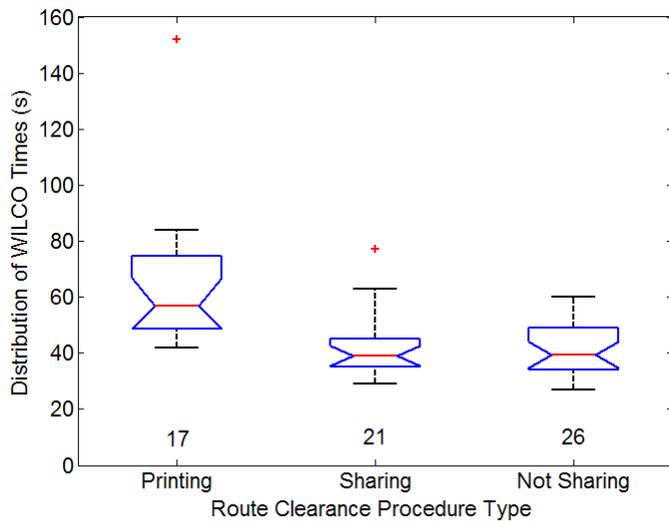
Figure 7. Response times for those horizontal, single aux waypoint messages accepted by the flight crew as a function of procedure type (see Figure 1).
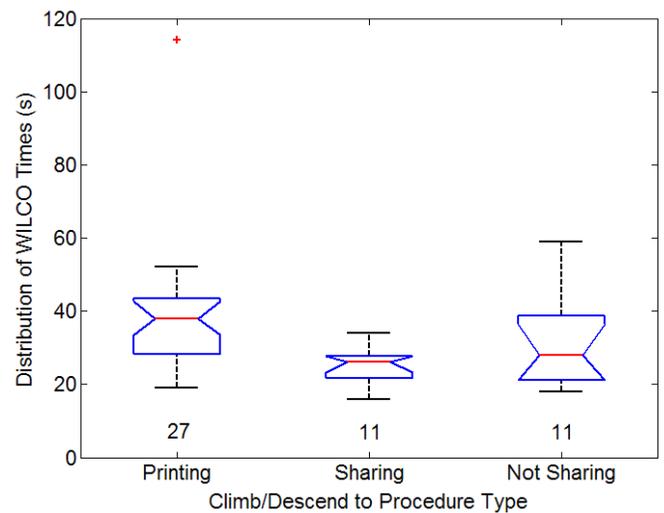
Figure 8. Response times for those vertical trajectory messages accepted by the flight crew as a function of procedure type (see Figure 2).

Responses to other questions about the acceptability of the procedures were gathered but are not all shown here because they tell the same story. For example, pilots felt that it was easy to maneuver through the FMS/CDU to manage ATC messages (mean = 4.1), and they stated that data link procedures moderately interfered with other crew duties related to normal flight operations (mean = 2.7, with the low number corresponding to less disruption). When asked about the ability to negotiate clearances using data link, the pilots indicated that it was only moderately effective (M =3.7), with ratings ranging from 1 (not at all effective) to 5 (very effective). In summary, flight crews reported positive attitudes about their ability to use this implementation of data link for communication and negotiation under TBO.

Another way to judge the merits of the different procedures is to compare the length of time required by the flight crew to respond to an uplinked message, which is referred to as the WILCO time. The WILCO times for the standard single auxiliary waypoint horizontal trajectory are shown in Figure 7. Response times for those horizontal, single aux waypoint messages accepted for each procedure type tested in the two simulations. A key for this and all other box-and-whisker plots in this paper is shown in Figure 6. The difference in medians for those response times between the shared and non-shared procedures of 0.5 seconds in statistically insignificant, however the difference between the printing procedure and the two non-printing procedures of 18 seconds is significant at the 95% confidence level. This result is expected given the additional time required for the printer to output a hard copy of the message and for both pilots to silently read and evaluate the clearance. This comparison is for all clearances using CPDLC message number 79 for which the pilots accepted the clearance without negotiation or comment, and so the clearance is consistent between the two simulations.

The equivalent plot for step altitude changes (using CPDLC messages numbered 20 or 23 for climbs and descents, respectively) is shown in Figure 8. The results in this case are similar to the horizontal case: the difference between shared and non-shared procedures is a statistically insignificant 2 seconds, but the difference between the shared and the printing procedure is significant at 12 seconds. The median response times of the non-shared and printing procedures are not significantly different at 10 seconds. The larger difference between the different types of procedures for horizontal trajectory changes versus vertical changes may be understood as the extra time required to read and mentally process a set of arbitrary waypoints. The vertical trajectory clearances simply specify a new altitude and vertical rate, which are considerably easier to digest than waypoints. The worst-case WILCO times for the printing procedure are longer in both the horizontal and vertical planes; however, these times are outliers and represent messages to which the flight crews forgot to respond. Overall, it appears that the response times for a given procedure and trajectory type are relatively consistent, and none of the procedures can yet be ruled out as candidates for TBO. These results do not yet include anything related to negotiations.

B. WILCO Response Times

The principal quantitative metric used in the TBO negotiations study, the second simulation, was the response time to a message. This time is generically referred to as the WILCO time whether or not the flight crew actually

Table 1. Numbers of messages sent during the TBO negotiations simulation (simulation two), median WILCO times and Inter-Quartile Ranges (IQR). Values are in seconds.

| Msg #	Number	WILCO Med. (s)	WILCO IQR (s)	Message Text
13	10	28	17	AT TIME EXPECT CLIMB TO ALTITUDE
15	4	41	14.5	AT TIME EXPECT DESCENT TO ALTITUDE
20	33	51	24.5	CLIMB TO AND MAINTAIN ALTITUDE
23	20	41	21.25	DESCEND TO AND MAINTAIN ALITTUDE
27	33	47	20.25	CLIMB TO REACH ALTITUDE BY POSITION
29	5	39	26.5	DESCEND TO REACH ALTITUDE BY POSITION
64	3	40	60.75	OFFSET DISTANCEOFFSET DIRECTION OF ROUTE
74	50	59	37.5	PROCEED DIRECT TO POSITION
75	2	29.5	23	WHEN ABLE PROCEED DIRECT TO POSITION
79	37	64	39	CLEARED TO POSITION VIA ROUTECLEARANCE
82	11	35	11	CLEARED TO DEVIATE UP TO DIST DIRECTION OF ROUTE
85	12	40.5	46	EXPECT ROUTECLEARANCE
87	11	38.5	12	EXPECT DIRECT TO POSITION
120	50	34	14.25	MONITOR ICAOUNITNAME FREQUENCY

accepts the message. This section presents results from the second study showing the effect of several parameters on the WILCO time and uses these effects to propose safe and efficient methods of implementing TBO. A summary of all the messages sent during the second simulation is given in Table 1. Each message listed in that table represents either an entire clearance or the beginning of a multiple message element clearance as specified in the Experimental Approach Section above, and the following results report the response times of important subsets of that data. Because of the large number of configurations tested in these simulations, only the most interesting and relevant results will be discussed.

1. Horizontal and Vertical Clearance Messages

An important distinction between different messages is whether they will change the aircraft trajectory in the horizontal or vertical plane, as currently a message is normally intended to accomplish a change in only one of these planes and the procedures to execute the two are substantially different. The distributions of WILCO times for all horizontal and vertical messages that were part of the second study's experiment matrix, regardless of the crew's response, are shown in Figure 9. A statistically significant difference between the medians of 14 seconds was measured. This difference arises because the review of a horizontal clearance takes longer than the review of a vertical one, both to understand the clearance and decide whether to execute it, because more tasks are required to physically execute a horizontal clearance, and because, in general, altitude clearances are considered more time-critical. It is important to note this distinction for the purposes of modeling and simulation of TBO, and also to select the appropriate amount of time a controller or ground automation system must wait before contacting the flight crew to follow up an unanswered clearance. Longer time horizons will allow a higher percentage of clearances to be delivered with a single communication, but they will also reduce the percentage of tactical ATC problems (e.g., conflicts with first loss of separation five minutes away) that can be solved with datalink. These results include cases in which the crews accepted and rejected the messages, and so will be more useful for modeling situations in which the crew's response is unknown. Cumulative Distribution Functions (CDF) of the response times for horizontal and vertical messages, plus
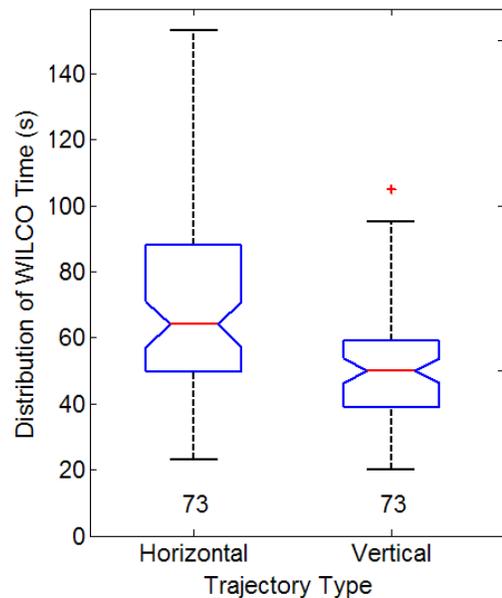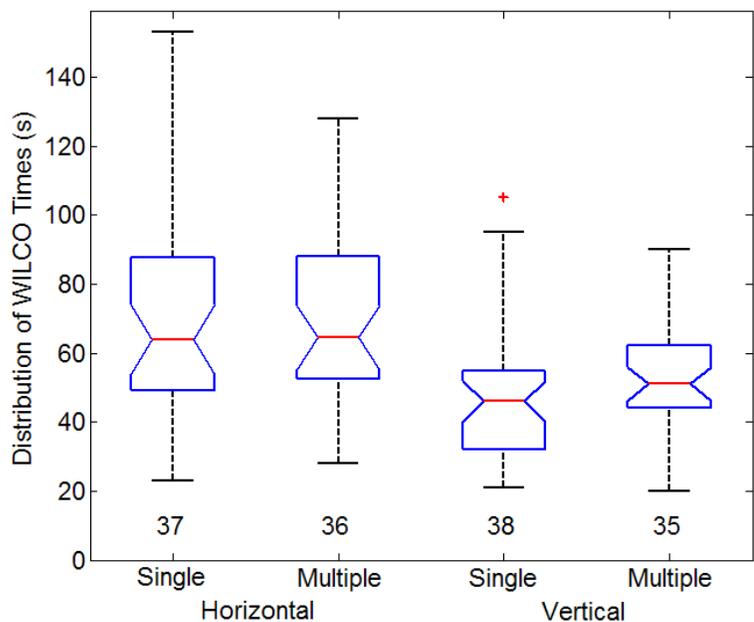

Figure 9. Distributions of WILCO times for horizontal messages (#74 and #79) and vertical messages (#20, #23, #27, #29).
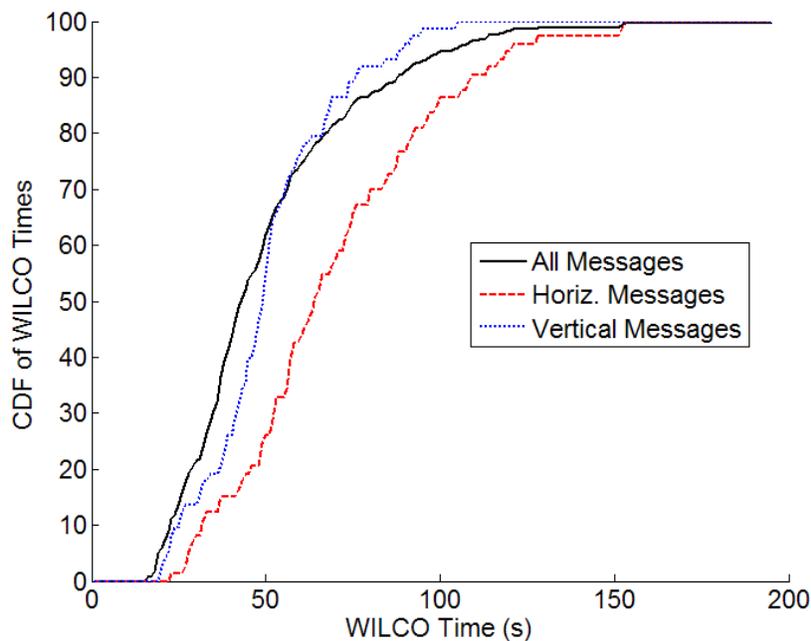
Figure 10. Cumulative Distribution Functions (CDF) of response time by type of message for study two (trajectory negotiations).

one for every message in the simulation (see Table 1) are shown in Figure 10.

2. Style of Message Composition

The large variety of message elements available in the CPDLC format allow for several different ways to construct and transmit a trajectory. The number of message elements (i.e., a single message number, like 79) that together constitute a full strategic trajectory was hypothesized to be a contributing factor to the WILCO response time and the ability to negotiate aspects of the trajectory. Trajectories composed of only one message were thought to be more quickly understood and therefore could shorten the response time, but at the possible expense of being able to negotiate a single, objectionable aspect of the trajectory. Other research studies have reported conflicting results on what effect message length has on the response time;[33,34] however, the effect of message length on the propensity to negotiate a clearance has not been measured.

The response times for the message constructions in simulation two, broken down by horizontal and vertical trajectories, are shown in Figure 11. There is no significant difference between the two constructions for the horizontal case, but the single message construction in the vertical case appears to be five seconds faster than the multiple element construction. This result is not significant at the 95% confidence level, but it does align with the expressed preference of pilots to receive vertical clearances for step altitude changes as single-element messages rather than two-element messages independently specifying altitude and altitude rate. No correlation was found between the message construction length and the frequency with which crews included freetext in their rejection of the clearance. This second result could be due to the small sample sizes that are appropriate for comparison, the difficulty of presenting exactly the same negotiation scenario to each crew or due to the negotiation procedure used here whereby appended freetext is considered negotiation. More study will be required to determine the best message construction for each trajectory type, but the unanimous opinion of the crews was that step climbs and descents should be specified with a single message element that includes a top-of-climb or bottom-of-descent point to allow flexibility in climb or descent rates due to aircraft performance limitations.

Figure 11. Distributions of WILCO response times as a function of the plane of the trajectory change and the message composition.
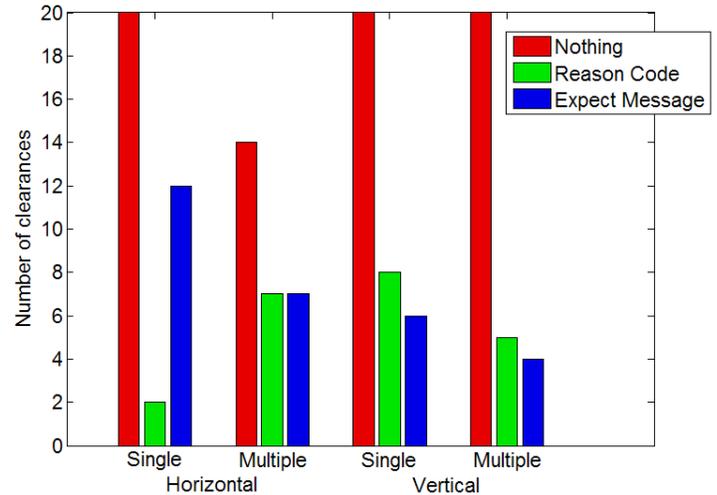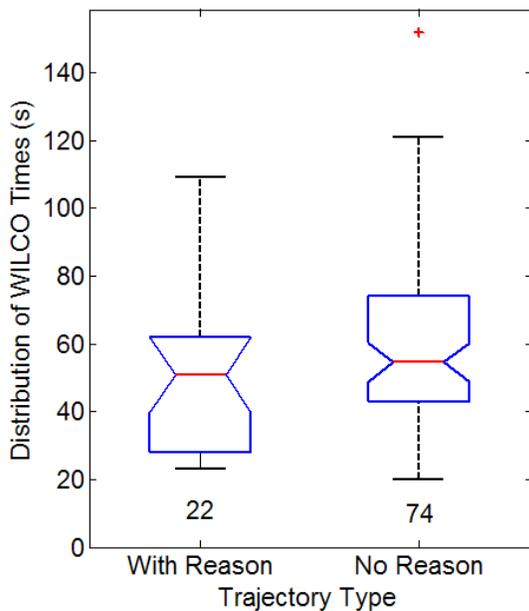
3. Reason Codes and Expect Messages

The CPDLC message set includes numerous elements that warn flight crews about upcoming clearances. In the second simulation expect messages and two elements that provide a reason for the clearance were used: "due to traffic," and "due to airspace restriction." While it is intuitive that additional information should be provided to the crews whenever possible, the effect of these additional elements on response times and clearance acceptability is not obvious. The chart in Figure 12 shows the number of messages in the second (negotiations) simulation that included one of these elements; due to a technical problem the reason codes were only appended to the horizontal, single element construction twice and so results will not be separated according to message construction. The reason codes did not appear to have a significant effect on the WILCO response

Figure 12. Number of messages with no additional elements, with reason codes, and with expect messages.

times, as shown by the distributions in Figure 13, although the median response is delayed four seconds when no reason is attached. That figure lumps horizontal and vertical trajectories together because the observed effect is the same in both cases. No effect was seen on the propensity of the crew to negotiate or not negotiate a clearance that has a reason. Crews reported that they always prefer to have a reason for the trajectory change, a desire that is regularly met in today's voice environment, but that they must consider any message coming from ATC to be important and so do not change their behavior based on that element's presence or absence. This effect has additional implications that will be discussed in the negotiations section.

The effect of expect messages on response time is similar to that of the reason codes and may be seen in Figure 14. Clearances preceded by expect messages, which were always sent approximately two minutes before the actual clearance, have a median response time that is 5.5 seconds faster than those clearances without such messages,

Figure 13. Distribution of WILCO response times as a function of whether a reason code is attached.
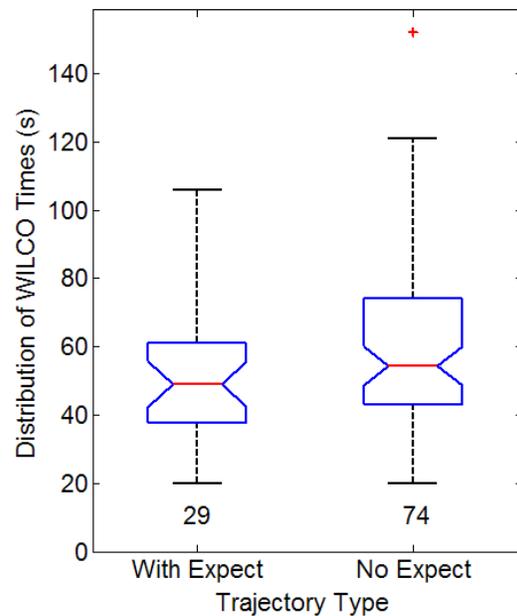

Figure 14. Distribution of WILCO response times as a function of whether or not an expect message was sent before the actual message.

however this difference is not significant at the 95% confidence level. Crews appeared to achieve faster response times with expect clearances by using the time between the expect messages and the actual clearances to decide whether the new trajectory is feasible and efficient, which eliminates part of the evaluation task when the instructions arrive, but this conclusion is drawn only from pilot comments during the debriefings. The roughly six second difference between these conditions may suggest an approach to estimating how much of the total response time is devoted to mentally processing the new clearance: the only mental processing that should occur for clearances that were announced with expect messages would be that required to confirm the two messages are the same. Pilots were generally in agreement that, given the choice of one or the other, they prefer to have reason codes rather than expect messages, but that, if airspace conditions allow, they would like to see expect messages as well.

4. Rejecting Messages and Negotiations

Four potential causes of negotiation were introduced in the second study to measure the time required by pilots to recognize a need to reject a message, decide whether to suggest a way to remedy the deficiencies of the clearance, and then code those suggested modifications in freetext. Two of the negotiation causes, the presence of weather and large, inefficient heading changes, apply to the horizontal trajectory clearances, and the other two causes, flight level changes above the current aircraft ceiling and unacceptable climb or descent rates, apply to the vertical clearances. The original intention of using several different causes was simply to measure the effect on response time of relatively common ATC-generated trajectory changes, but additional considerations for designing flight deck-compatible procedures arose from this research goal as discussed below.

A chart of the proportion of messages that crews accepted or rejected, broken down by negotiation cause, illustrates some of these considerations (see Figure 15). The four causes discussed above were suggested by crews in the first simulation as common reasons a crew would want to reject an ATC clearance; the fifth cause in Figure 15 is a measure of safety that will be discussed below. The negotiation cause that stands out is large heading changes; only 26% of the horizontal trajectory changes were rejected by the crews even though they required an initial turn-out angle from the original flight plan between 50 and 90 degrees. Angles this large would typically increase fuel use significantly and could even preclude the plane reaching its original destination if the additional path length were long enough (this occurred for but was not noticed by a crew flying to Frankfurt, Germany). The crews later reported that they were concerned about the large heading changes, but that they assumed such a large heading change was caused by an imminent problem whether or not a reason code was attached to the message. This tolerance will probably not extend, as in the simulation, to ground-based automation systems that regularly suggest such trajectories for conflict resolution.
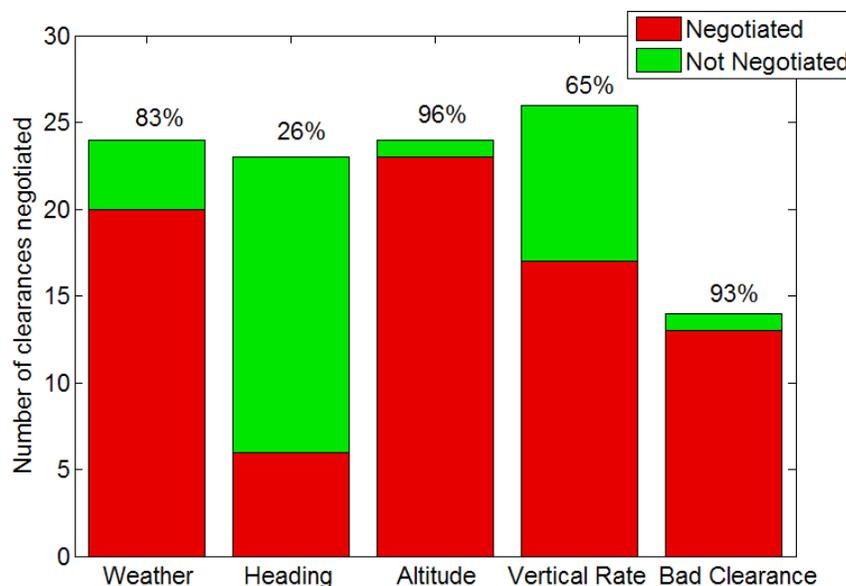
Figure 15.   Number and percentage of trajectory-based clearances negotiated as a function of negotiation cause.
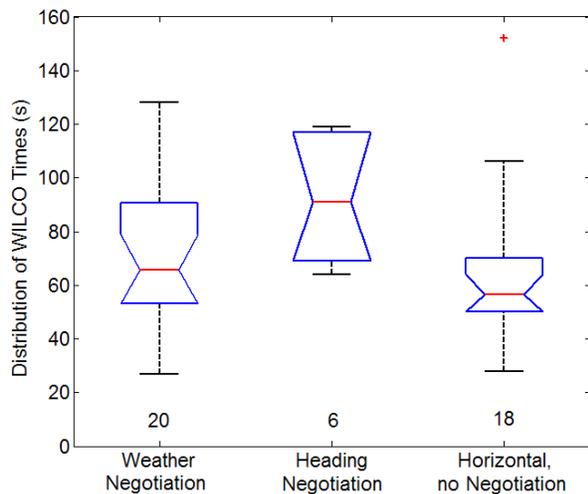
Figure 16. Distribution of WILCO times as a function of horizontal negotiation cause and whether negotiations were initiated. Median response times from left to right are 66, 91 and 57 seconds
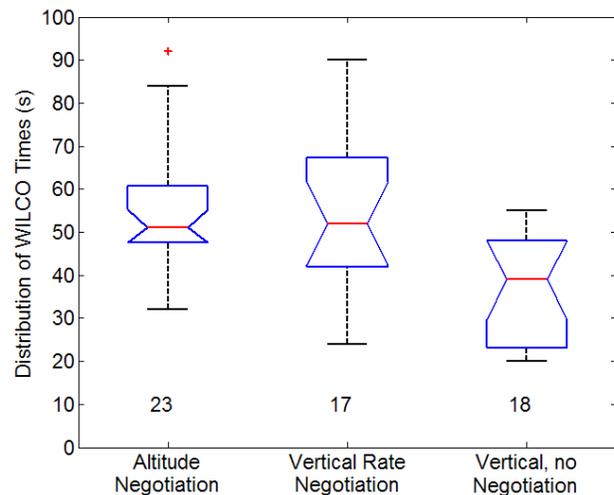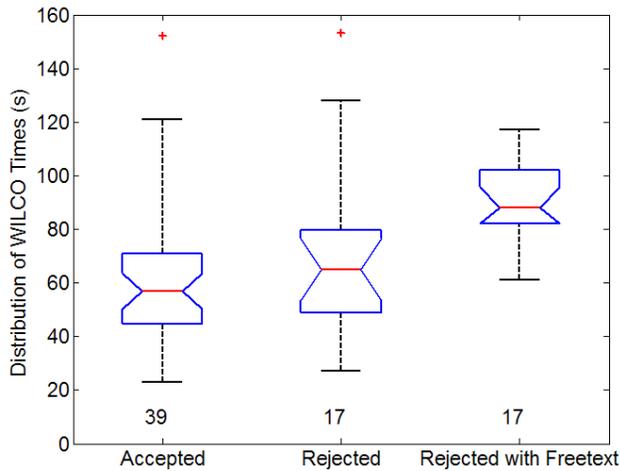

Figure 17. Distribution of WILCO times as a function of vertical negotiation cause and whether negotiations were initiated. Median response times from left to right are 51, 52 and 39 seconds.

The other unexpected result of these negotiations was the low percentage (65%) of vertical rate clearances that were rejected, almost all of which were climb and not descend messages. Near a 747's optimum altitude for its current weight it has a maximum climb rate under 1000 ft/min, so any clearance requiring a climb rate larger than this is likely to be rejected. However, no descent rate up to 3000 ft/min was ever rejected by any of the crews. They again assumed that such a drastic descent rate must be for an excellent reason and should be accepted, even if it would upset passengers in the back of the plane. The important consideration for ground based automation systems is that near term conflicts that have to be solved by changing one aircraft's altitude should consider a "duck under" rather than a "hop over" trajectory to maximize the probability it will be within the aircraft's performance envelope.

It is important to characterize the length of time it takes a flight crew to reject a clearance because these outlier cases will determine, through the preset WILCO buffer time, whether negotiations can be handled over datalink or whether they must be done by voice. Figure 16 and Figure 17 show the increase in WILCO response times as a function of horizontal and vertical negotiation causes, respectively. At the 95% confidence level the median response times of the negotiated clearances are not longer than the medians of the same types of messages that were not negotiated. Of the 102 clearances shown in those two figures, only two were responded to in more the two minutes, a required response time being considered for operational implementation. These results suggest that flight crews are generally able to make complicated decisions about their aircraft's flight plan and reject or amend the uplinked trajectory in a reasonable amount of time. The logical question that follows is whether those negotiations consisted of simple rejections or more useful freetext messages suggesting reasonable alternatives.

The distributions of WILCO times in Figure 18 and Figure 19 show the additional time required to consider and reject an unacceptable clearance (middle box plot) and the additional time taken to compose a freetext message to correct the clearance (right box plot) as compared with accepted clearances (left box plot). The messages with freetext do take longer than those simply accepted or rejected (with a WILCO or UNABLE message), but the differences in the medians are only 30 seconds for horizontal messages and 20 seconds for vertical messages. While that is quite significant in terms of the percentage increase in response time it is not excessively long when compared with a benchmark two minute required response time that was used in the Miami trials. The mean freetext message length for responses to horizontal messages was 19.4 characters, while the same measure for vertical clearances was 14.3 characters. The correlation between the length of the freetext message and the response time was not strong at 0.61 and 0.59 for horizontal and vertical clearances, respectively. This latter statistic suggests that the time required to physically enter the freetext message into the FMS does not account for all the additional response time; it is likely that deciding how to fix the unacceptable message accounts for much of the rest of the additional time.

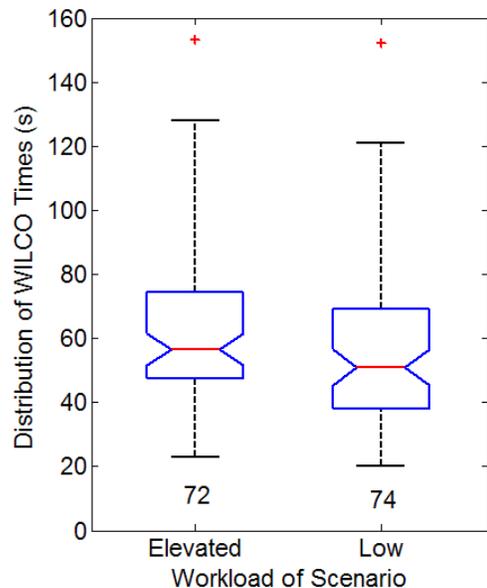**Figure 18. Distribution of WILCO times as a function of the flight crew response to horizontal clearances.**
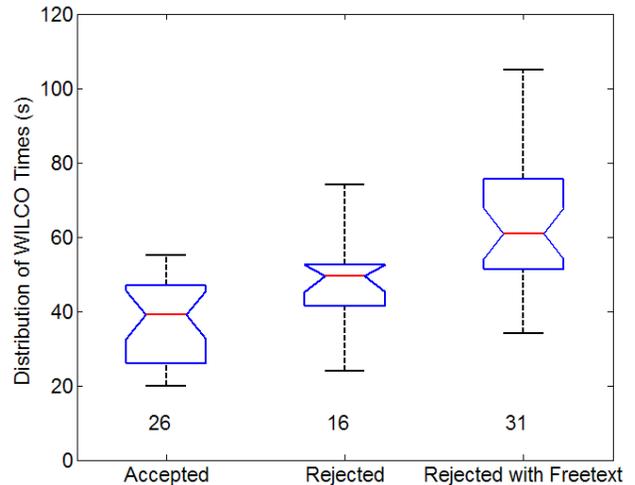
Figure 19. Distribution of WILCO times as a function of the flight crew's response to vertical clearances.

5. Level of Workload in Scenario

Half of the scenarios in the second simulation, two scenarios for each crew, included a hydraulic pump overheat event that required the crews to run through a minutes-long checklist and monitor the condition of the pump for a period of approximately five minutes. These malfunctions were introduced in order to distract the crews and increase their workload; however few messages were actually sent while a crew was going through the checklist. The research question is whether stress-inducing events like these, which may model operational conditions better than the more sterile simulation scenarios, will cause a significant increase in workload and impact the flight crews' communication performance. Figure 20 shows the distributions of WILCO times for the two workload conditions. The median of the elevated workload condition is six seconds longer than the median of the low workload condition, which is not enough to be statistically significant. Increasing levels of workload must eventually slow down response time, but the relatively low workloads experienced in this simulation do not shed light on when that transition will begin to occur.

C. Other Results

A common concern with transmitting ATC clearances over datalink rather than voice is the possibility that content or transmission errors will be more difficult to detect using the FMS datalink interface. This concern was tested by sending two or three technically incorrect clearances to each flight crew over the four scenarios. One incorrect clearance was in a horizontal trajectory and either failed to connect the amended flight plan back to the original flight plan or cleared the pilots to offset in a direction opposite to the requested direction. The incorrect vertical clearance asked pilots to climb to an altitude that was below the current altitude or descend to an altitude above the current altitude. In all but one case the flight crew noticed the incorrect clearance and rejected it or requested clarification, as shown by the rightmost bar in Figure 15. In this case the crew requested via datalink a deviation left of current course by 25 nmi for weather, a downlinked message that is not included in any of the above results, but the response from the controller was for a deviation *right* of current course. When the approval came back for a deviation the crew failed to notice that the direction had been reversed and flew the original trajectory they had requested. Consideration should be taken about how a

Figure 20. Distribution of WILCO times as a function of level of workload in scenario.

controller would respond to a downlinked clearance and explicitly indicate that the clearance had been modified; however, this condition was not part of the experiment so no definitive conclusions can be drawn from the experience.

The number of times the flight crews reverted from datalink to voice communications was recorded as an approximate measure of how commonly datalink is too slow or cumbersome to accommodate negotiations. In seven cases out of 148 the crews decided to finish the datalink exchange using voice rather than datalink; in all cases the reason was an imminent problem like weather or a heading change due to traffic that the crew felt needed to be dealt with immediately. Fewer than 5% of all messages in the experiment matrix (7 of 148), and 6.5% of messages that were intended for negotiation (7 of 108), required reversion to voice. These reversion frequencies are quite low given that almost all of the ATC messages were meant to be unsatisfactory to the flight crew. In operational use the proportion of messages that would be rejected, and consequently the frequency of voice reversion, should be much lower.

VI. Conclusions

This paper has discussed two simulation evaluations of flight deck procedures for their suitability in supporting TBO and datalink trajectory negotiations. All three procedures evaluated were qualitatively rated to be generally suitable for operational use, with the major complaint being the difficulty of understanding the entire uplinked message without checking several pages in the Flight Management System. The procedure that involved printing and silently reading the message was judged to be slightly inferior to the two non-printing messages, but this result could have been due to the increased workload crews faced when evaluating and responding to unacceptable clearances. The median response time for the printing procedure was twelve to eighteen seconds longer than the equivalent non-printing procedures.

The effects of workload, message construction type, additional situational awareness messages and negotiations were also measured as a function of horizontal or vertical trajectory changes. The results indicate that elevated workload did not have a significant impact on response times, most likely because crews are not actively working near their limit during enroute operations. The different message construction types did not change the response times significantly, but in the vertical trajectory change case crews did express a strong dislike for being issued a minimum climb rate. Crews did not have a problem with prescribed descent rates. Wide agreement was observed among the pilots about the desirability of being told the reason for a trajectory change even though the lack of such a reason did not change the frequency with which pilots accepted an uplinked message or the response time. Because including a reason code does not increase the controller's workload it is recommended that one accompany every clearance. When the crews did decide to negotiate a clearance the median response time was delayed by at least ten, and sometimes as long as 35 seconds. However, virtually all responses were received within the nominal two minute WILCO buffer time. Pilots were also consistent in being able to spot incorrect clearances, which helps to suggest that datalink communications consistently allow for error detection within critical clearance data.

In summary, trajectory negotiations using Controller-Pilot Datalink Communications appear to be feasible using a variety of procedures, and even cumbersome and basic negotiations with freetext and the current flight deck interfaces may be acceptable for near-term operations. The research questions that remain about the implementation of TBO are how best to objectively measure whether procedures and equipment are suitable, the expected benefits to users in a mixed-equipage environment, and, perhaps most crucially, how to design operations under failure and uncertainty modes.

Appendix

The following sections describe the procedures used in the two simulations. The first two procedures, labeled "Shared-Responsibility" and "Non-Sharing," were used in the September 2007 simulation. The last procedure, labeled "Printing," was used by five of six crews in the second simulation. The sixth crew in the second simulation used the shared responsibility procedure. At the start of the scenarios in both simulations the flight crews were flying in LNAV/VNAV with the MCP dialed to the cruise altitude. PM = Pilot Monitoring. PF = Pilot Flying.

Shared-Responsibility Procedure

This is the shared-responsibility flight deck procedure used when the controller issues a trajectory consisting of auxiliary waypoints with or without altitude constraints; any such constraints must be below the FMC cruise altitude. The aircraft may be climbing or level.
1. ATC message chime is heard.

2. PM or PF checks Engine Indicator and Crew Alerting System (EICAS) to confirm an ATC message was received and announces that fact.
3. PM navigates to the ATC page on the CDU and selects the first unread message.
4. PF navigates to the LEGS page.
5. PM reads the clearance aloud.
6. PM selects the LOAD prompt once to bring the trajectory up on the Navigation Display (ND). (PM should not ACCEPT the clearance until confirmation of its validity is established – see step 12.)
7. PF scans for discontinuities in the new flight plan in LEGS page, announcing their presence if they do occur. In this case immediately reject the message. Contact the controller over voice and get further instructions. The controller has two options:
   a. Tell the crew to wait for another datalink clearance.
   b. Issue (tactical) instructions as they would under today's operations.
8. PF scans the trajectory on the LEGS page to determine whether any altitude constraints are associated with the new waypoints. PF reads the constraint aloud if one is present.
9. PF scans the entire amended trajectory on the ND to ensure it is valid and feasible.
10. PM adjusts the ND range so that the distance to the WILCO buffer point is clearly visible (20 or 40 nm range) and monitors that point making sure the aircraft does not pass it before the trajectory is executed. The controller or automation system will contact the crew if they are nearing the WILCO buffer point and have not responded to the clearance.
11. When each crew member is satisfied with the new trajectory, they announce that the trajectory is good. If they find the new trajectory unsatisfactory they may reject it and should provide a reason.
12. PM selects the ACCEPT prompt, announcing "accepting the message."
13. PF selects the EXECUTE prompt, announcing "executing the trajectory."
14. PM selects the WILCO prompt (may also be labeled "Response Send").
15. PF/PM may optionally dial the new heading into the Mode Control Panel, but should remain on LNAV.

Non-Sharing Procedure

The following modifications to the Shared Responsibility Procedure were also evaluated in the first simulation, and allow the PM to do all the heads-down work required to execute the procedure. The PF is only required to fly the plane, examine the new trajectory on the Nav. Display and press the execute button once the new clearance is found to be acceptable.
4. PM navigates to the LEGS page only after loading the clearance in Step 6 above.
7. PM scans for discontinuities on the LEGS page and announces any that are present. PM then contacts the controller over voice as described in the sharing procedure.
8. PM scans trajectory on LEGS page and announces any (speed or altitude) constraints associated with the new waypoints.

Printing Procedure

The procedure used in the second simulation was based on the non-sharing procedure discussed above, but slightly modified to be more consistent with procedures currently used by several major air carriers. The PM continues to execute all the heads-down steps, but is required to print out the datalink message just after step 3, read it silently before passing it to the PF for their review, and then discuss the message before deciding to execute it. Step 5, reading the message aloud, is not done, but the PM must still LOAD the clearance onto the ND and examine the LEGS page for discontinuities or waypoint restrictions. Negotiations were allowed to proceed by appending freetext to the REJECT messages.

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