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Initial Evaluation of NextGen Air/Ground Operations with Ground-Based Automated Separation Assurance

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***Abstract*—NextGen air/ground operations with ground-based automated separation assurance have been initially evaluated with controllers and pilots in the loop at the NASA Ames Research Center. Nominal and off-nominal situations were investigated in a highly automated environment, under 2x and 3x traffic densities. The paper starts with a review of previous simulations on nominal operations, followed by a description of the underlying concept and the roles and responsibilities of controllers, pilots, and automation. The core of this paper discusses a simulation of air/ground operations, in which controllers and pilots were confronted with a challenging situation: Ground-based separation automation was managing the trajectories for all aircraft at 2x and 3x traffic densities without controller involvement. Routine and off-nominal events were carefully scripted that caused short-term conflicts, simulated emergency situations or required trajectory negotiations. It was found that the concept shows great promise to enabling the en route capacity increases targeted for NextGen. The medium-term conflict detection and resolution automation coupled with data link was able to solve over 98% of all conflicts during nominal operations, with a significantly higher success rate at 2x (>99 %) than at 3x. More than 95% of uplinked trajectories were acceptable to the flight crews. While controller workload was low in general and they were able to resolve over 75% of scripted off-nominal short-term conflicts, many issues were identified that need to be further addressed in the area of short-term conflict detection and resolution.**

Keywords: Separation Assurance; automation; air/ground operations; human-in-the-loop simulations; functional allocation

I. INTRODUCTION

Air traffic demand is anticipated to grow substantially in the coming decades. The Federal Aviation Administration (FAA) projects in its aerospace forecast for 2008-2025 that 78.0 million aircraft will be handled by FAA en route traffic control centers in 2025, as compared to 46.8 million aircraft handled in 2007 [1]. This increase can only be achieved if the capacity for managing much higher traffic densities than today can be provided. The main factor limiting en route capacity is controller workload associated with providing safe separation between aircraft. In today's very safe system, air traffic controllers take active control over each aircraft in their airspace and issue clearances to keep it separate from other traffic, expedite traffic flows, and provide additional services, workload permitting. Being actively involved with each flight provides the awareness required to detect and resolve potential losses of separation independent of automated aids. This manual process, however, can only be performed for a limited number of aircraft. In recognition of this fact, each airspace sector today has a defined maximum number of aircraft that are allowed to enter. This constraint exists as a way of ensuring that the demands on the cognitive resources of the air traffic controller(s) controlling this sector are not exceeded. Assuming that this level represents the sustained traffic load a controller can comfortably manage today, a fundamental change in operations has to occur to meet the projected traffic levels. The problem can be illustrated by simulating three times traffic on a current day controller display, as shown in Figure 1.

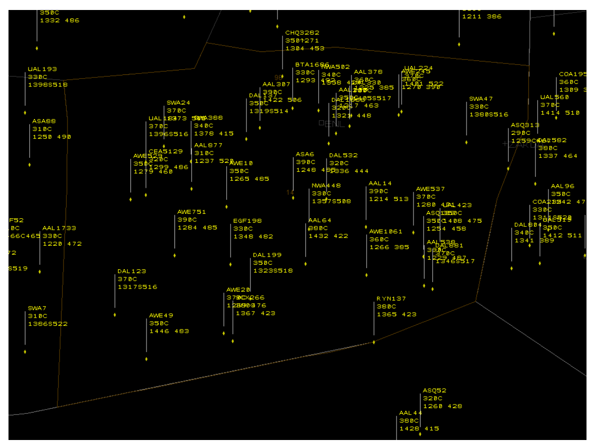

Figure 1. Current day controller display with 3x traffic.

For the Next Generation Air Transportation System (NextGen), it is envisioned that trajectory-based operations (TBO) will replace clearance-based operations in many parts of the airspace. New automated separation assurance functions are intended to help overcome the aforementioned limitations of controllers in manually maintaining safe separation between aircraft. The two primary separation assurance concepts are ground-based automated separation assurance [2] and airborne self-separation [3]. Research is ongoing in both areas.

Between 2002 and 2004, NASA conducted human-in-the-loop assessments of mixed operations with airborne self-separation at more than two times today's traffic density [3,4].

At the same time, the ground-based automated separation assurance concepts and technologies were developed by Erzberger et al. [2]. The concept of Cooperative Air Traffic Management (CO-ATM) was then formulated to integrate the best of both worlds [5]. CO-ATM postulates that ground-based automation in concert with data link for trajectory clearances can enable the required capacity increases while giving aircraft operators the option to incorporate additional equipage, if added performance-based services are deemed advantageous to their business model. CO-ATM also includes a framework for managing conventional, less-equipped aircraft in the same airspace.

A critical hypothesis in the pursuit of such concepts is that separation assurance responsibility can be successfully delegated to the automation. This requires the algorithmic development of such automation as well as instantiating an effective human/automation cooperation framework. As the cognitive engineering research investigates the functional allocation and the roles and responsibilities of humans and automation, it feeds back user input and usage data to the automation engineering process. Display and software prototypes under development at NASA utilize this process to reflect the shift in roles and responsibilities between humans and automation. An example, designed to enable managing the high traffic density envisioned for NextGen, is depicted in Figure 2 for the same traffic situation that can be seen in Figure 1. The general idea is to let the automation monitor and/or manage nominal trajectory-based operations of equipped aircraft (low-lighted on the display), while the operator handles off-nominal operations, provides additional services and makes decisions on situations that are presented to her (high-lighted on the display).

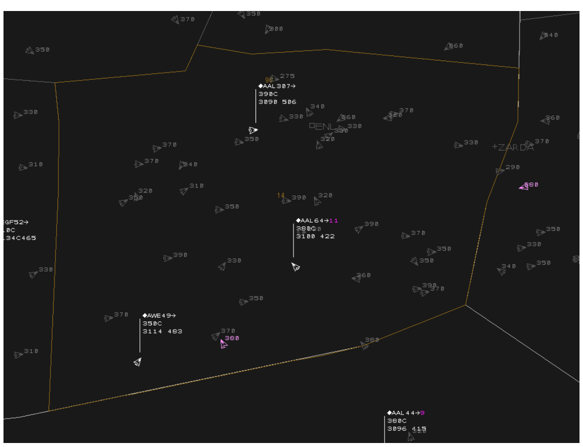

Figure 2. NASA's experimental controller display at 3x traffic

II. Prior Human-in-the-Loop Research on Ground-Based Separation Assurance

In order to safely shift the control paradigm towards higher levels of automation, the fundamental problem of human/automation integration and allocation of roles and responsibilities needs to be resolved. NASA is investigating these fundamental human/automation research questions within the context of the envisioned air traffic control operations with controllers and pilots in the loop. The human-in-the-loop research complements, utilizes and informs the concept definition, algorithm development and fast-time evaluation of separation assurance automation [6, 7].

Three part-task studies were conducted to answer three fundamental research questions, and to provide further insight into the human/automation performance and design.

1. *What is the appropriate level of automation for routine trajectory-based operations at higher traffic densities?*
2. *How acceptable are trajectories generated by the automation to controllers and pilots?*
3. *Is mixed equipage feasible in the same airspace?*

The first controller-in-the-loop study on this subject [8] was conducted in the Airspace Operations Laboratory [9] and examined three levels of conflict resolution automation in each of three traffic densities: current day density (1x), twice current day density (2x) and three times current day density (3x). Good surveillance information was simulated for all aircraft and all aircraft were data link equipped and capable of accurately flying trajectories that were generated and uplinked by the ground-based automation. In all conditions, the responsibility for conflict detection was assigned to the ground automation. In the first condition (labeled "manual") controllers resolved conflicts with a highly responsive graphical trajectory planning tool. In the second condition (labeled "semi-automated") controllers could request a conflict-free trajectory from the ground automation. In the third condition (labeled "automatic") the automation resolved all conflicts at a predefined time without controller involvement. Because the focus was on medium-term conflict detection, only conflicts that were detected three or more minutes before the predicted loss of separation were acted upon. Others were recorded as short-term conflicts by the data collection system for further analysis and not presented to the controllers.

One important finding of this study was that assigning the responsibility for conflict detection to the automation significantly reduces air traffic controller workload [8]. Therefore, reliable automated conflict detection is considered a primary enabler to handling significantly more aircraft than today. A second important conclusion was that higher traffic densities require higher levels of automation for conflict resolution. In the study, the manual conflict resolution mode was deemed appropriate for 1x and somewhat manageable at 2x. Manual operations at 3x were unmanageable and led to numerous separation violations. The semi-automated mode was considered appropriate for 2x. At 3x the semi-automated mode caused very high workload. This may be acceptable for short peak periods, but it is not sustainable. It was also found that the automated conflict resolutions were generally very acceptable to the controllers. Some operators were able to manually create more efficient trajectories at 1x. The manual mode at 2x led to less efficient trajectories than the more automated modes.

A companion study [10] was conducted at Ames' Flight Deck Display Research Laboratory [11] to investigate the acceptability of trajectories generated by the ground-based conflict resolution algorithm. Pilots considered almost all trajectories acceptable, but indicated that there was room for improvement. The study results suggest that with the appropriate flight deck equipment flight crews may be able to generate more efficient trajectories in some cases and that the ground-based solution does not always consider all flight deck constraints and pilot preferences. Some improvements identified by this study have since been integrated into the conflict resolution algorithm.

The third human-in-the-loop study, a part-task study on the feasibility of mixed operations, focused on the interplay of equipped and unequipped aircraft. Equipped aircraft were managed entirely by the automation via data link; unequipped aircraft were managed by air traffic controllers via voice communications. A detailed description of this study, including the analysis of workload, separation violations and complexity factors is available in [12]. The researchers conclude that "mixed equipage operations are feasible to a limit within the same airspace. The higher the traffic density of equipped aircraft, the lower the number of unequipped aircraft that can be managed within the same airspace. The simulation showed that the mixed equipage operations are feasible even under higher traffic density conditions such as 3X, however, there is a limit to which the controllers can manage it."

The results of the prior human-in-the-loop studies indicate great promise for the concept of ground-based automated separation assurance. Specific strengths and weaknesses of this concept under nominal operations have been identified and reported. While these results were instrumental in refining the operational concept for nominal situations, none of the prior research addressed how to cope with "off-nominal situations", such as emergencies, flight technical errors, trajectory mismatches, as well as data link requests and rejections in a highly automated environment,, in which the controller has very little situation awareness. The research presented in this paper is intended to provide early insights into this critical research area. In order to set the stage for the experimental evaluation the concept of operations, allocation of roles and responsibilities, and technical assumptions are described next.

III. Concept of Operations, Roles and Responsibilties, and Assumptions

A. *Air Traffic Environment and Flight Rules*

The year could be 2025. Data link has been integrated into air traffic facilities and many routine tasks such as transfer of control and communication are handled by the automation. Airspace is still divided into sectors, and all high altitude airspace is trajectory-based. Traffic levels range from 1x to 3x. The mix of aircraft categories is similar to today. All aircraft entering high altitude airspace are equipped with flight management systems, broadcast position and speed information via ADS-B. Aircraft meeting minimum equipage requirements can conduct their flights according to "trajectory-based flight rules" ("TFR"). TFR aircraft can always enter trajectory-based airspace, and are cleared to proceed, climb, cruise and descend via their uplinked trajectory. Flight crews of TFR aircraft receive most information via data link (including frequency changes) and do not verbally communicate with air traffic controllers unless by exception. TFR operations require data link capabilities to receive basic (FANS-like) data link messages including frequency changes, cruise altitudes, climb, cruise, descent speeds, and route modifications. They also need to meet a required navigation performance (RNP) value of 1. Aircraft without the appropriate equipage follow current day Instrument Flight Rules (IFR). They receive clearances and instructions like today, and are only permitted into trajectory-based airspace on an "as available" basis.

B. *Roles and Responsibilities*

The ground automation is responsible for maintaining safe separation between aircraft. It is responsible for detecting "strategic" medium-term conflicts (typically up to 15 minutes) between all trajectories and for monitoring the compliance status of all aircraft relative to their reference trajectory. The ground automation is also responsible for detecting "tactical" short-term conflicts (typically 0 to 3 minutes) between all aircraft. Whenever the ground automation cannot resolve a conflict without controller involvement, it must alert the controller early enough so that she can make an informed decision and keep the aircraft safely separated.

Flight crews are responsible for following their uplinked (or initially preferred) trajectory within defined tolerances, and for the safe conduct of their flight (just like today). Flight crews can downlink trajectory change requests at any time. The ground automation probes the request for conflicts without involving the controller. If the requested trajectory is conflict free, the automation uplinks an approval message, otherwise it alerts the controller that there is a trajectory request to be reviewed.

Air traffic controllers are responsible for issuing control instructions to IFR aircraft. They can use conflict detection and resolution automation to generate new trajectories for all aircraft. Controllers use data link to communicate with equipped aircraft and voice for non data link-equipped aircraft. The controller is supervising the automation and is responsible for making decisions on all situations that are presented to her by the automation, flight crews or other ATSP operators, such as controllers or traffic managers.

C. *Technology Assumptions*

The concept of automated separation assurance is enabled through a seamless integration of controller workstations, ground-based automation, data link, flight management automation and flight deck interfaces. The ground automation creates and maintains accurate trajectories for each flight. In order to reduce trajectory uncertainties, FMS values for climb, cruise/ descent speeds, and estimated weight are all communicated to the ATC system pre-flight. The goal is to make the conflict detection highly reliable and to detect trajectory-based conflicts with enough time before initial loss of separation (LOS). However, some sources of trajectory uncertainties remain and include flight technical differences, trajectory mismatches between the air and the ground, inaccurate performance estimates and inaccurate weather forecasts used by the air and the ground automation. A conformance monitoring function detects off-trajectory operations and triggers an off-trajectory conflict probe. The trajectory generation function used for conflict resolution and all trajectory planning provides FMS compatible and loadable trajectories. These trajectories account for the nominal transmission and execution delays associated with data link messaging. Automated trajectory-based conflict resolutions are generated for conflicts with more than three minutes to initial loss of separation. When conflicts are detected with less time to go, an automated conflict avoidance function can generate heading changes and send it to the flight deck via a separate high-priority data link path. On the flight deck, the message is displayed and communicated to the flight crew via speech synthesis for urgency and expediency.

IV. METHOD

A part-task study with pilots and controllers in the loop was conducted to explore the air/ground operators' response to off-nominal situations that can be expected to happen in an automated separation-assurance environment. The study was conducted during two one week sessions in July 2008 in the Airspace Operations Laboratory and the Flight Deck Display Research Laboratory. Ground-based separation automation managed the trajectories for all aircraft at 2x and 3x traffic densities. Off-nominal events were carefully scripted to cause short-term conflicts, simulate emergency situations or require trajectory negotiations. Dealing with these events involved controllers and pilots making informed decisions quickly in an otherwise completely automated environment.

A. Experimental Design

As indicated in Figure 3 the experiment examined two flight deck conditions, two ground-side conditions, and two traffic densities. All manipulations were conducted within subjects. An elaborate run matrix was used to gather data on all relevant combinations.

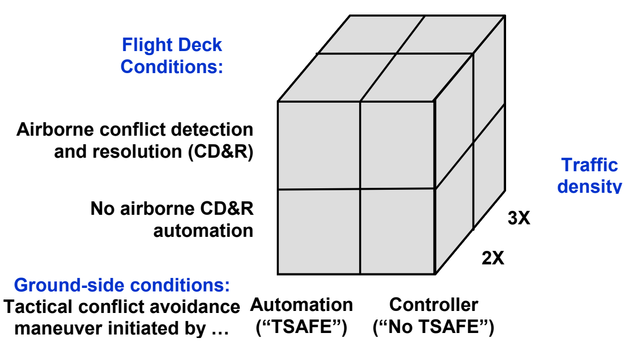

Figure 3: Experimental variables

The main ground-side manipulation was whether the initial conflict avoidance maneuver was issued by the automation or by the controller. This manipulation was used to gather data on the design and utility of automated short-term conflict resolution, because it was hypothesized that prompting operators to resolve conflicts in the last minute without traffic awareness was unacceptable. To investigate the issue, in half the runs, controllers were asked to resolve near-term conflicts without automation support. In the other half of the runs, the automation, which is part of the Tactical Safety Enhanced Flight Environment (TSAFE) [2] issued heading changes automatically when a short term conflict was predicted to result in a loss of separation in less than 90 seconds. The automation selected the aircraft to maneuver and transmitted the instruction via data link. On the flight deck, this information was relayed to the flight crew by a graphical display and speech synthesis. Once an aircraft had received this maneuver instruction, it could no longer conduct trajectory based operations until the controller generated a new trajectory and sent it to the flight crew. During this period the automation did not issue another conflict avoidance maneuver.

A primary flight deck manipulation was the availability of airborne conflict detection and resolution. In one condition flight decks were equipped with an interactive cockpit situation display, with conflict detection and resolution automation. The main research questions triggering this manipulation were centered on the acceptability of flight deck initiated downlink requests and uplinked conflict resolutions. It was hypothesized that the availability of flight deck automation would have an impact. The airborne conflict detection logic, however, was based on simulated ADS-B data with a range limit of 120 nm. It used trajectory intent broadcast from other aircraft. Therefore, the airborne automation used different data sources than the ground automation, which accessed its own trajectory data base and had no range limitation. This created an information mismatch that was also hypothesized to impact the trajectory negotiations.

1) Nominal Scenarios and Off-Nominal Events

Nominal traffic scenarios were designed to create an appropriate number of conflicts between the trajectories. As a result of the constantly ongoing conflict resolution process, the initial trajectories were altered, and by doing so created new conflicts. These conflict dynamics are considered nominal ATC operations. In order to create off-nominal situations, scripted events were injected into the scenarios by a dedicated flight deck operator. Table 1 shows an excerpt of the events and the operator actions that triggered the off-nominal situation.

TABLE I. SAMPLE EVENTS USED TO CREATE OFF-NOMINAL SITUATIONS

Event	Script
Loss of data link comms	<Flight123> is supposed to receive a new trajectory, but reports a data link malfunction.
Early descent	<Flight123> descends before its Top Of Descent (TOD). At 17 min begins descent.
Medical emergency	<Flight123> declares emergency and requests immediate landing.
Pilot rejects trajectory uplink	<Flight123> receives resolution and rejects it.
Unexpected turn	<Aircraft > makes turn north at PXV.
Pilot rejects & mods trajectory uplink	<Flight123> recieves resolution trajectory. The pilot rejects and mods resolution.
Pilot sends trajectory request	<Flight123> sends trajectory request to resolve conflict.
verbal clarification	<Flight123> requests clarification from controller.
High climb rate	<Flight123>. comes in at 5 mins. Engages v/s MAX UP.
Loss of cabin pressure	<Aircraft. declares loss of cabin pressure.
Expected turn, but AC straight	<Flight123> passes through PXV without turning towards the next waypoint.
Late descent	<Flight123> makesa late descent. At start, engages FLCH. At ~12:25 reverts to VNAV.
Loss of voice comms	<Flight123> does not respond.
Low climb rate	<Flight123> engages v/s at 1000 ft/min.

The off-nominal situations - the scripted near-term conflicts in particular - were designed to test the operator's ability to deal with unexpected situations. As opposed to today's ATC world, operators no longer maintained awareness of each flight. The simulation took this to the extreme and confronted the controllers with difficult unexpected situations and little time to gain situation awareness and make an informed decision. Even though the scripted events are labeled "off-nominal events", it should be noted that these were selected because they have to be expected to occur within the simulated NextGen environment as they do today. The simulation exaggerated the occurrence of these events by scripting three events into almost every 10 minute time slice. In certain scenarios up to three short-term conflicts were scripted to occur simultaneously.

2) Participants

A total of six air traffic controllers and twenty airline pilots participated in the two week study, with three controllers and ten flight crew members each week. Participant flight crews operated CDTI equipped desktop simulators as well as a two-person fixed-base simulator. All other aircraft were largely automated and operated by general aviation pilots to respond to controller communications and inject the scripted events. In the first week the ATC cadre consisted of one certified professional controller and two recently retired controllers;. In the second week, two current and one retired controller operated the controller stations. Data were collected for all controllers, and are used for system and flight deck operations analyses. In order to preserve the integrity of the ATC focused analysis, the results in this paper represent exclusively data gathered from the current controllers. All three were front line managers from three different en route facilities in the US (Indianapolis Center, Houston Center, and Fort Worth Center). They had no prior exposure to this project.

3) Airspace

The airspace used for the simulations was modeled after sector 91 in the Indianapolis Air Route Traffic Control Center (ZID). The traffic through the test sector that was included in the scenarios involved a mixture of 65 % overflights and 35% transitioning aircraft.

B. Apparatus

1) Laboratory and Simulation System

Air traffic control and pseudo pilot operations were conducted in the Airspace Operations Laboratory. Operations with participant pilots were conducted in the Flight Deck Display Research Laboratory. The primary simulation platform was the Multi Aircraft Control System (MACS), a JAVA program created at NASA Ames Research Center for air traffic operations research [13]. These laboratories and simulation systems have been used frequently to investigate new operational concepts, procedures, decision support tools and automated systems. The hardware and software can be configured to accurately emulate current day ATC operator stations as well as flight decks with full flight management and data link capabilities. On the ground side, controller positions as they exist in Air Route Traffic Control Centers, TRACON and Oceanic facilities can be accurately emulated. Figure 4 shows some of the controller positions in the AOL. Details on the experimental implementation can be found in [8].

Figure 4. Controller position in AOL

2) Controller workstations

An example controller display is shown in the introduction of this paper in Figure 2. During nominal operations controllers monitored a dark screen with mostly low-lighted targets. During these normal operations the ground-side automation continuously analyzed the trajectories of all aircraft for potential conflicts, and solved these conflicts when the time to loss of separation was predicted to be eight minutes or less. There was no indication on the controller screen except for a listing of the data link messages in the data link status list that alerted the controller to the trajectory changes. When a conflict was detected with less than three minutes before the loss of separation, full data tags of both aircraft were displayed and brought to the controllers' attention. In the conditions with automated conflict avoidance, the suggested avoidance maneuver was displayed in the data tag and issued 90 seconds before separation would be lost. In the other condition, controllers had to assess the conflict situation and issue a verbal command to resolve it. Details on the advanced separation assurance algorithms used in this study can be found in [2, 14].

3) Metrics

The primary study metrics were recorded using the comprehensive MACS integrated data collection system. This data collection system logs all relevant parameters for predicted and actual trajectories, flight state information for all aircraft as well as all operator inputs. The logs can be processed with standard spreadsheet programs or with custom tools built for post-processing data gathered in MACS-based simulations. The objective data are then used to analyze the operational effectiveness of the simulated operations, including efficiency and safety aspects. Controller workload is recorded via a workload assessment keypad that appears every five minutes in the menu bar of the controller workstation and prompts participants to asses their current workload on a scale of 1 to 7. Additional logs tailored specifically towards complexity analysis were also integrated for this research. These complexity logs, in conjunction with the workload ratings, were used to start analyzing complexity parameters for NextGen environments [15]. Post-run questionnaires as well as post-simulation debriefings are used to gather additional subjective data from the participants.

V. Results

A. *Conflict Analysis*

1) *Nominal Operations*

Figure 5 summarizes how many conflicts were processed by the automation during nominal operations. An average of 32 "nominal" conflicts occurred during the 30 minute 2x scenarios, as opposed to an average of 67 during the 30 minute 3x scenarios. In other words, nominal 2x ATC operations required one conflict resolution every minute, 3x nominal ATC operations required more than two. The automation handled nominal ATC operations without involving the controller under the following circumstances: The conflict was detected with more than three minutes to LOS; both aircraft were using Trajectory-Based Flight Rules (TFR) – as opposed to Instrument Flight Rules (IFR) which would require the controller to attend to a conflict; and the data link was functional to send the resolution message.

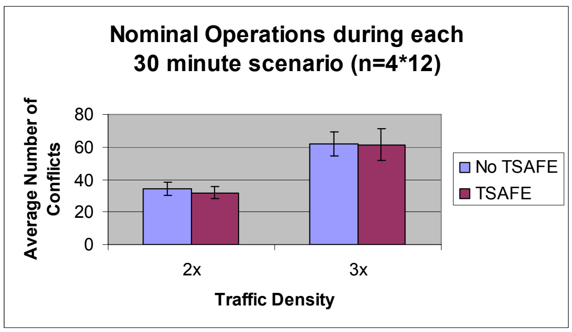

Figure 5: Average conflict counts during simulated nominal ATC operations.

Figure 6 indicates the number of operational errors that were observed during the simulation as a result of nominal operations. These numbers are in line with the system performance observed with the same CD&R software in earlier studies [6]. Figure 7 shows the respective conflict resolution rates.

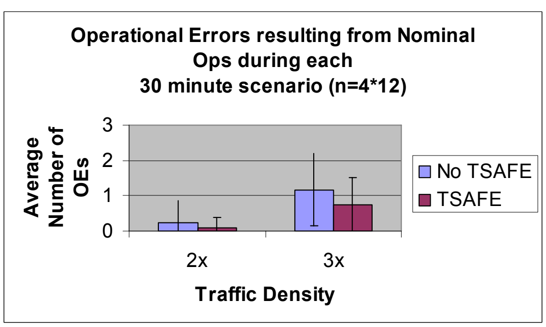

Figure 6. Operational errors resulting from nominal operations.

A Two-factor ANOVA with 12 replications for both measures reveals that there was a significant effect for traffic density for both total number of operational errors ($p=0.00046$) and resolution rate ($p=0.01318$). The total number of operational errors increases from 2x to 3x as a result of the increased number of conflicts. It is interesting that the resolution rate is reduced significantly as well. This indicates that the 3x environment is more complex, likely due to the fewer options for conflict resolution [15]. Performance of the tested research prototype ranges between 98.13 % conflicts resolved for 3x without the tactical resolver and 99.87 % conflicts resolved for 2x with the tactical resolution automation in nominal operations.

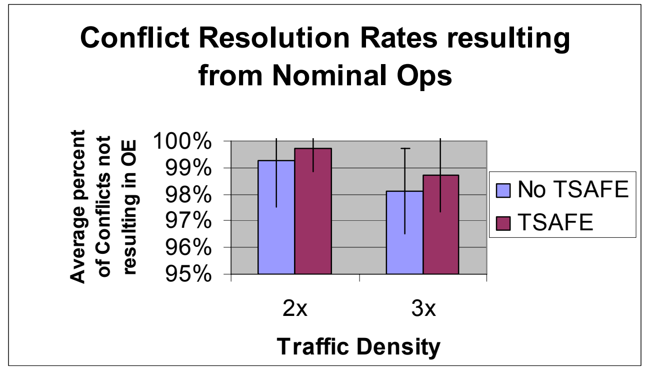

Figure 7. Conflict resolution rates.

These results also show that in nominal operations, the functioning of the tactical conflict resolver caused a generally advantageous trend, but needs further improvement as will be discussed later.

2) *Off-Nominal Operations*

Figure 8 illustrates that an equal number of near-term conflicts for all traffic densities and ground side conditions were scripted. This design was chosen to determine whether traffic density and/or tactical resolution modes would have an effect on the ability to cope with unexpected near-term conflict situations.

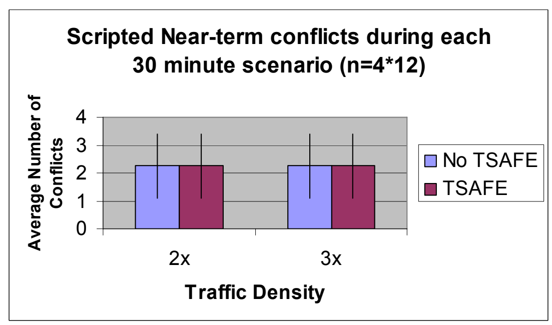

Figure 8. Events were scripted to cause an average of 2.25 near-term conflicts per scenario in all conditions.

Figure 9 shows the number of operational errors that occurred as a result of the scripted near-term conflicts

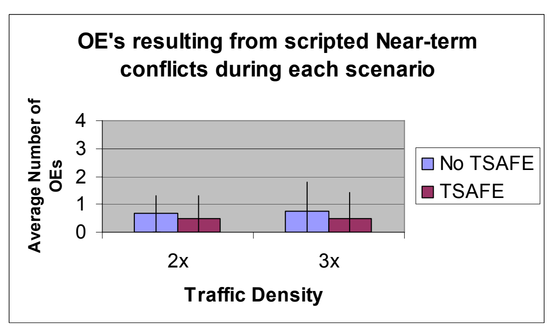

Figure 9. Operational errors resulting from scripted off-nominal events.

Unlike in normal operations, the operator/automation team response to the scripted near-term conflicts was insensitive to traffic density. The same number of operational errors occurred in both 2x and 3x traffic densities. One explanation could be that in these situations the non-conflicting traffic has little impact on the decision-making process. It is also remarkable that the operators were able to resolve 75% of the extremely difficult situations they were confronted with.

3) Operational Error Analysis

This section takes a closer look at the Operational Errors (OEs) that were observed during the simulation. Obviously, the design goal of the separation assurance research is to practically eliminate operational errors even for much higher traffic densities than today. In pursuit of this goal it is important to understand the primary cause of the observed OEs. A primary factor in OE prevention is the timeliness of the conflict detection. Figures 10 and 11 present the results for all OEs encountered during the data runs , and indicates how early before LOS conflicts were detected for both tactical resolution modes. The bars in the graph show how many of the conflicts that led to operational errors were detected within a given time interval. For example, in the condition without tactical resolution automation, 21 conflicts that led to operational errors were detected less than 1 minute before the initial loss of separation was predicted. In many of these situations, aircraft turn performance can make it impossible to avoid a loss of separation even if the turn maneuver started immediately.

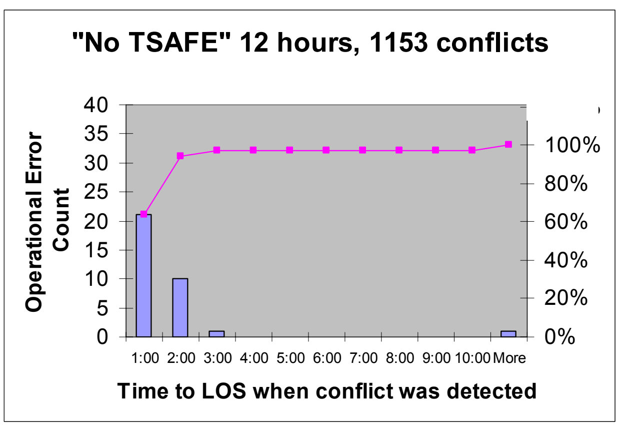

Figure 10. Histogram of Operational errors for the No TSAFE condition. OE's resulting from 1153 conflicts in 12 hours simulation time

Except for three cases, all operational errors were a result of a conflict that was detected less than three minutes before LOS. The auto-resolver was never activated for these cases, because the lower boundary for a trajectory-based resolution was set to three minutes to give flight crews sufficient time for an FMS based implementation. The tactical resolution automation in its very preliminary version was able to prevent some OEs, but should remain the focus of further development and testing. Clearly, prevention of near-term conflicts needs to be improved. With no tactical automation there is a linear relationship between Time to LOS and the number of OEs within three minutes. This indicates that the controller needs enough time to make an informed decision.

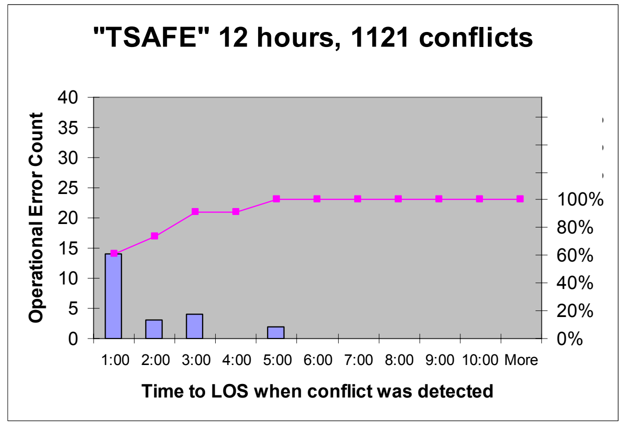

Figure 11. OE histogram for the TSAFE condition

In the automated condition the trend is not linear. Two and three minute conflicts are equally less likely to occur as one minute conflicts. The slightly higher number at three minutes or above may have been related to mode confusion. Controllers sometimes did not know whether the automation would take action and which action this would be, causing the automation and the controller sometimes to counter-act one another. The automation sometimes turned one aircraft in one direction at the same time as the controller turned the other aircraft in a conflicting direction. After having seen these cases, controllers tended to observe the automation's move first before issuing a complimentary control instruction.

The OE that was detected with more than 10 minutes to LOS in the manual maneuver condition (Figure 10) was interesting in that this aircraft was scripted to have lost data link communication and the controller did not change its flight status to IFR. Therefore, the flight was not high-lighted to the controller, but the automated resolution could also not be delivered because of the lacking data link capability. A system alert, when the data link message delivery failed would have helped in this case.

B. *Trajectory Negotiations*

As described before, one research objective was centered on the acceptability of flight deck initiated downlink requests and uplinked conflict resolutions. This section provides initial insight into this issue. (Note that due to experimental constraints, the subsequent downlink analysis is limited to a smaller sample set: CPCs in week 2 only, 32 runs total) than the other results in this paper.

1) Downlink requests

The operational concept that was tested in this study explicitly provided the ability for flight crews to make trajectory requests at any time. These requests were conflict probed by the ground system, and, if conflict free, approved. Otherwise, the request was presented to the controller for review. Flight crews managing flight decks equipped with airborne conflict detection and resolution automation were encouraged to downlink trajectory requests when they were alerted to conflicts.

Figure 12 depicts the downlink responses for the flight decks equipped with CDTI and CD&R for the 2x and 3x conditions. At 2x the automation approved 64 % of the downlink requests. At 3x this rate drops to 52 %. This generally low rate is likely due to the ADS-B range limit that cannot provide an equally long conflict free time horizon as the ground system. Another factor is the trajectory mismatch between the ground and the air. This mismatch occurs every time the ground system generates, uplinks, and assigns a new trajectory, and uses it for further conflict probing. However, the flight deck based CD&R will only process this trajectory once it is executed by the receiving aircraft.

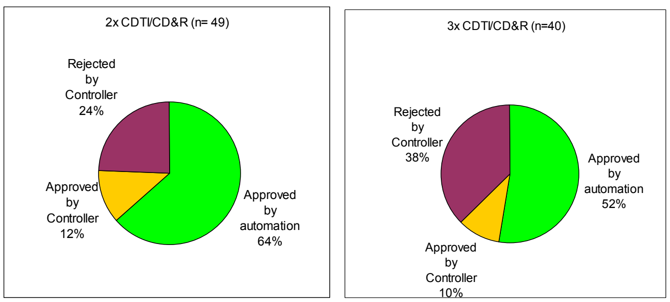

Figure 12. Downlink processing of CDTI/CD&R requests

Controllers approved an additional 10% to 12% of the downlink requests, even though they had initially been determined to be in conflict by the automation. Generally controllers rejected most requests that the automation could not approve.

The results show that user preferences may be accommodated by allowing flight crews to make their own trajectory request and vetting it through the ground automation. However, the large number of downlink requests rejected by the ground side automation suggests that the flight deck and ground side automation need to be more compatible. If this mismatch cannot be eliminated, chances are that trajectory requests, even when vetted through airborne CD&R have unacceptably low approval rates.

Various options to addressing this problem can be pursued. The flight decks used range limited ADS-B data and broadcast trajectory intent, whereas the ground side used unlimited surveillance information and an independent trajectory data base, including provisional routes, for CD&R. One possible solution is to give the flight decks access to the ground side trajectories and surveillance information. The ADS-B range limitation made it often impossible for the flight deck automation to provide the same conflict free time horizon (15 minutes) that the ground system used to check the trajectory request. Another option is to approve downlinked trajectory requests even if they are only conflict free for a shorter time horizon (e.g. ten minutes). A third option is to change the automation so that it tweaks downlink requests and sends a slightly modified conflict-free trajectory back to the flight crew instead of presenting the request to the controller.

2) *Uplink Processing*

The concept of ground-based automated separation assurance relies heavily on the acceptability of the generated trajectory resolutions by the flight crews. Additionally, it is important that rejected clearances can be handled appropriately. Therefore, some rejections were scripted and the acceptability rate of the others was analyzed as depicted in Figure 13.

The analysis shows that the majority of uplinks were accepted and the rejection ratio appears initially insensitive to the flight deck equipage. However, it should be noted that only 10 flight decks were equipped with CDTIs, and operated by participant pilots, and therefore no conclusive results can be gathered at this time. It is noteworthy that 31 of the 74 uplink rejections were scripted. If these are removed from the sample set, a rejection rate of only 2.3% (43 of 1873) was observed.

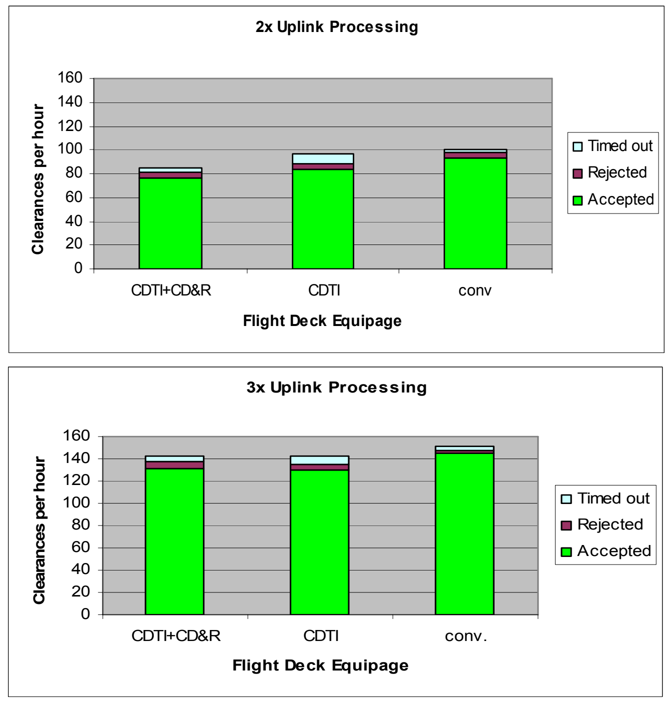

Figure 13: Uplink processing by flight deck equipage

C. *Controller Workload*

Controller workload is considered one of the primary factors limiting capacity in today's en route airspace. A primary purpose of the concept tested in this simulation was to overcome the workload constraint. Controllers had no responsibility with regard to conflict detection, but the scripted events were hypothesized to increase controller workload significantly. Figure 14 depicts the average and peak workload ratings reported by the controllers in 5 minute intervals during each run.

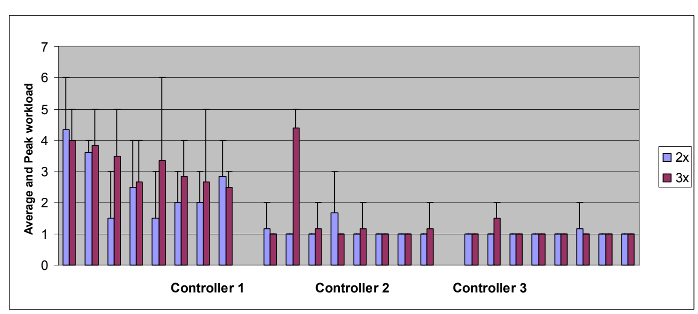

Figure 14. Controller workload per run

The rating was conducted on a scale of 1 to 7 with 1 being the lowest and 7 the highest. Ratings above 5 are typically considered unacceptable for sustained periods of time. Average and peak workload was generally low, with controller 1 reporting a higher workload than controllers 2 and 3. As Figure 15 indicates, there was no effect from the traffic density or the conflict avoidance mode on controller workload.

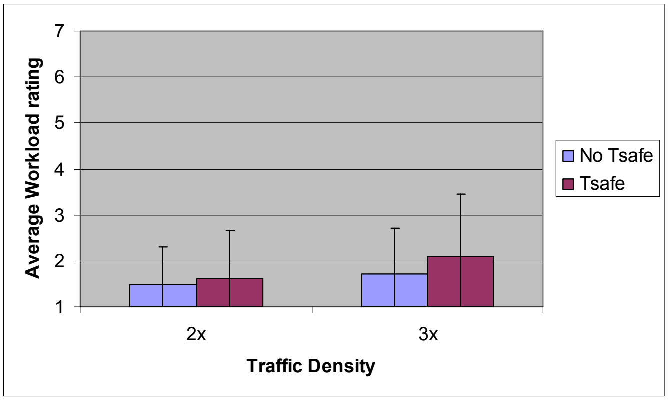

Figure 15. Average Controller workload by condition

D. Acceptability

An extensive Post-Simulation Questionnaire was used to collect participant input on many aspects of the operations. One question asked about the general concept acceptability: "How acceptable/feasible was the overall concept ? *1=completely unacceptable, 7=completely acceptable."* Figure 16 shows the controller ratings. 2x TSAFE and 3x TSAFE were rated equally acceptable, while the NoTSAFE conditions were ranked less acceptable.

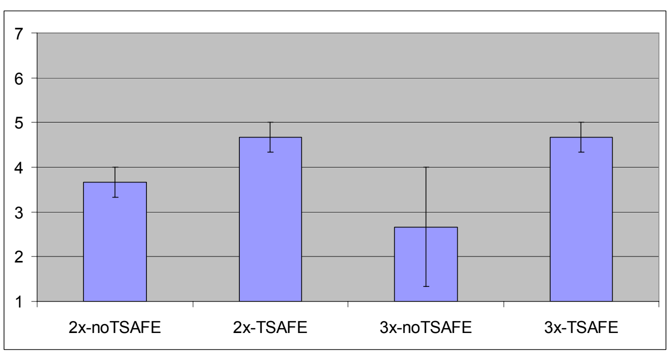

Figure 16: Acceptability ratings of the different conditions from post sim questionnaires

VI. Lessons Learned and Future Research

In this section, lessons learned and future research needs are summarized. Some of them are derived directly from the results presented above. Others are based on observations gathered during the study that could not be included in detail in the preceding analyses.

The first lesson learned from this study and prior simulations is that certain parts of the separation assurance automation are ready to be tested in an operational context. The conflict resolution research prototype used in the studies is very effective. Even though nominal operations in the NAS will not be fully automated in the near future, introducing a conflict resolution function in an interactive decision support tool mode can render benefits and is feasible at current day or somewhat increased traffic densities, as the very good performance under 2x suggests. Moving this technology from research to operational development and field testing would allow for further fine-tuning and provide an initial capability for what should become a core technology in NextGen. When implementing an algorithm that generates trajectory changes, specific attention needs to be placed on addressing the uncertainties associated with the flight crews' execution time and method for implementing those changes.

The concept of automated tactical conflict resolutions is appropriate. The idea of data linking a maneuver and communicating it to the flight crew - via voice output and a visual cue - appears generally feasible, acceptable, and accelerates the maneuver execution time. However, the automated resolutions must account for a short execution delay and should provide a conflict free maneuver, even if flight crews execute it 20 seconds after it was issued. The predictability and stability of the algorithm's maneuver selection should also be improved. These modifications to the automation are already underway, partly based on the feedback gathered from the study.

Research needs to continue focusing on short term conflict prevention. Various avenues can be pursued: The number of late conflict detections can be further reduced by improving trajectory prediction accuracy. Procedural solutions for certain cases may also be considered: positive control for climbing or descending aircraft could be implemented. Similar to today's operations, controllers or the automation could issue "paper stops" to protect the airspace above or below a certain altitude.

Another main area for future research is human/automation interaction in conflict resolution, in particular for - near-term conflicts. The mere fact that controllers were able to resolve a substantial amount of conflicts with very little notice and no initial situation awareness reflects on the human's unparalleled ability to make good decisions in bad situations. Relying on this ability, however, would be a bad design for many obvious reasons. Instead, every effort should be made to quickly present all relevant situational parameters to the operator and give them enough time and means to make a good decision. Conversely, if this cannot be assured, the automation needs to be able to resolve the situation by moving one or both aircraft on a heading or altitude that is safe for enough time to generate a new trajectory and resume trajectory-based operations. In the study, aircraft were left in IFR status after the automation issued a tactical maneuver. This required the controller to generate a new trajectory and send it to the aircraft so that the aircraft could resume trajectory-based operations. While on a heading, the conflict probing integrity for that aircraft was compromised, resulting in a higher risk for a short-term conflict. Therefore, every effort should be made by the automation to generate a trajectory solution as soon as feasible and issue it with appropriate operator involvement to the aircraft.

Finally, well aware that there are many more research issues to be addressed – it should be noted here that none of the part task studies to date have addressed the comprehensive problem of coordination and cooperation between controllers, traffic managers, airline operators, and most other stakeholders within and across facilities. If the results of the ongoing and future part task studies maintain the promise of the early findings, the concept needs to be evaluated in a larger multi-operator environment, and integrated with arrival and departure management, to start addressing some of the larger coordination issues that need to be investigated before pursuing any actual implementation.

VII. Conclusions

The HITL research so far has indicated that ground-based automated separation assurance is a generally sound concept for trajectory-based operations in high density en route airspace. Trajectory-based conflict detection and resolution automation integrated with data link should become a core NextGen technology and could possibly be operationally evaluated in the near future. Nominal operations cause generally low controller workload and open up resources for controllers and pilots to handle off-nominal situations or trajectory negotiations. Research needs to continue to focus on short term conflict prevention in order to minimize the occurrences of conflicts that are detected shortly before separation is lost. Another main area for future research is human/automation interaction in conflict resolution, with a particular focus on near-term conflicts. Even though the algorithm and controller interface need further improvement, the concept of providing automation support for tactical conflict resolutions has been shown to be appropriate.

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