AN INTEGRATED TOOL SUITE FOR EN ROUTE RADAR CONTROLLERS IN NEXTGEN

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Abstract

This paper describes recent human-in-the-loop research in the Airspace Operations Laboratory at the NASA Ames Research Center focusing on en route air traffic management with advanced trajectory planning tools and increased levels of human-automation cooperation. The decision support tools were exercised in a simulation of seven contiguous high-altitude sectors. Preliminary data suggests the controllers were able to manage higher amounts of traffic as compared to today, while maintaining acceptable levels of workload.

1 Introduction

The National Airspace System (NAS) is expected to face challenging increases in demand, as traffic levels are predicted to grow over the coming years [1]. Additionally, a major limiting factor in how much the air traffic control system can handle is the controller's workload and mental resources [2], [3]. Prior research has presented the potential benefits of data link, Automatic Dependent Surveillance-Broadcast (ADS-B), medium-term conflict probing, and trial-planning functions [4, 5, 6, 7]. This paper describes how all of these technologies have been integrated together into a prototype emulation of the Display System Replacement (DSR) platform, using the Multi-Aircraft Control System (MACS) [8]. Considering the application of a tool suite that includes automated functionalities and advanced decision support tools, the air traffic controllers are expected to experience a reduction in their workload, allowing them to handle increased levels of traffic.

The results in this paper were gathered during a real-time human-in-the-loop simulation conducted in 2009 in the Airspace Operations Laboratory (AOL) at the NASA Ames Research Center [8, 9]. Shown in Figure 1, the simulation airspace included seven high-altitude sectors (FL290 and above) from the eastern part of the Kansas City Air Route Traffic Control Center (ZKC). Each of the seven sectors was staffed with one radar controller, four of whom were current Certified Professional Controllers (CPCs), and three were recently retired controllers. Data was collected over 16 runs, eight of which were "Traffic Load" scenarios, and eight of which were "Weather" scenarios. The traffic load scenarios were designed as problems of higher traffic levels, and the weather scenarios included dynamic weather cells with "tops" of 50,000ft MSL, which would require lateral re-routes to deviate around the weather. All scenarios lasted 75 minutes, and consisted of approximately 75% en route, level flights at cruise altitudes, and 25% transitioning aircraft related to local area airports. In general, the scenarios exhibited slightly heavier flows from the West-East/East-West, as compared to the North-South/South-North flows.
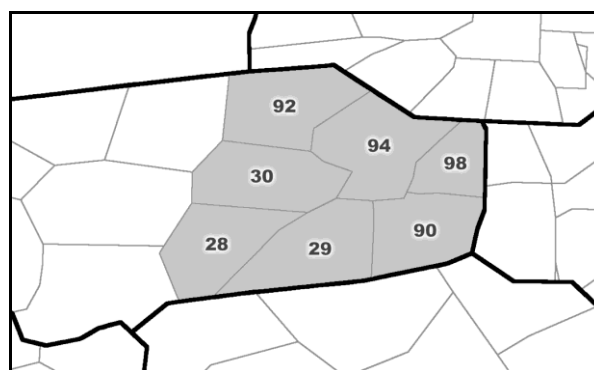

Fig. 1 Map of the airspace used in the simulation.

2 A Data Communications Environment

The operational environment used in this simulation assumed 100% aircraft equipage, meaning all aircraft had ADS-B, data communication (Data Comm) for both Transfer Of Communication (TOC) and trajectory change messages, and a Flight Management System (FMS) with integrated Data Comm communication to allow for loadable trajectory clearances.

Using Data Comm for the automated transfer of communication removed the need for controllers to verbally issue frequency change instructions to aircraft. The controllers still manually initiated and accepted handoffs, but did not have to verbally instruct each outgoing aircraft to change to the next frequency. Another assumption within the simulation was that aircraft would not do verbal check-ins, relieving the controllers from having to acknowledge the radio check-ins of each incoming aircraft. In the simulation, this was supported by the use of "monitor" TOC messages, rather than "contact" TOC messages, as shown in Figure 2. Participants from previous research in the AOL indicated this was the preferred mode of operation for full Data Comm equipage.

Fig. 2 View of Data Comm Transfer of Communication (TOC) message from the ATC (top) and flight deck (bottom) perspective.

The controller workstations also had trial-planning functions that allowed the controller to construct provisional trajectories and send them via Data Comm to the aircraft. Using primarily the trackball (keyboard commands were also available), the controller starts a trial-plan and can move, insert, and delete points along an aircraft's trajectory. Points can be dragged with the trackball to any location, allowing for both named points and latitude/longitude points. With a single command, the controller can then uplink the trial-plan to the aircraft as a packaged route that can be directly loaded into its FMS, as illustrated in Figure 3. At the same time that the trajectory Data Comm message is sent, the ground system's stored flight plan is amended. This updated flight plan is then used by the ground system for future computations.
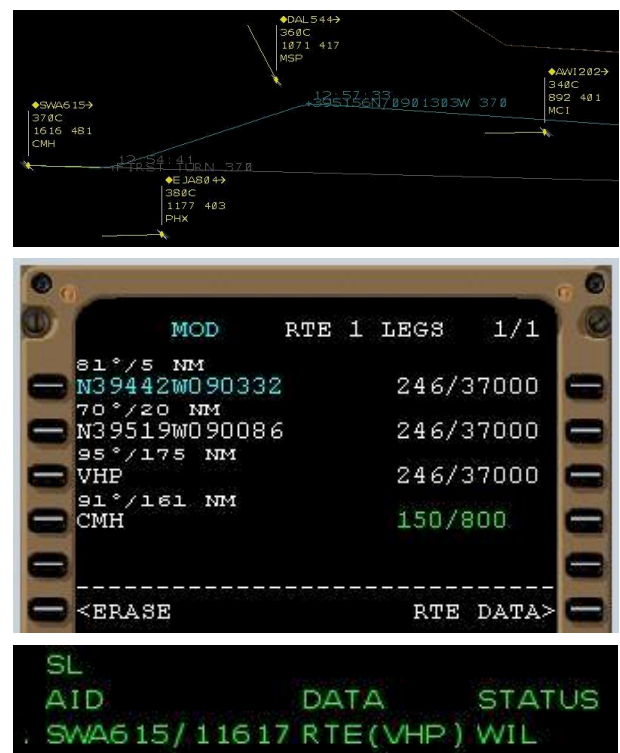

Fig. 3 A trial-plan prepared by the controller (top), then sent to the flight deck as an FMS-loadable message (middle), followed with the response message received (bottom).

The trial-planning function can also be used for altitude changes, either as a separate trial-plan or combined with a lateral modification. Data Comm-enabled trial-plans have the potential benefit of reducing a controller's workload associated with radar vectoring; turn-outs and turn-backs can be replaced with a complete "hand-drawn" trajectory designed by the controller. Flight crews accept the Data Comm clearances electronically as well, which further reduces frequency congestion by replacing the clearance read-backs.

3 Human-Automation Cooperation

Conflict detection automation was integrated directly into the DSR screen, complementing the controller's scan and minimizing disruptions to their workflow. The conflict detection probe within MACS uses a deterministic search for conflicts along the trajectories of the ground system's stored flight plans. In case aircraft are out of conformance with their trajectory, ADS-B state information from the aircraft is used to create a five-minute "dead reckoning" trajectory. Detected conflicts are presented to the controller both in the top right of the Flight Data Block (FDB) as a number (minutes until predicted loss of separation), and in a conflict list view.

The conflict detection probe also checks trial-planning trajectories. If the system detects a conflict between two aircraft, the controller can start a trial-plan and drag or move a point on the route of one of the conflict aircraft, and in real-time the conflict detection probe continuously checks the provisional trial-plan for conflicts with other aircraft. Potential conflicts are clearly indicated on the screen, and it becomes a visual search task for the controller to move the trial-plan until it appears conflict-free, as illustrated in Figure 4. This functionality was implemented in a manner that provides highly responsive feedback to the controller, making it very easy to use and still very useful in high workload and/or time-critical situations.

An on-demand automatic conflict resolution algorithm was also included, which provided efficient trajectory changes to resolve medium-term conflicts [10]. If the ground system detects a conflict between two aircraft, the controller can request a conflict resolution from the automation by clicking on the conflict indications in the flight data block or the conflict list view. Within a few milliseconds, a conflict-free resolution is presented to the controller as a trial-plan. Presenting the resolution in this way allows the controller to "tweak" the resolution if necessary, and then send it to the aircraft in the same way manual trial-plans are uplinked.

Additionally, a simple deterministic weather probe was incorporated, alerting the controllers to predicted weather penetrations. The weather probe information was presented to the controllers in the form a blue number (minutes until predicted weather penetration) in the bottom right of the FDB, as shown later in Figures 6 and 7. While trial-planning to avoid the weather, the controllers would move the trial-plan until the weather probe's number would disappear.
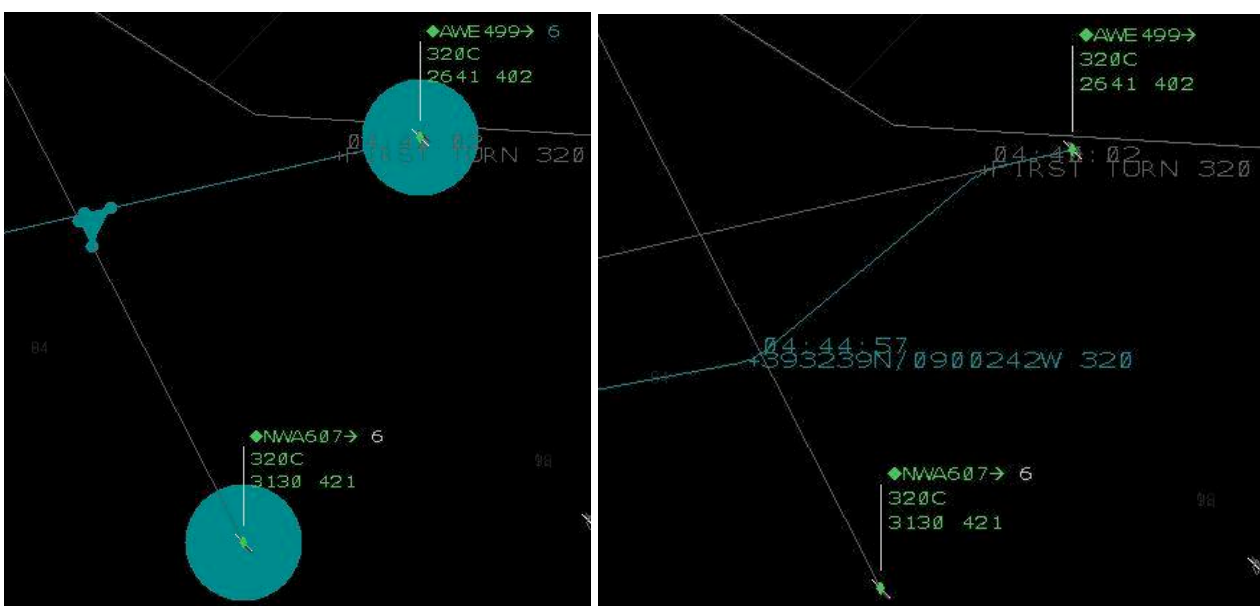

Fig. 4 The trial-planning function and conflict detection automation (left). A short visual search discovers that dragging the trial-plan to the south creates a conflict-free trajectory (right).
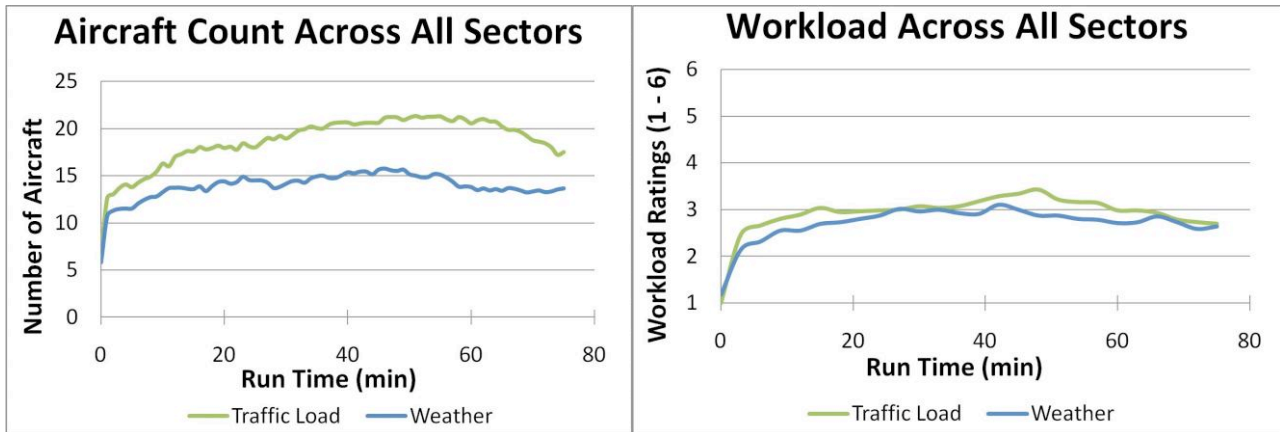
Fig. 5 Average aircraft count across all test sectors (left), and average workload-rating across all test sectors (right).

4 Traffic Scenarios and Workload

The controllers' experience of the two different traffic scenarios can be characterized in terms of aircraft count and real-time workload ratings. The aircraft count will serve to describe the general traffic density of the scenarios, and the workload ratings will give the reader an indication of how "busy" the controllers felt during the scenarios.

The average aircraft count recorded during the simulation is reported in Figure 5. The traffic load scenarios were slightly higher than the weather scenarios, being designed for traffic levels to peak near 22 aircraft at a given time inside the test sectors. The weather scenarios reached as high as 16 aircraft, but despite the lower aircraft count, had the additionally constraint of dynamic weather cells that needed to be avoided.

During each simulation run, the controllers were prompted every three minutes to report their current workload while controlling traffic. Using Workload Assessment Keypads (WAKs), they rated their workload on a 1 to 6 scale where ratings of 1 and 2 were considered to be low workload, ratings of 3 and 4 were considered to be medium workload, and ratings of 5 and 6 were considered to be high workload. The right side of Figure 5 indicates that the workload for the weather scenario was comparable to the workload of the traffic load scenario, suggesting that although the aircraft counts were different between the two scenarios, there were other characteristics that made them have a similar "feel," suggesting that

the scenarios were equally complex. These two sets of data serve to provide the reader with a general picture of the working environment experienced by the controllers, which can be seen as the input parameters into the controllers' use of the tools described in this paper.

5 Manual Trajectory Planning Usage Data

The trajectory planning tools at the sector positions were a continuation of radar controller tools that had been developed and tested in previous experiments in the AOL [8]. The primary goal behind building these tools is to provide the controller with highly-responsive trajectory manipulation tools that are integrated with Data Comm and represent fundamental building blocks for operations within the Next Generation Air Transportation System (NextGen) [11] operations. The controllers heavily used the trajectory planning tools for managing traffic and resolving conflicts, as discussed in the following sections.

5.1 Initiation Method

The radar controllers could start a trial-plan in any of a number of ways, either by clicking on certain fields within the FDB, or with certain DSR keyboard commands. Graphically from the FDB, the controller could use the altitude fly-out menu (displayed by clicking on the FDB altitude), or click on a trial-planning "portal", which would also display the direct-to route fly-out menu. Figures 6 and 7 show the trajectory planning access points within the prototyped FDB. Available DSR keyboard commands
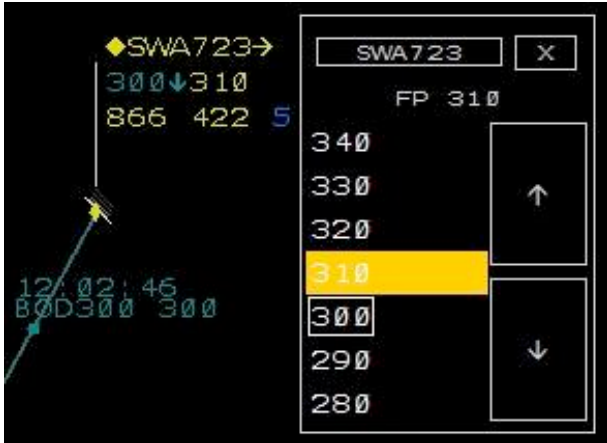
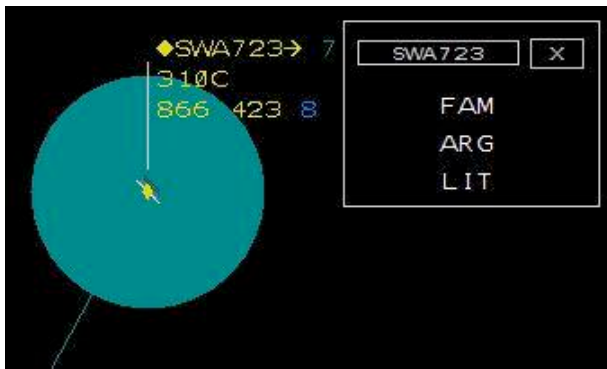Fig. 6 Altitude trial-planning from the altitude fly-out menu

Fig. 7 A trial-plan can be started from the FDB trial-planning portal (arrow symbol to the right of the callsign). Also displayed is the direct-to fly-out menu, another method for making modifications to the lateral routing.

were "TA" for altitude trial-planning, "TR" for route (lateral path) trial-planning, and "TT" for toggling on and off (i.e., starting and cancelling) trial-plans.

As mentioned before, the controllers used the manual trajectory planning tools often throughout the simulation. In total, 3,539 trial-plans were started during the simulation. However, trial-plans can also be canceled at any time, so this number is distinct from how many trial-plans were actually sent to aircraft. Data regarding trial-plan uplinks will be discussed in section 7.

Of all the trial-plans initiated, Figure 8 indicates that the controllers most frequently started altitude trial-plans (M=20.8 per run). Clicking the portal (represented in Figure 8 as "trial plan portal") and using the TR keyboard command (represented in Figure 8 as "trial plan route"), were nearly equally used (M=8.2 and

10.7 per run, respectively). It appears that the controllers were least likely to use the TT keyboard command (represented in Figure 8 as "trial plan toggle"), on average using it only 2.6 times per run.

The data shows that the controllers had a preference for trying altitude maneuvers in the traffic load scenarios. The increase in use of altitude maneuvers in the traffic load scenarios as compared to the weather scenarios suggests that, when given the option, the controllers preferred to use altitude for resolving traffic conflicts. Section 5.3 will further examine the use of altitude trial-plans in the presence of conflicts.
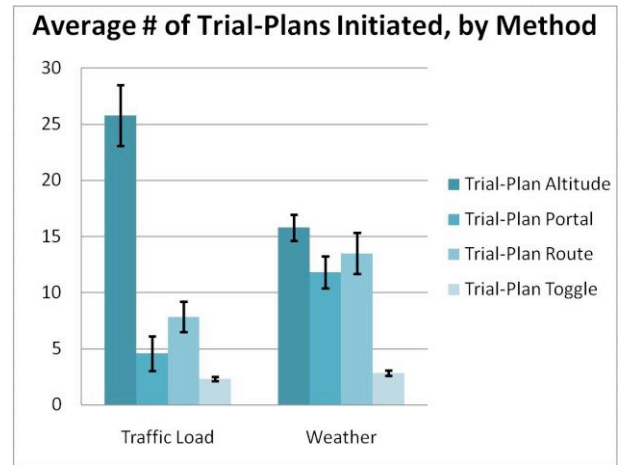

Fig. 8 Average number of trial-plans manually initiated by the controllers.

During the weather scenarios, due to the high tops of the weather cells, solutions to predicted weather penetrations were always lateral maneuvers. Consequently, when altitude trial-plans were used in the weather scenarios, it was in response to some traffic conflicts or for transitioning aircraft related to local airports.

5.2 Lateral Maneuvers

When controllers designed trial-plans that modified the lateral path of aircraft, data was analyzed to gain insight into what type of changes were made in those cases. Between inserting auxiliary waypoints and removing existing waypoints, the controllers more often inserted an auxiliary waypoint. Illustrated in Figure 9, controllers added auxiliary waypoints more than ten times more often than they removed existing waypoints.
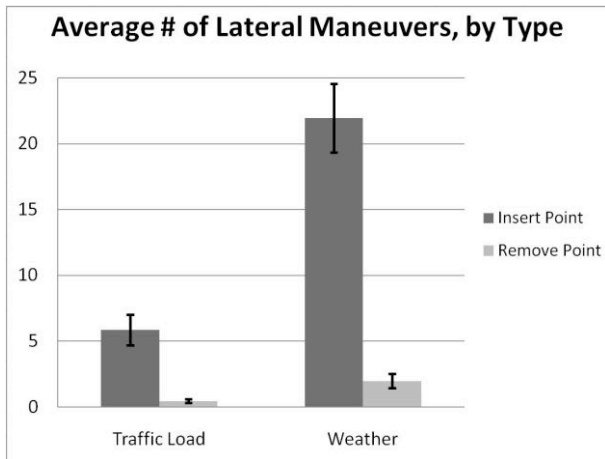
Fig. 9 Average number and type of recorded lateral manuevers associated with the manual trial-plans from the controllers.

The data (shown as average count per run), exhibits this pattern in both traffic scenarios, and is expected as such, because the controllers worked within a relatively short time horizon (e.g., 15 minutes), within which it was less likely that a shortcut or "direct-to" to a downstream fix would provide a sufficient heading change for an aircraft to avoid a loss of separation (LOS), let alone avoid a weather cell.

5.3 The Presence of Conflicts

Trajectory planning data was analyzed to investigate how the controllers used the manual trial-planning tools with special regard to conflicts. During the simulation, aircraft could potentially come into conflict with other aircraft, weather cells, or both. Figure 10 shows how often controllers used the trajectory manipulation tools in the presence of a conflict. From the data in Figure 10, we see that the majority of trial-plans were initiated when there was no conflict detected for the aircraft. This is indicative of two things: transitioning aircraft related to local area airports, and the controllers' natural tendency to organize the traffic with the application of "positive control."

For aircraft landing at local airports, it was common for the controllers to use the trial-planning functions to send a descent clearance to the aircraft, in order to start their descent early. An example of this, often seen in the simulation, was a cruise-altitude descent to

FL290, built with the trial-plan and sent to the aircraft via Data Comm.

Positive control is a more conservative strategy of keeping aircraft organized in a way that minimizes the potential of traffic conflicts. This approach, which in some way can be thought of as "staying ahead of the conflict probe," often involves changing the altitudes and/or routings of aircraft at opportune times, so as to distribute the traffic vertically as well as laterally in the sector.

These two possible explanations are supported by the data in Figure 11, which confirms that with no conflict present, more than two-thirds of the trial-plans initiated were for altitude changes. Interestingly, the weather scenarios showed a slight increase in the relative amount of route trial-plans, again likely due to the high tops of the simulated weather.
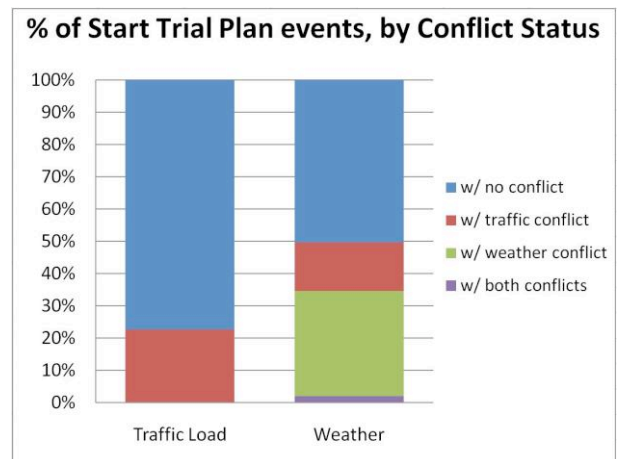

Fig. 10 Proportion of trial-plans started by the controller that were or were not in conflict at time of trial-plan initiation.
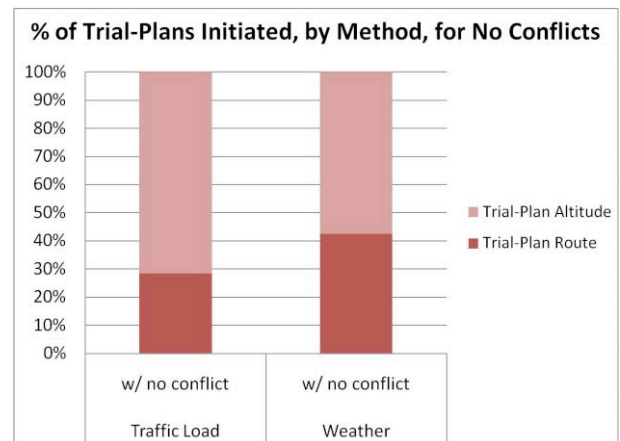

Fig. 11 Proportion of trial-plans, either altitude or route, initiated in non-conflict situations.

A similar altitude-preference was found for the trial-plans that were in response to a traffic conflict. In those cases, 89% of the time the controller's initial response was to try an altitude maneuver (see Figure 12). This is supported by controllers' comments that for traffic conflicts, altitude changes more quickly move conflicting aircraft away from each other.

As expected, when a weather conflict was detected for an aircraft, lateral trial-plans were most common. The relatively few altitude trial-plans that were initiated in response to a weather conflict were due to aircraft that were transitioning to and from weather-impacted airports. Because high altitude airspace was the focus of this simulation, (the test sectors were FL290 and above), and weather contingencies such as diverting to alternate airports were outside of the scope of the simulation, the controllers issued the appropriate altitude changes and handed the aircraft off to the low altitude airspace. Operations in the low altitude airspace were not properly simulated, and not intended to be included in these data analyses.
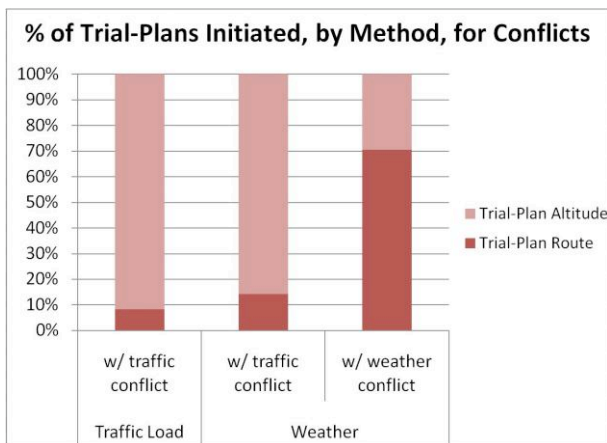

Fig. 12 Proportion of trial-plans, either altitude or route, initiated in response to traffic and weather conflicts.

6 Automation-Assisted Trajectory Planning Usage Data

Another trajectory planning tool available to the controllers was the Advanced Airspace Concept's (AAC) Auto-Resolver [10]. With this Decision Support Tool (DST), the controllers can ask the Auto-Resolver's automation, in the presence of a detected traffic conflict, to suggest a provisional trajectory that resolves the conflict. During the simulation, this function was made accessible to the controllers in four ways: with a Trackball-Enter on the conflict probe number in the upper-right of the FDB, with a Trackball-Enter on the trial-planning portal, with a Trackball-Enter on the altitude line of the FDB, and with a Trackball-Enter on the conflict list entry for the aircraft pair in conflict (see Figure 13).

Fig. 13 Two aircraft in conflict, FLG394 (top, southwest bound), and NWA283 (bottom, northwest bound), showing conflict probe numbers in the upper right of their FDB. The conflict list is also displayed.

More than just variety, the different access points to the Auto-Resolver help the operator communicate resolution preferences to the automation. Consider Figure 13: if the controller clicks in the conflict list, this implies they have no preference over which aircraft should be moved, and also no preference for which type of maneuver (lateral or vertical) is used. If the controller clicks the conflict probe number in the FDB of the NWA283 flight, this implies they prefer that the NWA283 receive the resolution, but still have no preference for which type of maneuver. However, if they click the trial-planning portal for the FLG394, the automation would understand that the controller prefers that the FLG394 receive the resolution, and that they prefer the resolution to be a lateral maneuver. If they instead click on the altitude line of the FDB for FLG394, this would imply a preference for a vertical resolution for that aircraft.

6.1 Request Method

Figure 14 shows another clear preference by the controllers. The data (shown as average count per run) indicates they most often requested the automated resolutions from the FDB, as opposed to the conflict list. More specifically, out of the nearly 600 requests to the automation for conflict resolutions, 94% of those requests were made from either the trial-planning portal or the conflict probe number in the upper right of the FDB. Note that data for these two access points are combined together. Unfortunately, at time of writing, they were unable to be analyzed separately.
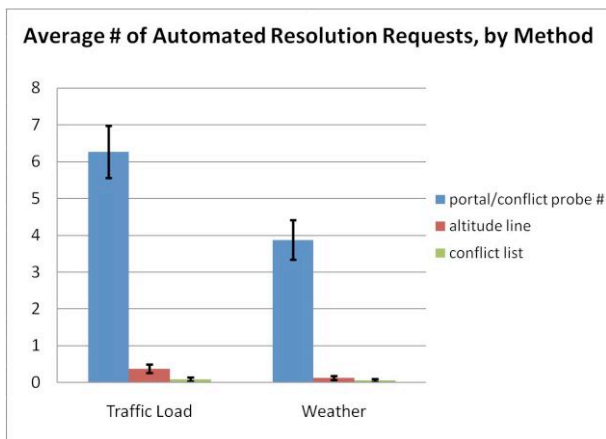

Fig. 14 Average number of requests from the controllers for automation resolutions. Data shown is organized by the different Auto-Resolver access points.

6.2 Success/Failure Rates

Each request of the Auto-Resolver to provide a conflict resolution trajectory can either succeed or fail. Data was also analyzed to help quantify how the Auto-Resolver functioned.

Figure 15 illustrates that the Auto-Resolver performed as a very effective DST, reliably providing the controller with conflict resolution trajectories. During the simulation there were only 22 recorded failures of the automation to generate a resolution, equating to a 3.8% failure rate. The failures to provide a resolution can be attributed to one of two causes. Primarily, there were known issues with the integration of the Auto-Resolver logic into the MACS software. These implementation short-comings have since been addressed in more recent versions of the MACS software, and also addressed with an updated version of the Auto-Resolver [10].

The second cause of these resolution failures was when the controllers requested the resolution under very short look-ahead times (e.g., less than two minutes until predicted LOS). With longer look-ahead times, the Auto-Resolver used during this simulation worked very well, but when presented with very short look-ahead times, resolutions to a predicted LOS were not always possible. The maneuver rate limits of the aircraft, in addition to the execution delays of operators, can cost valuable seconds that would be needed for such imminent conflicts. In these cases, a more direct, or tactical resolution would need to be provided directly to the flight crew (not through the FMS), as done with TSAFE [12], which was not used during this simulation.
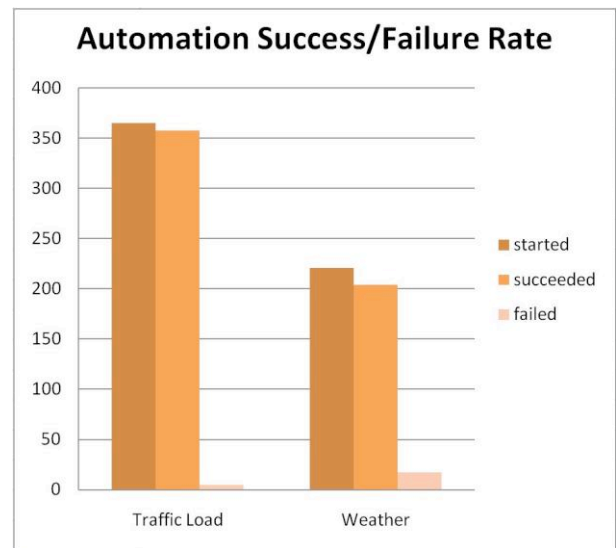

Fig. 15 Total number of times the Auto-Resolver automation succeeded and failed to provide a resolution for a traffic conflict.

7 Usage of Data Comm for Sending Trial-plans

An initial look at the number of trial-plans uplinked to aircraft seems to confirm the controllers' frequent use of the trajectory planning tools. Figure 16 (shown as average count per run) indicates that slightly more than 38 and 45 trial-plans were uplinked in the traffic load and weather scenarios, respectively. Given

that each run lasted 75 minutes, in the traffic load scenarios, this equates to approximately 31 trial-plan uplinks per hour, or roughly one uplink every two minutes.

The increase in the number of trial-plans uplinked in the weather scenarios is expected, and is likely due to the nature of the weather's movement. The weather forecast used to generate the weather probe numbers was intentionally not perfect, and as the weather moved over the course of the scenario, it was possible that an aircraft that was previously re-routed to avoid weather would need to be moved again. This is not unrealistic, and did contribute to more trial-plans being sent to aircraft during a weather scenario, at a rate of approximately 36 uplinks per hour.
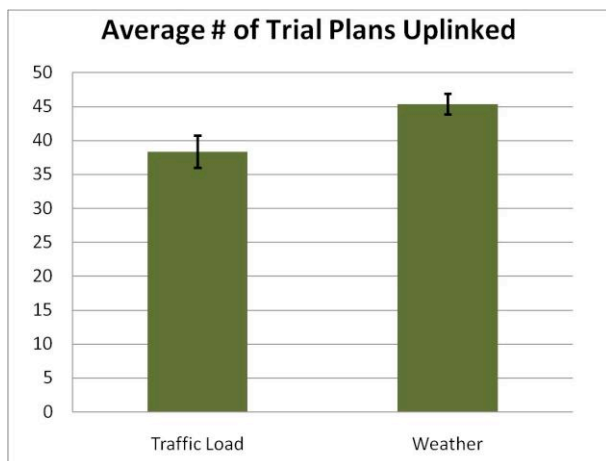

Fig. 16 Average number of trial-plans sent to aircraft, categorized by traffic scenario.

8 Subjective Feedback Data

In a post-simulation questionnaire, the controllers were asked to rate the tools in terms of how helpful they were (usefulness) and how easy they were to use (usability), on a scale from one through six, with one signifying not at all useful/usable, and six signifying very useful/usable. The average usefulness and usability ratings from the seven controllers can be seen in Figure 17. The data indicates that the automatic TOC was the highest rated function (M=5.9 for both usefulness and usability). This is not surprising, because radio check-ins from incoming aircraft and frequency changes for outgoing aircraft today constitute a large

amount of workload for controllers. Data Comm operations (and the tools that support them) where that task is no longer needed, would understandably be well-received by controllers. Even with the high ratings, the controllers did report a few minor problems with the Data Comm TOC, commenting that in a few cases they would have liked to initiate hand-offs while an aircraft still had open Data Comm messages, rather than waiting for the pilot response message.

The conflict probe was the second-highest rated tool (M=5.4 usefulness, M=5.5 usability), and similar to the automatic TOC rating, is a sign of how much of a controller's current-day workload is related to detecting traffic conflicts themselves. These ratings suggest that the conflict probe, as implemented in the MACS software, is very reliable, and therefore a very helpful tool.

The manual trajectory-planning tools were also highly rated, with all components receiving a rating of 5 or higher for both usefulness and usability. Most of the controller comments in this area spoke to their preference for altitude solutions. For example, the controllers mentioned that they would have liked an easier way to manually identify a conflict-free altitude with the trial-planning tool. Whereas for lateral solutions where the trial-planning task is a straight-forward "visual search while dragging" process, for vertical solutions, the trial-planning task involves trying different Flight Levels (FL) one-by-one. Trying each altitude involves two or more clicks of the trackball buttons, which can add up to a relatively long time if the controller needs to check several options before finding a clear altitude.

The automation-assisted trajectory-planning tools were rated as both useful and usable, with the lateral resolutions from the automation receiving higher ratings than the vertical resolutions (M=4.8 usefulness, M=5 usability, and M=4.3 usefulness, M=4.8 usability, respectively). However, comments from the controllers indicated that a few minor improvements were still needed.

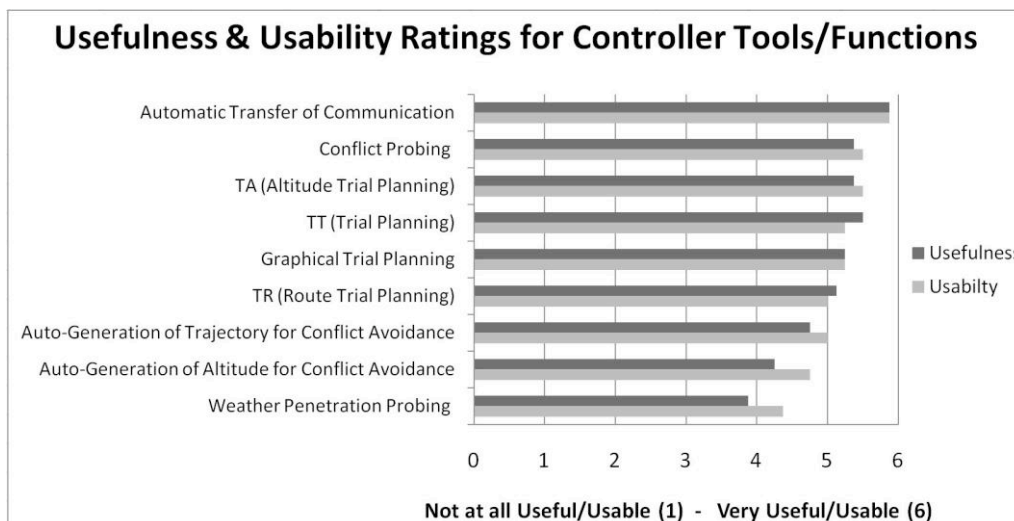The controllers commented that they would have liked the altitude resolutions from

Fig. 17 Usefulness and usability ratings from the radar controllers for the provided toolset.

the Auto-Resolver to account for standard direction of flight rules, and that the altitude resolutions should also avoid issuing higher altitudes to aircraft that were nearing their destination and would need to descend anyway. In general though, the controllers' comments were very positive towards the trial-plans generated by the automation. Some of the controllers commented that they "used the auto resolution more than [they] thought they would," and that they were thinking of ways to fine-tune the Auto-Resolver's logic to align with their control preferences. This type of thinking is evidenced by one controller's comment to have the Auto-Resolver pick lateral maneuvers (small, easy turns) for conflicts 8 - 12 minutes away, and altitude maneuvers for conflicts closer in.

9 Future Work

The simulation brought to light some areas for improvement and further research. The altitude trial planning will be improved by re-activating a functionality that was suggested and tested by McNally, Erzberger, Bach, and Chan (1999) [13]. This functionality probes all nearby altitudes and indicates their conflict status inside the altitude pop-up menu. This way a controller can see which altitudes are usable without starting a trial plan first.

In addition, the trajectory manipulation tools did not include control over the speed domain, something the controllers asked for. Further work needs to be done on how to best implement speed changes within the current trial-planning paradigm. Future analyses of tool usage data can also be expanded to include details on what type of trial-plans were uplinked (lateral, vertical, etc.) and the timing of the various steps involved in the trial-planning process. The authors also plan further analyses to compare what type of maneuver was preferred during a request from the Auto-Resolver, versus what type of maneuver was actually provided by the Auto-Resolver.

10 Concluding Remarks

This paper describes results gathered during a human-in-the-loop simulation that provided active CPC radar controllers with prototype tools supporting NextGen-type operations.

Although it was not the focus of the simulation, higher levels of traffic were worked with acceptable levels of controller workload. Not only were the observed traffic levels higher than today's traffic, the sectors were staffed with only the radar controller; not with any additional radar associate controllers. Simulating a two-controller sector team was outside the scope of this simulation, so this result in no way is meant to address staffing. Instead, the results speak to a potentially effective cooperation between human operators and the system automation. Specifically, these

results suggest that this suite of tools could help off-load routine tasks from the controllers and provide assistance with tasks that can be difficult for the controller. This could then allow the controllers to focus their resources on other tasks, such as providing higher levels of service to the airspace users, attending to high-complexity areas, or even manage more aircraft. Similarly, the notion of a controller discussing how the Auto-Resolver logic could be adapted to their individual control strategies and preferences indicates an initial level of trust in the automation was achieved during the operations simulated in this study. Overall, the results of this simulation have demonstrated that critical building blocks of NextGen operations, such as automated conflict detection, automated conflict resolution, trial-planning, and Data Comm, can be effectively integrated into the radar controller workstation.

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