NEXTGEN TECHNOLOGIES FOR MID-TERM AND FAR-TERM AIR TRAFFIC CONTROL OPERATIONS

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Abstract

This paper describes technologies for mid-term and far-term air traffic control operations in the Next Generation Air Transportation System (NextGen). The technologies were developed and evaluated with human-in-the-loop simulations in the Airspace Operations Laboratory (AOL) at the NASA Ames Research Center. The simulations were funded by several research focus areas within NASA's Airspace Systems program and some were co-funded by the FAA's Air Traffic Organization for Planning, Research and Technology.

Introduction

In the next two decades, the air traffic control system is expected to undergo fundamental changes to implement the NextGen vision of high capacity, low cost, and environmentally friendly air traffic control [1][2]. While there is a vast array of sometimes competing and/or contradicting visions, ideas, and concept elements that describe the aspects of future operations and technologies, very little is known as to what NextGen will actually mean for the operators of the systems.

To further an initial understanding of operational aspects, the Airspace Operations Laboratory (AOL) at the NASA Ames Research Center [3] has taken the approach of rapidly prototyping a first cut of critical elements of NextGen concepts and conducting frequent human-in-the-loop simulations. Examples of the type of work being done in this area are as follows: Funded by NASA's Airspace Systems Program, progress has been made in understanding critical aspects of effectively sharing separation assurance responsibilities between controllers and automation, and understanding the implications of mixed equipage on airspace complexity in a highly automated far-term environment [4][5] In close cooperation with the FAA, simulations in the AOL have investigated the mid-term concept of a Multi

Sector Planner that bridges the gap between strategic traffic flow management and tactical separation management. This position can manage airspace complexity as well as introduce more effective trajectory management into the system.

Simulating both far-term and mid-term operations with controllers and pilots in the loop has provided an opportunity to develop and evaluate prototypes of various technologies. Based upon the results of the evaluations key technologies have emerged that have proven to be particularly effective in the simulated air traffic environments. The paper will provide an overview of the key technologies, describe their design and provide results from their evaluations with controllers in the loop in simulations of mid-term and far-term NextGen operations.

Problem

Airspace Capacity Goals

The goals for NextGen and the current FAA demand forecasts [6] are in line with the European Air Traffic Management Master Plan [7]. They estimate that an increase in airspace capacity to approximately 150% to 170% of today's capacity will be required by 2020. Additionally, NextGen and SESAR have declared a far-term peak capacity target of up to 300% of current day airspace capacity. The problem is how to achieve a dramatic threefold capacity increase in the far-term and also meet the substantial airspace capacity targets in the mid-term.

Airspace Capacity Limitations

It is commonly understood that controller workload limitations are at the center of the airspace capacity problem. Traditionally during high traffic, one radar controller with the help of one radar associate is responsible for monitoring and controlling each aircraft within a given airspace

sector via voice communication. This includes many bookkeeping tasks, such as transferring control and communication for each aircraft that is entering and exiting the sector. The number of tasks associated with these routine operations is one primary factor limiting the number of aircraft a controller can safely handle. The other primary factor is the cognitive demand associated with monitoring and controlling each aircraft to maintain safe separation between them. Therefore, absent external constraints, such as convective weather, airspace capacity is primarily limited by

a) the controllers task load associated with clearance delivery, routine bookkeeping tasks and voice communication

b) the controllers cognitive load associated with monitoring and controlling all aircraft for separation assurance

Potential solutions

This paper discusses technologies for two ways of addressing the airspace capacity problem:

- Increasing sector capacity by using automation to reduce controller workload

- Managing sector capacity and complexity with advanced tools across multiple sectors

Increasing Sector Capacity

In order to increase the capacity of each individual sector the two primary controller workload factors stated above – task load and cognitive load - have to be addressed.

In the mid-term controller task load can be reduced with data com integrated technologies without changing the primary roles and responsibilities. This can provide a moderate increase in capacity. In the far term the same technologies can be used at a higher level of automation to significantly reduce the cognitive demand on the controllers. This is done by allocating the task of monitoring aircraft for separation losses to the automation. With technologies designed for this paradigm shift enough cognitive controller resources can be freed up to achieve sector capacities of two or three times today's capacity. The next major section in this paper entitled "Technologies for Tactical Air

Traffic Control Operations" will describe the technologies. Selected research results will be discussed later in this paper.

Managing Sector Capacity and Complexity

If sector capacity cannot be sufficiently increased, the traffic load at each sector needs to be managed such that the existing capacity is not exceeded. This can be achieved either by changing the airspace or by managing the load and complexity of traffic entering the airspace. The airspace sectors may be changed such that each sector only controls a manageable amount of aircraft. Due to the task load associated with aircraft entering and exiting the airspace, this approach is limited in its effectiveness, because even reduced sector sizes require the same amount of routine tasks as bigger sectors. In order to manage traffic load and complexity, aircraft often get rerouted or delayed. These measures are taken to make sure not to exceed the capacity of each individual sectors and often direct traffic to through les busy sectors. The section "Technologies for Capacity and Complexity Management" discusses some advanced capabilities designed to manage airspace demand and complexity that were evaluated during recent human in the loop simulations.

Technologies for Tactical Air Traffic Control Operations

Tactical air traffic control operations refer to separation management and trajectory management on a sector level. As described above the goal for modernizing tactical sector operations is to reduce workload and thereby increase sector capacity and improve flight trajectory efficiency by reducing the task load and the cognitive demand on the tactical air traffic controllers.

Approach

Research has evaluated mid-term and far-term operations in various simulations. Some primary results are summarized or referenced in this paper. The approach outlined below to implementing key technologies has shown great promise.

In the mid-term, technologies are implemented to handle routine tasks, improve communication and support the operator with advanced conflict detection and resolution tools. This will reduce the

task load for the controllers and introduce advanced tools into operational use without changing the primary roles and responsibilities.

Once the automation, in particular trajectory predictions and conflict detection have been sufficiently validated through operational use, and the required equipage is in place, the responsibility for monitoring aircraft for separation may be transferred to the automation. This will offload a major cognitive demand from the controller to the automation, thus eliminate a primary limitation to increasing airspace capacity.

The same technologies can be used in the mid-term and the far-term. The underlying automation can be validated in operational use and functions can slowly transition from the controller to the automation when both, humans and technology, are ready to do so. The infrastructure can be implemented regardless of potential changes in functional allocation, because the key technologies are expected to be beneficial even if the basic roles and responsibilities stay the same.

The key technologies are depicted in Figure 1. The concept uses ground-based trajectory management and is anchored in improved air/ground data communication and advanced air traffic controller automation. The rationale is to have minimal requirements on new flight deck equipage, keep the data com requirements manageable and focus on improvements on the service provider side. Currently, aircraft automation

is further advanced than ground-side automation and aircraft operators have invested into technologies that are rarely used. Airline fleets today are relatively homogenous and flight management systems have fairly well-known capabilities. Therefore, the approach promotes a ground system and data com infrastructure that makes more use of the existing airborne capabilities to solve the capacity problems before posing additional requirements on airborne functions.

Main Information Flow

Figure 1 also depicts the main information flow between the key technologies. A ground-based information management system maintains the trajectories for all aircraft and provides surveillance information, trajectories, environmental conditions, and traffic flow constraints to the air traffic controller workstation. The controller workstation has direct access to a common trajectory predictor, and automated conflict detection functions. These functions enable the air traffic controller to assess whether the current trajectory for any aircraft under his or her control is predicted to conflict with a hazard, such as other traffic, or convective weather. The controller can use the automation-assisted trajectory planning functions to create new conflict-free trajectories that are communicated to the aircraft and the ground-based information management system. Key parameters that define the trajectories are sent via data com. They can be loaded into the flight management system (FMS) of
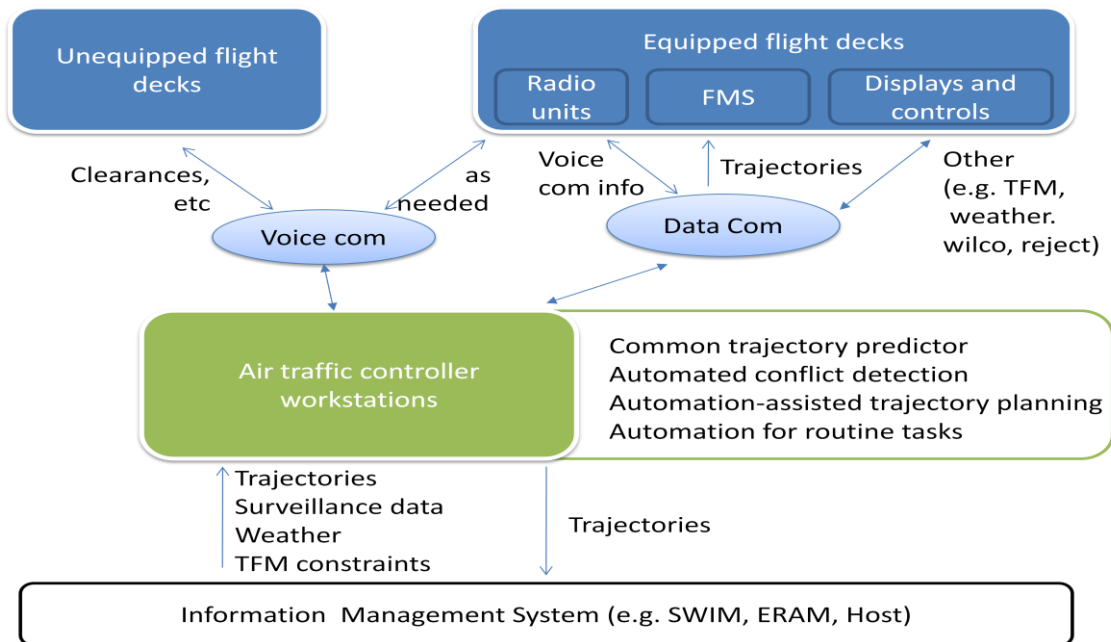

Figure 1: Information flow and key technologies to improve tactical ATC operations in the mid-term and the far-term

equipped aircraft, at which point the flight crew can review the proposed trajectory change. The flight crew can then accept and execute, or reject and erase the trajectory change. In this concept the service provider maintains independently generated ground-based reference trajectories and does not rely on trajectory information downlinked from the aircraft. Downlinked trajectory information can be used for conformance monitoring if available. Unequipped aircraft are handled similar to today, except that advanced tools enable the controller to create trajectory amendments more easily and input them into the information management system. However, since all trajectory changes have to be communicated via voice to the flight crews of unequipped aircraft, no significant reduction in controller workload can be expected if no aircraft are equipped. Research providing data on the effect of mixed equipage confirms this assertion. [8]

The above section presents the main information flow. Next, more details regarding the flight deck, and the data communication are presented. The controller workstation is discussed in detail after that.

Unequipped Flight Decks

All flight decks that are not capable of automated loading of trajectory information from the data com into the flight management system (FMS) are considered unequipped in this concept. Even if an aircraft is data link equipped, but does not have FMS integrated data com, it is considered unequipped and will be treated as such. Unequipped aircraft can be managed with clearances like today.

Because a common independent ground-based trajectory engine is used for both, equipped aircraft and unequipped aircraft, both can be managed in
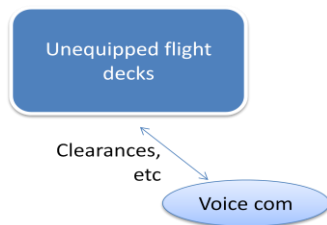

Figure 3: Unequipped flight decks

the same airspace. However, unequipped aircraft require much higher workload and will only get access to airspace resources as long as this does not prevent equipped aircraft from being serviced.

Equipped Flight Decks

Ground-based trajectory management does not require major new technologies for a flight deck to be considered "equipped" except for integrated data communication. Assuming state of the art flight management systems (FMS) for lateral and vertical navigation, the key enabler is the ability to communicate trajectories along latitudes and longitudes with varying constraints from the service provider to the FMS. This general ability exists within FANS-1/A equipped aircraft today and capabilities similar to the Route Clearance function need to be integrated into as many aircraft as possible.
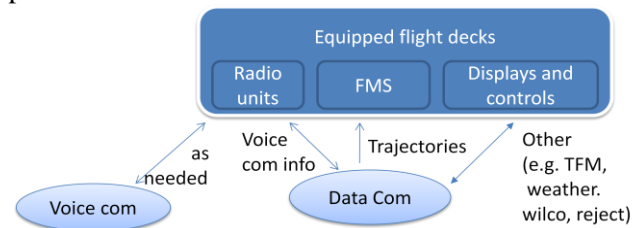

Figure 2: Equipped flight decks

This kind of FMS integrated data communication is required to make sure that the planned trajectories will be executed with a sufficient level of precision. Studies have indicated the feasibility of this approach [9].

The primary means of communication to equipped flight decks is data com. Voice communication is the exception rather than then the rule. Since voice communication may be a rare event, the flight deck radios could be linked to the data com. This way they can automatically tune to uplinked frequency changes and alert flight crews to incoming voice communication attempts from controllers. With little voice communication controllers will lose awareness of where specific flights are located. Radio information could be downlinked to the ground system, when a flight crew contacts the controllers via voice, so that controllers can easily identify the aircraft on their displays.

Additional uplink messages, such as weather reports, scheduling updates, or other information are presented on the displays that are appropriate for the data link implementation used on the respective flight deck. Additional provisions for

prioritizing and alerting crews to time critical information may be necessary, for example if a ground-based automated tactical conflict avoidance system such as the Tactical Safety Enhanced Flight Environment (TSAFE) [10] is required. Existing technologies may be appropriate for some purposes, but any final requirements are to be determined.

Required downlink capabilities include means for flight crews to accept and reject messages. Downlinks of active trajectories can be used for monitoring conformance to the ground-based reference trajectories and to improve the trajectory predictions. Downlinks of trajectory requests provide a means for communicating user preferred routes from the flight deck and can be beneficial for efficiency and economic reasons. The concept is designed, however, to provide the required airspace capacity with minimum flight deck upgrades and does not require trajectory downlinks, active or requests.

Air/Ground Data Communication

Some data communication contents have been discussed in the sections before. The concept does not require an extensive data link message set and focus can be placed on implementing and validating only the minimum set of messages needed for the primary functions.
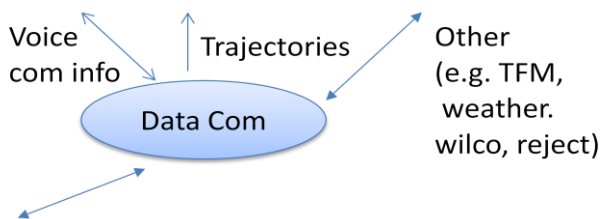

Figure 4: Primary functions of data com

Concept simulations and analysis to date indicate that the data com system would need to support at a minimum the following uplink messages:

- Trajectory information [or parameters] and trajectory constraints (route modification uplinks, altitudes, profile speeds, required times of arrival)
- transfer of communication (i.e. frequency changes)
- free text (encode anything in text format)

- responses to aircraft initiated requests

The data com system is expected to support the following downlink messages:

- Responses (wilco, reject)
- Free text (encode anything in text format)
- Requested trajectory changes

Additionally, it would be very beneficial for the system to support additional information provided directly from the aircraft

- Aircraft state and velocities
- Short term intent and flight modes (i.e. flight control system settings)
- FMS trajectory reports
- FMS inputs (e.g. speed profile, weight)
- Voice comm. frequency and activity

Aircraft state and velocities that could be provided via ADS-B are a possible means of achieving the surveillance performance required for a suitable trajectory prediction and conflict detection integrity. This integrity will be necessary for high density air traffic control. As discussed before, downlinking voice communication frequency and activity is one way of supporting controllers in identifying aircraft that originate air/ground voice calls.

Air Traffic Controller Workstation

Flight deck changes and data com requirements are intentionally conceptualized to be moderate. The air traffic controller workstation and underlying technologies, however, will have to undergo fundamental changes and improvements to enable this concept.

The primary inputs from the ground-based information management system to the ATC workstation are active trajectories and surveillance data for all aircraft, weather information and traffic flow constraints. The primary outputs of a controller workstation to the ground system are revised trajectories. These trajectories are also communicated from the ATC station via data com to the flight deck and integrated into the FMS of equipped aircraft. The air traffic controller communicates via voice directly to the flight crew when necessary.
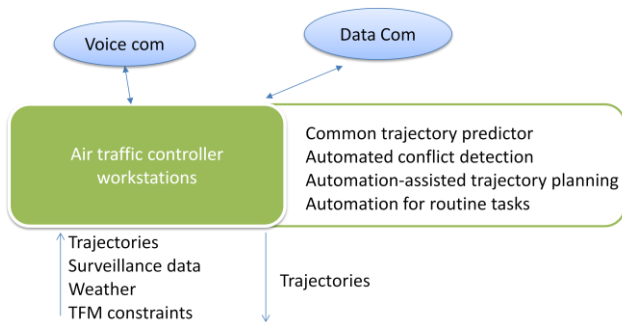
Figure 5: ATC workstation

The ATC workstation provides access to key functions that support the operator in managing high traffic densities effectively. Before describing these key functions in more detail, a few thoughts on trajectories are provided.

Trajectories

Trajectories (often referred to as 4DTs) are at the core of trajectory-based operations. The concept of ground-based trajectory management described here relies on the ground system to generate and maintain trajectories for all aircraft. These "active" reference trajectories take the place of what the flight plan (and the host route) represents in today's environment. It is the ground side reference of the future path that the aircraft will take. Unlike the flight plan, trajectories will incorporate detailed information about altitudes, speeds and times along the various trajectory change points. It is critical for high density operations that aircraft and their their ground-based reference trajectories are in sync. Good reference trajectories are the key enabler to most advanced functions. Imposing many (time) constraints along trajectories may appear to be a suitable approach to improve predictability. However, there is a substantial cost associated with this approach, because many aircraft do not have the required equipage. Even if they did, often constraints would be imposed when they are not necessary. For greatest flexibility, efficiency and cost effectiveness, the concept of ground-based trajectory management proposes to minimize uncertainties through improved trajectory prediction and execution, and to design control functions and procedures that cope with the resulting uncertainties. Constraints are only imposed when necessary for economic reasons (e.g. an important flight schedule requested by the aircraft operator) or

for flow management purposes (e.g. insufficient capacity to meet demand).

Common Trajectory Predictor

A good trajectory predictor is required to generate trajectories that are a close match to those that the aircraft will actually fly. Trajectory predictors are part of various components in the air transportation system today. Each FMS has its own trajectory predictor, which is used to generate the trajectory that the flight control systems on board the aircraft use as navigation and control reference. Many aircraft operators use flight planning tools that have underlying trajectory predictors for providing their fleet with wind optimal routes or weather reroute options. The service providers use trajectory predictors for flight monitoring, conflict probing, route planning, and arrival management.

Almost all of the trajectory predictors outlined above are different. Different input parameters are processed by different trajectory synthesis models to create different trajectory descriptions. This is not only true across stakeholders, such as aircraft, operators, or service providers, but also within the particular entities. For example the trajectories underlying the NAS's User Request Evaluation Tool (URET) [9] are different to those predicted for arrival management in the traffic management advisor (TMA) [10]and both are different to those used for flight monitoring and sector load predictions used in the Enhanced Traffic Management System (ETMS).

In order to increase the stability and predictability of the system it is highly desirable to use a common trajectory predictor whenever possible. This trajectory predictor needs to appropriately account for the flight dynamics of the aircraft as well as for the flight management functions wrapped around the dynamics. There are initiatives to change the trajectory predictors in various places including the airborne FMS. Often, however FMS are considered too expensive to change. Therefore, a more feasible approach could be to implement a ground-based common trajectory predictor that mimics the main flight management system path generation functions and uses the same primary input values. This ground-based common trajectory predictor can utilize substantially more computing power than is available in the aircraft. In

addition to properly accounting for flight management system control logic, the trajectory predictor also needs up to date input parameters, such as aircraft weight, altitude and speed schedules. These values could be obtained from the aircraft or from operators, if they are willing to share this information to improve the overall system effectiveness.

There is also the possibility of obtaining active trajectories directly from the airborne flight management system via data com. However, even if the many technological challenges in doing so can be resolved, the need for the common ground-based trajectory predictor remains. This is true as long as the ground-side is expected to conduct any kind of trajectory planning or management activities, including separation management, scheduling, flow management, load balancing, etc.

Automated Conflict Detection

Automated conflict detection is the primary technology expected to reduce the cognitive controller workload. In the mid-term environment the controller is expected to remain responsible for monitoring the airspace for potential conflicts. Automated conflict detection can aid in highlighting potential problems between active trajectories and probing provisional trajectories before issuing them to the aircraft. The conflict detection quality (the false alert/missed alert ratio) strongly depends on the quality of the trajectory prediction and execution. As improvements to the common trajectory predictor and data com integrated FMS are implemented into the system, trajectory-based conflict detection performance will also improve. The conflict detection will need to perform well enough to detect conflicts between on-trajectory aircraft reliably with sufficient time for a trajectory-based resolution. Research to date indicates that due to the many uncertainties in the air traffic environment, reliable traffic conflict detection can be expected for ten minutes or less to time to conflict [10]. In certain environments this time range may be extended or reduced by a few minutes. This represents sufficient time for trajectory-based solutions to separation problems. Therefore, the target for detecting conflicts between on-trajectory aircraft can be set to approximately 4-8 minutes.

Since aircraft will not always be in conformance with their reference trajectories, a second conflict detection function needs to provide a safety net, if the trajectory-based conflict detection fails and a loss of separation is predicted to occur with little time to go (e.g less than three minutes). In today's system the conflict alert on the controller's stations assumes parts of this function. Research has shown that advanced technologies such as the Tactical Safety Enhanced Flight Environment (TSAFE) can provide a safety net with improved performance. [10]

When the required conflict detection performance is achieved and validated with sufficient operational data, the responsibility for
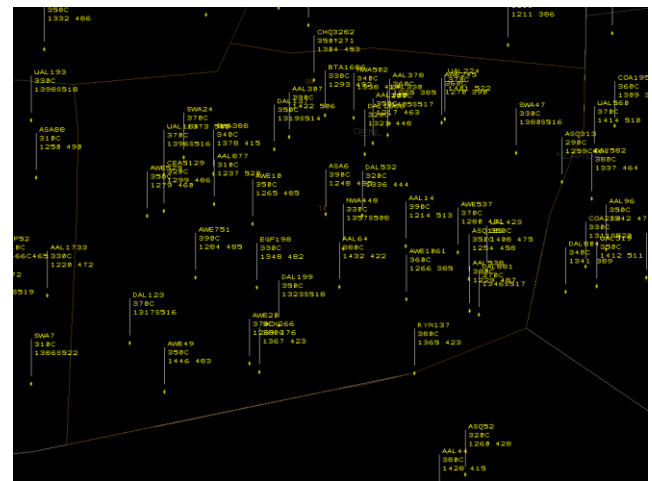

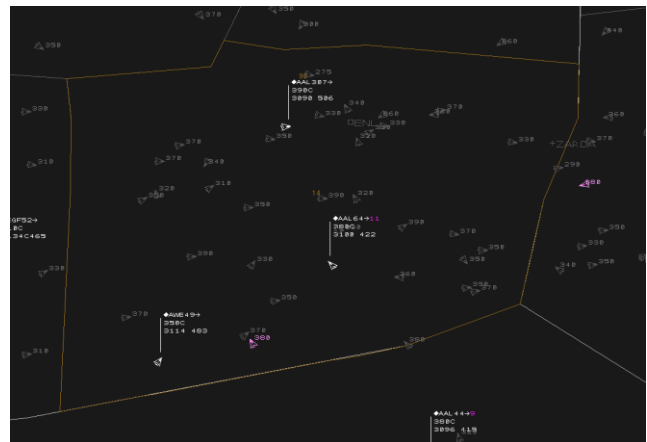**Figure 6: Current day display at more than twice current day traffic density**

Figure 7: Experimental display designed for automated conflict detection for the same situation as Figure 6

conflict detection can be assigned to the automation. This is expected to enable a significant increase in airspace capacity, but is a fundamental change in the air traffic control paradigm. Making the automation responsible for separation assurance will change the controller's task. Full situation awareness of all aircraft is no longer required to detect potential conflicts, as the automation assumes this role. Consequently, the surrogate tasks and information that are in place today for ensuring the controller's situation awareness are no longer necessary.

Aircraft can be handed from one sector to the next by the automation; routine radio communications are no longer required. Information, such as full data tags on aircraft are only required when knowing the callsign, altitude, or speed of a particular aircraft is important for a planning task. Figures 6 and 7 show how assigning the conflict detection responsibility to the automation can impact the display design by comparing a current day display at more than twice current day traffic density to a display designed for automated conflict detection and high traffic density.

Automation assisted trajectory planning

Automation assisted trajectory planning functions support the controller in creating and evaluating trajectory modifications for various reasons. These include separation management, hazard avoidance, such as areas of convective weather, implementation of traffic management initiatives or meeting flow constraints. A goal for the trajectory planning process can be to minimize the deviation from the original trajectory to solve a small separation problem. The trajectory can also be designed to provide a new wind-optimal route to the destination airport that avoids multiple convective weather cells and meets specific time constraints. Enabling user preferred climb or descent profiles or routing options are other functions within the scope of automation assisted trajectory planning.

The controller can use these functions in a highly interactive manner. The current NASA research prototype used for the simulations described in this paper incorporates automated trajectory planning functions for traffic and weather avoidance. When a hazard is detected the controller can access these functions either through the data tag or via conflict lists. The automation will then generate a provisional trajectory that solves the problem if possible. The controller can review this

Trial Plan Conflict / Auto Resolver: Route

Trial Plan into a conflict: Blue Trial Plan Graphics will appear
•**Make waypoint and drag until conflict goes away or,**
•**Enter on trial plan conflict # in FDB for auto resolve of trial plan conflict**
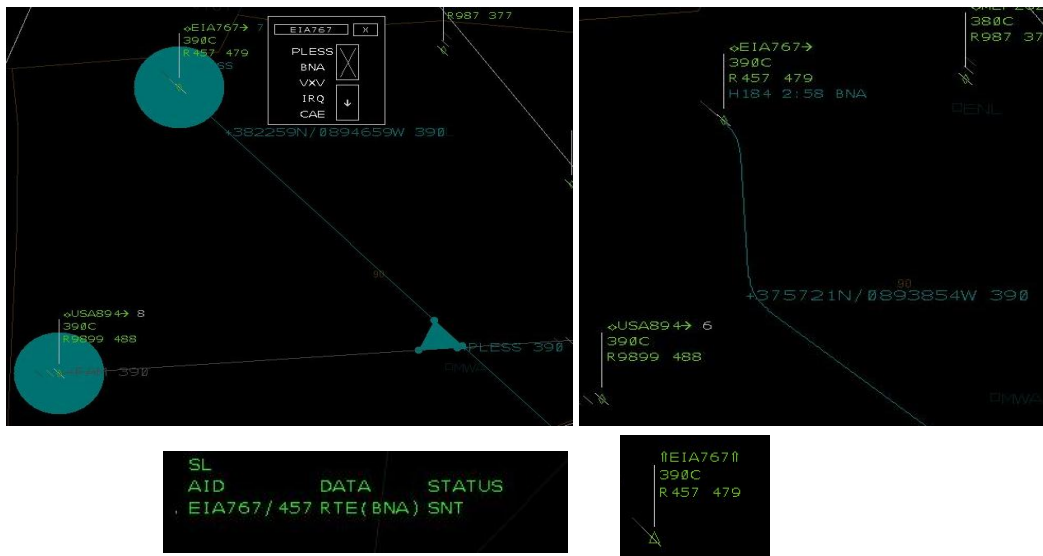•**Uplink to aircraft**

Figure 8: Excerpt from training material for air traffic controller [13]

trajectory, modify it graphically or via keyboard entries, get a different proposal, or erase the provisional trajectory. The modification process is identical to any provisional trajectory that the controller generated from scratch. Figure 8 shows an excerpt of the controller training material for a recent simulation.

Once a controller creates a new trajectory it can be sent to the aircraft via data link. At this time the reference trajectory in the ground system is updated and used for all further trajectory predictions and conflict detection functions. This implementation assumes that the trajectories will be nominally accepted and executed by the flight crew, because uplinked trajectories have the same status as clearances today and research shows a high acceptance rate of uplinked clearances [4]. In case a flight crew rejects a clearance, it is expected that the controller and the flight crew use voice communication to resolve the issue and generate a different trajectory that is acceptable.

The general philosophy behind this trajectory-based air traffic control process is to plan all flight modifications with the trajectory planning tools, and ensure the resulting trajectories are conflict free for the desired amount of time before issuing them to the aircraft. This way all trajectory changes can be appropriately propagated through the system and all trajectory predictions are up to date. This procedure is used for equipped and unequipped aircraft.

In some cases a trajectory-based solution may not be possible right away and a tactical instruction may be required. This can be the case especially if a traffic conflict is detected late and close to the initial loss of separation. In this case the controller or the automation may issue a tactical heading or altitude instruction without using the trajectory-based tools. This tactical instruction leads to the undesirable state of not having a valid strategic reference-trajectory and compromises conflict detection and other trajectory-dependent functions. Therefore, it is desirable to create a trajectory solution as soon as the imminent situation is resolved. In a recent simulation of off-nominal situations it was found to be problematic for the automation to take an aircraft away from its reference trajectory and have no means of automatically creating a new reference trajectory

that would allow the aircraft to resume trajectory-based operations [4].

Automation for routine tasks

Up to date reference trajectories are also required for automating many routine tasks such as transfer of control and communication. In today's system automated transfer of control (handoff) from one controller to the next is initiated at pre-defined points along a structured route system. The future system will be designed to use dynamic wind optimal routes. A structured route system with pre-defined points cannot be assumed. However, reducing the number of routine tasks that the controller has to conduct is a necessity for increasing sector capacity. Therefore, automation needs to compute transfer of control points along the non-structured trajectories. In the mid-term a proper handoff initiation may be sufficient, in the fart-term both initiation and acceptance should be entirely automated between controllers. In both cases data com will be used to make sure flight crews switch to the appropriate frequency. When this automation works reliably, flight crew check-ins are not longer required, reducing the amount of necessary voice communication even further.

Technologies for Capacity and Complexity Management

Whenever the expected traffic demand exceeds the capacity, actions are taken to solve this mismatch. Even if technologies like those outlined in the previous section can increase sector capacity, higher demand, unusable airspace or insufficient aircraft equipage can create an imbalance that needs to be addressed. The current system relies on aircraft count per sector to alert traffic managers and area supervisors of potential imbalances. Air traffic operators, such as traffic management coordinators (TMC) in coordination with area supervisors manage traffic flows to adjust the demand to meet the capacity. Airspace changes (e.g. combining and de-combining sectors) and workforce changes (e.g adding radar associates and trackers to the sector teams) are means for changing capacity in today's system.

Approach

In the future new technologies can be used to combine options for managing demand and capacity into advanced trajectory-based operator stations for flow and airspace planning. For simplicity these stations are referred to as planning stations in this paper. Planning stations include the traffic management coordinator stations, area supervisor stations, or newly defined position, such as a multi sector planner position [14]. New tools for situation assessment, planning and plan coordination are distributed throughout the system to create a common understanding of the current situation, available options and communicate and execute plans. Figure 9 shows some key technologies and main information flow.

Main Information Flow

All operator stations need access to the information management system for retrieving and providing information. Operators can use voice and data communication to communicate between each other. They use the functions provided at the planning stations to create provisional trajectories, traffic flow or airspace changes, that can be coordinated with other operators. Provisional trajectories for mutliple aircraft can be sent via the automation for review at other planning stations. Once the trajectories are ready to be issued they can be sent to the sector controllers for execution. Sector controllers evaluate if they pose a separation problem and send the trajectory changes to the aircraft as necessary. Under certain situations, planners may also be able to send downstren trajectory changes directly to the aircraft. The exact rules have to be determined, but in simulations a simplified rule was used that allows planners to send trajectory changes to the aircraft if the first change point is at least 30 minutes away.

Planning Workstation Functions

The planning station relies on accurate trajectory predictions to enable its functions. Real-time filtering and analysis tools provide for traffic flow and sector/load and complexity assessment. Multi-aircraft trial planning functions provide options for previewing the impact for several trajectory changes on the overall situation. Any plans can be sent to other operators for their review. A short summary of these functions follows:
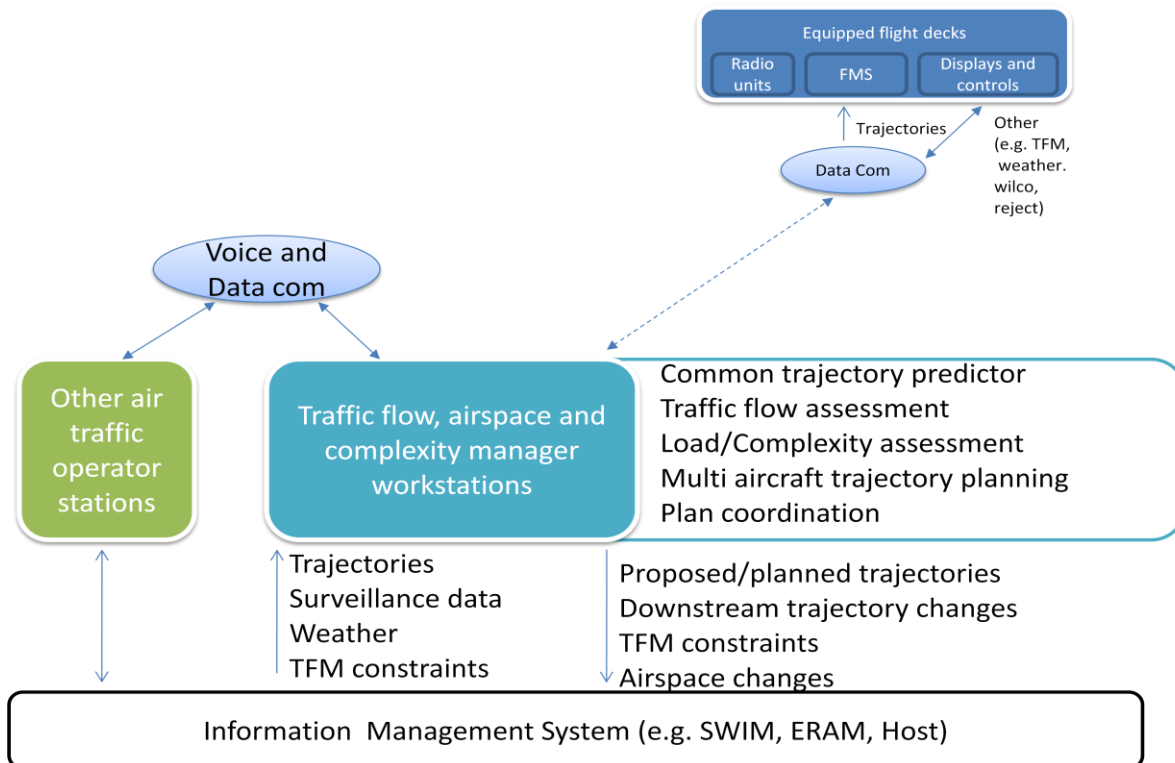

Figure 9: Infrastructure and flow between planning station and other components

Figure 10: Area flow planner display used in study on multi sector planning

Traffic Flow Assessment

In order to asses the traffic flow within a large congested airspace, new dynamic filter capabilities have been prototyped that allow operators to highlight only specifc aircraft. All traffic can be filtered such that only aircraft that fly to or from specific airports, or via designated routes, waypoints, or altitudes. Aircraft can be highlighted that pass through specific sectors, dynamically drawn objects or forecasted convective weather areas. Filters can be combined, dynamically added, deleted or edited and color coded. Aircraft that do not pass the filter test are pushed into the displays background, aircraft that meet the selected critera are highlighted. Figure 10 shows a display in which only aircraft that are predicted to penetrate the convective weather area are highlighted.

Load/Complexity Assessment

Similar to ETMS today, traffic loads for sectors are computed as the number of aircraft predicted to be in the sector for a given time frame. The results are presented in tables and graphs. When the operator selects a specific time slice these aircraft are also highlighted on the display. In order to account for complexity factors that go beyond a single number of aircraft, the graphs and tables can be switched to show only subsets of the aircraft,

such as the unequipped and transitioning aircraft, aircraft predicted to be in conflict, or aircraft predicted to penetrate weather hazards. In addition to these values a real time estimate of the sector complexity is also computed. The complexity calculation includes the factors described above as well as the sector shape and size. Therefore, operators can use the complexity values instead of the total number of aircraft to have a more accurate estimate of the workload within any given sector. The results presented in the following section indicate that planning controllers ranked this complexity computation as the second most useful overall tool.

All load graph and table values refelect active trajectories. Predicitions for provisional trajectories are given whenever new trajectory plans are viewed. These plans could have been initiated at the station or received from other stations. Figure 11 shows an example for how the peak sector load impact can be previewed when planning two trajctory changes.

Multi Aircraft Trajectory Planning

All the automation-assisted trajectory planning functions that exist at the tactical controller positions are also available at the planner positions. In order to assess the impact of moving
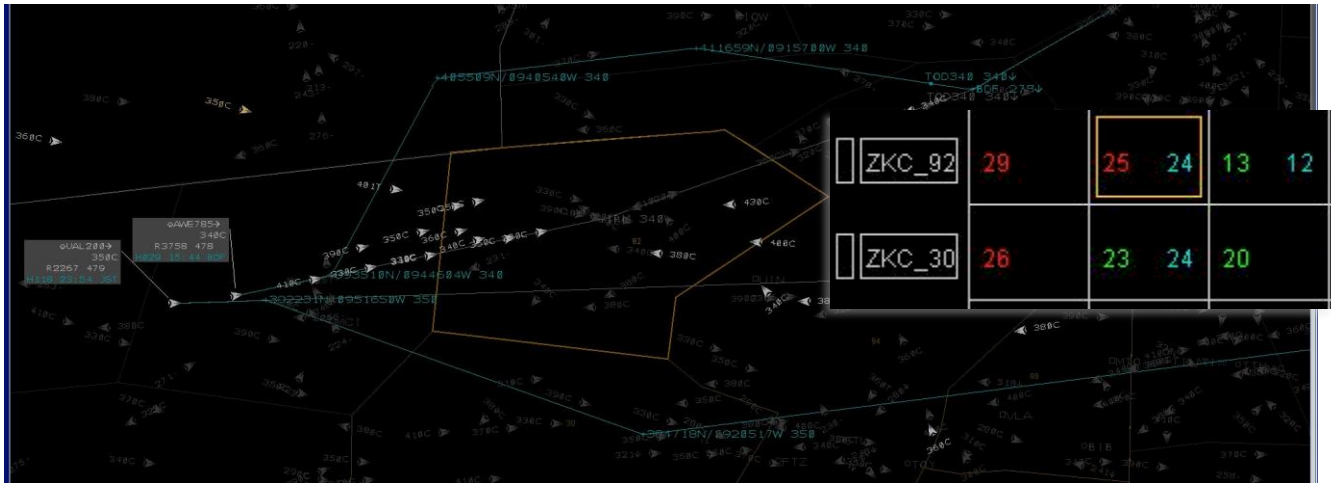
Figure 11: "What IF" trial planning of two trajectory changes and their impact on peak sector loads

an entire flow over a different routing, changing altitudes on multiple aircraft or other flow based trajectory management tasks, the planner can create a selection of several aircraft and manipulate their trajectories at the same time. This multi aircraft trajectory planning can be done graphically and/or via keyboard entries. All trajectories can be probed for conflicts and hazard penetrations as desired.

Plan Coordination

Plans can be coordinated between traffic planner/manager stations for review. A single command can send a selection of trajectories to a different station. The receiving operators can review the plan using their own complexity assessment tools and approve or disapprove individual trajectory changes. Once a plan has been agreed upon, it can be sent to the sector controller or directly to the aircraft under certain conditions. Coordination with area supervisors should precede trajectory changes impacting operations in the area. Each individual trajectory can be reviewed by the sector controller. When acceptable he or she sends the trajectory change to the aircraft. An approval message is automatically returned to the originator of the trajectory change and a new trajectory amendment is made in the information management system.

This short summary of planning tools describes a small subset of the entire suite. A detailed description will be made available in future publications.

Results: Estimated Sector Capacity

As outlined in the problem statement at the beginning of this paper the technologies described in the previous sections are intended to increase airspace capacity. Aspects of the technologies have been evaluated in a number of simulations, fast-time and real time. The results of these simulations were instrumental in further developing the technologies and their interactions. The main results of the evaluations can be found in the references to this paper.

Four controller-in-the-loop simulations were conducted in the AOL at NASA Ames Research Center since 2007 addressing various technologies and distributions of roles and responsibility. The simulations included a common sector within the airspace. Based on the results of this simulation Figure 12 was compiled to indicate an estimate of the capacity gains some of the modernization steps proposed in this paper may achieve. The sources for the data points in figure 12 are from left to right as follows:

1. current day: the monitor alert parameter (MAP) for the sector used for the comparison
2. advanced ANSP tools: 2008 HITL on mixed equipage. Controllers were able to handle 20 unequipped aircraft [8]
3. FMS integrated data link: 2009 HITL on multi sector planning: Controllers handled an average of 25 aircraft with data link
4. Automated conflict detection: 2007 study on levels of automation [5]. Automated conflict

detection and manual trial planning was manageable for 30 aircraft

5. Automation assisted conflict resolution: 2007 HITL on levels of automation.[5] Automated conflict detection and interactive trial planning was easily manageable for 30 aircraft, just manageable at 45 aircraft

6. Automated conflict resolution: 2008 HITL on off-nominal events [4]: 45 aircraft caused little workload as long as no off-nominal scripted events occurred.

automation that manages the large airspace surrounding the test sectors. During each 75-minute traffic scenario, more than 1000 aircraft twere operated by automated agents and seven general aviation pilots. These scenarios were designed to include traffic load imbalances between sectors and subjected aircraft and controllers to evolving convective weather situations. After the simulations all participants completed questionnaires about the different aspects of the simulation.
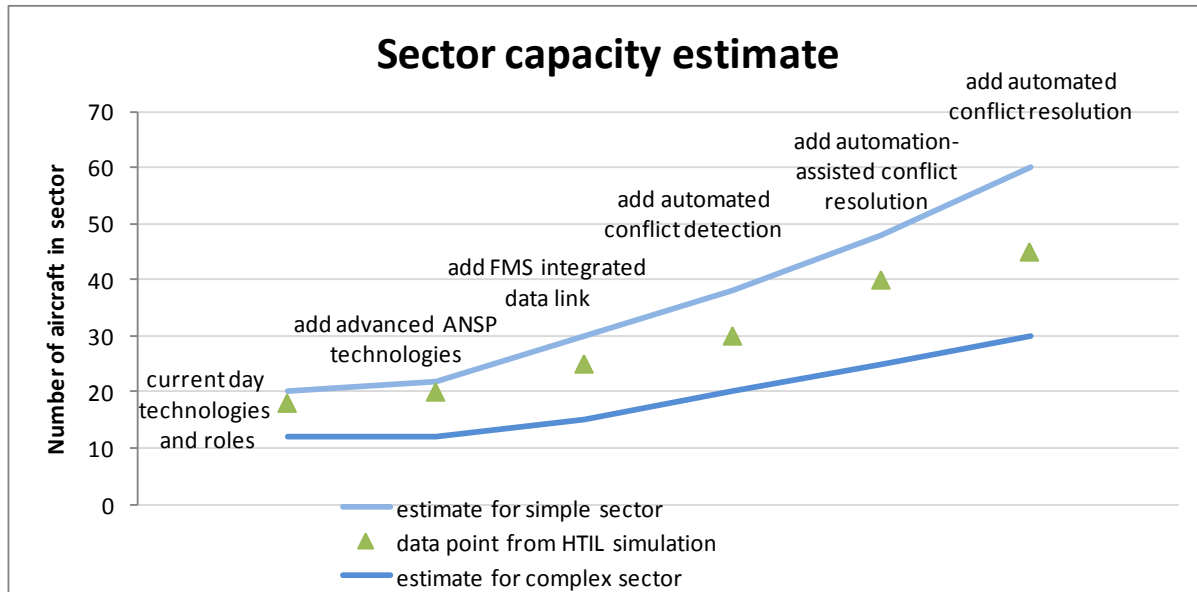

Figure 12: Sector capacity estimate based on controller-in-the-loop simulations 2007-2009

The low and high estimates included in the figure are not based on actual data. Instead they are based on the authors assessment of whether a given data point is an optimistic or pessimistic assessment of the actual capacity benefit that can be achieved.

Results: Operator Assessment

Air traffic operator assessments of the technologies were gathered during a recent mid-term human-in-the-loop simulation on multi sector planning. The experiment was conducted in two separate two-week sessions during the months of June and July 2009. For each two-week session, ten currently certified FAA air traffic controllers and managers participated at radar, supervisor, traffic management, and MSP test positions. Twelve recently retired controllers supported the participants and also monitored the advanced

Tools for Tactical Air Traffic Controllers

In one questionnaire, the tactical controllers were asked to rate the usefulness of some of the new tools that they used at the sector positions on a scale of 1 (not useful) to 6 (very useful). Figure 13 summarizes the results. The two highest rated functions were related to data link with the automated transfer of communication rated as the most useful, closely followed by the capability to uplink clearances. Conflict probing and trial planning were also rated very useful. The standard deviations for all these functions were less than 1. Automated functions for conflict resolution were rated as useful, but could benefit from minor improvements. Some controllers commented that generated altitudes did not account for direction of flight rules. The mechanisms for detecting and handling clearance requests from other positions
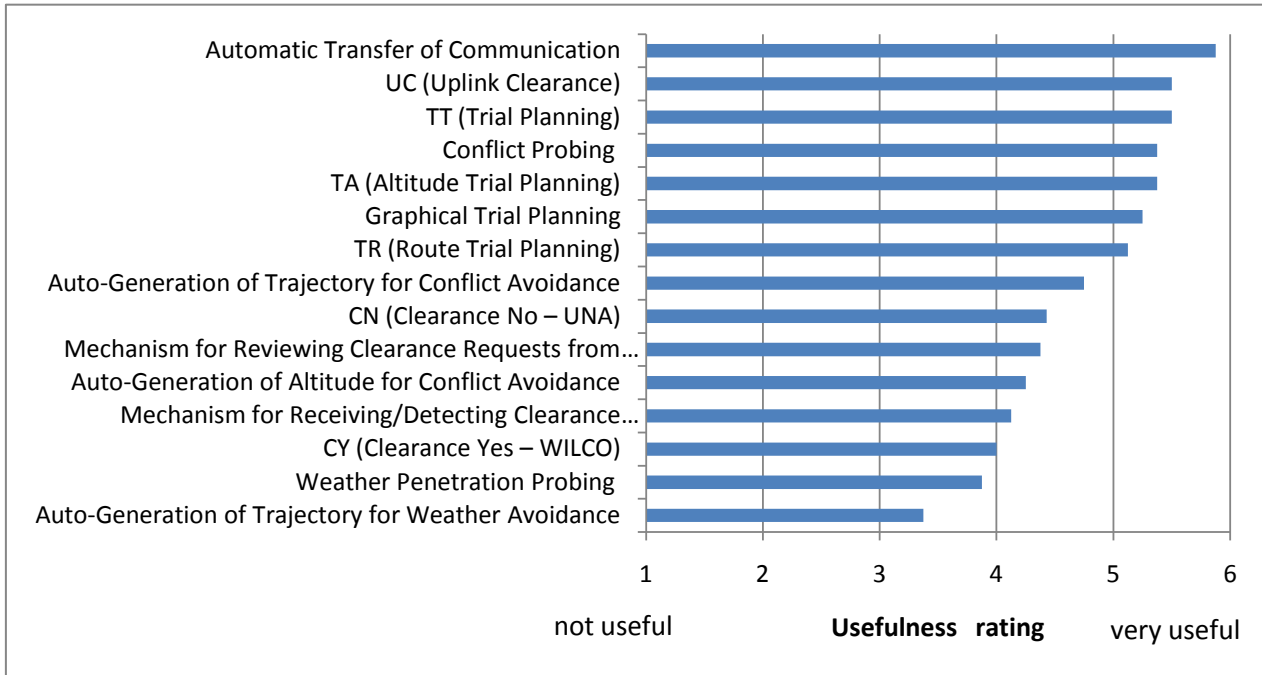
Figure 13: Usefulness ratings of sector controller mid-term toolset by eight air traffic controllers

were rated as useful as well. The weather tools received mixed ratings from the sector controllers with a standard deviation of 1.7 (weather probing) and 1.3 (weather resolution). Some controllers disliked that the little predictability of convective weather often made their trajectory changes not as good as expected, other controllers gave the functions high marks and liked the capability.

Tools for Traffic/Complexity Management

Eight operationally current air traffic operators with experience in both positions, area supervisor and traffic manager, rated the toolset for flow and complexity management. The comprehensive questionnaire asked the operators to rate a total of 68 functions on the air traffic controller workstations. The overall ratings were high with an average of 3.95 for team 1 and 4.45 for team 2. Tools and procedures were improved between the teams to address some deficiencies, which caused the improved ratings for the second team. Since discussing all 64 ratings is outside the scope of this paper. Figure 14 depicts only the ten highest rated tools and functions.
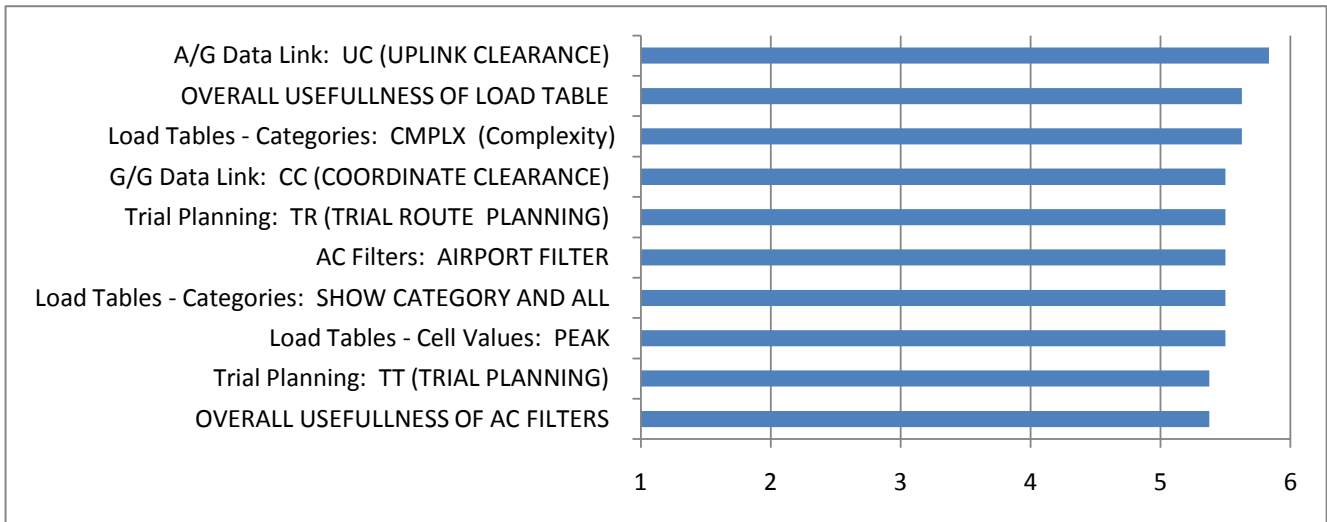

Figure 14: The ten most useful tools/functions as rated by area flow planners (out of 64 tools total)

Air/Ground data link from the planning position was rated as the most useful tool. The load table and the complexity category were rated second highest. Trial planning functions in general and route trial planning in particular were also part of the top ten.

The lowest ratings (1.5) were received for the complexity category "unequipped aircraft", which makes sense, because all aircraft in the simulation were equipped. Relatively low ratings (2.5 -3) were also received for some conflict related complexity categories. This reflects the uncertainty of conflict predictions and the clear delineation between separation management on the sector position and flow and complexity management on the planner position.

Concluding Remarks

Achieving the desired capacity for NextGen poses a significant challenge. Ground-based technologies can be developed and implemented and integrated with data com and modest upgrades to flight deck automation to increase airspace capacity in the mid-term. When transitioning separation management tasks from the controller to the automation the same technologies can be used in the far-term to provide the substantial capacity benefits desired for NextGen. Additional tools can be integrated into traffic management and supervisory positions that may improve traffic load and complexity management when capacity is insufficient. Simulations with research prototypes have indicated promising results. Follow on research is required to further specify the technologies, roles and responsibilities.

References

1. **Joint Planning and Development Office.** *Next Generation Air Transportation System - Integrated Plan.* Washington, DC : US Department of Transportation, 2004.

2. —. Concept of Operations for the Next Generation Air Transportation System Version 2.0. [Online] June 13, 2007. [Cited: August 10, 2009.] http://www.jpdo.gov/library/NextGen_v2.0.pdf.

3. **Prevot, Thomas, et al.** The Airspace Operations Laboratory (AOL). Keystone, Colorado : AIAA 2006-6112, 2006.

4. **Prevot, Thomas, et al.** Initial Evaluation of NextGen Air/Ground Operations with Ground-Based Automated Separation Assurance. Napa, CA : s.n., 2009.

5. **Prevot, Thomas, Homola, Jeffrey R and Mercer, Joey S.** Human-in-the-Loop Evaluation of Ground-Based Automated Separation Assurance for NextGen. Anchorage, Alaska : AIAA-ATIO-2008-8885, 2008.

6. **Federal Aviation Administration.** FAA Aerospace Forecasts FY 2008-2025. [Online] February 24, 2009. [Cited: August 14, 2009.] http://www.faa.gov/data_research/aviation/aerospace_forecasts/2008-2025/.

7. **European Comission, Eurocontrol, SESAR Joint Undertaking.** European Air Traffic Management Master Plan. *www.atmmasterplan.eu.* [Online] March 30, 2009. [Cited: August 18, 2009.] http://atmmasterplan.eu.

8. **Kopardekar, Parimal, et al.** Feasibility of Mixed Equipage in the Same Airspace. Napa, CA : ATM2009, 2009.

9. **Mueller, Eric and Lozito, Sandra.** Flight deck procedural guidelines for datalink trajectory negotiations. Anchorage, Al : ICAS2008, 2008.

10. **Erzberger, Heinz.** *Transforming the NAS: The Next Generation Air Traffic.* Moffett Field, CA : NASA/TP-2004-212828, 2004.

11. **MITRE/CAASD.** User Request Evaluation Tool. [Online] 2009. [Cited: August 31, 2009.] http://www.caasd.org/work/project_details.cfm?item_id=156.

12. **NASA.** Traffic Management Advisor. [Online] 2009. [Cited: August 31, 2009.] http://www.aviationsystemsdivision.arc.nasa.gov/research/foundations/tma.shtml.

13. **Brasil, Connie** (2009) Controller Training Material For Multi Sector Planner Simulation. NASA Ames Research Center

14. **Corker, Kevin,** et al.(2007) New Air Traffic Management Concepts Analysis Methodology: Application to a Multi-Sector Planner in US Airspace, ATM2007 Barcelona, Spain.