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ATC Technologies for Controller-Managed and Autonomous Flight Operations

Thomas Prevot[*], Paul Lee[†]
San Jose State University/NASA Ames Research Center, Moffett Field, CA, 94035

Nancy Smith[‡], Everett Palmer[§]
NASA Ames Research Center, Moffett Field, CA, 94035

This paper describes the ground-side automation prototyped in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center in support of two concepts related to Distributed Air Ground Traffic Management (DAG-TM) operations: *Trajectory-based air traffic control (ATC)* and *Mixed operations with airborne self separation*. The paper presents the design of the ATC automation and the evaluation of both concepts in large scale simulations. Advanced ATC automation was integrated into an emulation of state-of-the-art en route controller displays. The design of automation and controller tools for managing trajectories of data link equipped aircraft is the result of many years of air/ground integration research. The toolset includes highly responsive graphical trajectory planning and conflict probing functions, interactive timelines for aircraft scheduling, speed advisory functions and delay feedback indications for arrival metering. The automation is fully integrated with data link. To support mixed operations additional tasks had to be automated. Even though flight crews of "autonomous" aircraft are responsible for separating their airplane from all other traffic, a complex set of ground-based automation has to take over a number of additional services for autonomous aircraft that controllers and traffic managers otherwise provide for managed aircraft. The first part of the paper describes the design rationale for the ground-based automation in the context of current air traffic modernization trends. A detailed description of the prototyped ATC technologies is provided in the appendix.

The second part of the paper presents the ground-side perspective of each of the concepts effectiveness in terms of capacity, controller workload, safety, efficiency, and controller acceptability. Simulation studies using the trajectory-based ATC managed operations have demonstrated that controllers were able to manage separation and arrival times above current day traffic volumes by trajectory adjustments alone, without significantly changing roles and responsibilities of pilots and controllers. A joint Ames/Langley simulation of mixed operations shows a significant potential for much higher capacity gains. However, a number of safety concerns would need to be addressed before airborne self-separation could be operationally implemented in high density mixed environments. DAG-TM results indicate that trajectory-based ATC with integrated ground-side DSTs and airborne FMSs can safely increase capacity in the near to medium-term and could provide the environment required to enable concepts like airborne self-separation. DAG-TM research was funded by the Airspace Systems program as part of the Advanced Air Transportation Technologies project. DAG-TM activities were conducted by NASA Ames, NASA Langley, and NASA Glen Research Centers.

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[*] Senior Research Engineer, Human Factors Research and Technology, NASA ARC, MS 262-4, AIAA member
[†] Research Psychologist, Human Factors Research and Technology, NASA ARC, MS 262-4
[‡] Research Psychologist, Human Factors Research and Technology, NASA ARC, MS 262-4
[§] Human Factors Engineer, Human Factors Research and Technology, NASA ARC, MS 262-4

Nomenclature

AAC = Advanced Airspace Concept
ADS-A/B = Automatic Dependent Surveillance-Addressed/Broadcast
AOC = Airline Operational Control
ASAS = Airborne Separation Assistance System
ATM = Air Traffic Management
ATSP = Air Traffic Service Providers
CD&R = Conflict Detection and Resolution
CDTI = Cockpit Display of Traffic Information
CO-ATM = Co-Operative Air Traffic Management
CPDLC = Controller Pilot Data Link Communication
CTAS = Center/TRACON Automation System
DAG-TM = Distributed Air Ground traffic Management
DSR = Display System Replacement (Center Controller Workstation in the NAS)
DST = Decision Support Tool
E/DA = Enroute and Descent Advisor
FAA = Federal Aviation Administration
FD = Flight Deck
FMS = Flight Management System
JPDO = Joint Planning and Development Office
LOS = Loss of Separation
MACS = Multi Aircraft Control System
NAS = National Airspace System
NASA = National Aeronautics and Space Administration
NGATS = Next Generation Air Transportation System
TMA = Traffic Management Advisor
TRACON = Terminal RADAR Approach Control
RVSM = Reduced Vertical Separation Minima
STARS = Standard Terminal Automation Replacement System (TRACON Controller Workstation in the NAS)

I. Introduction

THIS paper describes research on air traffic management concepts for the next generation air transportation system (NGATS) and focuses on two approaches to modernizing the air traffic system: *(1) automation assisted trajectory-based air traffic control (ATC)* and *(2) mixed operations with airborne self-separation*. For practical purposes we will refer to these approaches in this paper as *trajectory-based ATC* and *mixed operations*.

The design of the controller tools described in this paper for trajectory-based ATC is the result of many years of research, and several iterations. The design of the automation for mixed operations was more exploratory and underwent significantly less iteration. Therefore, the design of the controller tools for trajectory management can be considered research-based recommendations, whereas the tools for dealing with mixed operations are examples that proved to be a very reasonable first iteration, but are much earlier in the design process. In spite of this qualification we feel that the automation design and the gathered results are useful input for designing the ground automation for the Next Generation Air Transportation System (NGATS).

A. The Next Generation Air Transportation System (NGATS)

In December 2004 the Joint Planning and Development Office (JPDO) transmitted the "Integrated National Plan for the Next Generation Air Transportation System" [1] to the United States Congress. The plan stresses the need for a new technology enabled approach to air transportation. It outlines a high-level vision for 2025 that combines increased automation with new procedures to achieve economical, capacity, safety, environmental, and security benefits.

The plan presents a number of operational concept elements that are aimed at tripling sector and airport capacity by 2025. New avionics will enable aircraft to operate with increasing levels of aircraft autonomy and increase flight deck situational awareness. Automation will make new air traffic management (ATM) concepts possible including shared or distributed separation management. ATM operations are envisioned to rely on end-to-end strategic traffic flow management, data link communication and information sharing to contract quiet and fuel efficient flight profiles between ground automation and airborne flight management systems and minimize adverse weather effects. Similar objectives are driving forces behind the development of the European ATM Master Plan aimed at creating a coherent and manageable research and implementation path [2].

These plans call for a rapid modernization of the airspace system and particularly stress the importance of synchronization and harmonization of airborne and ground deployments. Research and development are called upon to pick up the pace and investigate bold changes to the air transportation system even though resources for research and development are very limited. Therefore a compromise between in-depth investigation and pragmatic approaches has to be found that enables the progression of air transportation in a safe and secure environment. This paper describes a ground automation system that was rapidly prototyped to evaluate Distributed Air Ground Traffic Management (DAG-TM) concept elements in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center – which has shown the potential to quickly test various future concepts within an operationally rich simulation environment.

B. Distributed Air/Ground Traffic Management (DAG-TM)

The objective of Distributed Air/Ground Traffic Management (DAG-TM) was to develop operational concepts, procedures, and decision support technologies to meet the future demands of air travel. Its goal is to enhance user flexibility and efficiency and increase system capacity without adversely affecting system safety [3].

In the en route and transition airspace the concept elements “trajectory negotiation” and “en route free maneuvering” were investigated in simulations as part of DAG-TM. Trajectory negotiation focuses on integration of ground-based decision support tools (DSTs) and airborne trajectory planning tools via Controller Pilot Data Link Communication (CPDLC). Controllers can uplink trajectory clearances to equipped aircraft. Flight crews of equipped aircraft can downlink trajectory requests. On the ground-side this concept requires trajectory planning support for controllers integrated with data link. Research on trajectory negotiation was a continuation of earlier air/ground integration research at NASA Ames. The design of ground automation and controller tools for trajectory-based ATC presented in this paper is the result of lessons learned from all these activities.

Another en route concept element within DAG-TM is Airborne Self-Separation. Airborne Self-Separation is referred to as “free maneuvering” or “autonomous flight management” within the DAG framework. It delegates the separation responsibilities to the flight crews of properly equipped aircraft. By distributing both the tasks and the responsibilities from controllers to flight crews, the concept aims at gaining significant en route capacity and improving efficiency without compromising safety. By allowing the flight crews to fly preferred routes and altitudes, they may fly routes optimal for fuel efficiency. Air-ground communication enhancements and DSTs enable exploring the potential benefits and feasibility of delegating responsibility for maintaining separation to flight crews of properly equipped aircraft. Pilots and controllers use DSTs that process information to develop conflict-free flight path changes that comply with Traffic Flow Management (TFM). During the DAG-TM research, new Autonomous Flight Rules (AFR) operations were defined for free maneuvering aircraft. These operations essentially stated that pilots can choose their own routes, speeds, and altitudes without the controller’s approval, as long as they do not create short-term conflicts and assume responsibility for separation from other self separating and managed traffic. The controller is still responsible for separation between managed aircraft complying with standard Instrument Flight Rules (IFR) operations.

Even though flight crews of “autonomous” aircraft are responsible for separating their airplane from all other traffic, a complex set of ground-based automation had to be developed to support this type of airborne self-separation in high density mixed air traffic environments. Automation has to take over a number of additional services for autonomous aircraft that controllers and traffic managers otherwise provide for managed aircraft. These services include routine air traffic control (ATC) tasks, traffic management services, compliance monitoring and conflict probing. Routine ATC tasks such as flight plan amendments and transfer of communication have to be automated based on surveillance and data link information instead of operator inputs. Likewise, autonomous aircraft have to be scheduled over meter fixes and the scheduled times have to be communicated automatically to the flight crews for traffic management purposes. Autonomous operations have to be monitored for compliance and possible short-term conflicts have to be detected and highlighted to the controllers, who are asked to ignore autonomous operations otherwise.

Therefore, both, trajectory negotiation and airborne self-separation in mixed environments – like many other future air traffic concepts proposed by JPDO, FAA, NASA, RTCA, Eurocontrol, etc. – require well integrated air-ground DSTs [1-5,6]. In fact, the DAG-TM simulations have indicated that the air traffic control (ATC) technologies to support mixed operations in high density environments are an extension to the technologies required to support trajectory clearances and requests in a controller managed environment. Therefore, the ground system was developed to support both concepts of operations simultaneously. The conducted simulations have indicated that this approach to ATC automation design is feasible and beneficial. A number of selected results will be presented in the second half of this paper.

II. ATC Tasks, Responsibilities, and Automation

The design of the ground-based automation is primarily driven by the *air traffic control tasks* to be accomplished, the *distribution of roles and responsibilities* between the flight deck and the air traffic control system (as defined by the operational concept), and the *level of automation* derived from the controller/automation interaction philosophy.

In the following we will first summarize the air traffic control tasks. Then we will describe the distribution of roles and responsibilities and the level of automation of *trajectory-based ATC* and *mixed operations* in the context of other concepts of operations.

A. Air traffic control tasks

The air traffic control tasks within the NAS are defined in FAA order 7110.65 “Air Traffic Control” [7], which states “The primary purpose of the ATC system is to prevent a collision between aircraft operating in the system and to organize and expedite the flow of traffic. In addition to its primary function, the ATC system has the capability to provide (with certain limitations) additional services.” Therefore, the air traffic control tasks can be broken down, in order of priority, into *separation assurance*, *traffic flow management* and *additional services*. Furthermore, air traffic controllers have to conduct a number of *routine and bookkeeping tasks* like transfer of control and communication and data entries.

Separation assurance is the highest priority in the air traffic control system. Chapter 2-1-2 “Duty Priority” in FAA Order 7110.65 states: “a. Give first priority to separating aircraft and issuing safety alerts as required in this order. Good judgment shall be used in prioritizing all other provisions of this order based on the requirements of the situation at hand.” and “b. Provide additional services to the extent possible, contingent only upon higher priority duties and other factors including limitations of radar, volume of traffic, frequency congestion, and workload.” The task of separation assurance can be further broken down into *short-term conflict detection and resolution*, and *medium-term conflict prevention, detection and resolution*. Short-term conflicts are typically avoided by tactical maneuvers, medium-term conflicts are prevented by airspace design or specific flight rules. In case a medium-term conflict is detected, it can be resolved through strategic flight path changes. For the purpose of this paper we consider short-term conflicts, conflicts with less then four minutes to loss of separation (LOS) and medium term conflicts, conflicts with four to thirty minutes until LOS.

The purpose of *traffic flow management* is to organize and expedite the flow of traffic. High congestion routinely requires traffic management units to impose certain flow restrictions in order to limit the amount of traffic into airspace areas, in which demand is expected to exceed capacity. These flow constraints are then communicated to sector controllers, who have to control their traffic according the imposed constraints. In today’s environment, traffic flow constraints are often imposed as miles in trail (MIT) restrictions. These can be communicated directly to the controller, who will deliver the aircraft at the required distance. Controlling aircraft to achieve and maintain a certain distance or time between each other is the purpose of the *spacing* task. Miles-in-trail restrictions and other constraints like airport acceptance rates can feed into a *scheduling* process that computes scheduled times of arrival (STA) for each aircraft. These STAs are then relayed to the controllers, who apply *metering* techniques to deliver the aircraft at the scheduled times.

Additional services cover a range of additional tasks that controllers perform workload permitting. Many of these services are related to *accommodating user preferences* like weather diversions, new altitude or route requests.

Routine and bookkeeping tasks have to be performed in order to progress any given flight through the airspace. Controllers have to *transfer control and communication* of aircraft when they transition into a new airspace sector. Furthermore controllers have to make necessary *data entries* to relay flight plan amendments and clearance assignments to the ground automation and other operators within the air traffic control system.

B. Operational Concept and Level of Automation

The operational concept describes the context, i.e. the roles and responsibilities and the environment, in which the primary operators, the pilots and controllers, have to complete these tasks to move the aircraft safely and efficiently through the airspace. In this context the human/automation interaction philosophy drives the level of automation to aid or replace the operator in performing these tasks. Assuming that the air traffic control tasks will stay basically the same in the future, necessary improvements over today’s system can only be achieved by shifting more task load to other human operators (e.g. flight crews), i.e. changing the roles and responsibilities, and/or by adding new automation.

Figure 1 depicts notionally how much automation is involved in the ground-based air traffic control operations vs. the distribution of tasks and responsibilities to accommodate different concepts of operations.

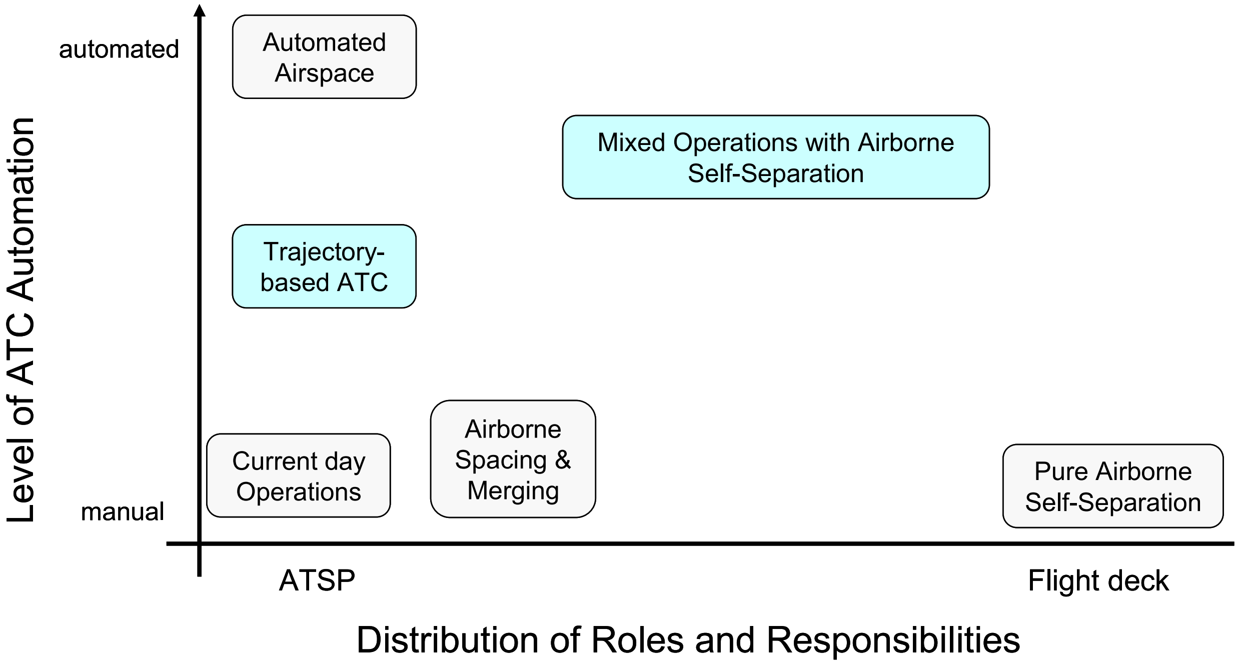


Figure 1. Level of ATC automation and distribution of tasks and responsibilities for various concepts

Current day operations are mostly manual with very limited automation support. The far end of the automation axis would be realized by an "Automated Airspace System", which would require a radical implementation of the "Advanced Airspace Concept" [8]. This concept assigns all separation functions to the ground automation and could theoretically assign all of the air traffic control functions to the automation, with the controller perhaps in a supervisory role. The far end of the responsibility distribution axis would be implemented by pure airborne self-separation[9], which requires a dramatic change in the operational concept and assigns all of the air traffic control tasks to the flight deck. The figure indicates that pure airborne self-separation – unlike mixed operations - does not require any additional ground-side automation. It can also be argued that a pure airborne self separation environment does not require ground-based air traffic control services at all.

An initial step towards assigning new tasks to the flight deck is the concept of airborne spacing and merging (ASAS 2[9]). This concept assigns only the spacing task to the flight deck, does not change the responsibilities for separation and does not require much additional air traffic control automation.

The two design points described in this paper fit into this framework as indicated in Figure 1: Trajectory-based ATC adds significant air traffic control automation to free up controller resources in order to handle additional traffic or to provide improved additional services. The concept does not require a change in responsibilities from current day operations. Therefore, trajectory-based ATC progresses the air transportation system along the ATC automation axes, but not directly along the responsibility distribution axis.

The concept of mixed operations assigns the responsibility for separation to self-separating aircraft. These aircraft can choose trajectories independent of standard airways and routes and have to blend into the flow of managed aircraft without increasing controller workload. Therefore, mixed operations require the trajectory-based ATC environment as enabling technology. Additionally, the ground automation has to automatically keep track of and perform all coordination tasks between managed and self-separating aircraft. Hence, even more automation than trajectory-based ATC is necessary to accommodate this major change in the distribution of roles and responsibilities. Because of its complexity mixed operations can be considered one of the most challenging problems in air traffic modernization.

It should be noted that the operational concepts depicted in Figure 1 are point designs. It is unlikely that one of these concepts will exclusively be used across the global airspace. Research should investigate interoperability and combinations of different concepts. Our research on *Trajectory-Oriented Operations With Limited Delegation (TOOWiLD)*[10,11] addresses a combination of trajectory-based ATC and airborne spacing and merging as a near- to medium-term option for gaining improvements by moderately progressing along both – the task allocation and the automation – axis. The concept of Co-operative Air Traffic Management (Co-ATM)[12] is aimed at creating a framework, in which automated airspace functions integrated with multi sector positions provide the necessary capacity gains and enable airborne self-separation upon operator choice.

III. Design Rationale

In order to explain our design rationale for the two concepts *Trajectory-based ATC* and *Mixed Operations* we will first briefly review how the different tasks are accomplished in the current air traffic control system. Then we will summarize our automation design. A detailed description of the controller interfaces can be found in the appendix of this paper.

A. Current air traffic control system

The current air traffic control system is characterized by sector oriented operations, voice communications and a flight plan based ground system. Two positions are available for each sector in the NAS: a Radar position (R-Side) and a Data position (D-Side). Depending on traffic density and complexity one, two, or three controllers control all aircraft in their sector Limited automation support is available primarily on the D-Side. The task allocation is summarized in Table 1.

Table 1. Task allocation in the current system.

Primary task	Sub tasks	Controller	R-Side Automation support	D-Side/TMU Automation support	Flight crew
Separation assurance	**Short-term conflict detection**	monitor traffic within the sector for potential LOS	Conflict Alert (< 2 minutes to LOS) J-Ring, Predictor		-
	Tactical conflict avoidance	Vectoring/voice	-	-	Execute maneuver
	Medium- term conflict detection	Monitor traffic within the sector	-	Flight plan based probe (URET) in some facilities	-
	Strategic conflict resolution	judgment, Clearance amendment or vectoring/voice	-	-	Program new flight path
	Strategic conflict prevention	Airspace design, standard routings and flight rules,	-	-	Follow flight rules
Traffic flow management	**Spacing**	Vectoring/voice	Range rings		
	Scheduling	Miles in trail or STAs	-	CTAS Traffic Management Advisor	-
	Metering	Vectoring/voice	Meter list		
Additional services	**Accommodating user preferences**	Judgment, Manual assessment Clearance amendment or vectoring/voice	-	-	Requests/voice
Routine and bookkeeping tasks	**Transfer of control**	manual	Auto handoff, if aircraft is en route		-
	Transfer of communication	Manual/voice	-	-	Initial contact with next sector
	Data entries	manual	-	-	

1. *Separation Assurance*

Controllers monitor the air traffic in their sector for potential conflicts. To visualize current separation and highlight particular aircraft, controllers can display 5 NM rings around selected aircraft. To predict future separation controllers can display predictor lines that start at the aircraft target symbol and end at the predicted position of the aircraft in a selectable time from now. The predictors are based on ground speed and track angle retrieved from the ground surveillance system and are therefore noisy and lagging in a radar environment and do not account for any planned trajectory changes.

To aid short-term conflict detection a conflict alert function is available to alert controllers to potential separation violations that may occur within the next two minutes. This conflict alert must be considered a last safeguard and should not go off under normal circumstances. To solve short-term conflicts controllers typically issue tactical instructions to one or both aircraft that are involved in the potential conflict, typically by changing heading and/or altitude. Avoiding short term conflicts and the resulting inefficient tactical maneuvers is the goal of medium term conflict detection. This will help with separation assurance and also expedite the flow of traffic and hence serves two of the primary purposes of the ATC system today. Many medium term conflicts are prevented by airspace design and instrument flight rules (IFR) defining e.g. different altitudes for different directions of flight. Beyond those built in safeguards, medium term conflict detection and resolution today relies heavily on the controllers' expertise, in terms of experience with the airspace and the traffic flows and preventive strategic clearances to keep aircraft routings and altitudes apart from each other. In some air route traffic control centers (ARTCC) in the NAS controllers also have access to the User Route Evaluation Tool (URET), implemented in the data side (D-side) of the workstation alerting controllers to potential medium term conflicts and given them tools to reroute aircraft. There is currently no medium term conflict detection or resolution tool integrated into the primary controller display, the radar side (R-side) display.

2. *Traffic flow management*

Controlling aircraft to meet traffic flow constraints is also conducted with very limited automation support. Spacing between aircraft is typically assessed using range rings and predictors on the display. Controllers then use their expertise to issue appropriate instructions to achieve and maintain the desired spacing. In a time-based metering environment controllers can display meter lists that show STAs and necessary delay numbers. Again, based upon expertise controllers issue appropriate heading, speed, and altitude instructions to absorb the delay necessary to deliver aircraft within one minute of their STA. This type of time-based metering will become available in every en route facility in the US, as a result of the national deployment of the CTAS Traffic Management Advisor (TMA).

3. *Additional services*

User requests are considered workload permitting and typically being granted when in line with global flow patterns known to the controller. A controller would – for example – typically not grant a direct routing request of a departing aircraft through a sector filled with heavy arrival traffic. In complex and/or dense traffic environments controllers are usually too busy providing safe separation and meeting flow constraints to even consider dealing with requests for preferred routings or altitudes. Most flight crews assess the situation by monitoring the frequency congestion and do not even attempt to submit requests for additional services during busy periods.

4. *Routine and bookkeeping tasks*

A significant amount of controller workload in the current day system is associated with routine and bookkeeping tasks like sector to sector handoff and transfer of communication. The transfer of communication is a particularly workload intensive task, because it requires the controller to detect when a handoff of an aircraft has been accepted by the next sector, then to verbally instruct the flight crew to switch to a new frequency, which is a lengthy radio transmission. Because controllers are used to receiving the initial contact message at their sector soon after handoff acceptance, the expectation is that the transferring controller pays specific attention to issuing the frequency change instruction quickly after the handoff was received. Automating this task using data link is a planned initial application of data link that was already field tested and is expected to provide significant productivity benefits.[24]

5. *Other factors*

Some other factors that limit the current system are related to information exchange limitations. Operations rely on crude flight path descriptions specifying the lateral path of a flight and the cruise altitude, but no intermediate altitudes or speeds. Automated functions like auto-handoff typically only work correctly as long as aircraft comply with the system stored flight plan which has to be kept up-to-date by the controller. Another limiting factor is radio communication. This limits the complexity and the number of information exchanges between the flight crew and the controller and frequency congestion in general has become a common problem in dense airspace.

B. Trajectory-based ATC

Trajectory-based ATC is targeting efficiency and capacity improvements without changing roles and responsibilities, i.e. without removing any of the above described tasks from the air traffic control system. Instead, the goal is to free up controller resources by introducing automatic functions to assist controllers in conducting the majority of tasks. To maximize effectiveness, new tools are integrated directly into the controller's workstation (R-Side). The advanced automation support is enabled primarily through improvements in the information exchange infrastructure, which can result in a truly integrated air/ground system[12]. The envisioned infrastructure provides data link communication for 4-D trajectories, and routine messages between controllers and the flight crew, and enhanced surveillance information provided by e.g. ADS-B. In this concept data link is not used for exchange of time critical messages from the ground system to the flight deck, which is in compliance with the requirements of medium-term data link systems. The infrastructure makes it possible to maintain highly reliable 4-D trajectory predictions within the ground system. Once these 4-D trajectories are available for all aircraft, automation can provide knowledgeable assistance for all tasks that depend on estimating the flight progress. A closer look at the tasks outlined in table 1 reveals that all but two --the transfer of communication and some data entries -- rely on 4-D trajectory predictions, either based on flight state extrapolations or planned flight paths. The two remaining tasks are communication functions in which data link can provide additional support.

In other words trajectory-based ATC can fill the gaps in the column "R-Side automation support" of table 1 with tools that are designed to assist controllers in performing their task. The human/automation integration philosophy is to relieve controllers of many of the routine manual tasks and provide reliable and responsive computer calculations for complex flight path predictions. Consequently, controllers can concentrate on planning and decision-making tasks, thus increasing capacity and the efficiency of the traffic flow.

Table 2 Task allocation for Trajectory-based ATC

Primary task	Sub tasks	Controller	R-Side Automation support	Flight crew
Separation assurance	**Short-term conflict detection**	monitor traffic within the sector for potential LOS	Improved Conflict Alert (< 2 minutes to LOS), Commanded trajectory based Conflict probe (1-5 minutes) J-Ring, Predictor	-
	Tactical conflict avoidance	Vectoring/voice	-	Execute maneuver
	Medium- term conflict detection	Monitor traffic and conflict feedback within the sector	Planned trajectory based Conflict probe (4-30 min)	-
	Strategic conflict resolution	Trial plan and data link route/altitude amendments	Trial planner with responsive conflict feedback integrated with data link	Load new flight path
	Strategic conflict prevention	Strategic conflict detection and flight rules,	Conflict probe	Follow flight rules
Traffic flow management	**Spacing**	Vectoring/voice	Range rings	
	Scheduling	STAs	Timeline with scheduling functions	-
	Metering	Uplink provided speed advisories, trial plan delay trajectory, data link route and/or cruise altitude changes	Timeline, Delay feedback Speed advisory and trial planner integrated with data link	
Additional services	**Accommodating user preferences**	Conflict probe of downlinked trajectory and data link response	Trial planning/conflict probing	Requests/voice
Routine and bookkeeping tasks	**Transfer of control**	Manual/Automatic as desired	Auto handoff for all aircraft along trajectory	-
	Transfer of communication	Manual/Automatic as desired	Automatic or manual release via data link	Initial contact with next sector
	Data entries	Manual/ Automatic upon accepting or sending if trial planned or advisory	One click data link host amendment from trial planner	

Table 2 shows that improved automation support is available for almost all tasks. Figure 2 shows an example of a controller display for trajectory-based ATC. A detailed description of the controller tools is provided in the

Appendix of this paper. The following sections explain the automation support in the context of the air traffic control tasks.

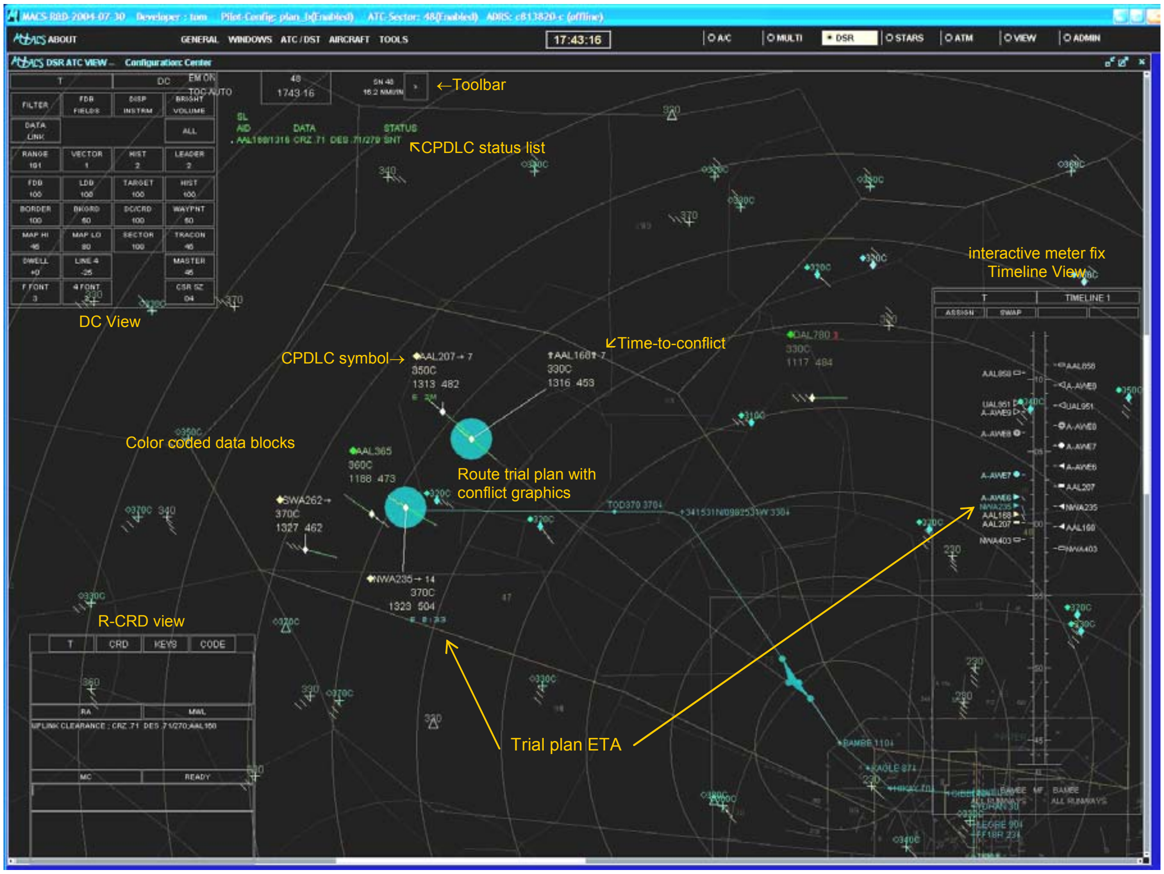


Figure 2. Example controller display

1. Separation Assurance

Trajectory-Based ATC supports controllers in assuring separation on a strategic level. Besides improvements to the short-term conflict alert and detection functions no automation has been added to support the tactical conflict resolution task. As long as controllers can maintain appropriate traffic awareness, they are extremely proficient in issuing tactical maneuvers that avoid an imminent LOS. In order to be able to assign the short-term conflict resolution task to the automation, a number of open issues would have to be resolved, which go beyond the strategic approach of trajectory-based ATC used in our design. Instead, the primary design goal was to allow controllers to resolve all potential conflicts and metering problems strategically using highly responsive and well-integrated trial planning functions and one click uplinks of the trial planned trajectories. The medium-term conflict probe supporting this task uses a variety of sources to provide the most reliable trajectory prediction, including the FMS downlinked trajectory, the flight control system targets for altitude, heading, and speed, flight plan and metering information. A flight status tracking and compliance monitoring function decides how to generate trajectories for tactical conflict prediction, strategic conflict prediction, and traffic management purposes. Trajectories for these purposes can be different and are only identical if the aircraft complies with its reported trajectory and the reported trajectory complies with the ground based flight plan.

Potential conflicts are indicated in the data tag as time-to-conflict and in a conflict list. Clicking on either brings up the conflict graphics depicting the conflicting aircraft and the likely conflict location. The controller can then activate the trial planning function and probe route and/or altitude changes for conflicts. (Figure 1 shows an example trial plan for NWA285.) During the trial planning process conflict feedback is continuously provided. At the same time a controller drags a new point along the route, potential LOS locations are indicated graphically without visible delay (within a few milliseconds). This kind of responsiveness is arguably required for using trial planning on the R-Side for congested airspace[13]. Fast conflict feedback was achieved by pre-computing and storing the future locations of all aircraft for small time increments (e.g. 15 seconds) during the regular conflict prediction cycle and using a smart comparison logic during the trial planning process at the controllers workstations. Details go beyond the scope of this paper, but can be provided to interested readers.

Once an appropriate route/altitude change has been determined it can be data linked with a simple command to the aircraft. The new trajectories can be loaded by the flight crew into the FMS using the data link load function. If acceptable, flight crews execute the new trajectory and send their acceptance message to the controller. The flight plan in the ground system is amended automatically and no further action on the controller's part is required.

2. *Traffic flow management*

The automation designed for trajectory-based ATC provides additional support for scheduling and metering. Support for the spacing task has not been part of this automation, but has been integrated for follow-on projects.[10]

Scheduling support is provided by integrating interactive timelines into the R-Side display. This allows controllers to view the STAs of aircraft under their control in the context of the remaining traffic to the same metering point. Functions for swapping and re-assigning STAs are integrated into the timeline.

Once an aircraft is assigned a particular STA the ground automation provides *metering* support. It determines every few seconds, whether a modification to the aircraft's cruise and descend speed profile is necessary and sufficient to deliver the aircraft at the desired time over the metering fix. The information is then depicted in the aircraft's data tag. If no modification is necessary, no advisory is shown, indicating to the controller that no action is required. If a speed change is sufficient and necessary, the speed profile is shown and the controller can data link the advisory with a simple command to the flight crew. In case a speed change is insufficient, the system provides an early/late indication. This field shows the controller that the aircraft needs to be delayed or sped up with other means than a speed assignment. The controller can then activate the trial planning function and probe route and/or altitude changes for conflicts and meter time compliance. (Figure 1 shows an example trial plan for NWA285.) During the trial planning process delay and conflict feedback is continuously provided. The early/late indication in the data tag and the estimated time of arrival are updated for the trial plan trajectory enabling controllers to create route changes that absorb all or part of the required delay precisely. Once an appropriate route/altitude change has been determined it can be uplinked to the aircraft as previously described.

3. *Additional services*

In trajectory based ATC, user preferences can be submitted from the flight deck as full trajectory requests. These can either be generated through the FMS or using an advanced Cockpit Display of Traffic Information (CDTI) [14]. This allows flight crews to generate complex trajectories instead of limiting their requests to simple route or altitude changes that can be accommodated by voice. A downlinked request is indicated to the controller in the data link status list and with a down arrow symbol in the data tag. Workload permitting the controller can click on the symbol, which displays the request graphically and automatically checks it for conflicts. The controller can then decide whether to grant the request or deny it and easily uplink the decision to the flight deck. When a trajectory request is approved, the system will automatically amend the flight plan for the aircraft. This straightforward procedure was found acceptable in simulation studies on trajectory negotiation [15,16].

4. *Routine and bookkeeping tasks*

Having reliable trajectory predictions for all aircraft and data link integrated into the controller workstation allows the automation to perform routine tasks like transfer of control and communication. The current ATC system enables auto handoff functions only at adapted sector coordination points for aircraft that comply with their flight plan. A trajectory-based system provides auto handoff capabilities for free routings using trajectory predictions to estimate sector entry and exit times, which in turn trigger the auto handoff function when necessary. Therefore, auto handoff functions can be used as the standard operating mode if so desired. In addition data link was implemented for transfer of communication modeled after the CPDLC implementation used for operational evaluation in Miami Center.[24] When the receiving controller accepts a handoff a "contact" or "monitor" data link message is prepared and either held for controller release or automatically sent to the aircraft.

As mentioned throughout this section, many of the bookkeeping tasks like flight plan amendments are automated when the controllers use the trial planning and data link functions. All standard data entry permission mechanisms still apply. For example, controllers have to have control over an aircraft to amend its flight plan or need data link eligibility to use the data link functions. As in today's system mechanisms exist to override these permissions on a case by case basis.

Automating these routine and bookkeeping tasks frees up significant controller resources. There will, however, likely be instances in which the automation acts at an unwanted point, e.g. transferring communication of an aircraft that the controller still needs to talk today. There are already procedures in place to deal with these cases and these procedures need to remain. The results so far have indicated that letting the automation handle these routine functions with the controller intervening only by exception is an acceptable and beneficial approach. This task allocation between the controller and the automation mimics the task allocation between the radar and the data controller in the current system.

5. *Other factors*

Trajectory-based ATC removes many of the other factors limiting the current system. Data link exchange of trajectories and routine messages replaces many of the radio transmission, thus solving the frequency congestion problem. This allows controllers and flight crews to use the voice channel for urgent communications or to provide additional services. On the other hand, pilots are no longer able to assess the controller's workload simply by the amount of radio chatter. It was already observed in simulations that pilots would make lengthy low priority voice transmissions or send complex trajectory requests in situations, in which controllers were in fact too busy to deal with any kind of request.

Ultimately, all automation effects can only be fully assessed in the context of a realistic operational environment. Trajectory-based ATC is designed to provide an expandable framework for introducing new automation without changing too many variables at the same time.

C. Mixed Operations with Airborne Self-Separation

The concept of mixed operations that was implemented under DAG requires that flight crews of self-separating aircraft separate themselves from all other traffic. This was part of a set of "autonomous flight rules" (AFR) that were defined in contrast to the instrument flight rules (IFR), under which the managed aircraft were controlled with traditional responsibilities. For simplification purposes we will refer subsequently to self-separating aircraft as *AFR aircraft* and to controller-managed aircraft as *IFR aircraft*.

In section II of this paper we discussed that mixed operations with airborne self-separation require a higher level of automation than trajectory-based ATC. The reason is that the idea of self-separation is not to train pilots as controllers and conduct a manual control task. Instead the airborne automation is made responsible for conflict detection and resolution. However, the airborne automation can only provide separation services effectively if all surrounding traffic follows predictable flight paths and the flight path intent is available to the AFR aircraft. It seemed therefore appropriate for our design to use trajectory-based ATC as the environment in which to conduct mixed operations. Thus, controllers handled all IFR traffic according to the description provided in the previous section. AFR aircraft leveraged this environment and were intended to operate quasi-invisible. Table 3 summarizes the task allocation as it relates to interactions between ATC and AFR aircraft during mixed operations.

The idea of airborne self-separation is to minimize the impact of AFR aircraft on controller workload. The following sections describe our approach to realizing this philosophy and some of the challenges that were discovered in the process.

1. *Separation assurance*

To achieve the desired capacity increases, self-separating aircraft needed to have little or no impact on controller workload. A key concept designed to achieve this goal was that the flight crews flying under AFR were responsible for separating their aircraft from all other aircraft, including IFR aircraft. The controller was responsible for separation assurance of IFR aircraft only when the conflict was with another IFR aircraft.

To minimize the interactions between AFR and IFR aircraft the following rules were established. Pilots of AFR aircraft were expected to resolve all conflicts for which they were responsible at least 2 minutes before loss of separation (LOS). Conflicts between AFR and IFR aircraft should be announced to the controllers only when the pilot did not resolve the conflict by 3 minutes before LOS, i.e. one minute before the pilot was required to resolve the conflict. Controllers could contact the pilot to coordinate a resolution, ask for pilot's intent, etc., but they were not required to do so. In addition, pilots and controllers could not make flight path changes that caused a predicted LOS in less than 4 minutes.

Hence, controllers were asked to ignore AFR aircraft in their sector as far as possible and were not responsible for detecting and solving conflicts involving AFR aircraft. However, they were responsible for making sure that flight path changes to managed aircraft would not result in a short-term conflict with an AFR aircraft. Consequently, in this concept controllers are asked to ignore many aircraft in their airspace most of the time, but need excellent awareness of the same aircraft some of the time. Especially, they need to consider the AFR traffic before instructing an IFR aircraft to change its route or altitude. Adding to the complexity of the problem was the conceptual idea of making controllers aware of short term IFR/AFR conflicts, so that they could contact the AFR aircraft with a traffic callout if necessary. However, controllers could not simply move the IFR aircraft to resolve the conflict because the maneuver could have coincided with a maneuver conducted by the flight crew of the AFR aircraft. As a result controllers and the automation had to deal with a set of conflicting guidelines under certain situations that may instruct them to (1) ignore AFR aircraft, (2) don't create a short-term conflict with an AFR aircraft (3), be aware of short-term IFR/AFR conflicts, and (4) don't move the involved IFR aircraft if you see a conflict. This presented a dilemma that made it impossible to implement a clean design. The first requirement would have been best met with suppressing information on AFR aircraft from the display, but this would not have met the second and the third requirement. As a compromise we decided to display AFR aircraft as limited data tags with information about their data link status, altitude, RTA assignment status (described in the next section) and their control status. Controllers can adjust the brightness of limited data tags separately, allowing them to customize the presentation to their personal preference. The limited AFR data tags change to full data tags with a time to conflict indication, whenever the system predicts a short-term AFR-IFR conflict. Controllers were encouraged to trial plan all route and altitude changes, so that the new trajectories could be checked by the automation before issuing the clearance. The ground-based conflict probe looks for short- and medium-term IFR/IFR conflicts and short-term AFR/IFR conflicts. AFR/AFR interactions were not examined by the ground-based conflict probe.

The complicated description of IFR/AFR conflict management in this section indicates the complexities associated with IFR/AFR interactions. The results presented later in this paper reflect the potential confusion surrounding the issue, which is a conceptual problem rather than a problem with the automation.

Table 3. Task allocation for interactions between ATC and self-separating aircraft in mixed environments

Primary task	**Sub tasks**	**Controller**	**R-Side Automation support**	**Flight crew**
Separation assurance	**Short-term conflict detection**	monitor traffic within the sector for potential LOS	Improved Conflict Alert (< 2 minutes to LOS), Commanded trajectory based Conflict probe (1-5 minutes) J-Ring, Predictor	Flight deck automation and monitoring
	Tactical conflict avoidance	Contact flight crew	-	Avoid conflict
	Medium- term conflict detection	-	-	-
	Strategic conflict resolution	-	-	Automation assisted flight path change
	Strategic conflict prevention	-	-	Follow flight rules
Traffic flow management	**Spacing**	-	-	
	Scheduling	STAs	Timeline with scheduling functions	
	Metering	Gatekeeper function	Automatic uplink of RTA	RTA compliance
Additional services	**Accommodating user preferences**	-	Process downlinked trajectories	Can select their flight path freely
Routine and bookkeeping tasks	**Transfer of control**	-	Auto handoff for all aircraft along trajectory	-
	Transfer of communication	-	Automatic via data link	Initial contact with next sector
	Data entries		Automatic from downlinked data	

2. *Traffic flow management*

Coordination between traffic flows of IFR and AFR aircraft in mixed environments can be achieved by time-based metering. For arrival problems the ground-based scheduling automation, e.g. TMA in the NAS, generates scheduled times of arrival for metering fixes. The scheduled times get assigned or "frozen" at approximately 200 NM from the airport. Controllers manage trajectories of IFR traffic to deliver aircraft within a certain interval (15 seconds) of these scheduled times as described in the section on trajectory-based ATC. Whenever the automation assigns an STA to an AFR aircraft it automatically sends this time as Required Time of Arrival (RTA) to the flight deck. No controller action is required to perform this task. It is up to the flight crew of the AFR aircraft to find a proper trajectory that meets the time.

The controller responsible for the sector with the metering fix is also the "gatekeeper". If an AFR aircraft is unable to comply with a metering restriction the flight crew is supposed to contact the controller, who will decide on the proper course of action. Therefore, controllers have to occasionally provide traffic flow services to AFR aircraft. Controllers can also continuously monitor the predicted traffic flow compliance on their timeline which indicates estimates and schedules for IFR and AFR aircraft (see also figure 2).

3. *Additional services*

The concept of airborne self-separation is all about accommodating user preferences. As AFR aircraft can choose their trajectories freely as long as they don't create any short-term conflicts, routing preferences are accommodated by design. However, in dense transition airspace AFR aircraft have to adhere to the created schedules and are therefore very limited in the potential improvements they can achieve. However, if airborne self-separation were considered to be desirable for overall traffic flow improvements, additional user preferences could be worked into the scheduling process.

4. *Routine and bookkeeping tasks*

In order to make AFR operations work within the framework of IFR traffic without tasking the controller, the ground automation has to conduct all routine and bookkeeping tasks automatically. Even though controllers are not managing AFR aircraft track control is still transferred between sectors for consistency purposes. Therefore, the automation examines the trajectories of AFR aircraft for boundary crossings and transfers control to the appropriate sector. Once control is transferred a "MONITOR <frequency>" transfer of communication message is automatically data linked to the aircraft. This makes sure that voice communication between controllers and flight crews of AFR aircraft is possible in the geographical airspace sector that the aircraft is currently flying in. Additionally, aircraft downlinked parameters are used to update the flight plans of AFR aircraft in the ground automation. The flight plan is amended with the routing that the aircraft is transmitting in its trajectory report, the assigned altitude is gathered from the pilot selected altitude, if reported. This enables a consistent ground side processing of AFR and IFR aircraft.

5. *Other factors*

Accurate automatic ground side processing of AFR flights relies heavily on the quality of the trajectory predictions. The main source for trajectory predictions are the aircraft reported trajectories. However, these reports can differ significantly for different aircraft. Some aircraft report their planned FMS trajectory that describes the complete planned flight path from the current position to the runway. Others report only a subset of the trajectory that is currently used to drive the flight control system. This inconsistency increases the complexity and difficulty in maintaining accurate predictions in the ground automation necessary to provide services to AFR aircraft in mixed environments. To provide short-term separation assurance support to the controllers the ground automation should have knowledge about accurate state and flight control system targets. For traffic flow management, additional services and routine and bookkeeping tasks the ground automation requires the complete description of the planned trajectory. Therefore, mixed operations require an elaborate air/ground infrastructure from a ground automation standpoint alone. The infrastructure necessary to provide the sophisticated airborne functions for self-separation in dense, mixed environments imposes additional requirements that go beyond the scope of this paper.

IV. Simulation Evaluation

This section presents key ground-side results for trajectory-based ATC and mixed operations. Simulations were conducted over several years to evaluate different aspects of the concepts and refine the procedures and automation. Most of the results presented here were gathered in 2004, when a joint human-in-the-loop DAG-TM experiment was conducted at NASA Ames and Langley Research Centers to investigate the feasibility and operational benefits of mixed operations with controller-managed and self-separating aircraft. Some results on trajectory-based ATC were gathered during simulations of integrated air/ground operations (managed and mixed) at NASA Ames Research Center in 2002 and 2003.

All DAG-TM simulations described in this paper used the airspace illustrated in figure 3. It included portions of Albuquerque Center (ZAB), Fort Worth Center (ZFW) and Dallas-Fort Worth TRACON (DFW) (Figure 3). Controller participants worked four test sectors in the northwest arrival corridor: three high altitude sectors (Amarillo in ZAB, Wichita Falls and Ardmore in ZFW), and one ZFW low altitude sector (Bowie). Three retired controllers worked peripheral sectors, labeled Ghost North, Ghost South and a TRACON position to handle the surrounding traffic.

Arrivals transitioned Amarillo high and Wichita Falls high from the northwest and Ardmore high from the north. The two main streams of arrivals merged in the Bowie low sector before entering the TRACON at the BAMBE meter fix. The traffic mix in Amarillo consisted of arrivals and overflights in level flight. Wichita Falls had a significant portion of the arrivals in level flight and descent, mixed in with overflights and some departures. Ardmore had arrivals, departures, as well as a significant number of overflights.

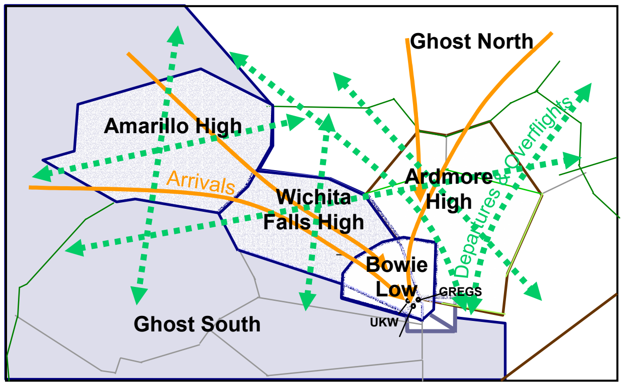


Figure 3: Simulated Airspace

Air traffic control was simulated in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center. Each of the four test sectors was staffed with a certified professional air traffic controller from a US-ARTCC. During some simulations a 5th controller served as tracker to support the radar controllers. The AOL also hosted multi aircraft stations for all IFR operations that were not flown by pilot participants. Airline pilots at NASA Ames participated in the simulations flying a full mission simulator and desktop-based glass cockpit simulators. During the joint Ames/Langley simulation additional pilots flew desktop simulators at NASA Langley, bringing the total to 22 commercial airline pilots. Additional AFR traffic for mixed operations was controlled by multi aircraft pilots and autonomous agent support at Ames and Langley.

In order to evaluate the effectiveness of the concepts, comparisons were made between (1) trajectory-based ATC and current day operations, and (2) mixed operations at various traffic levels and trajectory-based ATC. Each comparison is presented subsequently according to the tasks identified in the previous sections of this paper in the following order:

1. Traffic load, complexity, and workload
2. Separation assurance
3. Traffic flow management
4. Additional services
5. Automation support
6. Controller acceptance

A. Comparison of trajectory-based ATC with current day operations

As stated in section II of this paper trajectory-based ATC is targeting efficiency and capacity improvements without changing roles and responsibilities. Instead, the goal is to free up controller resources by introducing automatic functions that assist the controllers in conducting the majority of tasks.

1. Traffic load, complexity, and workload (trajectory-based ATC)

The results in the analysis for trajectory-based ATC were – except where indicated – gathered during the all-managed trajectory-based condition of the joint Ames/Langley simulation. This condition exposed controllers to the traffic loads shown in Figure 4 for about 30 minutes during each run. A nominal Monitor Alert Parameter (MAP) is also indicated for reference based on FAA regulation 7210.3 (FAA 2004). This figure shows that the controller in the pure en route sector (AMA) had track control over 22 aircraft on average, peaking up to 31. The transition sector (SPS) that had the majority of arrival traffic and a significant amount of overflights handled 15 aircraft on average with a maximum of 22. The other transition sector (ADM) handling an equal combination of departures, overflights and arrivals controlled 18 aircraft on average with a maximum of 26. The low altitude sector only handled 7 aircraft on average, because both high altitude sector controllers absorbed most of the delay, so that the low altitude sector controllers' task basically involved taking and giving the handoffs and fine-tuning the aircraft merge at the metering fix.

The traffic loads show that en-route and transition sector controllers were able to handle as many aircraft or more than the current day maximum for a significant period of time, and peaking at a maximum of about 150% of the current day sector capacity.

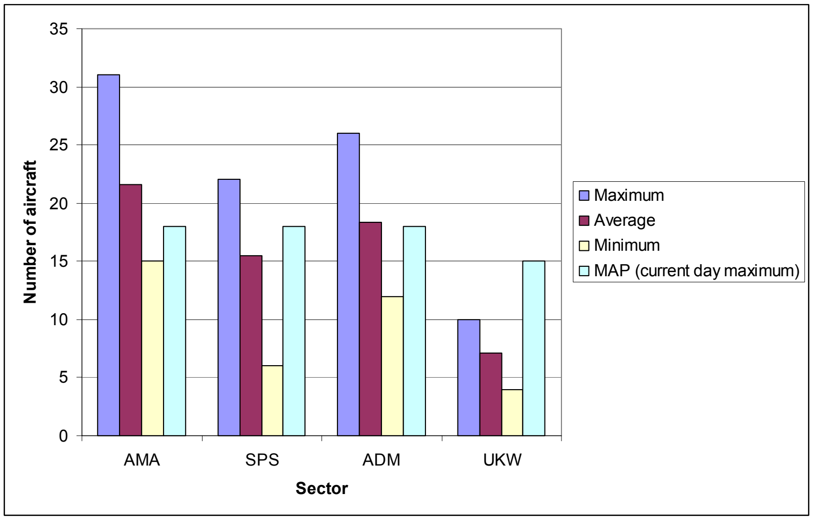


Figure 4: Aircraft count per sector during IFR operations in 2004 DAG-TM simulations from 20 to 50 minutes runtime

The relationship between sector count and workload provides further evidence to a potential capacity increase. With only one controller managing each position, high altitude controllers were able to control all aircraft effectively at these traffic levels. Subjective workload assessments were collected from controllers using the Air Traffic Workload Input Technique (ATWIT) [19]. Controllers were required to rate their workload on a scale of 1 to 7, at 5-minute intervals throughout each simulation run.

Figure 5 shows the maximum number of owned aircraft and the controller workload at each 5-minute time block for the four test sectors.

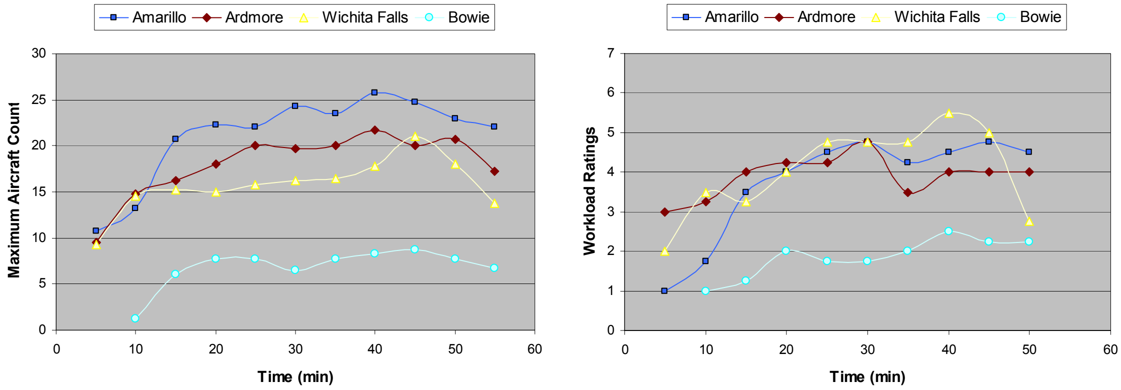
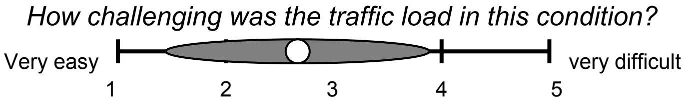


Figure 5. Maximum aircraft count and workload ratings over time in all managed condition

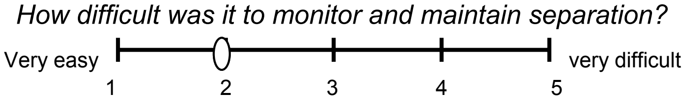
The relationship between sector count and workload (Figure 5) shows that these peak counts sustained over approximately 30 minutes resulted in moderately high but manageable workload. When asked in post-simulation questionnaires controllers rated the traffic loads between easy and difficult:



The traffic load in UKW was rated least challenging (1.5), the ADM traffic that was a complex mix of departures overflights and arrivals and the SPS traffic were rated difficult (4). The pure enroute sector AMA that had no transitioning aircraft but the highest traffic load was rated neither easy nor difficult (3).

2. Separation Assurance (trajectory-based ATC)

In post-simulation questionnaires all controllers rated the task of separation assurance in trajectory-based ATC as easy.

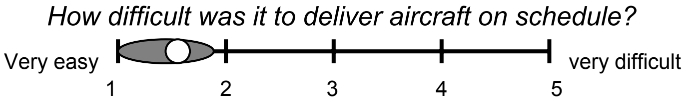


Throughout the simulations in 2002, 2003, and 2004 there was no indication that trajectory-based operations had a negative safety impact compared to current day operations. Controllers used the trajectory tools to plan their operations efficiently and solve potential conflicts early. Some controller comments are representative of this strategy: "*Reroute DFW departures out of arrival paths (ie along the sector borders). Climb overflights out of the way of arrivals. Bend path of arrivals away from departures. Initiate route modification for delay absorption early (ie as soon after aircraft enters sector*.)" and "*Route changes and altitude changes were the primary techniques used for traffic situations. Usually, shortcuts and removing waypoints solved most problems*"

Controllers still applied safety measures to protect against LOS, even if the trajectory de-confliction did not work out as planned, because of non-conforming aircraft or prediction uncertainties. A typical safety measure was issuing temporary altitudes even for uninterrupted descents. Typically aircraft would continue their most efficient descent without interruption, but in case something went wrong it would not result in a LOS.

3. Traffic flow management (trajectory-based ATC)

In post-simulation questionnaires half the controllers rated the task of delivering aircraft in trajectory-based ATC as very easy (1), the other half as easy (2).



This simulation did not include a current day control condition to quantify the subjectively assessed traffic flow benefits of trajectory-based ATC. However, simulations at NASA Ames in 2002 demonstrated that metering accuracy was improved indicated by a significant reduction in the standard deviation of the arrival time error. Figure 6 depicts the metering accuracy results from the 2002 simulations[18], which were achieved with an earlier iteration of the controller tools described in this paper.

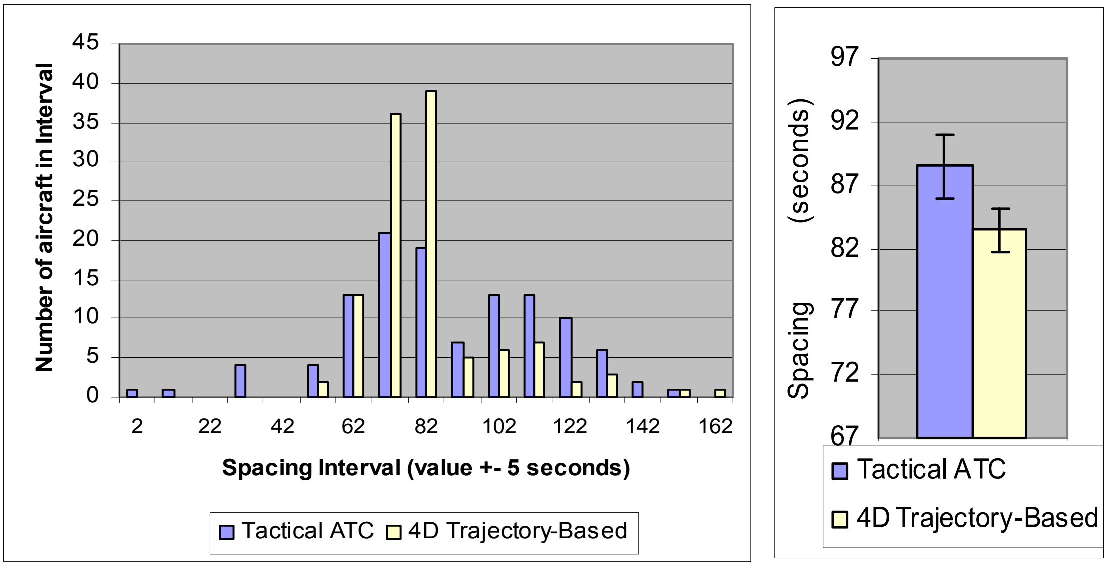


Figure 6. Inter-arrival spacing. Histogram (left) and mean and standard error (right)

The 4D trajectory-based operations resulted in a significant reduction in variance of the inter-arrival spacing at the metering fix, demonstrating that aircraft were delivered more consistently. There was also a marginal reduction of the inter-arrival spacing itself, bringing the mean within 1.5 seconds of the target spacing of 82 seconds. In the current day condition, more aircraft were delivered vertically spaced with less than 5 nmi lateral spacing than in the trajectory-based condition.

4. Additional services (trajectory-based ATC)

During the 2002 simulations[18] mentioned in the previous section it was found that trajectory-based operations increase flight efficiency by providing close to optimal descent profiles. Simulations in 2003[15,16] investigated how well the trajectory-based approach could accommodate user requests submitted via voice and data link and found that pilot-controller negotiations of trajectory changes are operationally feasible. Pilots and controllers found a simple procedure adequate, and most requests were approved, if not immediately, then after traffic conditions changed. When controllers rejected requests that had been made by voice, they waited for a second pilot request before approving it. In contrast, when the controllers rejected data linked requests, they viewed the requested route, found some problems with the surrounding traffic, and then immediately uplinked a route that was similar to the downlinked request, but one that also avoided potential conflicts. Controllers only concern was about one potential adverse impact of these silent (off radio) communications: pilots unaware of the controller's data link-mediated interactions with other pilots may overload the controller with requests.

5. Automation (trajectory-based ATC)

Controllers rated the usability and usefulness of the ground-side automation and DSTs (Table 4). Overall controllers felt the tools assisted them in making more efficient decisions. Also, they felt CPDLC route uplinks and datalinking the Transfer of Communication (TOC) reduced workload and frequency congestion, which gave them the extra time for traffic flow management and additional services, as necessary.

Average usefulness ratings ranged from 3.5–5.0 (1 = Not useful, 5 = Very useful). Speed advisories, the trial-planning tool, the CPDLC interface for TOC, the CPDLC interface for clearances and requests, and the graphical display of trial plan conflicts all were rated very high. The usefulness rating for the conflict list increased noticeably from 2002 simulations with an earlier version reported in[18] (2004 usefulness rating = 3.8, 2002 usefulness rating = 2.8). The conflict list was redesigned to use time-to-LOS as the main determinant for both the color (i.e. red = less than 2 minutes to LOS, yellow = 2 -5 minutes, white = greater than 5 minutes) and the location on the list (e.g. impending conflict near the top of the list). The conflict list in the 2002 simulation used two dimensions: time-to-LOS and likelihood of LOS, which was found to be confusing to the controllers. Also false alerts were much less frequent due to the redesign of the conflict logic.

Table 4. Controller rating of usability and usefulness of displays and tools

Tool Feature	Useful	Usable
Speed advisories	5	4
Trial-planning tool	5	5
CPDLC interface for TOC	4.8	4.5
CPDLC interface for clearances and requests	4.8	4.3
Graphical display of trial plan conflicts	4.8	4.5
Arrival timelines	4.6	4.3
STA assignment/swap functions	4.5	3.5
Graphical display of conflict alerts (i.e. flashing data blocks)	4.5	4
DSR emulation of existing functions	4.5	4.3
Color coding of information	4.5	4.5
Data link status list	4	3.5
Graphical display of active IFR conflicts	4	4
Conflict list	3.8	3.3

Average usability ratings ranged from 3.0–5.0 (1 = Very difficult to use, 5 = Very easy to use). The trial-planning tool, CPDLC interface for TOC, graphical display of trial plan conflicts, and color coding of information were the features that received the highest ratings. The trial-planning tool received a considerably higher usability rating than in the 2002 simulation (2004 usability rating = 5.0, 2002 usability rating = 3.0)[18]. The greater usability rating was a result of the high responsiveness and the seamless integration of the trial planning tool with the R-side display which provided immediate conflict feedback. Full CPDLC integration for easy uplink of trial plans allowed the controllers to work the traffic without issuing many vectoring instructions.

The questionnaire also asked about the preferred display location of the following information: delay absorption information on the timeline, datablock, or both; conflict information on the list, datablock, or both; and data link status information on the list, datablock, or both. All controllers agreed that delay information should be on both the timeline and the datablock, but 3 out of 4 controllers thought that conflict information should only be on the datablock and half thought that data link information should only be on the datablock. No one thought that any of the information should be in the lists alone. In general they thought that lists added to display clutter and were often ignored when busy. Although too much information on the datablock could have been a problem, none voiced any issues with the IFR datablocks in the simulation, which were designed to minimize display clutter and maximize readability

6. Acceptability to controllers (trajectory-based ATC)

To assess acceptability of the concept the questionnaire asked controllers to rate some of the features that they had experienced during the simulations in comparison to current day operations. Table 5 summarizes these results.

Table 5: Controller responses to comparing trajectory-based ATC to current day operations

	Question	Range	UKW	SPS	ADM	AMA		Average
1	How useful was the ability to obtain speed advisories when trying to deliver aircraft to a meter fix STA?	extremely useful (5) not very useful (1)	5	5	5	N/A		5
2	What impact do you think the ability to datalink clearances had on your overall workload?	greatly reduced (5) greatly increased (1)	5	5	4	N/A		4.67
3	How effective were cruise and descent speed clearances for controlling arrival traffic compared to current operations?	much more effective (5) much less effective (1)	4	5	4.5	N/A		4.5
4	How effective were trial plan route amendments compared to vectoring used in current day operations?	much more effective (5) much less effective (1)	5	5	5	4		4.75
5	How effective were trial plan altitude amendments compared to current day operations?	much more effective (5) much less effective (1)	3	5	5	4		4.25
6	How useful was the ability to datalink clearances compared to voice clearances?	much more useful (5) much less useful (1)	5	5	5	5		5

Clearly, the operations were very well accepted and preferred over current day operations. While controller acceptance is important, objective improvements need to be achieved to justify investing in the automation. These objective improvements were demonstrated as aircraft vectoring was practically eliminated and controllers could handle traffic loads clearly above today's values without excessive workload. Some specific comments on the operations underline the high acceptability of trajectory-based ATC operations:

"CPDLC's reduction of frequency congestion was a very useful workload reduction tool that allowed one the time that was necessary to use the other tools."

"*Uplinking route and altitude changes reduced controller workload greatly*"

"*implement this today would save time, money and make controllers' job safer and better and give more time for conflict resolution and custom service."*

B. Comparison of mixed operations with trajectory-based ATC

A joint human-in-the-loop DAG-TM experiment was conducted at NASA Ames and Langley Research Centers in 2004 to investigate the feasibility and operational benefits of mixed operations with controller-managed and self-separating aircraft. The experiment addressed two primary issues: the feasibility of conducting operations with autonomous and managed aircraft in the same airspace and the ability of en route capacity to scale the traffic by increasing the autonomous portion of the air traffic without adversely effecting controller workload[17]. The airside and ground-side results of the study are presented in other reports[17,26]. This section focuses exclusively on the ground side perspective.

1. Traffic load, complexity, and workload (mixed operations)

The experiment consisted of four experimental conditions, incorporating a within-subjects design (Figure 4). Each condition was run five times, four of which were used in subsequent analyses. As described in detail in the previous section condition 1 –the trajectory-based ATC condition - was conducted at slightly above current day maximum traffic levels (Level 1). For the second condition (C2) 30% of the managed IFR aircraft were converted into autonomous (AFR) aircraft.

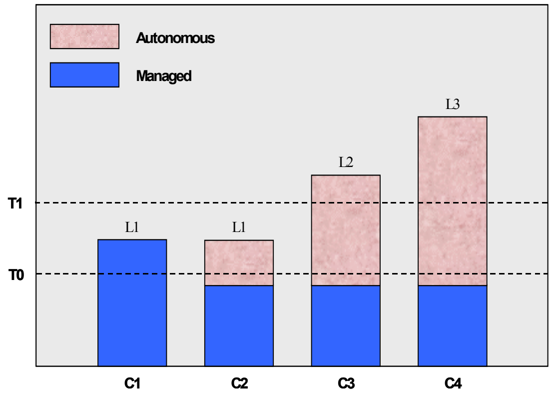


Figure 7. Experimental Conditions

Conditions C3 and C4 included the same number of managed aircraft as Condition C2, but added increasing numbers of AFR aircraft. Varying traffic volume between scenarios was accomplished by only altering the number of overflights. The traffic volume increase was greater for Amarillo and Ardmore than for Wichita Falls. The sector geometry of Wichita Falls prevented a significant increase in total aircraft count without also significantly increasing traffic complexity. The arrival problem, while demanding, remained relatively constant throughout all scenarios. Accordingly, the low altitude sector (Bowie), which had arrival traffic only, maintained a relatively constant traffic volume across conditions. Figure 8 summarizes the aircraft count during the peak traffic period and the controller workload in each sector across conditions. For the Amarillo sector, peak traffic averaged 26, 26, 35, and 44 for C1-C4; for Ardmore, 22, 22, 32, and 43; for Wichita Falls, 21, 19, 25, and 27; and for Bowie, 9, 9, 8, and 9. For the mixed conditions (C2-C4), the IFR portion of the aircraft count was approximately 70% of the IFR count in the all managed condition (C1) and it remained constant across the three mixed equipage conditions. The peak total traffic occurred on the average at 35 – 45 minutes into the scenario.

When assessing their workload controllers were able to dissociate the traffic complexity from their actual workload. The IFR portion of the aircraft count was approximately 70% of the IFR count in the all managed condition (C1) and it remained constant across the three mixed equipage conditions. The peak total traffic occurred on the average at 35 – 45 minutes into the scenario.

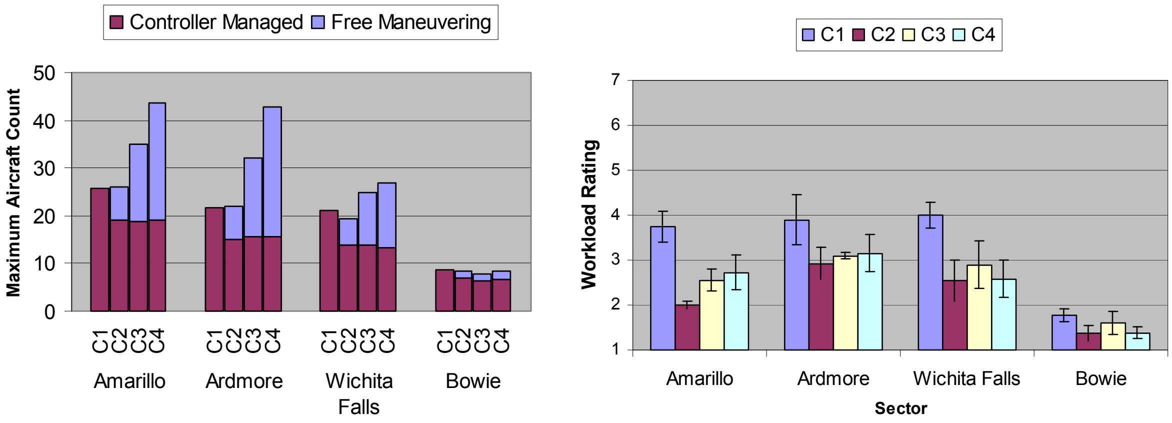


Figure 8. Aircraft count (during peak traffic periods) and workload ratings of mixed operations in each condition per sector

Figure 9 on the right shows average workload ratings per sector across the four conditions, which shows a similar pattern as that of IFR aircraft on the left of Figure 9. The workload ratings showed higher workload for trajectory-based operations (C1) than for mixed operations with fewer IFR aircraft (C2-C4), suggesting that mixed traffic posed no significant workload. Furthermore, the workload was relatively flat for C2-C4 despite a significant increase in AFR traffic, suggesting that AFR aircraft did not create a significant amount of workload.

Controllers rated the traffic complexity in post-simulation questionnaires and found the trajectory-based condition (C1) in which they had to manage all aircraft more complex than conditions with mixed operations, in which they only managed 70 % of these aircraft. However as AFR traffic levels increased controllers noticed an increase in traffic complexity that is a likely result of increased display clutter, more potential IFR/AFR conflicts and the reduction in available maneuver space for changing trajectories of the managed aircraft.[25]

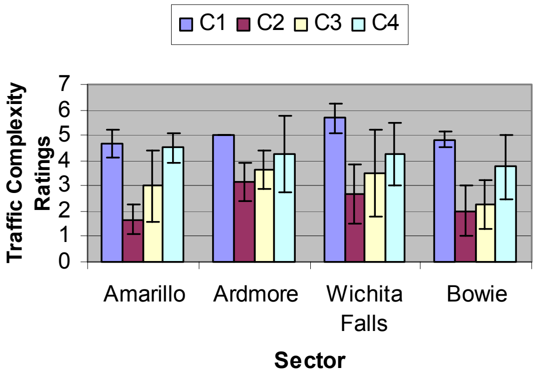


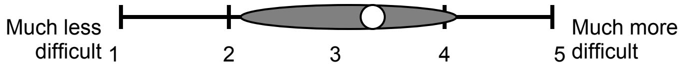
Figure 9. Traffic Complexity Ratings

The fact that the controllers could control the traffic at all with a total aircraft count exceeding the current day MAP values by far, demonstrates the potential en route capacity gains in mixed operations. Moreover, controller workload appears to correlate primarily to the number of managed aircraft, whereas the number of autonomous aircraft in the airspace has little impact on controller workload, but does affect the complexity of managing the IFR aircraft in the airspace.

2. *Separation assurance (mixed operations)*

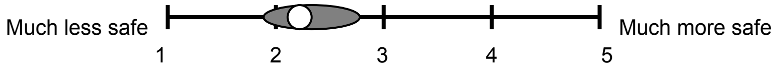
In post-simulation questionnaires controllers on average rated the task of separation assurance in mixed operations slightly more difficult than in the all managed trajectory-based ATC condition:

How difficult was it to monitor and maintain separation during mixed operations compared to all managed condition?



Furthermore, they rated mixed operations as less safe than managed operations:

How safe do you think operations were in mixed operations compared to all managed condition?



Barhydt and Kopardekar[17] report pair wise preference comparisons between all possible pairs of simulation conditions with respect to overall safety. These comparisons were analyzed to determine a ranking for each condition. Figure 10 summarizes the safety rank scores of condition by each controller position. The data show that ranking the four conditions from most to least safe, the controllers consistently ranked the all managed condition (C1) as the safest and the L3-mixed condition (C4) as the least safe.

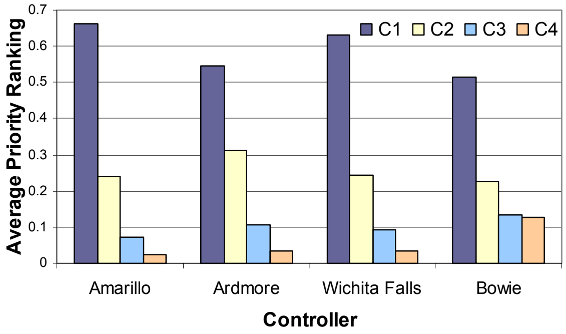


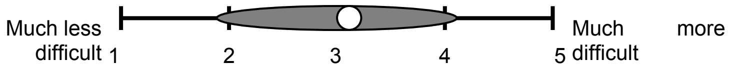
Figure 10. Average Controller Safety Assessment

The most common concern pertained to AFR-IFR conflicts in higher traffic levels. Controllers observed an increased number of short-term conflicts and separation violations in higher traffic levels[17]. The ground side tools provided controllers with conflict alerts whenever AFR-IFR conflicts were unresolved with less than 4 minutes to LOS. The increases in unresolved AFR-IFR conflicts were mainly due to pseudo-pilot AFR flights, which had greater difficulty in resolving conflicts as the traffic volume increased. The participant pilots, who flew single-piloted AFR aircraft simulators, seemed to be less affected by the traffic increase. The volume of impending AFR-IFR conflicts that the controllers observed in the high traffic conditions – caused mostly by the limitations in the pseudo-pilot stations or autonomous agent pilots – led to their safety concerns. The ability to resolve AFR-IFR conflicts well before they are presented to the controllers will be critical to future success of mixed operations. At the present time the safety of mixed operations in high density traffic remains an open issue that requires further research to be answered with sufficient confidence.

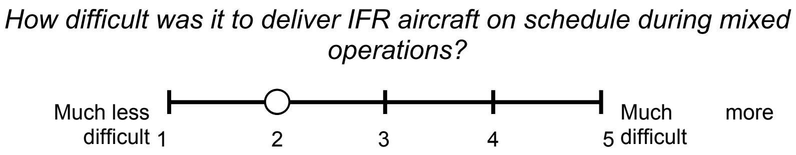
3. *Traffic flow management (mixed operations)*

In the post-simulation questionnaires controllers rated the task of sequencing aircraft in mixed operations to be of the same difficulty as in managed operations:

How difficult was time-based sequencing in mixed operations compared to all managed condition?



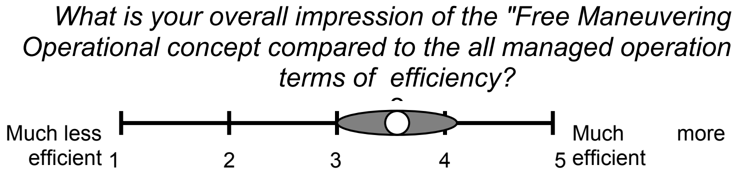
They rated the task of time-based metering of IFR aircraft to be simpler in mixed operations than in all managed operations, which is likely due to the reduced number of IFR aircraft they had to meter:



One challenge for controllers under mixed operations was to manage the STA for all IFR arrivals in the presence of AFR aircraft. Controllers did not have many problems delivering aircraft within ±15 seconds of their STA. The number of IFR flights that deviated from the STA was quite small – less than 3%. AFR pilots also had little difficulty in conforming to the schedule. Arrival conformance varied little regardless of whether the subject-piloted aircraft was AFR or IFR. Similarly, complying with the TRACON crossing restriction of 11,000 (±300) feet and 250 (±10) knots was not a particular problem for controllers or AFR pilots. IFR aircraft were equally likely to conform to the crossing restriction in the mixed as well as the all managed condition.

4. Additional services (mixed operations)

Controllers were not required to provide additional services to AFR aircraft. However they rated mixed operations in post-simulation questionnaires more efficient than all-managed operations:



At the same time controllers also commented that some conflict resolution maneuvers conducted by the pilots appeared to be less efficient than they could have been. One controller commented on the question above: "*This is tough to judge. I saw a number of AFR aircraft make abrupt, fuel inefficient maneuvers*"

5. Automation (mixed operations)

The controller ratings of the DSTs provided for mixed operations in addition to the DSTs provided for trajectory-based ATC described in the previous section are summarized in table 5

Table 5. Controller rating of usability and usefulness of displays and tools

Tool Feature	Useful	Usable
Graphical display of AFR-IFR conflicts	3.5	3
Graphical display of AFR aircraft (i.e. limited data block)	3.5	3.8

The lowest combined usefulness and usability rating of all the DSTs provided was for the graphical display of AFR-IFR conflicts (M = 3.5, M = 3.0, respectively). Controllers commented that frequent AFR-IFR conflict alerts lead to display clutter, partly because the alerting method involved displaying the AFR aircraft's expanded data blocks. The display of AFR aircraft as limited data tags was considered borderline useful and somewhat usable (M = 3.5, M = 3.8, respectively). Overall the issue of providing appropriate information on AFR aircraft remains open and requires a conceptual solution first, clarifying how controllers are supposed to treat AFR/IFR interactions.

As far as routine tasks and bookkeeping of AFR aircraft are concerned, as discussed in section III, the automation worked "behind the scenes", conducting automatic transfer of control and communication and data entries. An analysis of the task loads demonstrated that the number of routine tasks the controllers conducted was in fact only correlated to the number of IFR aircraft, indicating that the automation conducted this task effectively for the AFR aircraft. Figure 11 shows the average number of handoffs that were initiated and accepted during a simulation run. Since AFR aircraft required no manual handoffs by the controllers, the number of handoffs mirrored the managed aircraft count in Figure 9. In addition, pilot check-ins were also not required for AFR aircraft. Overall, reduction of these routine tasks for AFR aircraft seemed to have contributed to the overall reduction in controller workload.

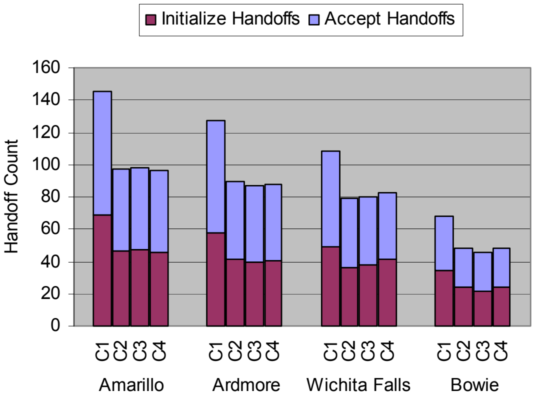


Figure 11. Number of handoffs

6. Acceptability to the controller (mixed operations)

At the end of the simulation, controllers were asked to rate the acceptability of different aspects of mixed operations. As described controllers had a positive impression on metering efficiency. They thought that mixed operations was actually slightly more efficient than all managed operations (M = 3.5; 1 = much less efficient, 5 = much more efficient) and that it was just as easy to sequence planes in mixed as in managed operations (M = 3.0; 1 = very easy, 5 = very difficult). They also thought that it was easier to deliver managed aircraft to the meter fix during mixed operations (M = 2), likely due to the fact that they had fewer aircraft to manage when some of the arrival aircraft were self-separating.

In contrast, they had somewhat negative impressions on situation awareness and safety. They rated mixed operations to be less safe than managed operations (M = 2.25; 1 = much less safe; 5 = much safer) and they thought that it was slightly more difficult to detect non-conforming aircraft (M = 3.25). They also thought that it was somewhat more difficult to cope with unplanned events (M = 3.75; 1 = much less difficult, 5 = much more difficult) and to maintain/monitor separation (M = 3.25).

Burdening AFR aircraft to resolve all AFR-IFR conflicts was also marginally acceptable (M = 2.9; 1 = completely unacceptable, 5 = completely acceptable). When an AFR-IFR conflict was imminent, controllers thought that the procedures and phraseology for resolving the conflict was somewhat unacceptable (M = 2.3). However, the phraseology for requesting pilot intent was rated somewhat acceptable (M = 3.8).

The controllers elaborated further when asked about the acceptability of the concept during debrief discussions. In general, controllers' comments highlighted four significant safety issues regarding concept acceptability: automation dependency, situation awareness of AFR aircraft, near-term AFR-IFR conflicts, and overall traffic density.

The first three concerns were specific to AFR aircraft. One of their concerns was that if the conflict detection automation "misses" an AFR-IFR conflict, the conflict may not be independently detected by the controller because they are discouraged from monitoring autonomous aircraft. Although they were not responsible to resolve these conflicts, they felt that they should be able to independently monitor conflicts that may endanger passenger safety. The automation dependency concern has a wider implication when applied to the flight deck automation as well. When the flight deck automation fails to detect conflicts, the consequences are far greater since the pilots do not have the domain expertise to independently monitor the potential conflicts. Therefore the flight crews depend completely on the automation for accurate conflict detection.

Controllers were also concerned with degraded situational awareness of AFR aircraft. In order for AFR flights to not add any workload for the controllers, they need to be nearly invisible to the controllers (e.g., limited depiction on the controller's display, no controller responsibility, little interaction with IFR aircraft). However, if information about AFR traffic is suppressed, the controller is less prepared to provide service for exceptional cases, such as unresolved near-term conflicts and RTA revisions. Less awareness leads to inability for the controllers to deal with emergency situations but more awareness undermines the scalability premise.

Controllers commented extensively on the near term AFR-IFR conflicts. They felt in general that waiting until an IFR-AFR conflict is within 2-3 minutes seems too late to start critical decisions. They also felt that there was the potential for ambiguous information because it was not always clear if the AFR aircraft was taking action to resolve the conflict that it was responsible for. The general feeling of "not knowing" what the AFR aircraft was doing caused additional concern and even when they knew the aircraft intent, they weren't always sure if the intended action was appropriate. One of the key lessons learned from the study was the importance of clear and unambiguous procedures for both pilots and controllers when handling short-term AFR-IFR conflicts. If the resolution responsibility is to be shared between the pilot and controller under these situations, then some level of air and ground system compatibility may be required. Alternatively, if the responsibility is to remain solely with the AFR pilot, then the decision to alert the controller to these conflicts should be re-visited.

Finally, an interesting point raised by the controllers was that the current day rules and procedures have excess buffers built in to absorb errors by the controllers and/or by the system. It might not be good idea to strip away all of the safety buffers by dramatically increasing the traffic density. They were concerned that increased traffic density reduced options for maneuvering IFR aircraft out of critical situations. One controller commented that "...resolution was always more difficult in high mixed environment because AFR aircraft are in the way of IFR aircraft." In general, they were not sure how one determines what capacity increases can be achieved without compromising safety.

V. Conclusion

Automation-assisted trajectory-based ATC can improve air traffic operations while maintaining current day roles and responsibilities. Capacity may likely be increased by some 50 % and metering accuracy can be improved significantly. Simulations have not raised safety concerns and the operations are very acceptable to the controllers. A set of well-designed ground-based DSTs integrated with data link is required to enable these operations.

The joint Ames/Langley simulation study of the DAG-TM En Route Free Maneuvering concept element demonstrated potentially bigger en route capacity benefits for mixed operations. When the majority of the aircraft were self-separating, the total aircraft count far exceeded the current day MAPs in the high altitude sectors. In these high traffic situations, controller workload remained manageable and was actually lower than those of managed operations with more IFR but fewer total aircraft. The data suggest that workload is correlated primarily with the managed portion of the traffic, validating one of the key assumptions that AFR aircraft has minimal workload impact on the controllers.

Despite reporting manageable workload with high traffic levels of mixed traffic, controllers reported increasing traffic complexity imposed by the additional AFR aircraft. At the highest traffic level, AFR aircraft limited the potential maneuver space for IFR aircraft and caused display clutter even though they were shown as limited datablocks that took little display space. Increased AFR traffic also increased the number of AFR-IFR conflicts – mostly due to limitations of multi-aircraft stations and/or autonomous agent pilots. These conflicts were main contributors to safety concerns by the controllers.

Mixed operations would not have been feasible without the well integrated trajectory-based air/ground system that connects Flight Management Systems, airborne decision support tools, traffic flow management systems with tools for scheduling and trajectory planning, ground-based decision support tools, integrated CDPLC/DSTs, and broadcast of up-to-date state and short-term intent information. In this paper, we focus on the impact of the ground-based automation on the success of the overall concept. The ground DSTs have been significantly re-designed from our past studies to improve the responsiveness and accuracy of the tools. The design of individual display components has also been significantly improved. The integrated air/ground system and the corresponding decision support tools described here are a key component to excite maximal benefits in many of the future concepts that are discussed today. Therefore, the tools, procedures, results, and lessons learned from this study and simulation architecture should provide a solid foundation to test different concepts in the future.

Appendix. Detailed Description of the Prototyped ATC Technologies

The following sections describe the automation assisted en route controller workstations developed in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center to support research in DAG-TM. It also describes controller DST support for self-separating aircraft. Aircraft flying under ‘Autonomous Flight Rules” are referred to as “AFR” aircraft throughout this section. All decision support tools were integrated in the Multi Aircraft Control System (MACS) [20]

All new En route ATC tools– trial planning, speed advisories, CPDLC, conflict prediction – were emulated and implemented in the MACS Display System Replacement (DSR) interface. This section provides a description of the DAG-TM en route controller DSTs as supported in MACS. Note that MACS is a prototyping environment intended to emulate and simulate existing or envisioned tools. MACS software is not intended to be used in any real system. It is designed to evaluate concepts and implementation prototypes with practitioners early in the research and development process to provide guidelines, specifications, and requirements for the actual system.

A. DSR Emulation

The controller positions in the AOL emulate the look and feel of the operational DSR controller workstations used throughout air traffic control centers in the United States. Some of the main properties of these controller positions are:

- Display attributes and objects such as opaque or transparent “views” (windows), including functional “R-CRD” and “DC” views that support most basic ATC operations (Figure 1)
- 2048 x 2048 pixel large format displays
- specifically designed DSR keyboard and trackball
- DSR quick-action key, function key and alphanumeric keyboard entry alternatives to “point and click” trackball operations.

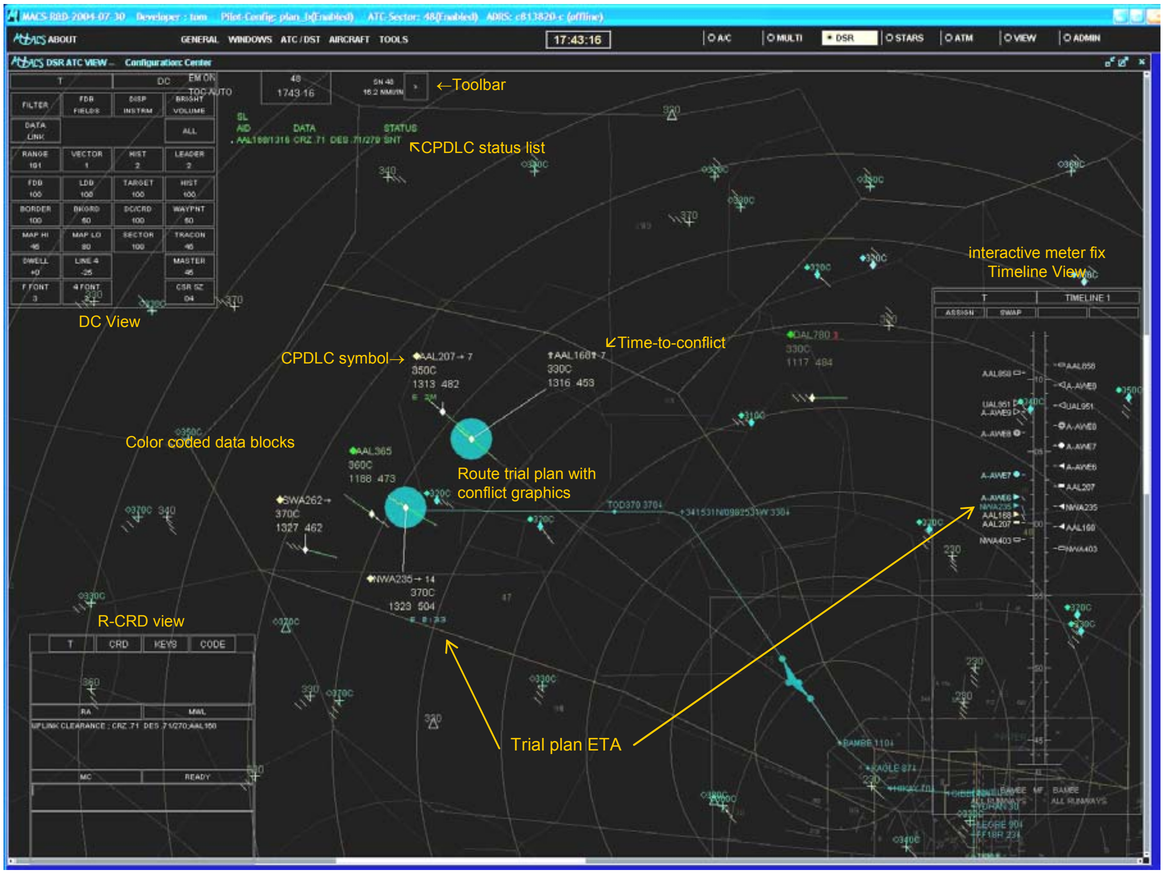


Figure A1. MACS DSR Controller Display

Figure A2 shows operators at two of the DSR emulation stations in the AOL's Center controller room.

Figure A2. DSR emulation hardware, including high resolution monitors, DSR keyboards & trackballs, and touchpad-controlled VoIP voice communications system.

Using MACS DSR stations as controller interface has a number of advantages: (1) to reduce simulation training time by eliminating the need to teach new methods for familiar operations, (2) to support more rapid interface prototyping, and (3) to enable platform independence using the Java programming language. Most strikingly, controller training has been accelerated, with their ability to concentrate on learning new tools and concepts when being trained for simulations.

The DSR software emulation was based on a description of the DSR computer human interface (CHI) provided in the 2002 DSR user's manual [21]. The MACS DSR emulation represents a subset of the functions described in that document. It covers all basic R-position operations needed to control traffic using the large format display, DSR keyboard and trackball. Functions that require additional hardware (keypad selection device, flight strip printer) or support other positions, tasks or goals (A- or D-position, DYSIM operations, EDARC test functions, security functions) have not been implemented.

Apart from some operational quick-function or special key operations not yet supported by the MACS DSR emulation, the main difference between the MACS DSR emulation and the DSR in the field is new integrated automation prototype snot yet available in the operational environment (or only at limited sites). These include speed advisories, metering timelines, CPDLC, trial planning, and conflict prediction. When an operational or research precedent exists – for example, the CPDLC Build 1 implementation in Miami Center [22] or the CTAS Direct-to (D2) interface for R-side conflict presentation and trial planning [23] – it was used as a model for the MACS DSR implementation. The following sections provide a detailed description of the MACS DSR en route interface and tools.

B. Flight Data Block

The prototyped DSR radar display uses three aircraft flight data block configurations: limited, full and expanded. As shown in Figure A2, data blocks are color coded as arrivals (tan) or overflights/departures (green), and some content differences exist between these two categories. Special features of the "AFR" data blocks are described in the next section.

As in current NAS operations, the controller's display defaults to a limited data block when the aircraft is in another sector, and to a full data block when the aircraft is in "own" sector. Exceptions to this rule, forcing the full data block to be displayed, include: (1) aircraft is inbound and in handoff status, (2) controller has track control, (3) aircraft is in "pointout" status, (4) aircraft is in a predicted conflict within the sector, or with another aircraft that is "owned" by the sector, or (5) controller clicks on the aircraft target to toggle display of the full data block.

The expanded data block is shown whenever the controller dwells on the aircraft's data block or target. The expanded data block shows additional information (Figure 3) and is brighter than the full data block. Other displayed information (e.g., in the timeline or conflict list) also brightens to help the controller quickly access all relevant data about a given flight.

1. Data Block for Autonomous Operations

Some content differences (and color coding differences) exist between data blocks for AFR and IFR aircraft. Table A1 summarizes these content differences; Figure A3 provides labeled examples illustrating color coding.

Regardless of location, the default presentation for AFR aircraft is the limited data block. The full data block is only displayed when (1) the AFR aircraft is predicted in conflict with an IFR aircraft, or (2) the controller clicks on the target to toggle the display of full and limited data blocks.

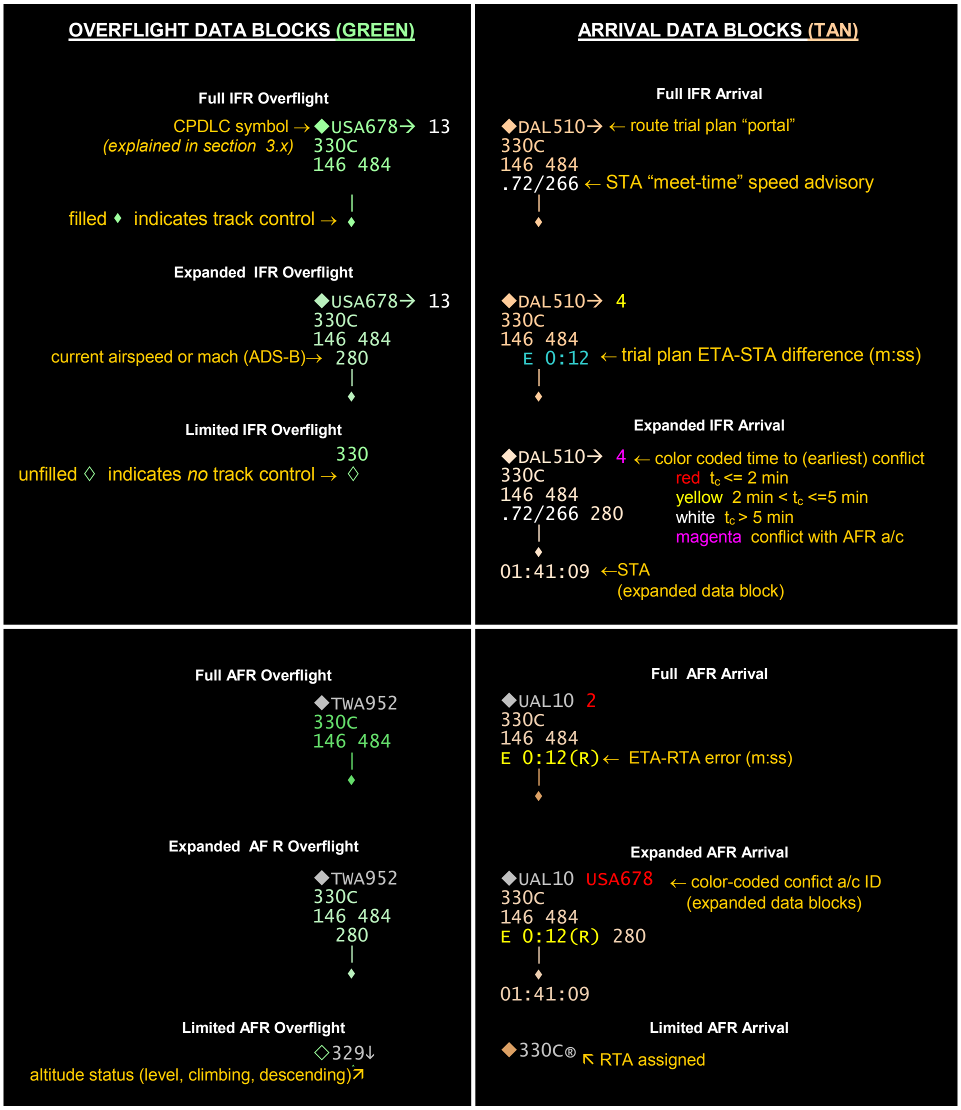


Figure A3. Prototype DSR flight data block. Overflights (green) are shown on the left, and arrivals (tan) on the right. Managed ("IFR") data blocks are above line, and autonomous ("AFR") data blocks below.

Table A1. Prototype DSR Data Block Content

All data blocks	**IFR Data Blocks**	**AFR Data Blocks Only**
Flight ID	Time to earliest conflict	Conflict flight ID
Type of flight (arrival or overflight)	Conflict level	RTA (arrivals only)
Altitude (actual and cleared)	Speed advisory (arrivals only)	RTA-assigned indication (arrivals only)
Current airspeed	STA (arrivals only)	ETA–RTA error (arrivals only)
Track control status	Trial plan ETA–STA difference (arrivals only)	
CPDLC status		
Vertical trend indication		

C. Time-based Metering

Time based metering is used in DAG-TM operations to provide an orderly arrival flow to a TRACON meter fix. Mixed autonomous/managed operations use time-based metering as a method for merging managed and autonomous aircraft; autonomous aircraft are assigned a meter fix RTA that represents their 'slot time' for entry into the TRACON and transition to managed status.

1. Arrival Scheduler

The prototype arrival scheduler used in the AOL resembles the CTAS Traffic Management Advisor (TMA). It assigns arrival times (STAs) for all aircraft inbound to a meter fix located at the TRACON boundary. The scheduler has several inputs: (1) the arrival aircraft's estimated time of arrival (ETA) at the meter fix (based on a nominal speed profile and direct routing to the outer fix); (2) the desired meter fix spacing (specified either as minutes or miles in trail), and (3) a weight-class based runway spacing matrix. The scheduled time of arrival (STA) is continually updated until the aircraft crosses the "freeze horizon," when the STA is automatically assigned After the freeze horizon, the ETA continues to be updated, and the controller can still manually adjust the STA using "assign" or "swap" functions.

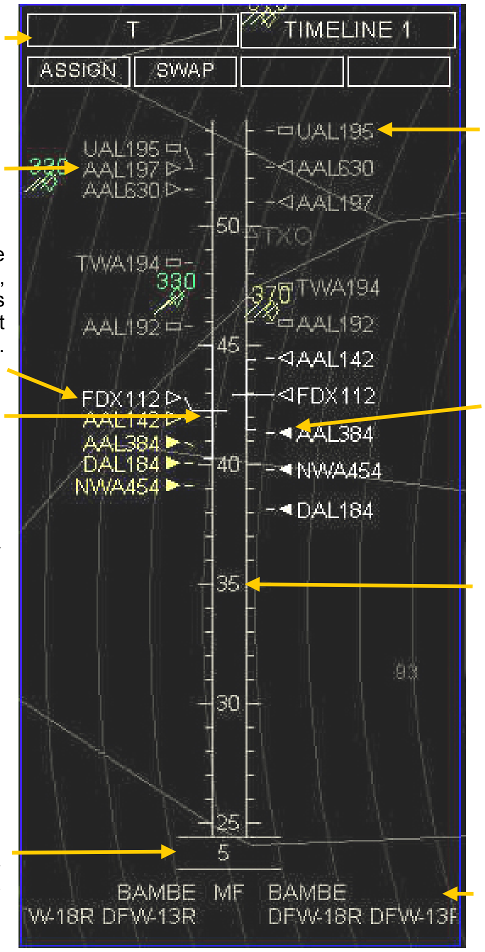
2. Timeline View

Schedule information can be displayed to the controller in a Timeline View (Figure A4, A5) or a meter list format. It may also be displayed in the flight data block (Figures A3, A5).

Depending on how the position is configured, the SWAP and ASSIGN keys may be displayed on the Timeline View. The SWAP function exchanges STAs for two selected aircraft. ASSIGN can be used either to toggle STA status between frozen and unfrozen, or to schedule a new STA for the aircraft. Methods for these functions are described in Table A2.

Table A2. Sector controller methods for changing STA (Scheduled Time of Arrival)

SWAP STAs for two aircraft:	click "SWAP" [cid1] [cid2] "ENTER"	exchanges STAs for specified aircraft
Freeze/unfreeze STA status:	(1) click "ASSIGN"	initiates "assign" operation
	(2) click STA tag for selected a/c	toggles STA state
ASSIGN new STA for single aircraft:	(1) click "ASSIGN"	initiates "assign" operation
	(2) pick & drag STA tag to new time	selects aircraft and enters time in R-CRD
	(3) type keyboard "ENTER"	completes "assign" operation



Timeline View label, & keys to assign or swap STAs and toggle opaque/transparent window background.

Aircraft ID tags on left align with the aircraft's ETA.

Color-coded tags indicate: white for selected or dwelled aircraft, datablock color if the sector has track control, and dim grey if it does not have track control.

White brackets are displayed on the left and right side of the timeline when an aircraft is dwelled (highlighted white). Brackets on the left (ETA side) indicate how much the ETA could be adjusted by increasing or decreasing the aircraft's speed without altering its route. Brackets on the right (STA side) indicate the minimum spacing needed between the aircraft and those leading and following it.

The timeline may show current time at the bottom, or a **gap** may be used to reduce its length by suppressing display of the earliest [n] minutes (5 min. here).

Aircraft ID tags on right align with Scheduler-assigned **STA.**

Weight class symbols. Filled symbol indicates frozen STA.

Time labels (minutes past the hour) are displayed in the center of the timeline, with tick-marks at 1 minute intervals.

The base of the timeline displays criteria used for including aircraft in the schedule (in this case, only aircraft crossing BAMBE, landing on DFW runways 18R or 13R).

Figure A3. Interactive meter fix timeline.

3. Data Block Metering Information

Additional metering-related information is shown in the arrival aircraft's flight data block (Figure 3). This includes the STA (shown next to the target symbol when the aircraft is dwelled), and a speed advisory which can be uplinked via CPDLC or issued by voice.

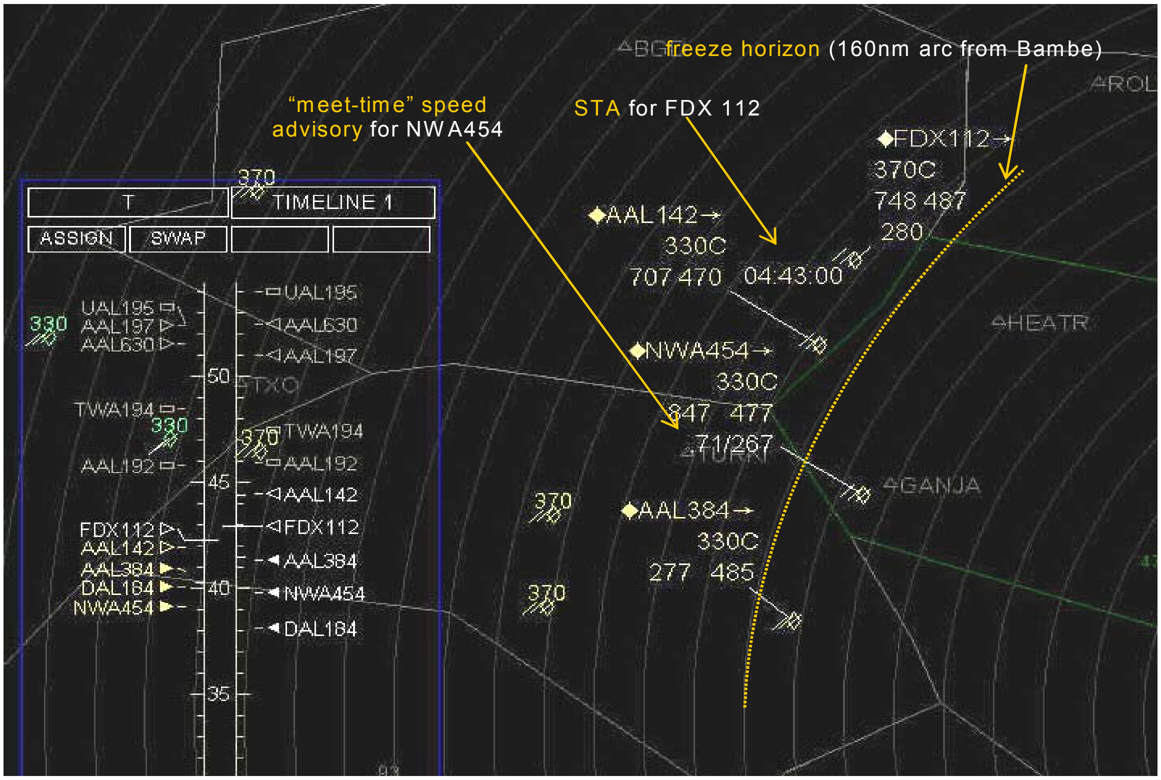


Figure 5. Timeline View in DSR display

4. Procedures and Clearances for Time-based Metering

Speed Advisories and VNAV Descents

The speed advisory includes a cruise speed and descent speed that will deliver the aircraft to the meter fix at the assigned STA along its current lateral route. When these speeds are loaded into the aircraft's flight management system (FMS), and flown in vertical navigation (VNAV) mode, the aircraft descends on a predictable 4-D trajectory. This trajectory includes a top of descent location which maintains the assigned descent speed at idle thrust until it is time to decelerate to acquire the charted meter fix crossing restriction. The ground automation is capable of independently computing this trajectory and using it to predict conflicts and monitor meter fix ETA compliance.

Precision Descent

The Precision Descent is a DAG-TM procedure that clears an aircraft to fly a VNAV descent that has specific constraints. These constraints are either speeds (as described above) or a specific meter fix arrival time (required time of arrival, or RTA). The controller can uplink both types of constraints (as well as lateral route modifications) to the aircraft using CPDLC.

The speed advisory or RTA uplink in itself is NOT a descent clearance. The Precision Descent is always issued by voice with the following phraseology:

"Cleared for precision descent [Cross Bambe at 11,000' and 250kts.]"

Explicit statement of the charted meter fix crossing restriction is optional.

The controller's expectation for a precision descent is that the aircraft will:

- Maintain current lateral routing.
- Maintain cruise altitude and Mach until its VNAV top of descent.
- Initiate descent at its VNAV top-of-descent point.
- Descend at cruise Mach until reaching the assigned descent speed, then maintain assigned descent speed.
- Maintain assigned descent speed within plus/minus 10 knots.

- Cross BAMBE at 11,000 feet and 250 knots.

Clearances and methods for using the precision descent are summarized in Table A3.

Table A3. Metering Clearances and Uplinks

Precision Descent (Metering) Clearances:		
Precision Descent, verbally assigned speed:	*"NASA123, cleared Precision Descent at 290 knots. [Cross Bambe at 11,000 ft & 250 kts.]"*	
Precision Descent, uplinked speed:	(1) uplink speed advisory	
	(2) issue voice clearance: *"NASA123, cleared Precision Descent. [Cross Bambe...]"*	
Precision Descent, uplinked RTA:	(1) uplink RTA	
	(2) issue clearance: *"NASA123, cleared Precision Descent. [Cross Bambe ...]"*	
Metering Uplinks:		
uplink RTA:	UR [cid]	uplink current RTA to specified aircraft
uplink speed advisory:	UC [cid]	uplink advised speeds to specified aircraft
uplink route clearance:	UC [cid]	uplink trial plan route to specified aircraft

5. Time-based Metering and Self-Separation

The metering implementation supports self-separation in several ways:

1. RTA assignment is used as a mechanism for merging autonomous and managed aircraft: the schedule is based on a predefined meter fix spacing during mixed operations, assuring meter fix separation for AFR aircraft arriving within 15 seconds of their assigned RTA.
2. The scheduling process checks to determine that an assigned RTA can be achieved on a direct route at an airspeed within the aircraft's speed envelope. This allows RTA assignments to AFR aircraft to be completed by the automation without controller involvement. The controller is only involved if the flight crew requests a different RTA .
3. The controller can reschedule RTAs in off nominal situations, or in response to a pilot request.
4. ETAs & RTAs for autonomous aircraft are displayed to the controller on the timeline in a manner that clearly differentiates them from managed aircraft.

D. En Route Conflict Prediction

A conflict prediction tool has been developed to support DAG-TM concept evaluation. The look and feel of this tool resembles the CTAS conflict probe that is part of the CTAS D2 tool [23] but differs in several ways, since it was designed to operate in a more technically advanced operational environment. The key difference is that the prototyped conflict probe is designed to use better information about aircraft intent. ADS-B broadcast of aircraft state was assumed to be available available, and more frequently provided than the 12-second update radar track information available at ARTCCs today. Downlinked FMS intent information is available whenever it changes. Up-to-date forecast wind information is available to flight deck and ground, improving trajectory prediction accuracy. The prototyped conflict probe has been designed to use the best intent information provided from the flight deck for assessing active route conflicts, and ground-based trajectory calculations are used for trial plan route evaluation or off-path operations.

The format used for presenting conflict information is modeled after the D2 interface [23]. It includes the conflict list and conflict graphics described below and shown in Figures A6 and A7.

1. Conflict List

The conflict list, presented on the sector controller's display, is a color coded list of all conflicts that meet the filter criteria set for that specific sector (Figure 6). Conflict filter parameters and elements of the display are adjusted from a setup panel and the conflict list itself. Filter parameters include sector ownership of one or both aircraft, conflict location within own airspace, time to conflict, minimum vertical and lateral separation criteria, and managed or autonomous aircraft status. The look-ahead time filter may be adjusted to a value between 5-20 minutes.

ID 1	ST1	ST2	ID 2	TIME	H-SEP	V-SEP
AAL 432	-	-	DAL510	8	3	0

Figure A6. Prototyped DSR Conflict List.

Display and filter settings that are adjusted using the keys at the top of the list are described in Table 4. Display of the keys themselves is toggled on/off with the “KEYS” button.

Conflict list entries (and time-to-conflict values in the data block) are color coded as follows:

- RED FONT: time-to-conflict is 2 minutes or less.
- YELLOW FONT: time-to-conflict is more than 2 minutes and less than or equal 5 minutes.
- WHITE FONT: time-to-conflict is more than 5 minutes but less than max. look-ahead time.
- MAGENTA FONT: predicted conflict is with an AFR aircraft.

Table A4. Functions associated with conflict list keys

Key	Function
O/T	**Toggle opaque or transparent window, with/without border**
AUTON	**Toggle display of managed-autonomous aircraft conflicts**
KEYS	**Toggle display of Conflict List Keys**
SUP	**Suppress display of conflict pair (toggle text brightness)**
FONT	**Display and adjust font size**
MINS-M [n]	**Display (and adjust) time filter for conflict detection involving a pair of managed aircraft:** default = 15 minutes.
MINS-A [n]	**Display (and adjust) time filter for conflict detection involving** **AFR-IFR conflict pairs:** default = 4 minutes.
ST	**Indicate aircraft state at time of conflict:** • **↑ = climbing, ↓ = descending, – = level flight.** • “d” **(for “dead reckoning”) indicates the aircraft is off trajectory.** **In this case, the time filter is reduced to 5 minutes.**
LBL	**Toggle labels display on/off**
FPG	**Toggle automatic display of conflict graphics for selected pair**
UNT	**Toggle display of units**
TIM	**Toggle display of time to conflict (first loss of separation)** (min)
VS	**Toggle display of predicted minimum vertical separation** (x100ft)
HS	**Toggle display of predicted minimum lateral separation** (nm)

2. Conflict Graphics

Conflict graphics are displayed by clicking on an entry pair in the conflict list or the time to loss of separation (LOS) in the data block. Figure A7 shows conflict graphics for a selected aircraft pair. Solid red 5-mile circles highlight the aircraft targets. The red area at the intersection of the white route lines indicates the region where separation loss is predicted to occur.

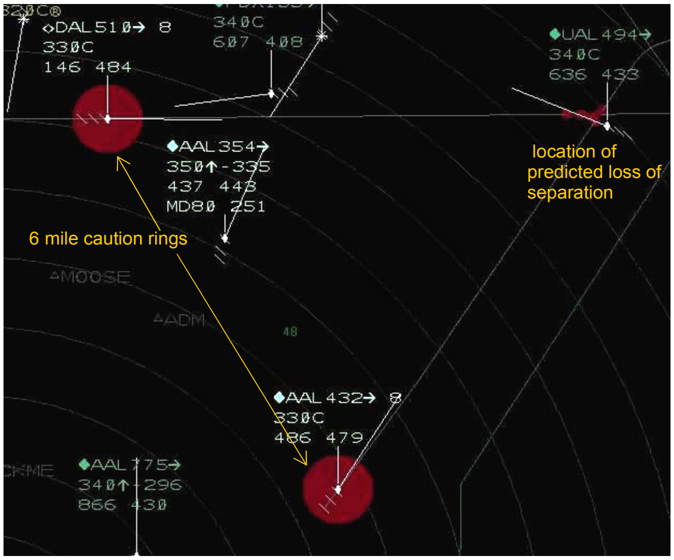


Figure A7. Conflict graphics for AAL432 and DAL510.

3. *Short-term Conflict Alert*

The prototyped DSR display also includes a short-term conflict alert function. Dead reckoning from current aircraft position is used to detect any predicted loss of separation within 2 minutes. If a conflict is detected, flight datablocks for the aircraft pair flash bright/dim. This behavior, and the criteria used for conflict determination, are modeled after the conflict alert function used in ARTCCs today.

4. *Conflict Prediction and Autonomous Operations*

The 'time-to-conflict' value displayed in an IFR aircraft's data block will be magenta if that conflict is predicted with an AFR aircraft. Conflicts between AFR and IFR aircraft are listed in a separate group below IFR-only conflicts in the conflict list (AFR-only conflicts are not shown). Because in DAG-TM operations the autonomous aircraft is responsible for solving all active autonomous-managed conflicts, presentations of these conflicts is suppressed unless time-to-conflict is short (e.g., t_c<3 minutes). This design avoids alerting the controller unnecessarily to conflicts that will be resolved without his or her intervention. At the same time, it allows the controller to become involved, as a safety precaution, when the conflict is imminent, providing a safeguard in the event of autonomous flight deck (automation or pilot) error.

E. Trial Planning

Trial planning allows the controller to develop route or altitude clearances and check them for conflicts and ETA changes before issuing them to the aircraft. Examples of the controller's display supporting route and altitude trial planning are shown in Figures 8 and 9.

When a trial plan is opened, the active FMS route and a cyan trial plan route appear. If the aircraft is a metered arrival, a cyan delay also appears, and the trial plan ETA (also in cyan) replaces the active ETA wherever it is displayed. Finally, cyan conflict graphics indicate predicted conflicts with the trial plan. After reviewing the trial plan, the controller may send it to the aircraft as a route or altitude clearance uplink. Methods for trial plan creation are summarized in Tables 5 (route trial plans) and 6 (altitude trial plans). The trial planning interfaces are modeled after the route trial plan interface developed for D2 [23] and the DSR altitude assignment fly out menu 21.

1. *Route Trial Plans*

Route trial planning provides a graphical interface for the controller to add or delete multiple en route waypoints from an aircraft's current route of flight. These include controller-defined waypoints and named waypoints from the published NAS database. The sequence of route trial planning actions is listed in Table A5; its interface is shown in Figure A8.

Table A5. Route Trial Plan Actions

1. open a trial plan route:	PICK on "portal" (→) next to callsign in flight data block
2. add a trial plan waypoint:	(a) dwell and PICK anywhere along the cyan route
	(b) move the trackball to relocate the waypoint

	(c) ENTER to input the new waypoint's location.
3. remove a trial plan waypoint:	PICK on an existing waypoint on the cyan route
4. cancel trial plan:	PICK on "portal" (→) in flight data block or type “TT” [ENTER]
5. uplink trial plan route as clearance:	UC [cid]

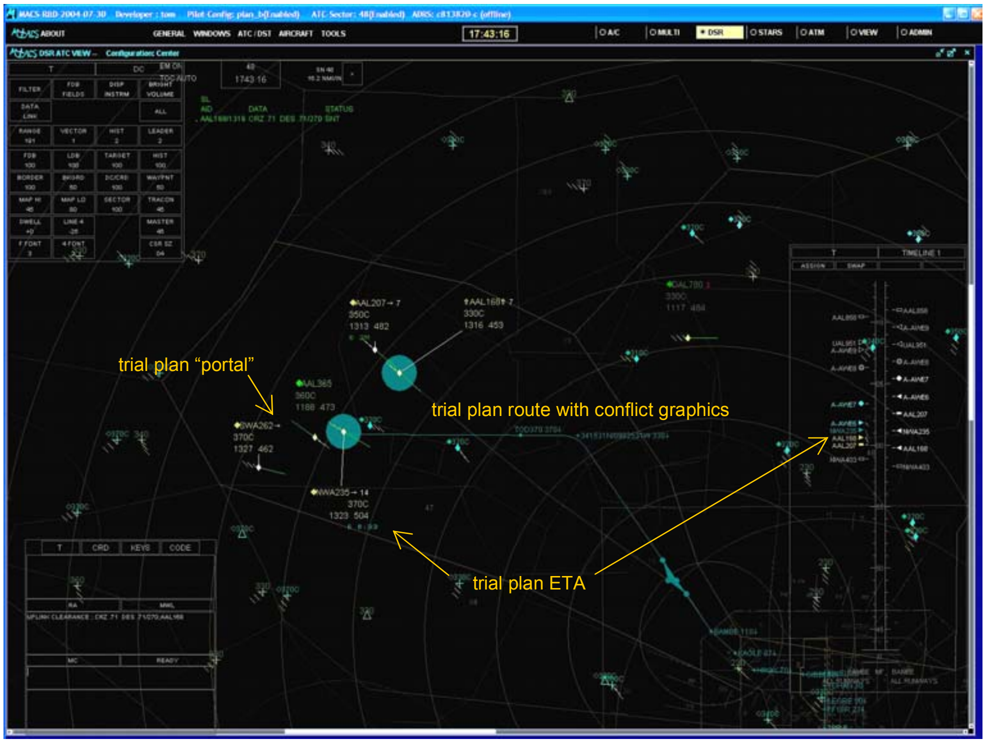


Figure A8. This figure describes feedback provided when trial planning is used to construct a delay route for arrival aircraft NWA235.

2. *Altitude Trial Plans*

Altitude trial planning uses an enhanced version of altitude entry functions that were introduced with an upgrade to the operational DSR interface. These operations use a pop up (or “fly out”) menu (Figure 9), and are described in Table 7. Table 6 describes the actions used to trial plan an altitude. By trial planning, the controller gains the ability to (1) check clearance impact before issuing it, and (2) send the clearance to the aircraft via CPDLC. The altitude trial plan interface is shown in Figure A9.

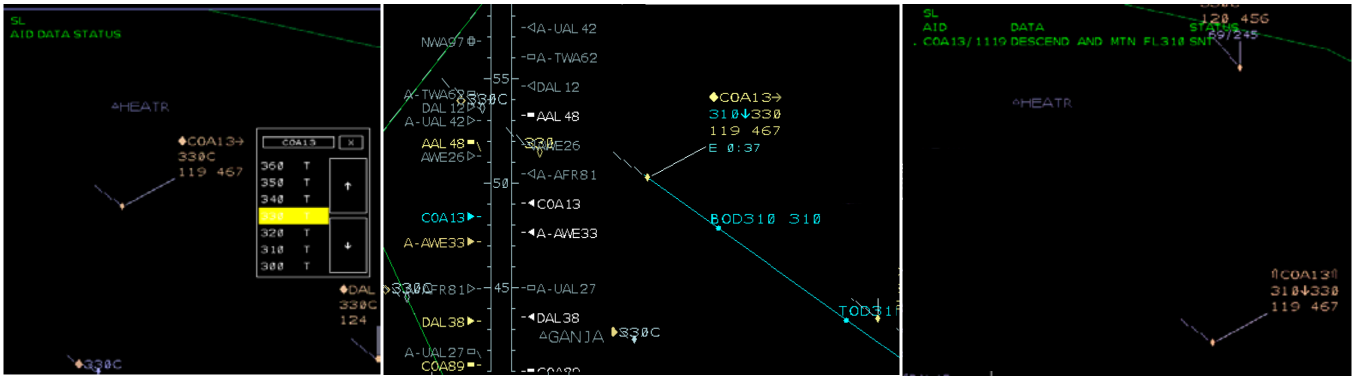


Figure A9. Altitude Trial Plan interface. The altitude fly out window is shown on the left. In the middle, cyan trial plan information for COA13 is shown. Altitude uplink clearance feedback is displayed on the right.

Table A6. Altitude Trial Plan Actions

1. open altitude "fly-out" menu:	PICK or ENTER on altitude field in flight data block
2. select an altitude:	dwell and PICK on a value > FL210 to select a trial plan altitude.
3. uplink trial plan altitude as clearance:	UC [cid]
CANCEL trial plan:	type "TT" [ENTER]
CANCEL *before* selecting trial plan alt.:	click on "X" in window or click anywhere outside fly-out window.

Table 7. Altitude Change Actions

1. open altitude "fly-out" menu:	PICK or ENTER on altitude field in flight data block.
2. assign new altitude:	(a) ENTER on value to assign new altitude (or)
	(b) ENTER on "T" adjacent a value to assign temporary altitude.
CANCEL (exit without change):	click on "X" in window or click anywhere outside fly-out window.

3. *Trial Planning and Autonomous Operations*

The controller cannot use trial planning to develop a clearance for an AFR aircraft. Trial planning does support autonomous operations, however, by alerting the controller to potential AFR-IFR conflicts associated with an IFR trial plan. This is the controllers' best safeguard against creating any unintended conflicts with AFR aircraft, and reduces the need to monitor AFR aircraft status and location.

F. Controller-Pilot Data Link Communication (CPDLC)

CPDLC Build 1 [21] is the first domestic controller-pilot data link implementation in the NAS, and has been field tested at Miami Center. This system was used as a model for the prototype DSR CPDLC implementation; however, some functions available at Miami Center are not supported by the MACS prototype implementation. Another difference is the added DAG-related data link functions that are *not* part of the Build 1, including: support for pilot request downlinks, RTA uplinks, and trial plan or advisory clearance uplinks. Our prototype implementation of these functions follows the syntax and format of existing Build 1 functionality as closely as possible. For example, frequency change functions (UH, UF) provided a model for RTA uplinks: HELD messages can be generated automatically for RTA-equipped aircraft when the STA is frozen, and sent automatically or released by the controller using a "UH [CID]" command. RTA uplinks can also be sent using the command "UR [CID]".

Terminology and concepts key to this CPDLC implementation (e.g., "eligibility," "status," "transaction") are defined in Table A8.

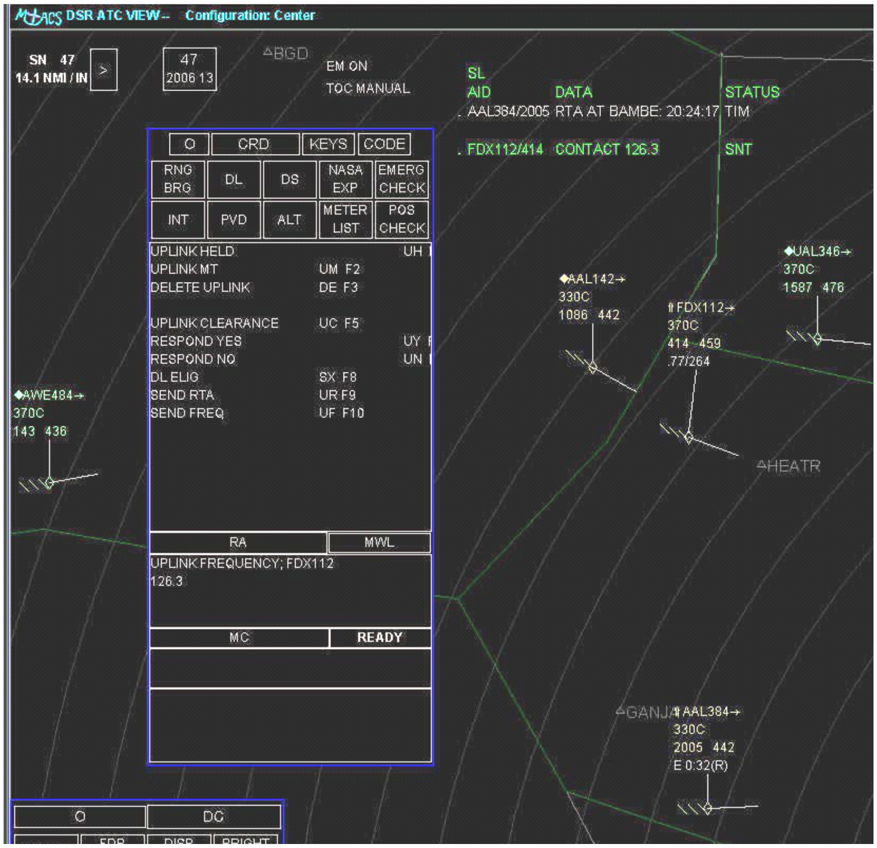
Table A8. CPDLC Terminology (from Miami Center's CPDLC Build 1 implementation)

CPDLC	controller-to-pilot data link communication
downlink	a message sent down from the flight deck to the ground.
eligibility	sector can communicate with aircraft via CPDLC. Only one sector at a time has eligibility.
menu list	list of text messages that can be sent using "UM". Can be turned on/off from the DC View.
status list	a list of ongoing transactions. Status list entries are sorted into 4 categories (**held**, **positive**, **non-positive**, **downlink**) and have 4 elements: (1) a "." for selecting the transaction, (2) aircraft ID, (3) transaction specific info, (4) the transaction's current status.
transaction	a CPDLC exchange (uplink and reply, downlink and reply) between flight deck and ground.
uplink	a message sent up from the ground to the flight deck.
transaction status types:	
closed	a "closed" transaction (status of NEG, UNA, AFF, WIL, ROG) is completed; no further actions are expected or possible. Closed, positive transactions (AFF, WIL, ROG) automatically drop off the list after 6 seconds. Closed non-positive transactions must be deleted by the controller.
held	held transactions (status of HLD) are found in the top status list category. There are two possible types of held transactions: transfer of communications, created when a handoff is accepted and TOC mode is MAN; and RTA uplink, created when an arrival aircraft crosses the freeze horizon. Held transactions are sent by the controller with the "UH" command.
nonpositive	"non-positive" transactions (status of TIM, NEG, UNA) are found in the third entry category in the the status list. A non-positive transaction may be **open** or **closed**.
open	an "open" transaction is waiting for a reply from the flight crew to the controller or from the controller to the flight crew. SNT, TIM and REQ are open states.
positive	"positive" transactions (WIL, AFF, ROG, NRR) comprise the second category in the status list. A positive transaction may be **open** or **closed**.
request	The last (fourth) transaction category are downlink requests, which may be **open** (REQ) or **closed** (AFF, UNA). Closed requests are automatically removed from the list after 6 seconds.

The fllowing section describes methods for performing most of the operations supported by the prototyped CPDLC implementation. Often there are several different methods for performing the same operation. Table 10, at the end of the section, provides a summary list of the 2-character keyboard methods for performing the basic CPDLC functions.

1. CPDLC Interface

The CPDLC interface includes several components in the DSR display: two R-CRD menus, some added buttons on the DC View, a CPDLC message "Status List", a CPDLC "Menu Text" list, symbology in the flight data block, and a banner entry. Figure 10 illustrates most of these components within the full DSR display. Detailed descriptions of each element are provided below.



AID	DATA	STATUS
. AAL384/2005	RTA AT BAMBE: 20:24:17	TIM
. FDX112/414	CONTACT 126.3	SNT

UPLINK HELD UH
UPLINK MT UM F2
DELETE UPLINK DE F3

UPLINK CLEARANCE UC F5
RESPOND YES UY
RESPOND NO UN
DL ELIG SX F8
SEND RTA UR F9
SEND FREQ UF F10

UPLINK FREQUENCY; FDX112
126.3

Figure A10. prototype DSR CPDLC example.

Data Block CPDLC Information

There are 5 different CPDLC data block symbols (illustrated in Figure A11):

1. A down arrow (🡇) indicates that a request has been “downlinked” from the flight deck. Salience of this symbol may be increased using color or blinking.
2. An up arrow (🡅) indicates that a message has been “uplinked” from the controller to the aircraft. The uplink may be a clearance, frequency, or text message.
3. A filled diamond (◆) indicates that the sector has “eligibility”, and can send and receive messages to the aircraft. Data link eligibility usually accompanies track control, but the transfer mechanism is separate.
4. An unfilled diamond (◇) indicates that the sector does not have “eligibility” (i.e., cannot communicate with this aircraft via CPDLC).

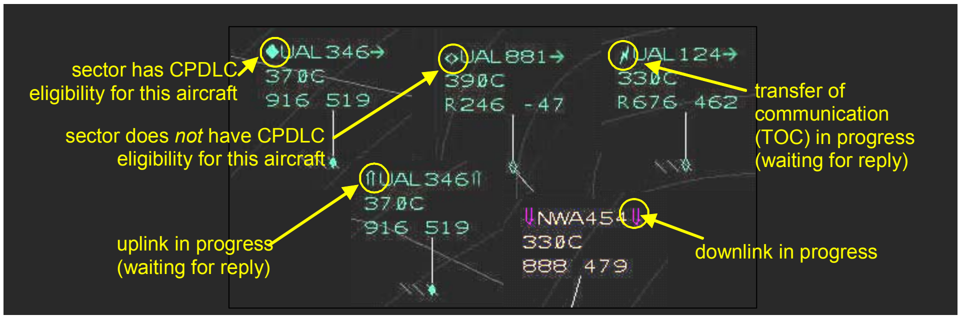


Figure A11. Prototype DSR Data Block Information.

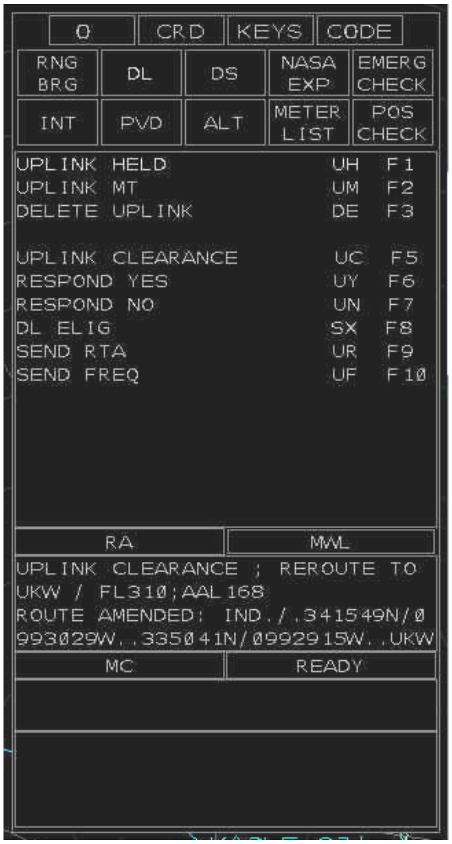
5. A lightning bolt (ϟ) indicates that a transfer of communication (and transfer of eligibility) is in progress. The process is completed when the flight crew accepts the frequency change (TOC) uplink message.

2. *R-CRD menus*

Figure A12 shows the "DL Category Menu" on the R-CRD, accessed from the R-CRD's "DL" key. The prototype implementation includes 5 of the 9 CPDLC Build 1 operations (UPLINK HELD, UPLINK MT, DELETE UPLINK, DL ELIG, SEND FREQ), and 3 custom DAG-TM operations (RESPOND YES, RESPOND NO, SEND RTA). These operations can be initiated by several different methods:

- PICK the R-CRD menu entry, (or)
- type the two-character code shown in column 2 (e.g., "UC" for UPLINK CLEARANCE), (or)
- use the function key listed in column 3 (F5 for UPLINK CLEARANCE)

A second CPDLC menu, the "DS Category Menu," is accessed using the "DS" key. This menu is used to configure or suppress the status and menu text lists on the DSR display. Ours is a subset of Miami Center's Build 1 menu. The three supported operations are also available from the DC View.



```
UPLINK CLEARANCE ; REROUTE TO
UKW / FL310;AAL168
ROUTE AMENDED: IND./.341549N/0
993029W..335041N/0992915W..UKW
```

Figure A12. R-CRD Data Link Menu

3. *Status List*

The Status List (Figure 13) provides the controller a list of ongoing transactions for his or her sector. There are several methods for toggling display of the list: from the DC View (DL key), from the R-CRD DS category menu, or by typing "DL ON" / "DL OFF" in the R-CRD. The first line of the Status List is its label ("SL"). The second line labels the list's three columns. The first column, "AID," for aircraft ID; "DATA" identifies the transaction and includes transaction-specific information; and "STATUS" shows the transaction's current status.

The Build 1 Status List sorts entries into three categories based on status: (1) held, (2) non-positive (open or closed), (3) positive (open or closed). The AOL implementation adds a 4th category for “pilot request” downlinks, which can be highlighted in cyan or magenta (Table 8). Handoffs cannot be initiated for an aircraft that has either “open” or “non-positive” entries remaining in the status list; the controller must manually delete these entries using the “DE…” or “DE /OK…” commands.

```
SL
AID         DATA                 STATUS
UAL 124/676 CONTACT  135.45 (IFR) TIM

UAL346/916 Reroute  to PGO        SNT
```

Figure A13. CPDLC Status List with 2 entries (one non-positive, one positive). This example has no entries in the held or downlink categories. See text and table 5 for a

Four different types of communications are supported by CPDLC: transfer of communication, uplink messages, uplink clearances, and downlink requests.

4. Transfer of Communication

Transfer of communication for CPDLC aircraft is an automation-assisted process for transferring both radio communications & data link eligibility from transferring to receiving sector after the handoff of track control is complete. This process includes either a manual or automatic uplink of the receiving sector's radio frequency, depending on the selected "TOC mode." TOC mode can be changed from the DC View. Transfer of communication is described in Table A9.

Table A9. Transfer of Communications Procedure

1.	Sector handoff is initiated by transferring controller. A handoff cannot be initiated while open or non-positive transactions for the aircraft remain in the status list.
2.	Handoff accepted. Depending on whether TOC mode is MANUAL or AUTO, a frequency uplink message is either:
	(a) automatically sent to the aircraft (TOC AUTO), or
	(b) automatically created and "HLD" in the status list (TOC MANUAL). When ready, the transferring controller sends the message to the aircraft with the "UH" function.
3.	the data block on both sectors has a lightning bolt ("↯") next to the call sign indicating a TOC in progress.
4.	The pilot receives the message, tunes the new frequency, and responds via CPDLC to the uplink message (WIL).
5.	CPDLC eligibility transfers to the next sector as soon as the "WILCO" is received.
6.	The data link symbol in the data block reflects the transfer of eligibility: "◇" (hollow diamond) for transferring controller, "◆" (filled diamond) for receiving controller.
7.	The flight crew will check in by voice if the message was "CONTACT…". They will *not* check in by voice if the uplink message told them to "MONITOR…".

5. Uplink Clearances & Messages

Uplink clearances currently supported in our prototype CPDLC implementation include RTA, altitude and speed clearances (speeds based on meter-fix speed advisories), and route modification clearances. These require a CPDLC reply (“wilco”, “unable”) from the flight deck. Text messages (e.g., “Check stuck mike”) may also be sent; these may or may not require a response.

6. Downlink Requests

Route modification requests can be downlinked from the flight deck and are presented to the controller as trial plan proposals (Figure A14). The controller may either accept or reject these requests. No mechanism is currently provided for sending a modified 'alternative' proposal as part of the same transaction.

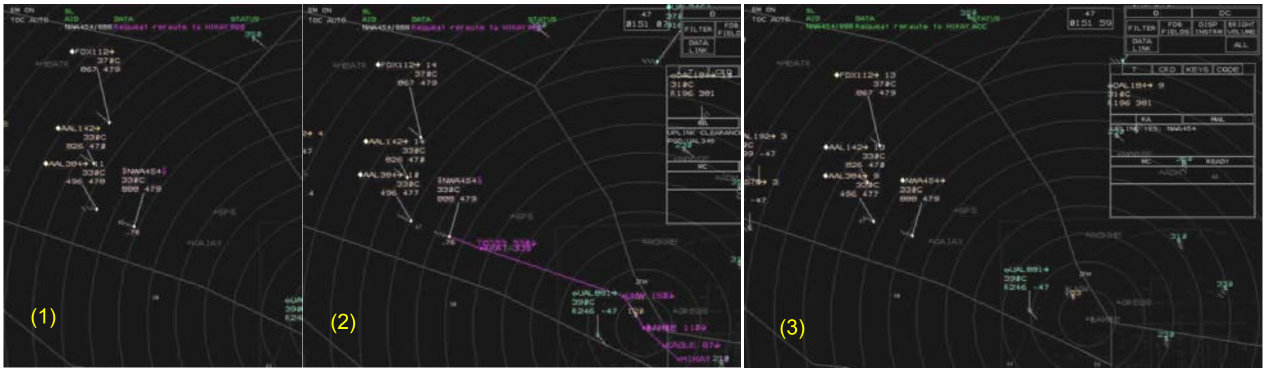


Figure 3.14. MACS/DSR downlink request interface: (1) Ground automation has received a donwlink request from AAL384.Magenta controller cues shown in datablock and status list. (2) Route request accessed by clicking on the magenta arrow is displayed with ground automation feedback (as in trial plan). (3) The controller has approved the request ("ACC" uplink sent to flight crew).

7. CPDLC and Autonomous Operations

CPDLC supports autonomous operations by greatly reducing the need for controller interaction with AFR aircraft. For most sectors, in fact, controller communications with AFR aircraft is minimal to none. The controller or pilot can initiate contact at any time, however, since the flight crew is required to monitor the radio frequency of the airspace that they are flying through. Transfer of radio (and CPDLC) communication is handled from the ground completely through the automation, with no controller involvement.

CPDLC also permits RTA assignment to AFR flights for TRACON (managed airspace) entry to be handled automatically without controller involvement.

Table A10. Summary of CPDLC Keyboard Commands

Transfer of Communications:		
uplink frequency:	UH [cid]	send held message (keyboard)
	UH (slew & ENTER on ".")	send held message (trackball)
	UF [cid]	send default frequency (sector with eligibility)
	UF [frequency] [cid]	send specified frequency
	UF [sector ID#] [cid]	send default frequency for specified sector
transfer elegibility:	SX [cid]	transfers eligibility to sector with track control
	SX /OK [cid]	transfers eligibility to sector *without* track control
change TOC mode:	"TOC mode" button in DC View	"TOC Manual" to "TOC Auto" to "TOC Off"
Status List Management:		
delete message:	DE [cid]	delete all closed messages for specified aircraft.
	DE (slew & ENTER on ".")	delete selected (closed) message.
	DE /OK …	over-ride for deleting open messages (must specify message or aircraft)
turn on/off SL display:	SL ON (or) SL OFF	
	"DL" button in DC View	
Uplink Clearances:		
uplink RTA:	UH [cid]	send held message (keyboard)
	UH (slew & ENTER on ".")	send held message (trackball)
	UR [cid]	uplink current RTA to specified aircraft
uplink speed advisories:	UC [cid]	uplink advised speeds to specified aircraft
uplink route clearance:	UC [cid]	uplink advised trial plan route to specified aircraft
Reply to Downlink Request:		
Affirmative, approved:	UY [cid]	sends positive (approved) response to flight deck
Negative, unable:	UN [cid]	sends negative (denied) response to flight deck

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