AIAA Modeling and Simulation Technologies Conference and Exhibit
21 - 24 August 2006, Keystone, Colorado

AIAA 2006-6112

The Airspace Operations Laboratory (AOL) at NASA Ames Research Center

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The Airspace Operations Laboratory (AOL) at NASA Ames Research Center hosts a powerful simulation environment for human-in-the-loop studies of air traffic operations. The capabilities have been developed at NASA Ames and cover a wide range of operational environments from current day operations to future operational concepts like those envisioned for the Next Generation Air Transportation System (NGATS). The research focus in the AOL is on examining air traffic control and management operations across multiple air traffic control sectors in rich air/ground environments that can include oceanic, enroute and terminal airspace. Past research involving the AOL includes distributed air/ground traffic management studies on trajectory negotiation, airborne self-separation and airborne spacing. Ongoing research with various government and industry partners include trajectory-oriented operations with limited delegation; multi sector planning; the US tailored arrivals initiative; airline-based sequencing and spacing, and airborne merging and spacing. In the future we expect using the AOL extensively for early exploration of operational questions crucial to the NGATS, like human-automation interaction, roles and responsibilities in distributed environments and required automation capabilities. This paper first gives an overview over philosophy, physical layout, software and connectivity of the AOL. Next, the available real-time capabilities are described in detail followed by a description of some important offline capabilities. The paper concludes with a summary of past and present research in the AOL and concluding remarks.

Nomenclature

AAC	=	Advanced Airspace Concept
ADS-A/B	=	Automatic Dependent Surveillance-Addressed/Broadcast
ADRS	=	Aeronautical Data link and Radar Simulator
AOC	=	Airline Operational Control
ASAS	=	Airborne Separation Assistance System
ASDI	=	Aircraft Situation Display to Industry
AOL	=	Airspace Operations Laboratory at NASA Ames

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ATM	=	Air Traffic Management
ATOL	=	Air Traffic Operations Laboratory at NASA Langley
ATOP	=	Advanced Technologies and Oceanic Procedures
ATSP	=	Air Traffic Service Providers
CD&R	=	Conflict Detection and Resolution
CDTI	=	Cockpit Display of Traffic Information
CHI	=	Computer Human Interface
CO-ATM	=	Co-Operative Air Traffic Management
CPDLC	=	Controller Pilot Data Link Communication
CSD	=	Cockpit Situation Display
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
ETMS	=	Enhanced traffic Management System
FAA	=	Federal Aviation Administration
FD	=	Flight Deck
FDDRL	=	Flight Deck Display Research Laboratory at NASA Ames
FMS	=	Flight Management System
JPDO	=	Joint Planning and Development Office
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

SIMULATING air traffic operations is challenging. Complex interactions between air traffic controllers, flight crews, traffic managers, airline operators and their respective automation systems result in the organized or chaotic movement of thousands of aircraft through the airspace. Covering all the potential interactions in simulation is impossible. Therefore, each simulation has to be designed to cover those aspects that are relevant to answer particular research questions. Realizing the vision for the Next Generation Air Transportation System (NGATS) outlined by the Joint Planning and Development Office[1] will require simulations to address numerous research questions.

The NGATS vision calls for a system-wide transformation leading to a new set of capabilities that will allow the system to respond to future needs of the Nation's air transportation. The list includes communication and physical infrastructure, the acceleration of automation and procedural changes based on 4-dimensional (4D) trajectory analyses to substantially increase capacity with safety and efficiency of the National Airspace System (NAS), and dynamic reconfiguration of airspace to be scalable to geographic and temporal demand. A key element of the NGATS vision is the complete transformation to the concept of Trajectory-Based Operations in a Performance-Based environment.

The primary focus of NASA's NGATS ATM-Airspace project is to explore and develop integrated solutions providing research data to define and assess the allocation of ground and air automation concepts and technologies including the human roles necessary for the NGATS.[2]

Simulations will be a primary research tool. In order to address the NGATS Airspace research needs ambitious operational concepts with highly advanced automation support will have to be rapidly prototyped and evaluated in simulation. These simulations need to be visionary and realistic at the same time. Realizing NGATS operational concepts cannot be limited to today's technologies, and distribution of roles and responsibilities. At the same time disregarding the many aspects that make today's system safe and relatively efficient would also be a mistake. Furthermore, it can be expected that today's state of the art aircraft will still represent the majority of aircraft in the

NGATS environment and that the operators, controllers and pilots trained in the next decade will represent a majority of operators for the NGATS. Therefore, finding the appropriate transition path will also be crucial in implementing the NGATS vision and simulations need to be able to address both, the far-term vision and the transitional stages.

The Airline Operations Laboratory (AOL) at NASA Ames Research Center has been designed for studying air traffic operations in the current environment, possible NGATS environments as well as the transitional stages between now and then. In fact, emulation of current systems and rapid prototyping of envisioned functions are the primary threads followed in the AOL's development and use and are therefore represented throughout this paper.

Following this introduction Section II of this paper gives an overview over philosophy, physical layout, software and connectivity of the AOL. In Section III the available real-time capabilities are described in detail, including the individual operator stations. Many aspects need to be considered when investigating research questions in human-in-the-loop simulation. These include scenario generation, lab configuration, data collection and analysis. Section IV of this paper provides an overview over some important AOL offline tools for scenario generation and data analysis. Section V summarizes past and present research conducted in the AOL which centers on air/ground integration of trajectory oriented operations, data link communication and airborne separation assistance[3, 4] and includes Distributed Air/Ground Traffic Management (DAG-TM)[5], Multi Sector Planning[6], Tailored Arrivals[7], and Trajectory-Oriented Operations with Limited Delegation[8]. Section V also provides additional references to details about these individual research areas. A few short remarks conclude this paper.

II. Overview

The hardware and software in the AOL is highly configurable and designed to let the research questions define the simulation environment. Everything from airspace, number, role and position of participants and confederate operators to automation and communication technologies can vary to provide the required test bed. To enable this kind of flexibility the entire software used in the AOL has been developed "from scratch" at NASA Ames Research Center and the lab has been laid out to provide maximum versatility. The range of existing capabilities is depicted in Figure 1. When necessary simulation components are outside the scope of the AOL's existing or immediate prototyping capabilities, other laboratories can be connected to the AOL and provide additional operator stations such as full mission flight simulators, advanced flight deck functions, or tower positions.

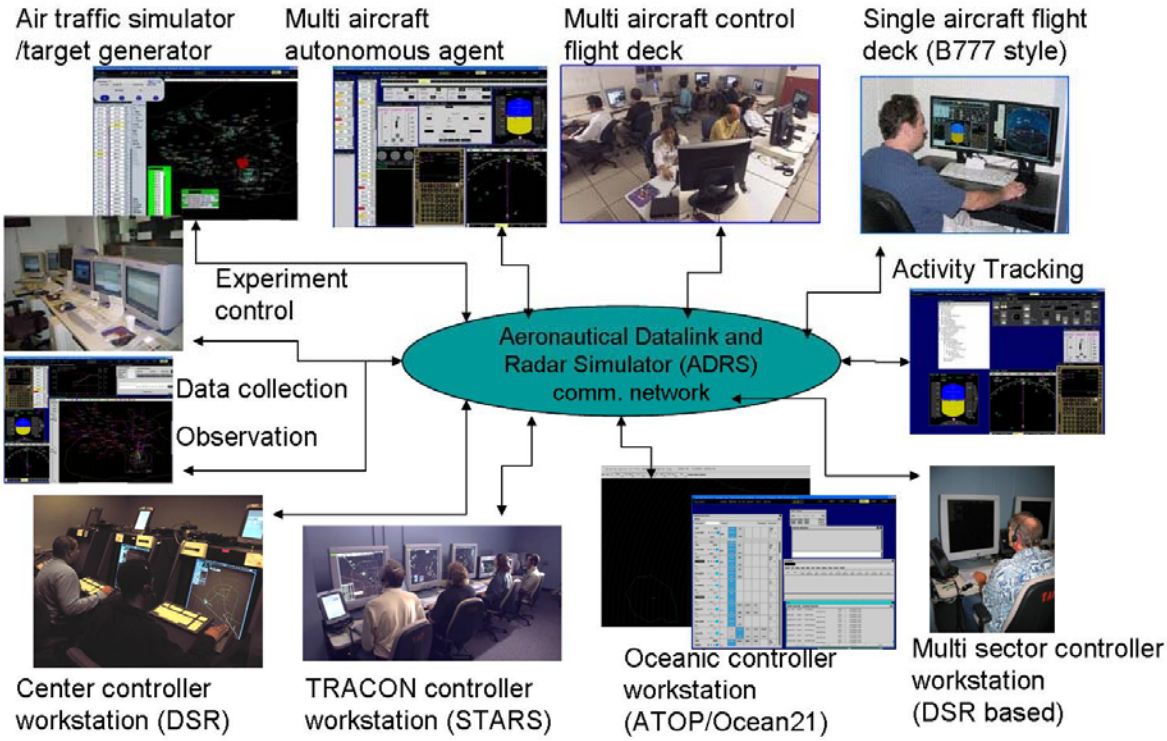

Figure 1: Overview over existing capabilities in the AOL

This section starts with a short discussion of the rationale behind the physical lab configuration and the software used to drive the operator stations and the underlying automation. Next the real-time components of the software are introduced and the AOL's physical layout is presented. At the end of this section connectivity to other laboratories and simulators as well as the "live" data connection are discussed.

A. Rationale

The rationale for designing the AOL and its capabilities follows two primary threads:

- Emulating existing systems
- Rapid prototyping of envisioned capabilities.

1. Emulating Existing Systems

Operators in the air traffic system are very well trained experts who are used to a specific work environment. This environment is defined by many aspects including obvious factors such as the workstations hard- and software, but also less apparent variables such as the lighting in the room, the ambient noise, or the location of the nearest wall clock. Not matching some of these aspects in the simulation can have a major impact on the operators' performance, while others matter less. After about a decade of simulations with air traffic controller participants in the AOL we now believe to have addressed the most important aspects of the work environment. Several elements were crucial in transitioning the controller positions from what might be considered a "video arcade" to a believable air traffic control simulation.

- Emulating the fielded controller's display behavior and supporting automation in all critical aspects
- Using the fielded controller keyboard, trackball and screen to interact with the emulation
- Locating the controller positions in rooms with the appropriate paint and lighting
- Isolating participant positions from distractions during simulations
- Simulating current day flight deck technologies appropriately so that controllers can issue standard and non-standard clearances
- Emulating current day communication, navigation and surveillance technologies for achieving the appropriate system response to controller instructions
- Staffing non participant controller positions with subject matter experts that interact with the participants in a realistic manner

According to post simulation questionnaires the emulation in the AOL has reached an adequate fidelity level [9,10], but there is certainly always room for improvement. These improvements are made if a limitation in the emulation significantly impacts operator performance during the investigation of a particular research question.

2. Rapid Prototyping of Envisioned Capabilities

Accurately emulating existing systems is an important step in conducting meaningful human-in-the-loop research on air traffic operations. Most research questions however ask about new operational concepts, roles and responsibilities enabled by envisioned future technologies. Current day emulation can serve as a baseline that can be validated or calibrated against current day operations. The new operational environment can then be compared to this baseline. In order to avoid introducing too many variables into this comparison the design philosophy followed in the AOL is largely based upon rapidly prototyping new capabilities as extensions and enhancements to the current day emulation. The resulting system may implement drastically different technologies, roles and responsibilities for the operators and the automation, but integrated in a known and easily trained environment. Therefore, for example new decision support automation is implemented in line with the CHI concept of the respective current day system. Many highly advanced tools have been integrated in the AOL in this manner and have consistently achieved high usefulness and usability ratings by air traffic controllers. Moreover, they provided the performance required for simulating a variety of future operational environments[3,8,9,10]. The intent of AOL prototypes is to serve the research purpose, and provide the required functionality, and not to be an operational implementation. The main idea is to simulate envisioned capabilities quickly to investigate a specific operational concept early in the research process. Successful prototypes may result in requirements and specifications for operational systems but are not intended to be transferred directly into operations.

B. Real-time Software

The design philosophy puts many constraints on the real-time software. From a human factors research standpoint it is very important to provide the adequate level of fidelity. From a concept exploration standpoint it is

very important to have an environment for rapid prototyping and integration of envisioned technologies. Different research questions can require different airspace and traffic characteristics, participant positions and varying levels of technologies. Most existing high fidelity simulation systems are expensive and difficult to modify or extend. Most research prototyping environments are focused on the engineering aspects of new automation but use generic low fidelity operator interfaces. After struggling and somewhat coping with this dilemma for several years within the Terminal Area Productivity program the AOL research team was faced with the challenge to investigate substantial elements within various Distributed Air Ground Traffic Management (DAG-TM) concepts in 2001. This research required new levels of fidelity and advanced capabilities for ground automation, airborne automation and CNS infrastructure.

Based on our prior experiences we decided to stop all modification efforts to existing systems and developed a new system that would provide the required realism and serve as the rapid prototyping environment at the same time. Only the previously developed communication process was carried forward which also maintained communication links to all previously used systems. The new simulation environment consists of only two components: The Multi Aircraft Control System (MACS)[11] provides all operator interfaces and hosts all emulation and advanced automation software and the Aeronautical Data Link and Radar Simulator (ADRS) serves as the communication network between MACS stations and external simulation components[12,13].

1. MACS (Multi Aircraft Control System)

MACS provides the environment for rapid prototyping, controller and pilot-in-the-loop simulation, and evaluation of current and future air/ground operations for the National Airspace System. The existing suite of capabilities allows researchers to configure a wide range of air traffic environments, from accurately emulating current day operations to simulating many of the operations envisioned for the NGATS as well as the transitional stages between now and then. Additional capabilities can be prototyped as required for the specific research. In order to evaluate envisioned operational environments an unlimited number of MACS operator stations can be configured and connected via the ADRS networking infrastructure. These operator stations include high fidelity air traffic controller workstations in the oceanic, en route and terminal domains, medium fidelity “glass cockpit” flight decks for confederate pilots and flight crew participants, as well as experimenter, observer, and analyst stations. Figure 2 shows an example configuration used in a recent study with eight controller stations (five participants and three confederate “ghost” positions), six multi aircraft pilot stations, one simulation manager and one data analysis station were used. MACS also has built-in scenario and target generation capabilities, which are used to generate and run the traffic problems tailored to the specified challenges such as high volume, and weather. An integrated and flexible data collection system is used to collect the quantitative measures of interest at each operator station as well as overall traffic progression, including aircraft states, conflicts, sector counts etc.

MACS is implemented entirely in the JAVA programming language and is therefore portable to all platforms. All MACS operator stations are instantiations of the same software running in different operator modes. MACS is developed and implemented by the AOL development team who also maintains the source code repertoire. Only one version of MACS is installed in the AOL at any time, which always includes the latest development software. Update freezes occur just prior to simulations until the simulation is finished. Because of its portability MACS can be developed and run standalone on desktop and portable computers as well as in the full laboratory environment.

The design and development of MACS was based on extensive experience in running, modifying, and integrating many different existing flight simulators, target generators, decision support tools and communication infrastructures for various research projects. In working with these existing systems, it became apparent and frustrating that many functions were missing and often very similar functions were implemented in many different, often complicated, and sometimes proprietary ways. Capabilities needed or available on one system were incompatible with the other system or had to be added to all subsystems. This made prototyping of new integrated functions difficult and very time and resource consuming.

MACS is designed for rapid prototyping. The main idea is to provide a central object oriented representation of all information available, process the information with an extensive library of commonly used methods, and provide displays and controls to view and stipulate the situation from various operator perspectives. The centrally represented data include among many others aircraft lists, weather, data link messages, aircraft performance characteristics, flight states, trajectories, flight plans, flight deck inputs and controller inputs. Commonly used classes and methods include items such as trajectory generators, conflict probing algorithms, surveillance simulators, aeronautical calculators, basic display layouts and symbols, input processing routines and communication functions.

Each MACS station uses exactly the same software. As mentioned only one baseline version of MACS is continuously maintained and all functions are part of this version. Setup files and startup options specify which functions and information are available to each operator depending on their role in the simulation and the experimental objectives. Thus, any MACS station can be one or more of the following applications:

- An air traffic simulator
- A medium fidelity flight deck with full flight management system (FMS) capabilities
- A high fidelity air traffic controller workstation with advanced automation (Oceanic, Center , and TRACON)
- An experiment control station
- A data collection system
- A scenario generation tool
- A rapid prototyping environment for new air traffic control and management automation
- A rapid prototyping environment for flight deck automation
- An analysis tool
- A system to participate or control large scale distributed simulations with many operators
- A standalone application to assess and demonstrate new ATM concepts on any state-of the art computer

The operator mode for a given session is selected during startup and drives which displays are made available, which functions are activated and which situational knowledge can be used. The performance of the station is automatically being optimized for the specific operator mode.

Figure 2. MACS Operator mode selection panel

To preserve the integrity of the information used for the various operators MACS pays specific attention to processing and displaying only that subset of situational knowledge that would realistically be available at the respective operator's position. For example, an air traffic controller today usually does not know the precise location of an aircraft, only the position estimated by the surveillance system is available. MACS provides setup functions to select the sources and accuracies of the surveillance system providing data to the controller to remain true to the current reality and at the same time enable research using more accurate position data of the future. At the same time the flight deck displays and functions use the more accurate flight state information that is realistically available on the aircraft.

Because MACS is intended to be used by many different operators and for human factors experiments, three of the primary design goals of the MACS architecture were to achieve a very responsive system performance, a high level of reliability and an easily extendable system. MACS is implemented as a highly multi-threaded java application. Each functional block and each user selectable display is controlled by its own thread. A thread can be best described as a parallel process. In MACS threads are only activated if they are needed for the specific operator mode. For example, an en route air traffic controller workstation does not need to run the aircraft simulation or provide access to flight deck displays, or oceanic ATC displays. Therefore if a specific operator mode like "Center-

Controller" is selected the threads enabling irrelevant functions are never started and do not cause any extra system load.

Threads that are active during a session register with a special thread observer that is tasked to check all other active threads for proper functioning and restart those that appear to have malfunctioned. This process allows the system to cope with the majority of minor failures, simply be restarting the malfunctioning thread. The system "heals itself" without the operator knowing it and makes for a very reliable and robust application. The run cycle times of the threads are automatically adjusted to the system loading. If excessive system load is expected, because for example an unusually high amount of aircraft has to be processed, many threads are automatically changed to be updated at a lower frequency. This helps avoid deadlocks or not keeping up with high priority tasks that could negatively impact the rest of the simulation, or the look and feel for the operator. Experimenters and Developers can monitor and adjust thread behavior via a built-in control panel. Currently, the most demanding operator mode "Developer" starts all 160 threads, the least demanding "TRACON-Controller" starts 54 threads.

Very often entirely new functions or displays need to be integrated into the system. In MACS this process is very simple, because new functions or displays can be added with only few lines of code as only a few common classes need to be extended and added to two source files. This will ensure proper window and thread management of the new functions and gives the new capabilities direct access to all data and methods publicly available inside MACS. For example an initial prototype of the Advanced Airspace Concept conflict resolution logic that had been developed in JAVA in a different platform was added to MACS in a few days and is now available for further evaluation and can be updated with new code at any time.

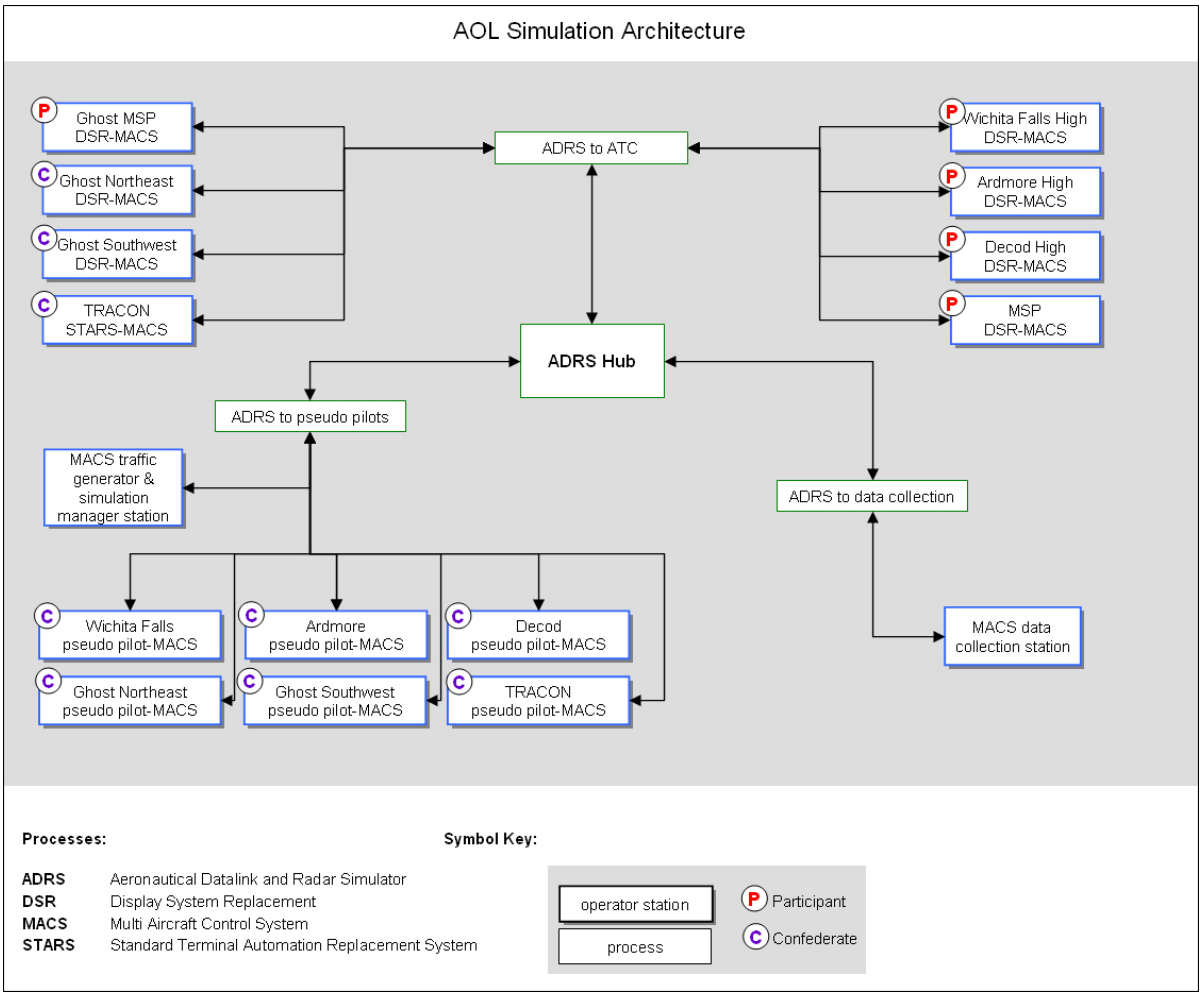

Figure 3. Simulation architecture used in a 2006 experiment on Multi Sector Planning

2. ADRS (Aeronautical Data Link and Radar Simulator)

The ADRS is the central communication process/network enabling information sharing between MACS stations and other "external" simulation components. Within an air traffic operations simulation the ADRS serves as a limited Host Computer System (HCS) emulator. It maintains and amends flight plans, as well as manages information to be shared between clients, such as scheduling and metering information and controller inputs (e.g., handoff information). The ADRS also performs surveillance functions including radar simulation. A radar simulation module inside the ADRS simulates radar sweeps, radar noise, cone of silence areas, and alpha beta tracks the radar data. Data link communication is also simulated through the ADRS. Data link messages, of several formats ranging from custom to ARINC702 standards, are received from simulated aircraft or ground facilities and converted, delayed, and forwarded as required. Aircraft state and trajectory information are maintained by the ADRS as well. Information from a target generator is received by the ADRS and, in conjunction with its own data, is harmonized, maintained, and distributed to all connected clients.

The ADRS is implemented in the C programming language and can be compiled and executed on Solaris, Macintosh and Windows platforms. New components can either plug into the ADRS if they implement one of the different communication protocols the ADRS provides or the ADRS code can relatively easily be modified to meet the new components needs. For small simulations one ADRS process can handle all the necessary communications, larger simulations can launch a network of ADRSs. Though used in many different ways, each ADRS software program is identical. Each ADRS can serve many additional ADRS clients, which themselves can serve additional clients. There is no limit to the number of servers and clients to be included in the simulation, because adding another ADRS-node can expand each node.

All ADRSs share all required information to allow clients to connect to any node and receive the same data quality and quantity. Therefore the number of simulation hubs can be tailored to network loading and real time requirements. If for example one ADRS appears to suffer from delays because of the number of network intensive clients an additional process can be started and half of the clients can be moved to the second one. All processes communicate with the ADRS via TCP/IP socket communication and use custom protocols tailored to the individual process types. A single ADRS or a network of ADRSs can be compared to an internet for air traffic simulations. Simulation components can connect to the ADRS at any time before or during a simulation. All ADRS nodes provide the same information quality. All information is shared between the different ADRS nodes without any particular action to be taken by the user. Clients have complete control over what data they receive and how frequently. The data interfaces work on a subscribe/response basis and clients can receive all available data including precise aircraft positions and states, flight plans, four-dimensional trajectories, controller inputs, air traffic management information, simulated radar targets, aircraft guidance inputs, health status information. It can simulate ADS and CPDLC data link capabilities and convert data into formats that simulated aircraft and ground automation can understand.

C. Physical Laboratory Layout

The AOL is located at NASA's Ames Research Center in Moffett Field, California. A part of the Human Factors Division within the Exploration Technology Directorate, the AOL houses workstations for participant controllers, confederate controllers and pilots, AOC/TMU planners, observers, and experimenters. The AOL can be broken down into four areas: two being for air traffic control (ATC) workstations, a main area for pseudo-pilots, and one area for the experimenters. Pictures and diagrams of the AOL's current ATC areas are provided in Figures 4, and 5, the pseudo pilot area is depicted in Figure 6 and a diagram of the pseudo pilot area and the experiment control room is shown in Figure 7.

Figure 4. Air Traffic Control Areas (Room 278 left and room 286E) within the AOL

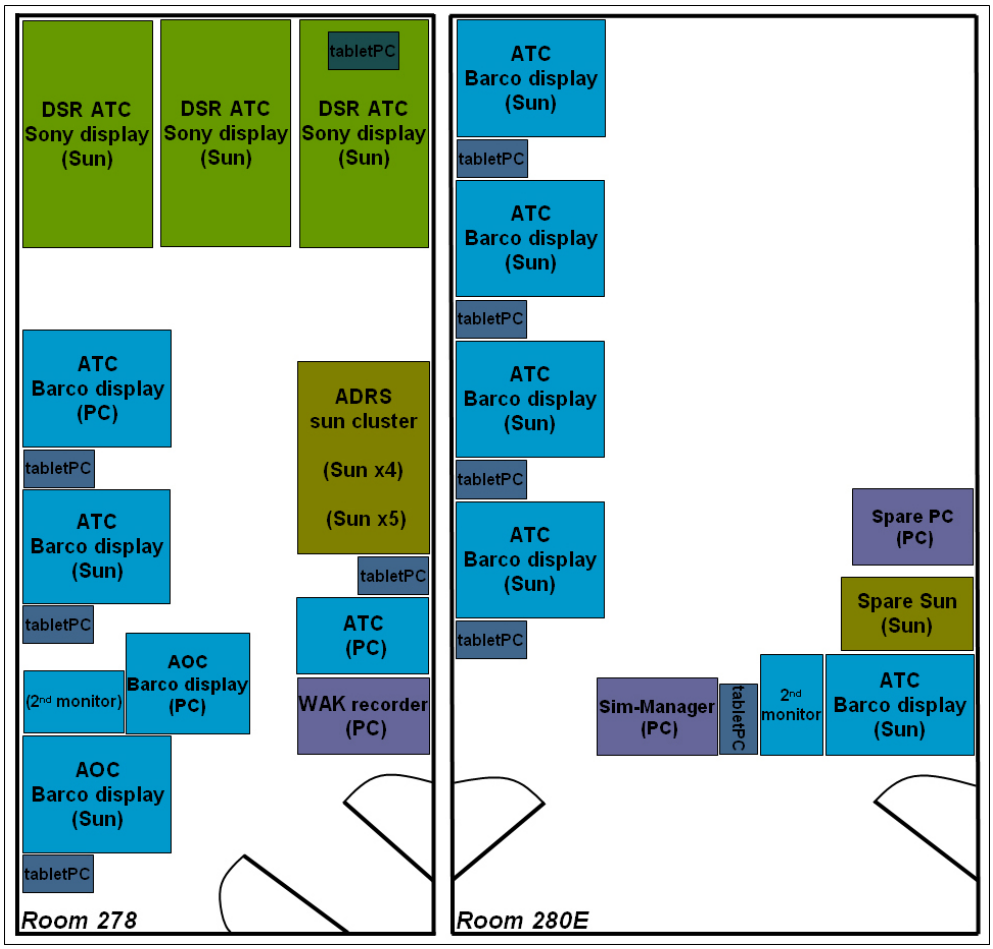

Figure 5. 2006 Layout of the AOL's two ATC areas.

Most of the ATC workstations are Sun Microsystems computers, and are mounted to a shared drive on a Sun Microsystems application server. Most of the Microsoft Windows PCs, including all the pseudo-pilot workstations, are mounted to a shared drive on a Windows application server. Having almost all of the workstations mounted to a shared drive on an application server makes software updates efficient in the AOL, since software changes and database updates only need to be done on the two servers. This keeps all workstations up-to-date with the latest software version. Because all operator stations use the portable MACS software any position can be located on any workstation to accommodate the number and type of participant and confederate workstations required for a specific study.

Additionally, the ATC and pseudo-pilot workstations in the AOL are all connected via a digital voice communication system[13]. The internet-based Voice over Internet Protocol (VoIP) works on Windows PCs. Since the ATC workstations are Sun Microsystems computers, small Windows Tablet PCs with touch screens are used to give those workstations access to the voice communication system. Section III.E.1 will discuss the VoIP communication system in more detail. For the experimenters, five Windows PCs serve as the simulation-manager and data collection workstations. The AOL's data collection capabilities will be discussed in more detail in section III.G. The AOL incorporates a master clock with a GPS time receiver, which synchronizes the clocks of all machines with a time broadcast over the network. Lastly, a few additional computers are available for guest access, typically for summer student interns, as well as for experiment participants to check their e-mail and browse the internet during simulation breaks.

Figure 6. The pseudo-pilot area within the AOL

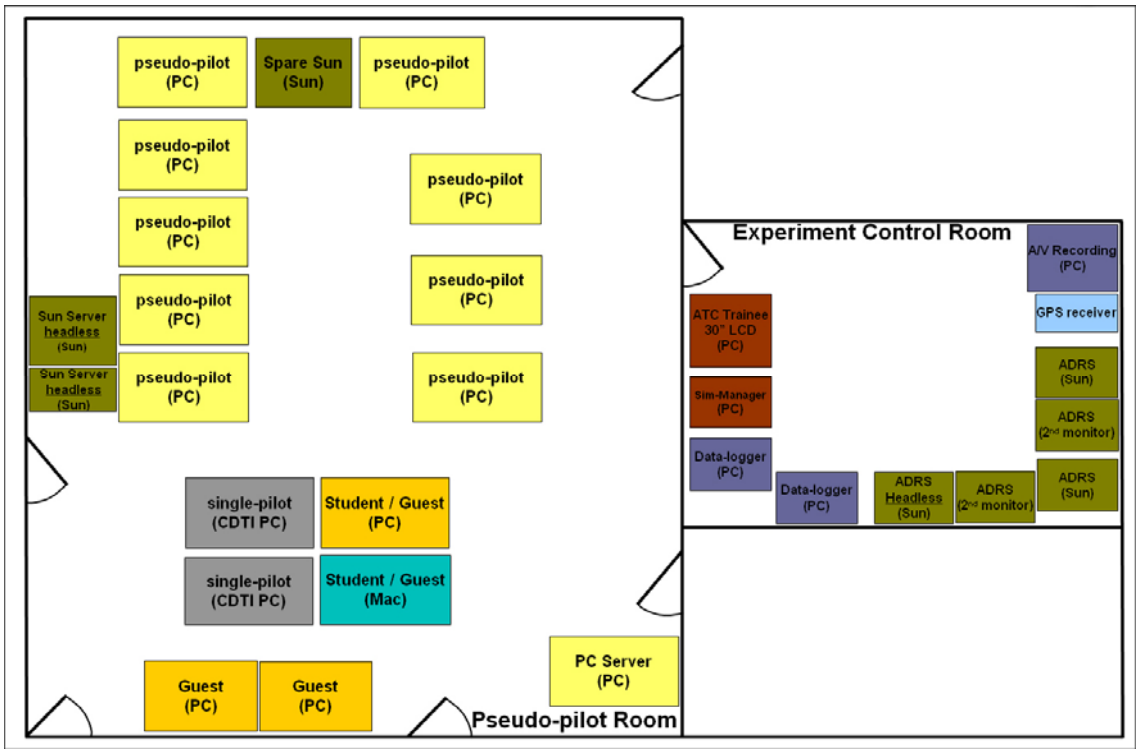

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Figure 7. Layout of the AOL's pseudo-pilot and experimenter's areas

D. Connectivity to Other Labs

The primary focus of simulations in the AOL is on evaluating air/ground operations within a limited number of air route and terminal airspace sectors from a ground side perspective. Many new concepts shift roles and responsibilities from the ground operators to the flight crew and require a pro-active flight crew role and advanced automation. Other research questions may require additional ground facilities like a tower or a command center to be simulated. In these cases the AOL can be connected to other simulations or simulation components via the ADRS. The Flight Deck Display Research Laboratory (FDDRL) at NASA Ames Research Center[13] is frequently connected to the AOL in order to investigate flight deck aspects. The flight deck capabilities are closely integrated with the AOL and use MACS single pilot stations as their flight simulator and a highly advanced Cockpit Situation Display CSD connected via the ADRS.

Other laboratories have also been connected to the AOL providing additional simulation capabilities. These include NASA Langley's Air Traffic Operations Laboratory (ATOL)[16], NASA Ames' full mission Advanced Concepts Flight Simulator (ACFS). During Distributed Air/Ground Traffic Management (DAG-TM) simulations in 2004 all these components participated in one simulation that included 12 airline pilots at NASA Langley, 9 airline pilots at NASA Ames, 4 participating and 3 confederate controllers at NASA Ames Research Center and up to 14 additional multi aircraft pilots at both centers. Over 25 MACS stations were part of these simulations. The architecture is shown in Figure 8.

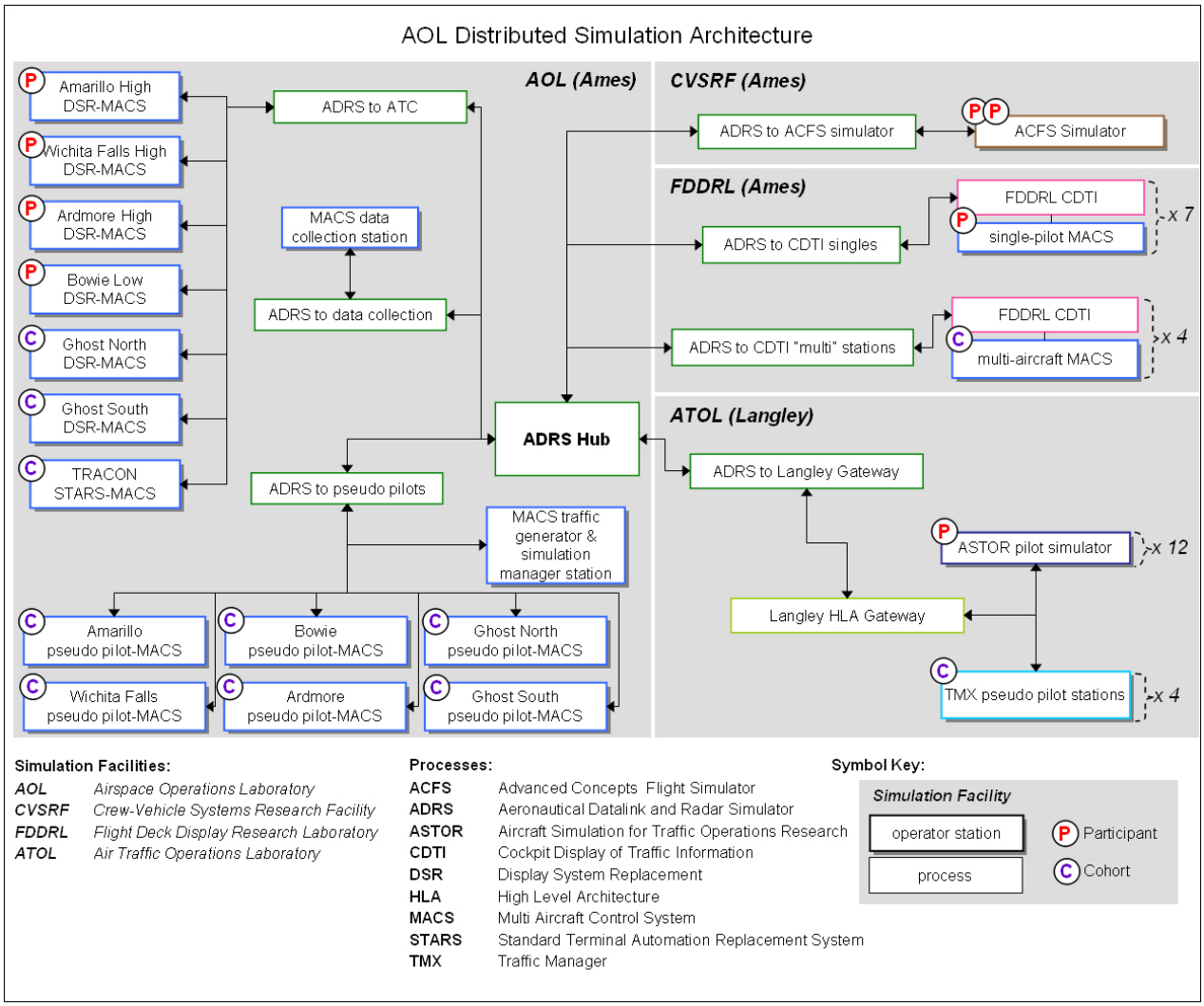


Figure 8. Simulation architecture used during DAG-TM experiments in 2004

Additionally the AOL was connected to NASA Langley's Research Flight Deck for Terminal Area Productivity studies. The AOL has connectivity to the Virtual Airspace Simulation Technologies Real-Time (VAST-RT).[18] This connectivity allows the AOL to participate in distributed simulations with the NASA Ames' Airspace Traffic Generator (ATG), Future Flight Central (FFC) tower simulation, and Crew Vehicle Systems Research Facility, which host the ACFS and a certified Boeing 747-400 simulator.[19] By way of VAST-RT the AOL should also be able interface with the Aviation Sim Net [18] This capability has not been exercised to date.

E. Connectivity to "live" traffic data

While the AOL's primary use is for simulation purposes only, it can also be connected to "quasi-live" traffic data. The ADRS can be connected to two different Enhanced Traffic Management System (ETMS)/Aircraft Situation Display to Industry (ASDI) data feeds. A Center TRACON Automation System(CTAS) based ETMS data router developed at NASA Ames and a multicast data server developed by MITRE and used at the UPS Louisville facility for field testing of airline-based sequencing and spacing tools. The ADRS establishes the connection to either one of these data servers and maintains all the flightplan and state information. As in simulations the ADRS can then distribute the information to any connected client, making the live data accessible to all AOL components. The primary uses for the data are for scenario generation purposes and to calibrate the aircraft performance models used in the simulation. In addition this connection is used for shadow testing of rapidly prototyped operator interfaces and alogirthms.

III. Real-Time Simulation Capabilities

This section describes the real-time simulation capabilities in detail. Target generation and aircraft simulation in the AOL can be distributed between many operator stations. After a short description of this process the available flight deck capabilities are outlined. These flight deck capabilities are used for generating a realistic air traffic environment for controller-in-the-loop research and at the same time serve as basic desktop simulators for pilot-in-the-loop research with additional flight deck displays typically provided by the FDDRL. The different current day air traffic control positions that are emulated in the AOL are presented next followed by one of the primary research areas realized in the lab: Advanced automation assisted controller workstations. The currently available workstation prototypes are described with some of the main functions that they provide. Any current or future operational concept makes assumptions about the environment in terms of Communication, Navigation, and Surveillance (CNS) and available weather predictions. An overview over data collection capabilities in the AOL concludes the real-time simulation capabilities section.

A. Target Generation and Aircraft Simulation

The MACS built in target generation and aircraft simulation capability makes use of an aircraft performance data base for the majority of common aircraft types. Aircraft performance data include descent and ascent ratios, speed envelopes, and flaps and gear schedules. Using this performance data base MACS is capable of accurately emulating aircraft movements through space without using a high fidelity simulation model. This enables MACS to simulate the motion, flight guidance and flight management functions of hundreds of aircraft in real-time on any state of the art computer. The aircraft behavior has been validated against high fidelity simulators, used by a number of airline pilots and deemed adequate for the research purposes. Unlike most target generators MACS emulates higher level flight control and management loops allowing all properly equipped aircraft in a simulation to use state of the art Flight Management System (FMS) functions.

The MACS target generation and simulation philosophy is different to traditional pseudo pilot systems such as the Pseudo Aircraft System (PAS)[20] or the Target Generation Facility (TGF)[21]. Traditional target generators and pseudo pilot systems, typically use a central simulation manager hosting the target generation and aircraft dynamics calculations and separate operator stations to send input commands to the flight simulation. In contrast MACS initializes all aircraft targets at a simulation manager station, and then lets other pilot stations take over control and simulation (including the target generation) of the different aircraft. The simulation virtually travels with the control of the aircraft. Figure 9 contrasts the MACS simulation architecture to the classic architecture.

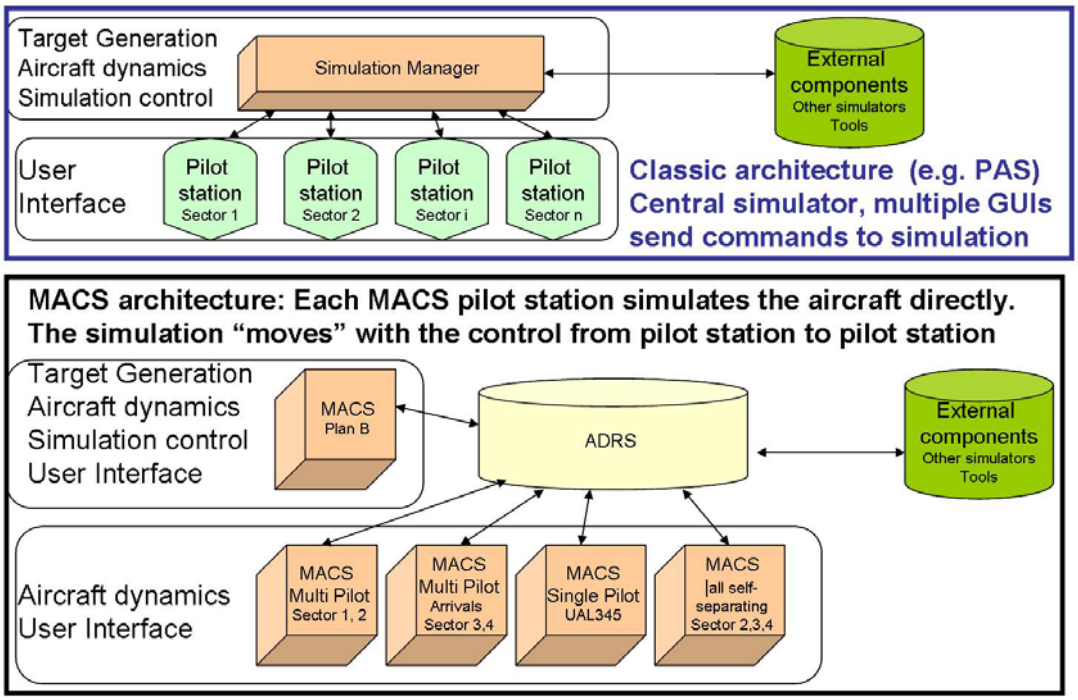


Figure 9. Classic pseudo aircraft system architecture (top) and MACS architecture used in the AOL

Each pilot station communicates its configuration initially to the ADRS. The configuration message can contain information such as “control all arrivals in sector 47 and 48”. The ADRS then assigns aircraft control to individual stations during the simulation. Each MACS pilot station tracks the status of all aircraft controlled and uncontrolled during the simulation, enabling it to take over control at any time. A “Steal” feature allows a station to overwrite the ADRS assignment and force control to its station. This feature is used for single pilot stations that maintain control of one particular aircraft during the entire simulation. A “Plan-B” station takes control over all aircraft that are not controlled by any particular pilot station. Therefore if a pilot station is shut down or suffers a “fatal” software crash the plan-B station immediately takes over and automatically controls the aircraft until it is picked up by another station. This distributed simulation approach has the advantage of not suffering from any kind of communication delays between input commands and aircraft response. The displays respond immediately to pilot inputs. The logic makes it extremely robust and insensitive to individual station failures.

B. Flight Deck Capabilities

The general assignment of control to individual stations has been discussed in the previous section. As mentioned MACS provides full flight guidance and flight management capabilities to all aircraft. As with all MACS software the flight management and guidance functions are implemented as generic functions that provide the same capabilities as fielded system, but use an entirely different implementation. Additionally the MACS pilot stations provided advanced functions such as precision Required Time of Arrival capabilities, airborne spacing guidance, and conflict detection. Implementation of electronic flight bag emulation is currently in progress. The Next two sections explain the flight deck capabilities for the multi and the single aircraft stations in more detail.

1. Multi-Aircraft Station

All simulations conducted in the AOL, come with full pilot involvement- there is no “background” traffic. All aircraft are piloted by either confederate (multi-aircraft) or participant (single-aircraft) pseudo-pilots. The pseudo pilot workstations in the AOL are MACS desktop flight simulators handling multiple aircraft simultaneously. The confederate pseudo-pilots are typically General Aviation (GA) or student pilots. During a simulation, these multi-aircraft pseudo-pilots can be “flying” anywhere from one to tens or hundreds of aircraft. Typically each pseudo pilot working inside a participant controller’s airspace controls ten to twenty-five aircraft. Because these pseudo-pilots are responsible for the command entries of several aircraft, their cockpit displays are configured as generic input devices designed to enable quick entry of ATC commands.

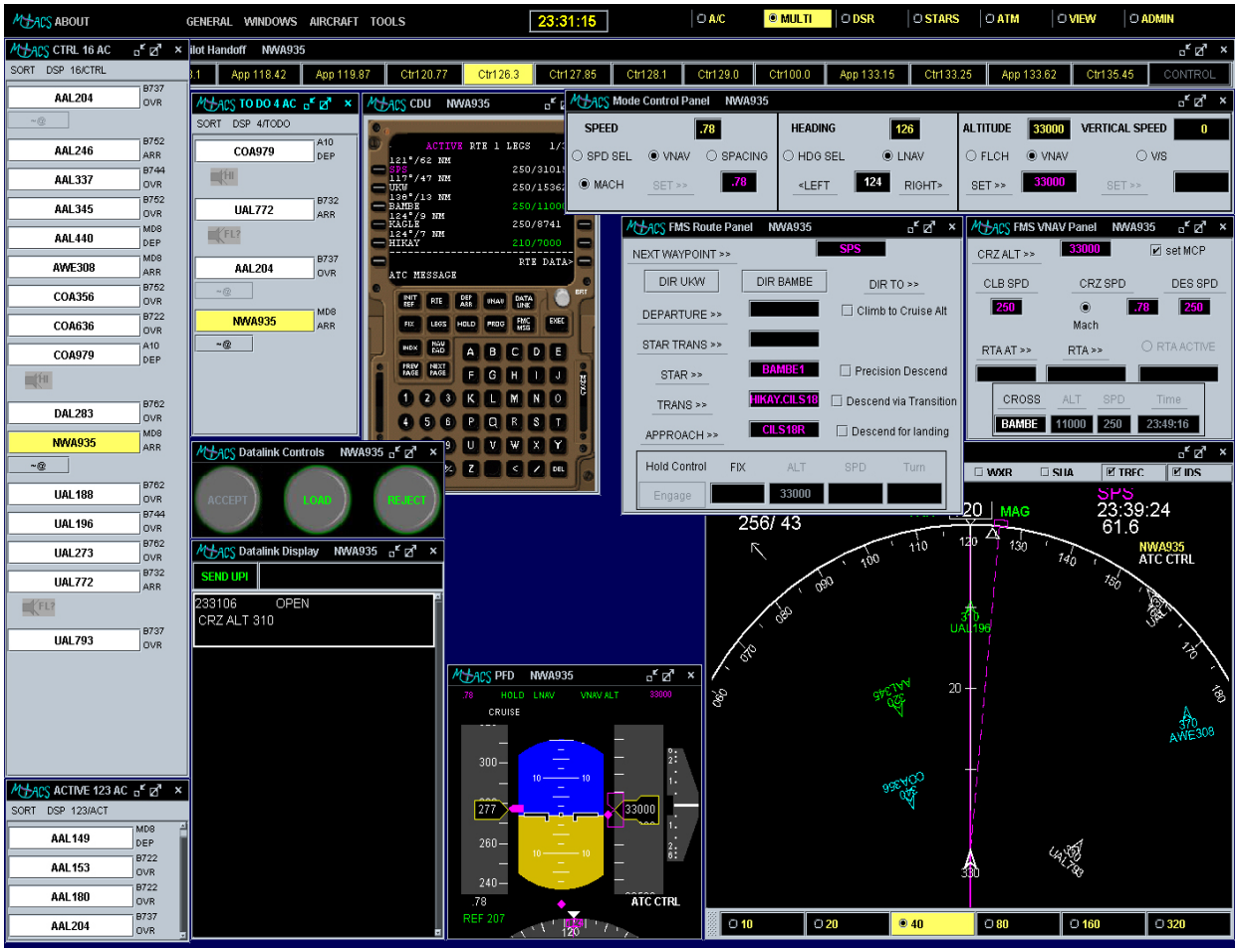


Figure 10. MACS multi-aircraft pseudo-pilot workstation

Figure 10 depicts an example of a MACS pseudo pilot station. In this example this MACS workstation has control of 16 aircraft, a subset of the simulation's active 123 aircraft. The Control (CTRL) list (on the left) shows the aircraft being controlled by this workstation, and the Active list (lower left) provides access to all aircraft currently in the simulation. Four of the controlled 16 aircraft require the pseudo pilot's attention, displayed in the To Do list. The operator can select any aircraft displayed in any of the aircraft list windows, or can click on the aircraft symbol in the Map display (lower right). Connected to ATC via digital radio, the pseudo pilot waits for ATC clearances, or requests them. If ATC issues a clearance to an aircraft, the pseudo pilot only needs to select that aircraft from their Control list. With an aircraft selected, the pseudo pilot can enter basic autopilot commands on the Mode Control Panel (top right) and can enter LNAV and VNAV commands on the "FMS Route Panel" and "FMS VNAV Panel" (center right). The "Pilot Handoff" panel (top bar) allows the pseudo pilot to handoff the aircraft to the MACS pseudo pilot controlling aircraft on a different frequency.

MACS can also provide reminders to the operators when actions must be taken. The icons in the aircraft lists in Figure 2.3.2 are some examples for those reminders prompting the pseudo pilot to check in (e.g., COA979), request a lower altitude clearance (e.g., UAL772), or respond to a data link message (e.g., NWA935 and AAL204). Other reminders can include frequency changes or entering a STAR transition or an approach routing. A MACS station can also be run in an automatic mode where, instead of reminding the operator, the actions are performed automatically. This functionality can allow developers to run prototype tests with automatic pilot-agents for controller display development, scenario development and controller training, and can also automate those parts of the airspace that are outside the immediate subject area. This functionality can be used only partially as well, assisting a busy pseudo pilot with simpler tasks, such as frequency changes.

2. Single Aircraft Station

MACS can be configured to use cockpit displays reflecting the look of a modern aircraft, emphasizing the correctness of the controls. During simulations these single pilot stations are typically combined with a Cockpit Situation Display (CSD) providing a Cockpit Display of Traffic Information (CDTI) with advanced trajectory management functions and weather and terrain depictions. Pilots operating typical MACS/CSD single pilot stations and observers in the FDDRL are shown in Figure 11.

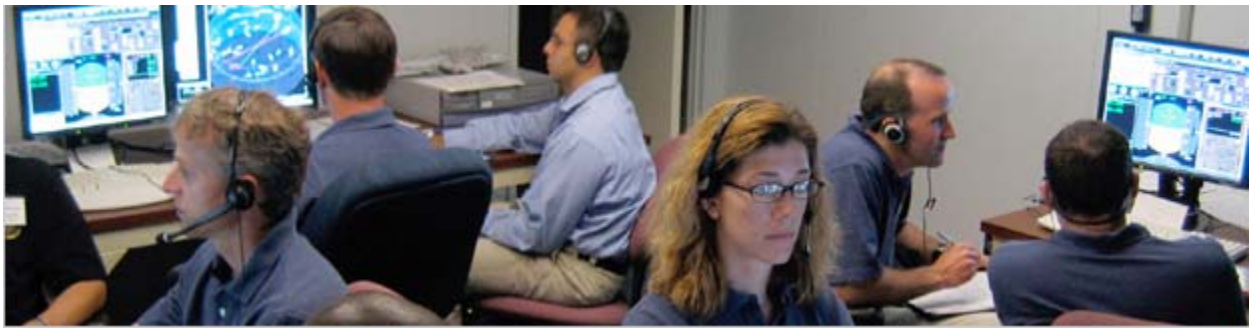


Figure 11. Pilots operating MACS/CSD single aircraft stations in the Flight Deck Display Research Lab (FDDRL) during a joint simulation with the AOL

3. Automatic Pilot Stations

MACS pilot stations can also be configured to run in automatic mode. In this case the station will, instead of prompting operators to take an action, automatically carry out the action. Events that can automatically be processed include frequency changes, altitude settings, and data link message processing. This functionality is used during simulations for all peripheral pilot positions and for system testing and training for all positions. All pilot positions that interact with test controllers are staffed with human operators to simulate the voice communication and implemented clearances that are not processed by the automatic pilot station functions.

C. Emulated Controller Workstations

MACS provides realistic emulations of controller workstations for Oceanic, En route and Approach Controllers workstations and can process the keyboard inputs from the fielded input devices. The emulations were created by using training manuals and operator interface descriptions and reverse engineering the underlying logic within the MACS framework. Since controller displays have many common properties, much of the internal functionality is used by all of the controller workstations.

1. En Route Controller: Display System Replacement (DSR)

The center 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.
- 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.

The DSR software emulation was based on a description of the DSR computer human interface (CHI) provided in the 2002 DSR user's manual21. 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. Figure 12 shows the MACS DSR emulation of a current day sector position.

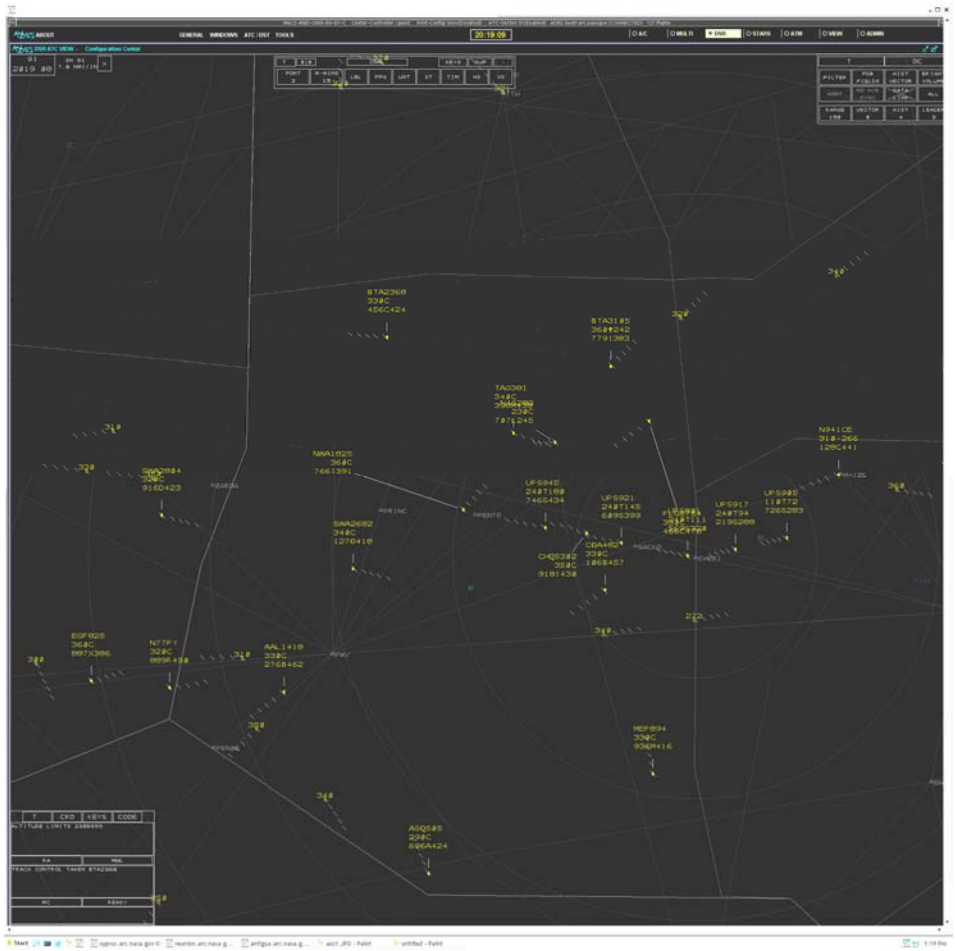


Figure 12. MACS based Display System Replacement (DSR) center controller workstation emulation

2. Approach Controller: Standard Terminal Automation Replacement (STARS)

Approach controllers can participate in the simulation using the MACS emulation of the Standard Terminal Automation System (STARS).[23] The majority of the past research conducted in the AOL has a focused on arrival operations. Even if the focus is on Air Route operations the AOL typically includes approach controllers as participants or confederates to make sure traffic flows provided by center controllers transition appropriately into the terminal area and are acceptable to TRACON controllers. The MACS based emulation includes all standard STARS functions and can be enhanced with advanced tools. Figure 13 depicts the MACS STARS emulation.

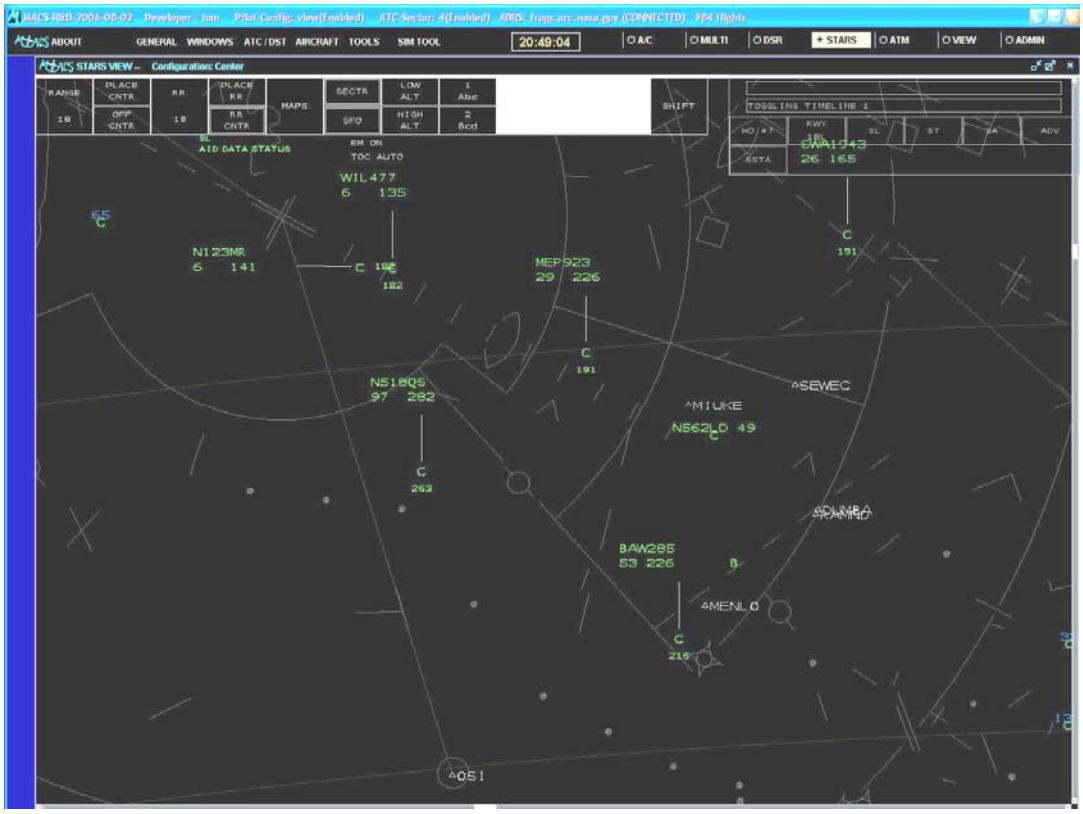


Figure 13. MACS STARS emulation configured for San Francisco airspace

3. Oceanic Controller: Advanced Technologies & Oceanic Procedures (ATOP)

The AOL most likely contains the only emulation of the new Advanced Technologies & Oceanic Procedures (ATOP)[24] system deployed in US oceanic facilities. The MACS ATOP represents an accurate emulation of most functions of the fielded system, including the electronic flight strips, data link message interfaces, sector queues, etc. The emulation was created and used for the Tailored Arrivals project described in Section V. Figure 14 shows the AOL's ATOP station.

Figure 14. ATOP station in the AOL.

As explained before the MACS/ADRS is fully portable and can be used on any state of the art computer. Therefore, all emulations are also available without needing the AOL's hardware. Figure 15 shows the ATOP emulation instantiated on a laptop and connected to a "live" ASDI traffic feed.

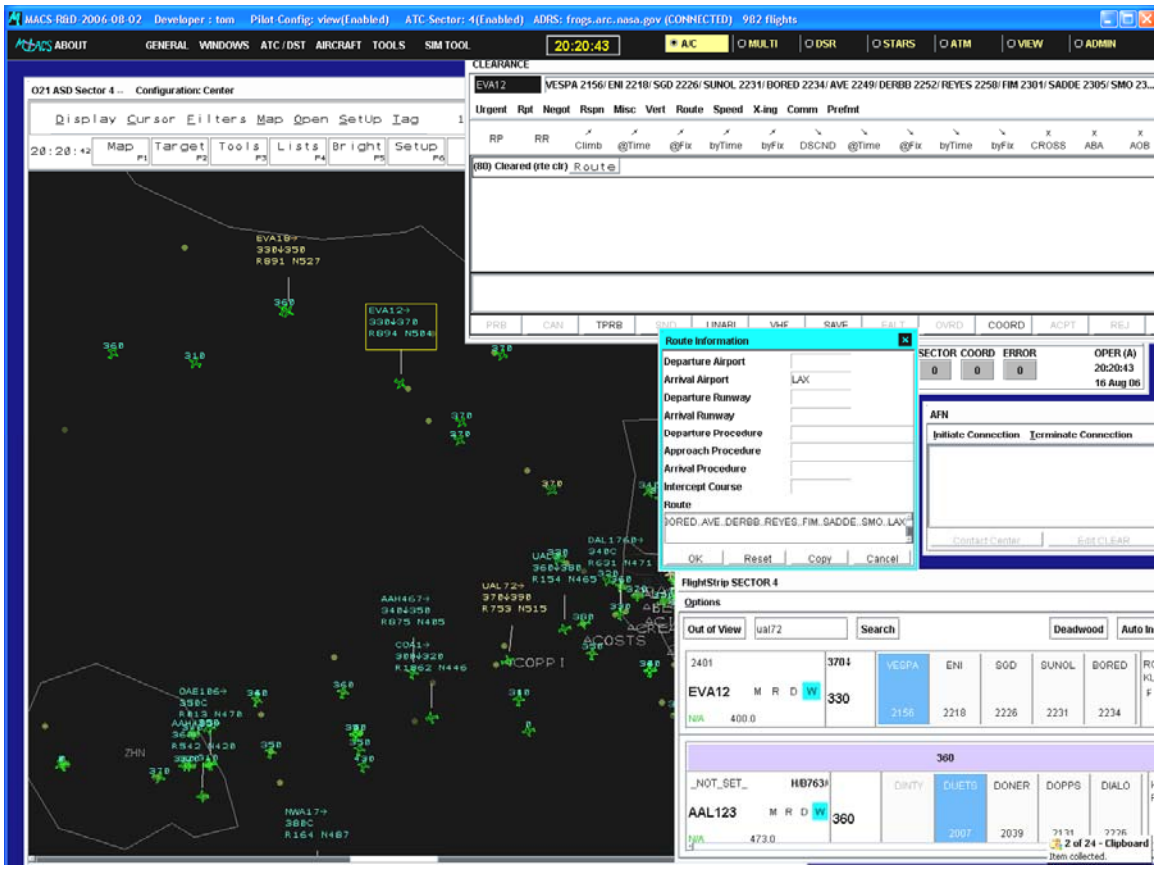


Figure 15. ATOP emulation on a laptop connected to ASDI "live" traffic

4. Traffic Manager: Traffic Situation Display (TSD) and Traffic Management Advisor (TMA)

In past studies it was not required to accurately emulate a traffic management station. However, the AOL hosts a basic Traffic Situation Display emulation as used in traffic management units throughout the US. Figure 15 shows the traffic situation display with a flight control area depicting Oakland Center (ZOA) traffic from EMTS/ASDI connection.

CTAS Traffic Management Advisor timelines can also be configured in MACS and connected either to the MACS internal simplified scheduling mechanism or to CTAS itself.

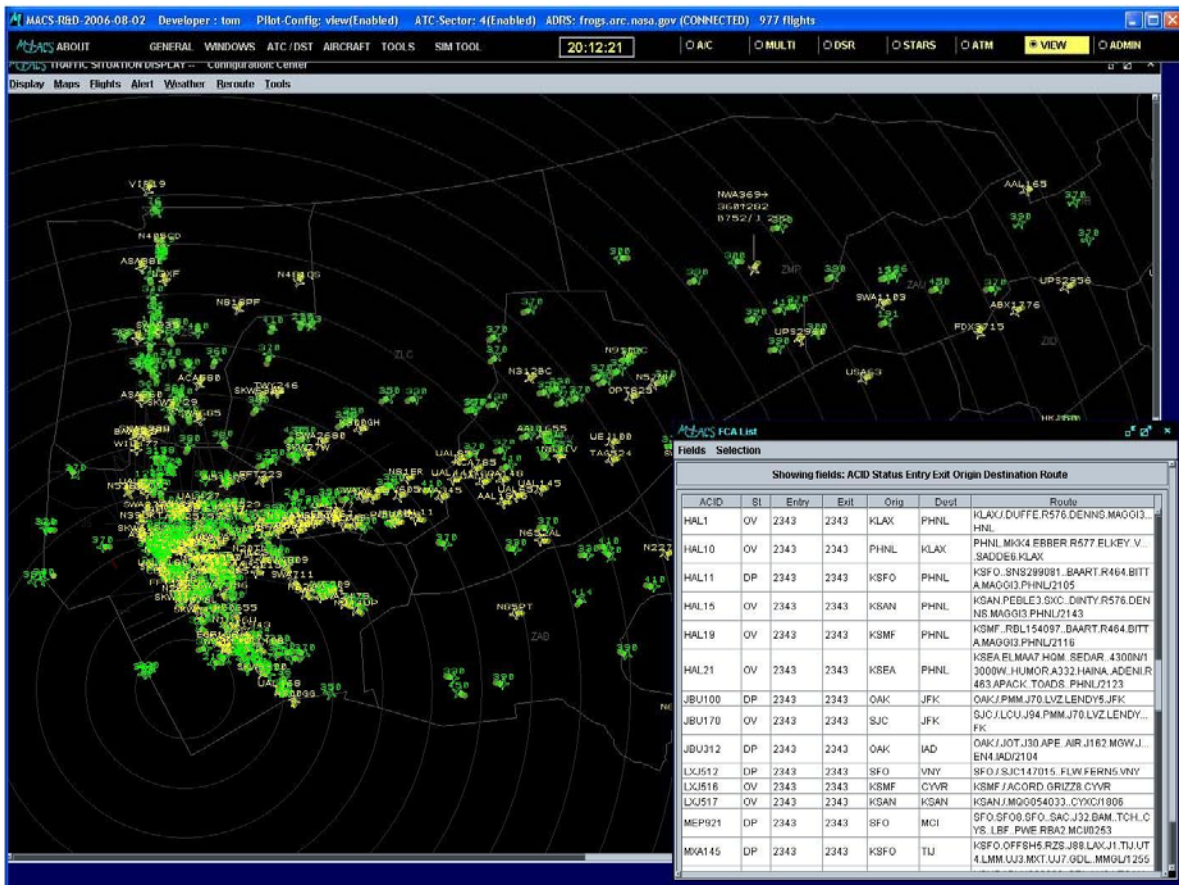


Figure 16. Traffic Situation Display showing Oakland Center traffic from ETMS/ASDI connection

D. Prototyped Workstations

MACS was designed for rapid prototyping of advanced functions. This section gives some examples of operator stations that were prototyped and successfully tested in the AOL.

1. Automation Assisted Controller Workstation with Integrated Data Link

Apart from some operational quick-function or special key operations not supported by the MACS DSR emulation, the main difference between the MACS DSR emulation and the DSR in the field is that the integrated automation functions are not 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 [25,26] or the CTAS Direct-to (D2) interface for R-side conflict presentation and trial planning [27] – it was used as a model for the MACS DSR implementation of the automation assisted controller workstation.

Figure 17 shows an example for an automation assisted DSR workstation with scheduling and spacing support for the same situation displayed in Figure 12. The workstation uses color to distinguish arrival aircraft from other traffic, a timeline contrasting scheduled and estimated times of arrival for aircraft at the runway threshold and small additions to the data tag indicating the data link and airborne spacing status of an aircraft.

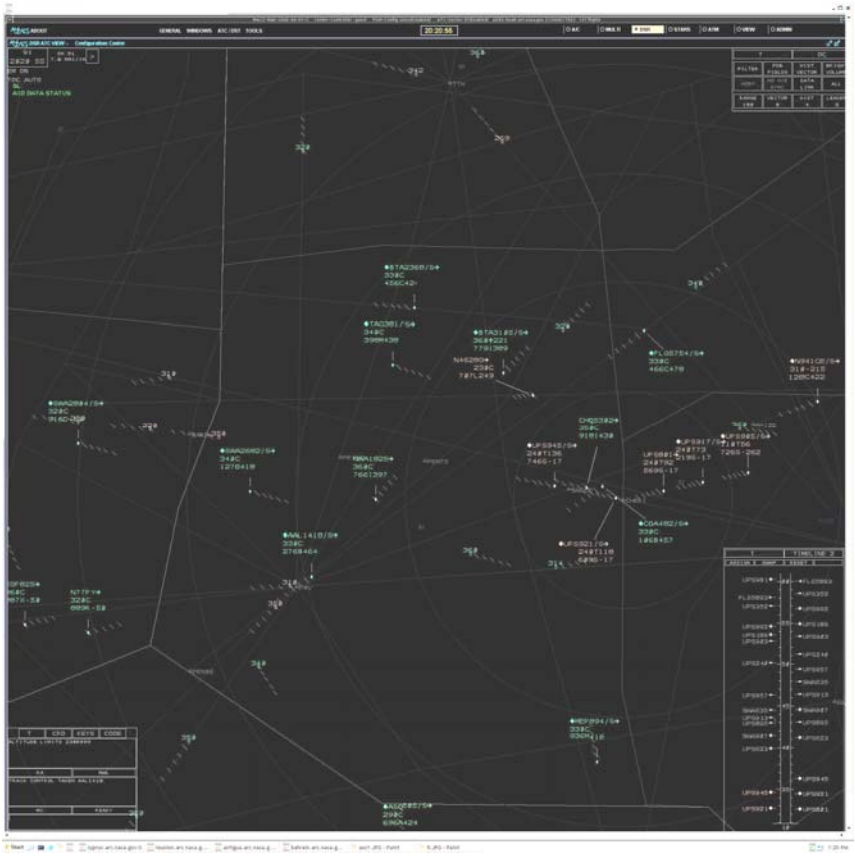


Figure 17. Automation assisted Center controller workstation

In addition to scheduling and sequencing support some of the key functions integrated into the automation assisted controller positions are

- Data link for transfer of communication
- Trial planning of routes and altitudes integrated with data link
- Trajectory-based conflict probing
- Ground to ground coordination of trajectory changes

The automation for trajectory planning, communication, and conflict probing was designed to support the radar controllers in assessing and modifying the trajectory and issuing clearances as necessary. Particular emphasis in the implementation was given to integrating a highly responsive trial planning function seamlessly into the controller's task sequence to make it useful in high workload situations. Figures 18 and 19 depict examples of a controller assessing and modifying the trajectory of an aircraft according to his/her sector plan.

Figure 18. Controller trial plans new trajectory

Figure 19 depicts an example route modification. Before the aircraft enters his/her airspace the controller checks the route. In this example UAL572 is predicted to fly directly through a severe storm. With the trial planning tool the controller can pre-plan and communicate a route change that will have the first turn inside his/her airspace instead of waiting until the aircraft reaches the sector or coordinating a radar vector with the upstream controller.

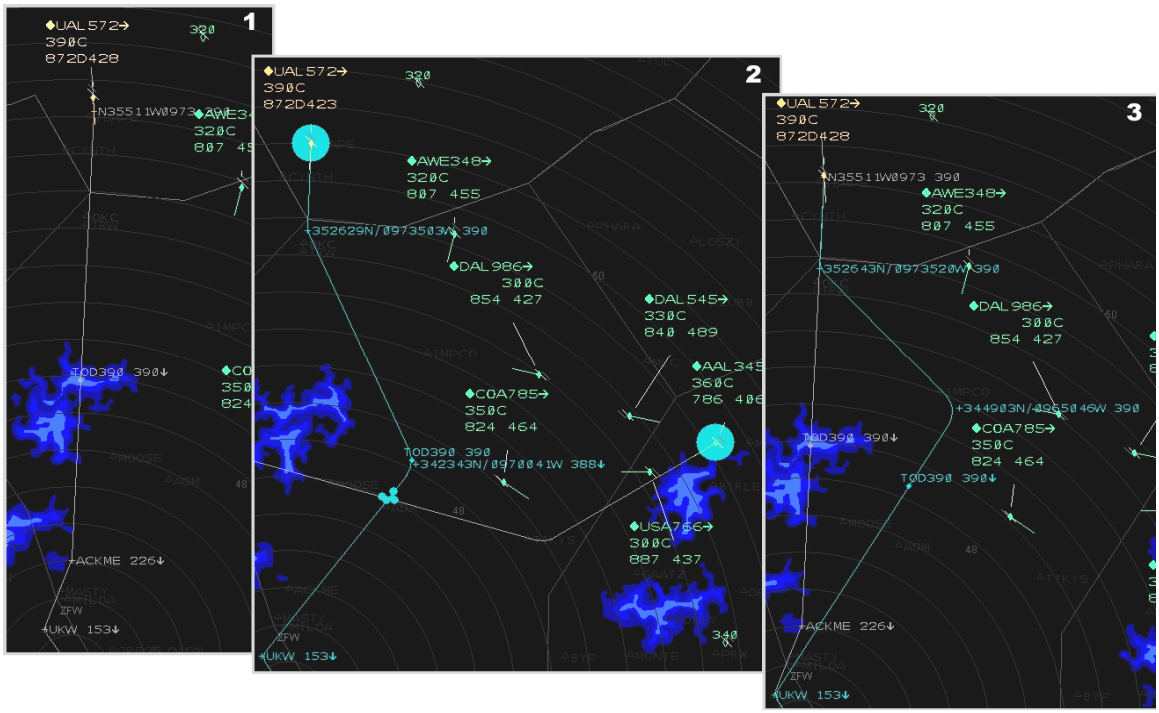


Figure 19. Route trial planning with conflict feedback around weather

To access trial planning the controller picks a designated data tag item ("portal") and a provisional trajectory is displayed immediately. The automation inserts a point two minutes in front of the aircraft to give the controller and the flight crew time to plan and execute a stable trajectory change. Trajectory points can be inserted, moved or deleted by clicking on the trial plan, or a waypoint on the display. Points can be dragged with the trackball to any desired location. In the process, the trajectory is continuously recomputed and checked for potential conflicts, giving the controller rapid feedback about the precise path and potential traffic problems he or she is creating. A potential conflict with another aircraft is indicated by solid circles around the aircraft position symbols.

The solution can then be uplinked to the aircraft using a "UC" (Uplink Clearance) command that will automatically package the trial plan into a format that can be sent via the data link system into the aircraft's flight management system as a loadable "cleared route clearance" (which, for example, is supported by the FANS data link system). The flight plan is automatically amended in the ground system. The controller can incorporate an altitude change into the same trajectory modification or create a new trial plan in a separate step using the data tags altitude fly out menu. The trial plan trajectory will then be generated using the new altitude. The altitude change will be incorporated into the data link message and the new assigned altitude will automatically be sent to flight deck and the ground system. After generating and communicating the trajectory change the controller can move on to his or her next task and keep checking the data tag indication for message acknowledgement during the regular scan. The data link status list has provisions to highlight message timeouts and non-positive responses.

Arriving aircraft (like UAL572) as well as departing aircraft require clearances to descend or climb to their next altitude. The automation-supported ground system continuously checks the planned trajectory of all aircraft for potential conflicts. If no conflict indication is given, the system predicts the planned path to be conflict free. Controllers can use this information to help assess whether or not to issue a clearance and update the flight data as in current day operations without having to make any specific entries for updating the automation. The tools are designed to support strategic trajectory changes by data link and tactical changes (heading vectors, speed changes, interim altitudes) by voice. Whenever an aircraft diverts from its predicted trajectory the system creates short-term

trajectories using the current state values and flight data entries available. In addition to the function described here many decision support functions and visualization aids have been implemented and are described in other publications.[28,29]

2. Multi-Sector Planner Station

Several instantiations of Multi Sector Planner positions have been prototyped and are available in the AOL. The multi sector planner positions' capabilities are based upon the functions available for the automation assisted controller workstations. The AOL implementation of this workstation is similar to a controller position zoomed out to view multiple sectors with different rules driving the aircraft data tags and many automated functions to support the operations.

New functions to support multi sector planner operations include ground to ground data link for coordination of trajectory changes and interactive traffic load tables and graphs to predict sector loads. Using the many MACS configuration options multi sector planner positions have been configured for several specific purposes:

Figure 20a. Multi sector planner position

"Multi-D"

This position was designed to allow one radar associate to serve as the data controller for multiple radar controllers. The position provides the capability to perform flight data entries, accept and initiate handoffs and data link trajectory changes to the sector controller positions and/or the aircraft. The main purpose of this position is medium term conflict detection and resolution to reduce the sector complexity on the R-Side. [6,31]

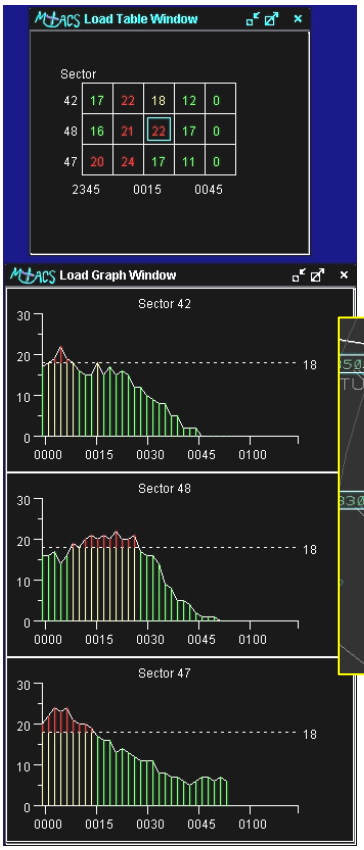
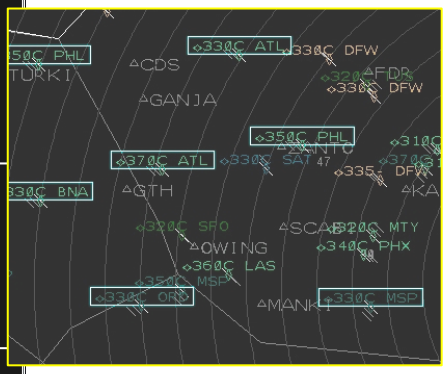


Figure 20b. Interactive sector load graphs and table

"Area-flow"

This position was designed to manage the sector loading for a specific airspace area. Interactive load graphs allow the operator to view predicted sector counts and identify aircraft contributing to a particular load. Conflict probing is available for trial plans and, specific flights can be color coded at the area flow position by different criteria (e.g., direction of flight, destination, altitude, etc.)

In order to help the MSP assess the predicted sector load the prototyped system predicts the number of aircraft that will be present in the sectors of interest and displays the counts in a table and a graphical format. (Figure 20) The indication changes color whenever a predicted load exceeds a pre-set value similar to a monitor alert parameter (MAP). The value can be adjusted for additional complexities like weather. When the MSP recognizes excessive sector load s/he can determine the specific flights that are contributing to this load by selecting the cells within the load table or a vertical bar in the load graphs. This highlights all aircraft that are contributing to the load with rectangular boxes around the data tag on the traffic display. A typical goal of the area flow planner is to reroute as few aircraft as possible and therefore find those that create multiple problems. Therefore, the load table has been designed to accept selecting multiple cells to display those aircraft that are a factor only for all selected cells.



Before rerouting the flights the area flow planner has to make sure that the new routes will be acceptable to all impacted regions. Two adjacent area flow

planners can communicate verbally, adjust the plan, and decide who will implement the reroutes. Either MSP can construct new trajectories using the trial planning functions as described before and send the coordination requests to the sector controllers. As the plan is being executed and the route changes are implemented the load graphs and tables reflect the newly predicted sector loads. Upon successful implementation none of the sectors should be predicted to exceed the pre-set maximum.

Arrival Planner/Airline Operator Station

Another type of multi sector planner position has been created for the TOOWiLD research described in Section V of this paper. This position is designed to sequence and space arrival flows to a specific runway. The position could be located at the airline operations center or in air traffic control facilities. Flights filed for a particular runway are highlighted and different scheduling information and advisories are presented to the operator. For flights that are still far away from the aircraft a spacing tool (in this case the Cruise Speed Calculator shown on top of Figure 21) provides speed advisories to space arriving aircraft enough so that t route or altitude changes will not be required. A timeline provides a runway schedule and estimated times of arrival for aircraft predicted to conduct Continuous Descent Approaches (CDA).

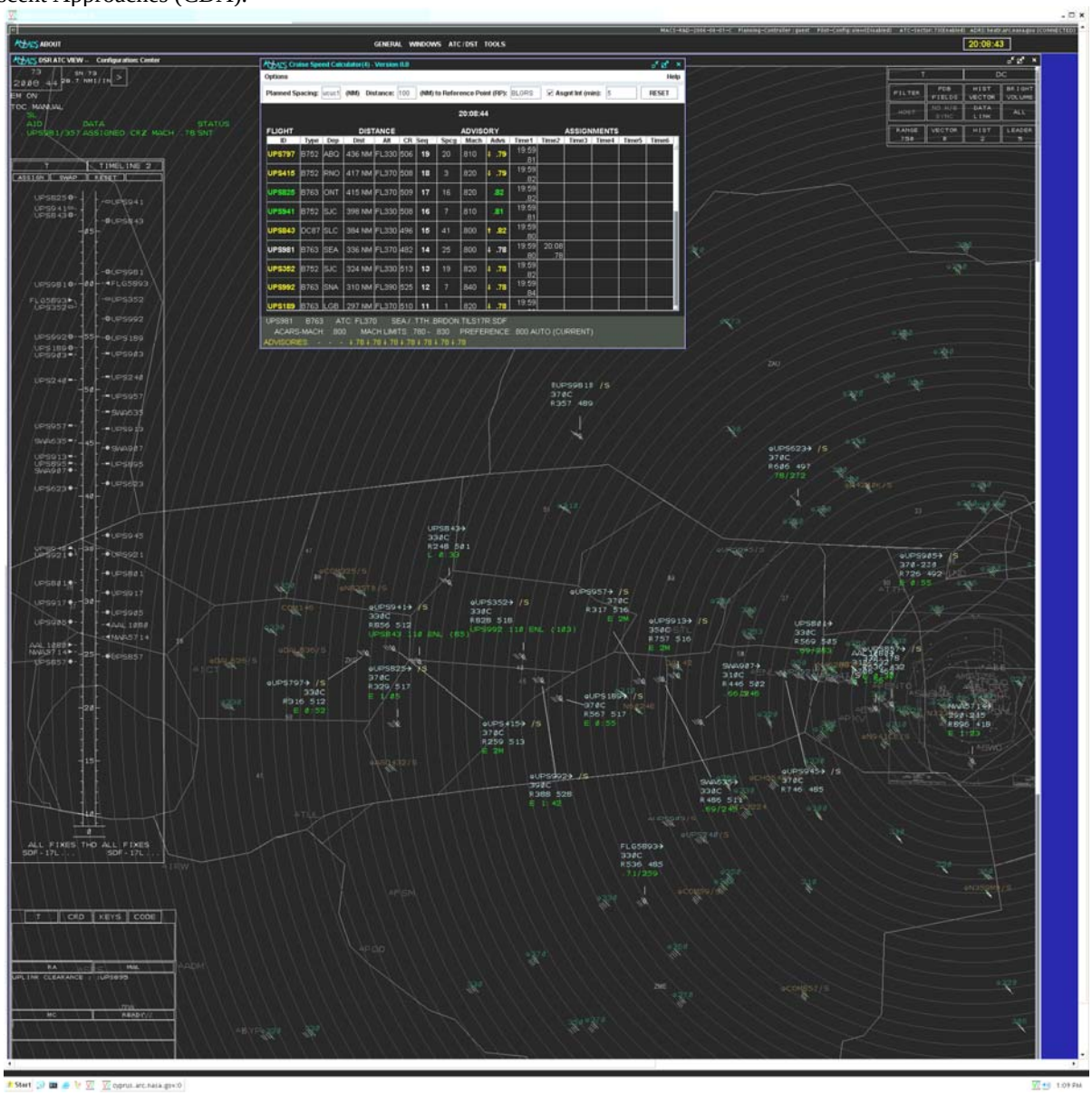


Figure 21. Arrival Planner display

The data tags of the aircraft presents advisory information for speed schedules to be flown along these CDA's or suggested aircraft pairs and spacing intervals for airborne merging and spacing operations. The speed or spacing instructions can then be communicated to the aircraft. If the position is located at the airline or has access to an ACARS data link connection the information can be send via existing data link channels.

E. Communication, Navigation and Surveillance

1. Voice communication

To emulate radio voice communication, a Voice over Internet Protocol (VoIP) system has been developed and integrated at NASA Ames.[15] With VoIP, voice signals are routed over the internet infrastructure. No phone lines or traditional telephony switches are required. Control of the frequency switching is strictly through the Graphical User Interface (GUI). They can be deployed independent of, or interfaced with other voice communication endpoints (such as specific headset/microphone and frequency selection hardware). The DagVoice software (Figure 22) can be launched on controller, pilot, and experimenter workstations across laboratories and even across research facilities, as long as those stations have access to an internet connection. DagVoice is a multi-channel, multicast voice client application designed with a user-interface akin to the Voice Switching and Control System (VSCS) used in ATC facilities. The user can monitor and broadcast through multiple channels simultaneously. The voice system supports 14 voice channels. Each channel represents a unique frequency, hosted by a multicast voice server running on a dedicated computer in the FDDRL at NASA Ames Research Center. Official limitations are unknown, but more than 50 users across all channels can be accommodated without significant performance impact.

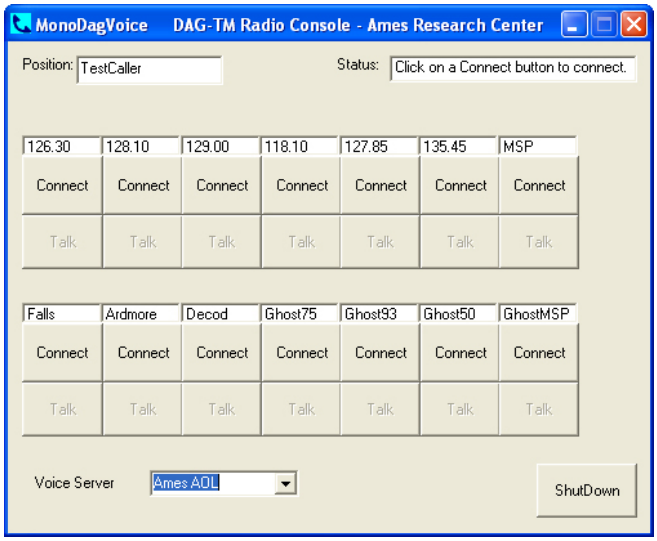


Figure 22. DagVoice frequency selection panel

2. Data link communication

The AOL supports data link communication in several ways. ADS-B equipage can be selected for individual aircraft in the traffic scenario and the surveillance processing function can be configured to use ADS-B data in addition to simulated radar data. Besides standard state information 4D FMS trajectories can also be downlinked and distributed to the individual operator stations for further processing. A comprehensive set of CPDLC functions is available using a modified ARINC702 data link message format. The available data link message set and its integration into the operator stations is described in earlier papers.[28]

3. Surveillance

The ADRS incorporates a realistic radar simulation module that emulates radar data for Center and TRACON airspace. The MACS controller stations can be configured to use different types of surveillance sources, \which will be reflected on the displays as well as the underlying processing functions. Selectable surveillance sources include Center radar, TRACON radar, ADS-B or perfect state information.

F. Weather

In the AOL two types of atmospheric conditions are addressed: Winds and convective weather. The simulation can be configured to use independent values for environment winds, flight deck forecast winds for FMS computations and ground side forecast winds for computations in the ground-based decision support tools. Each set of winds can be defined as Rapid Update Cycle (RUC) winds which have lateral and vertical variations in wind strength and direction as well as temperature and as vertical only winds, which represent no lateral variations.

Convective weather cells are simulated in two different ways. NexRad storm files can be loaded and replayed during the simulation or polygonized complex storm cells can be manually created and edited as described in Section IV. These storm cells are then animated during the simulation and can move at constant velocities and change shape and direction at any time. An example for MACS generated weather cells in shown in Figure 19.

G. Data Collection

During a simulation in the AOL, several types of data are recorded. Subjective data, like workload ratings, questionnaires, voice recordings, and observation notes are all collected. Objective metrics are also logged in the form of system output logs, both from MACS and the ADRS.

1. WAK

The Air Traffic Workload Input Technique (ATWIT) gathers workload ratings from participants in real time. Workload Assessment Keypads (WAKs) are used to query the participant to rate their level of workload on a scale of 1 to 7, from low (1) to high (7) workload. The AOL has a hardware version of the WAK as well as a recently-developed software version of the WAK. The WAK is a keypad with buttons labeled 1 – 7, of which participants press one key to select their level of workload when prompted. The WAK prompts participants for a workload rating at regular time intervals (e.g., every five minutes). When prompted, the WAK emits a tone, and the keys light up. The keys stay lit for 20 seconds, or until the participant responds by selecting a key. After 20 seconds, if the participant has not responded, the key backlighting goes off and a non-response is recorded. The hardware version of the WAK is a separate keypad that is placed to the side of the controller's radar screen. The software version of the WAK pops up a small keypad display on the operators screen. Similar to the hardware WAK, the keypad display of the software WAK remains visible for 20 seconds or until the participant responds by selecting a key. If the participant does not respond within 20 seconds, the keypad display disappears until the next prompt. For each prompt, the WAK recording software logs which key was pressed (workload rating) as well as the time of the response.

2. *Post-run Questionnaires*

After each simulation run, participants provide feedback via ratings and general comments. Ratings include a modified NASA TLX scales that measure mental demand, temporal demand, physical demand, effort, frustration, and performance, Controller Acceptance Rating Scale (CARS) to measure concept acceptability, and the overall realism/performance of the simulation set-up.

3. *Post-simulation Questionnaires*

After the simulation, participants provide further feedback via ratings and general comments. The questions include the general acceptability of the concept/procedures and general tool acceptability in terms of usability and usefulness.

4. Voice recordings

The voice communication system above allows recording of communication on selected channels and voice frequency selections.

5. *Observers*

Observers focus on recording actions that would not be recorded by the computer system. Observers usually have well-defined tasks such as recording controller-to-controller verbal interactions or recording the context of all separation violations. These tasks vary for each study. In addition, the observers also record potential system errors/bugs and various interesting observations that provide situational context that may be useful in understanding the data afterwards.

6. Automated Data Collection by the ADRS

As the central communication process the ADRS has knowledge over all information that is shared in the simulation. This includes all aircraft state information, predicted FMS trajectories, pilot inputs, guidance outputs, flight data inputs, flight plan amendments and data link messages. This data is routinely collected in a time stamped ASCII format that can be visually inspected or post-processed by data analysis tools, such as DProc described in the Data Analysis section.

7. MACS data collection system

Each MACS operator station can be configured to collect many data items using the MACS built-in data collection system. Using a setup panel experimenters can select relevant events such all operator inputs, waypoint crossings, detected conflicts, as well as periodic logs of sector counts, aircraft state and trajectory information to be collected on each station individually. A typical AOL configuration collects all operator inputs at the operator station and uses an extra data collection station to record all periodic and system wide data. Figure 23 shows an example of the MACS data collection setup panel.

Figure 22: Data collection setup

8. Data Quicklook/Analysis views

During any simulation MACS can also be used to view data plots in real time. All trajectories as well as individual flight state histories or fix crossing parameters can be displayed for all aircraft in the system. Figure 23 shows an XY trajectory plot and a flight state history for "live" data from an ASDI connection. The analysis view is also present in Figure 4 during a simulation.

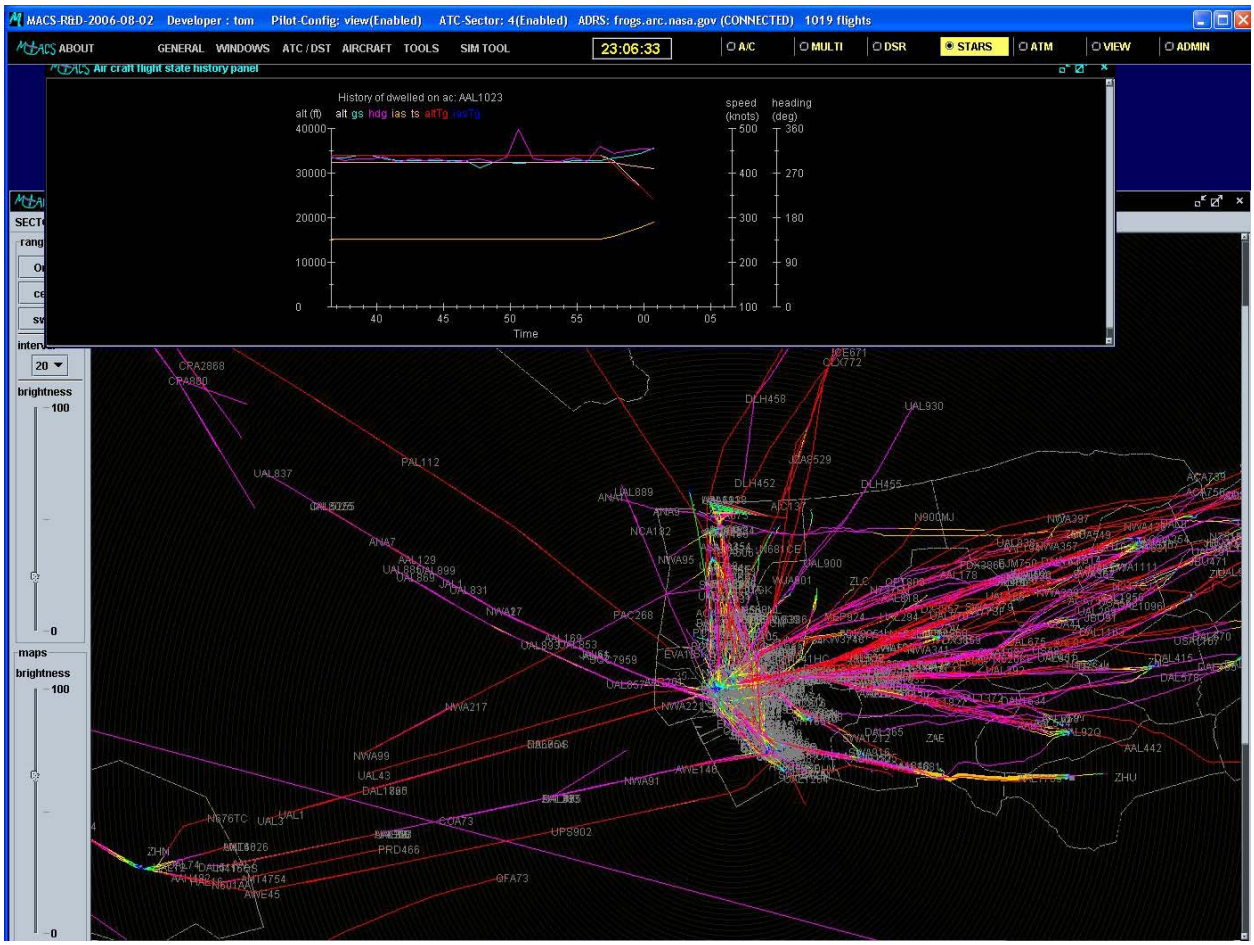


Figure 23. Real-time XY trajectory and flight state history plot for "live" ASDI data.

IV. Offline Capabilities

The AOL hosts a set of powerful offline capabilities for scenario generation and data anlysis. This section describes the process of Scenario generation, Weather editing and Data Analysis in detail.

A. Scenario generation

1. Live data recording

MACS offers the ability to record live traffic data from an ASDI/ETMS feed centered on an airspace region of choice. This data can be recorded via two methods depending on the type of data that is required. Regardless of the recording method used, the recorded data is ultimately written to a text file that can be subsequently used for scenario generation or analysis. For easier editing and analysis purposes this text file is often accessed through Microsoft Excel.

One method for live data recording is done through the Simulation Setup panel in MACS. Through this panel, the type of data that will be recorded from the traffic feed will consist primarily of the information needed to create a simulation scenario. This includes such information as callsign, aircraft type, FMS route, speed, heading, and altitude (see Figure 24 for a more complete listing). This recording can be done at any time of day and for a length of time determined by need and storage capacity.

Of course, all MACS data collection capabilities available for simulation can be used for live data recording as well as. One efficient live data capture is accomplished through the use of the Cruise Speed Calculator (CRZ) setup panel. The data that is output from this method is specific to the concerns involved in a merging and spacing (M&S) environment. The type of information that is recorded through this method includes such items as aircraft

sequence position, speed advisories, predicted spacing to lead aircraft, and closure rate. A unique feature of data recording through the CRZ setup panel is that the user is able to filter the aircraft that are to be included in the output file based on any combination of departure airport, destination airport, Airline Company, or a specific fix appearing in an aircraft's filed flight plan.

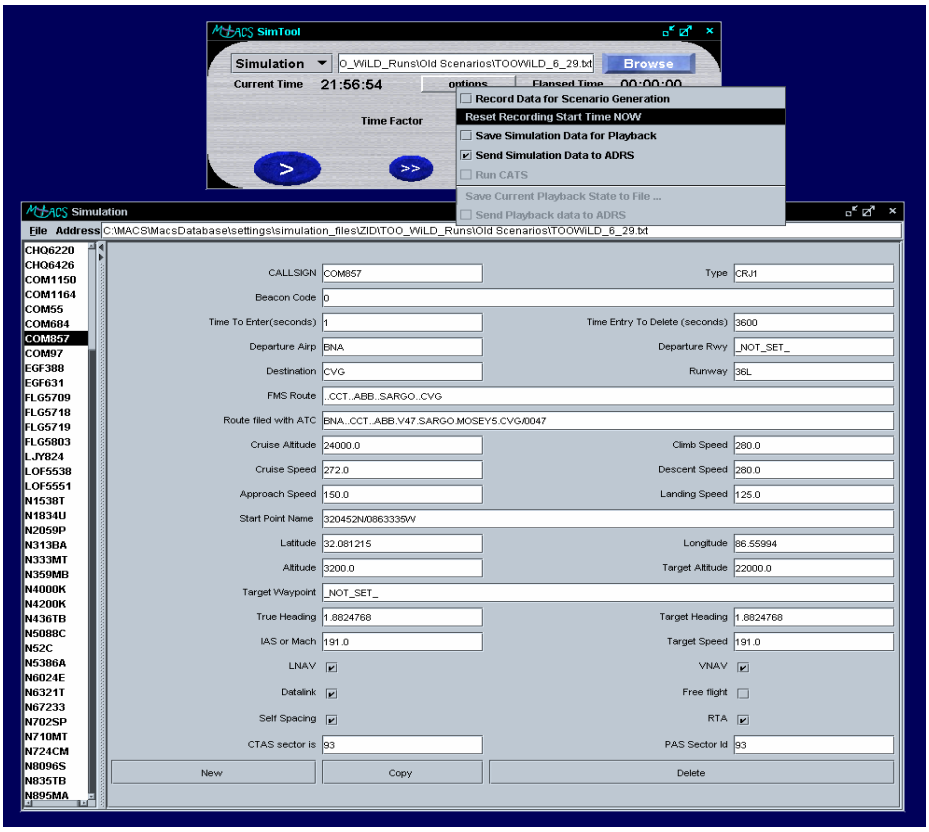


Figure 24. Data recording interface used in scenario generation.

2. MACS Traffic Scenario Editor

The scenario editing feature in MACS enables the user to dramatically alter or fine-tune a previously created scenario, or create a scenario from the ground up using data extracted from live traffic feeds or manually generated according to the user's needs.

Through MACS's Simulation Configuration View, it is possible to selectively filter the aircraft that are to be included in the scenario based on geographic location. This is particularly helpful when building a scenario from live traffic feeds as there are often a number of aircraft included in the initial file that are outside of the area of interest. The scenario filters allow the user to specify a sector or geographical region and a time period. MACS then predicts all aircraft trajectories and includes those flights in the scenario file that will travel through the defined region within the given time period. This feature allows a user to reduce a live data recording with up to thousands of flights to the tens or hundreds that will be flying through the actual simulation airspace.

The scenario editor then allows the user to directly edit the properties of individual flights that are to be used in the final scenario (see Figure 25 for an example of the scenario editor). The types of information that can be edited include, but are not limited to, callsign, aircraft type (along with the performance characteristics of that particular aircraft type), time to enter scenario, starting location, filed flight plan and ATC route, altitude, heading, equipage, and speed. The scenario editor also allows the user to click and drag individual aircraft to any desired location with a concurrent change in the flight's assigned ATC sector and recorded latitude and longitude that represent its starting location. The initial heading of the aircraft is updated while it is moved as well with reference to its target waypoint. This moving function, much like the scenario editing feature itself, is particularly helpful when the researcher would like to use an existing MACS scenario as the foundation for a new one. This saves a great deal of time as the initial steps of data collection and data conformance in the scenario generation process can be bypassed. Additionally, the

ability to edit an existing scenario allows the user to easily manipulate key features (e.g., traffic flows and arrival patterns) in support of the research objectives that the new scenario will support.

To that end, a number of graphical aids are available to further assist with the scenario editing and management process. Examples of these aids include range rings that can be selectively placed at any point of interest and scaled to distances ranging from two to 20 nautical miles. Other support aids consist of waypoints that can be displayed and referenced individually, mapping features that allow for the display of different airspace sectors, display filters for aircraft, weather and special use airspaces, and the ability to display the entire filed route of an aircraft as seen in Figure 25.

In addition to the scenario editing capabilities associated with individual flights, the scenario editor is also the tool through which weather can be both created and edited as described next.

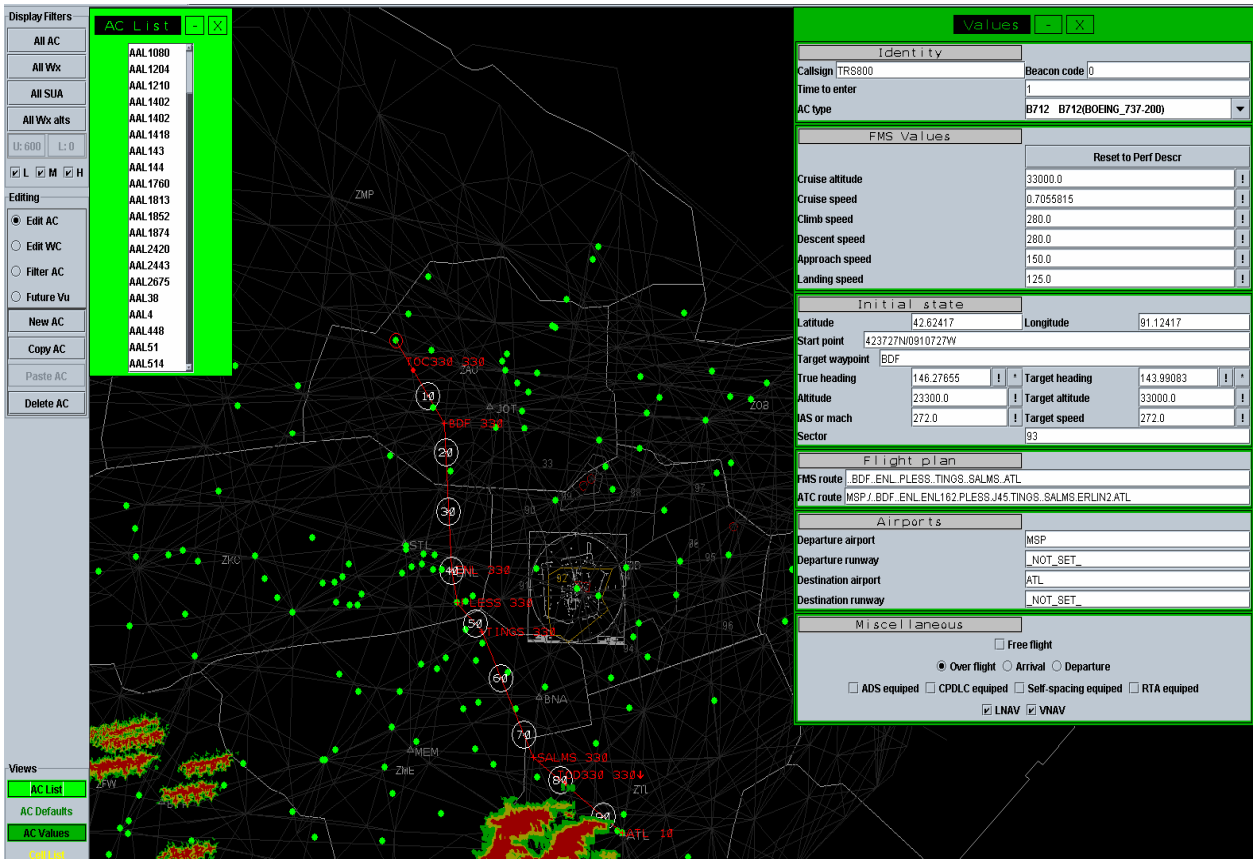


Figure 25. Scenario editing feature in MACS.

3. MACS Weather Scenario Editor

The MACS interface contains a weather creation and editing feature that provides the user with the means to create convective weather cells as part of the scenario generation process. This unique and organic feature allows the user to incorporate the presence of weather into a scenario as a way of adding a heightened degree of complexity to any given airspace. The characteristics of the weather cells can be varied along a number of dimensions according to the objectives of the user. For instance, it is possible for each individual weather cell to consist of a total of three levels of intensity-low, medium, and high (see Figure 26). Each intensity level is created as a separate polygon and can therefore be assigned a color that will distinguish it from the other intensity levels. The polygons that represent the intensity levels can be overlaid upon one another in order to create the appearance of a unified, multi-faceted weather cell as part of a larger front. Because the design and construction of these cells is polygonal in nature, the level of creativity with respect to cell shape can range from simple to elaborate. Additionally, the number of cells that can be grouped together as well as the size and complexity of each cell and resultant front is virtually unlimited.

As an added element to boost the realism of the weather as well as to impose control, uniformity, and predictability, each individual cell is programmable with respect to the direction and speed that it is to move in. This

capability affords the user complete freedom with regards to the behavior of the finished weather product; the cells can either move together in complete unison or move separately in a number of independent directions and speeds.

In addition to the direction and speed that can be set for each weather cell, the time that they are to enter and exit the scenario can be defined as well. This capability can be used in a straight forward manner whereby the weather cells simply appear and disappear at some predetermined time while their properties remain static throughout the course of their movement. However, it is also possible to create an entire series of weather cells that are timed to enter and exit in a seamless fashion such that when one cell exits and its replacement enters, it appears as though the weather cells and the front itself is undergoing a dynamic change in both shape and distribution of intensity throughout the course of the scenario.

An added feature of the weather generation process in MACS is that the user can assign the altitudes at which the finished weather product is to occupy. This allows the user to decide how to selectively impact different regions of airspace with the presence of weather. For example, ATC stations that have the altitude settings set at a value that is outside the vertical range of the weather will not be affected locally as it will not be displayed to the participant. However, those stations with the altitude set at a value within the weather's range will require the participant to react differently in response to the weather's presence.

Outside of the weather editing function just described, there is another feature within MACS through which the user can apply wind characteristics to particular areas of the desired airspace. This weather setup feature specifically allows the user to define wind speeds and directions as well as the locations and altitudes at which these wind properties will be in effect. Although not graphically visible to the user, the effects of the defined wind characteristics are manifested through the differing performance levels of flights that can be observed as a result of traversing different wind field regions.

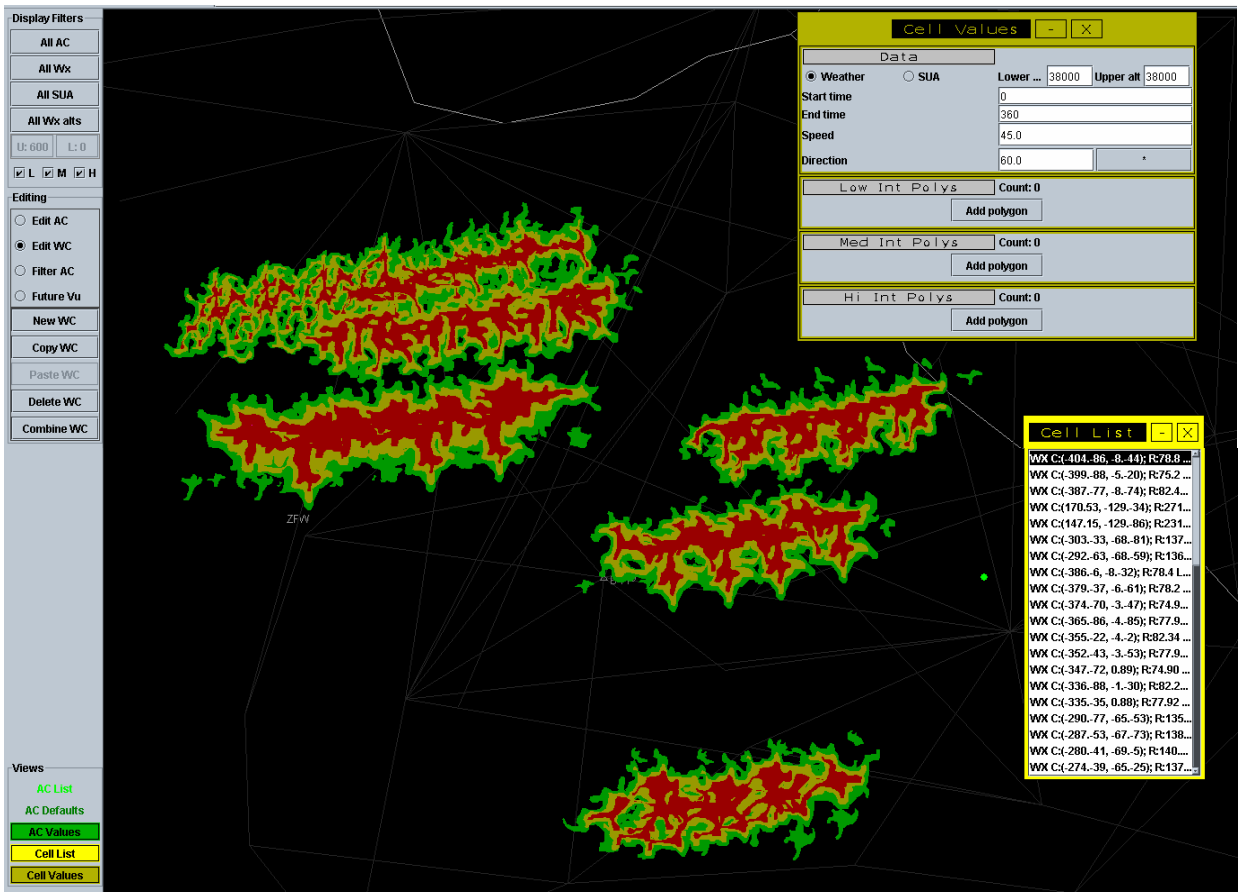


Figure 26. Weather creation and editing feature in MACS. Note the weather cells' intensity levels

B. Scenario Generation and Fast-Time simulation with the Trajectory Centered SIMulator (TCSIM)

The Trajectory-Centered Simulator (TCSim)[32] was developed to support fast-time agent-based simulation studies to complement human-in-the-loop research in the AOL.[33] TCSim is also a useful tool to support traffic scenario development. TCSim is written in Java, and runs in fast time. Figure 27 shows a snapshot of the TCSim graphical interface. The interface enables researchers to visualize traffic flows, airspace, schedule timelines, and simulation time. Menus enable researchers to select displays, perform file operations, adjust the airspace view by zooming and panning, and control the simulation with run, pause, and initialization functions. 'Hotkeys' can also be used to control the simulation and configure the interface.

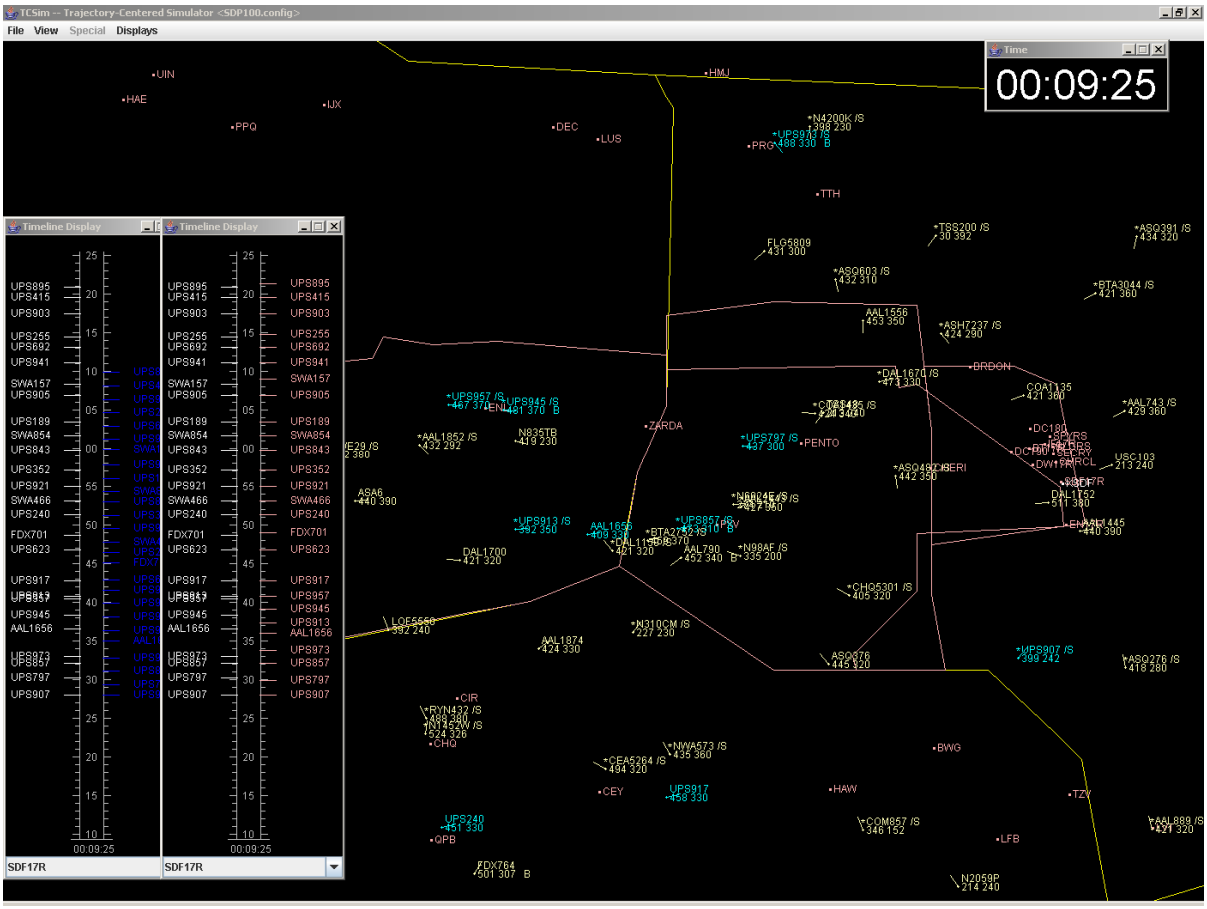


Figure 27. TCSim interface with arrival schedule timelines.

TCSim can use the same FMS procedure specifications, waypoint data, and wind information as MACS. TCSim can also read and write MACS simulation data file formats, and includes a scenario editing mode that enables developers to modify the initial states and routes for individual aircraft (Figure 28).

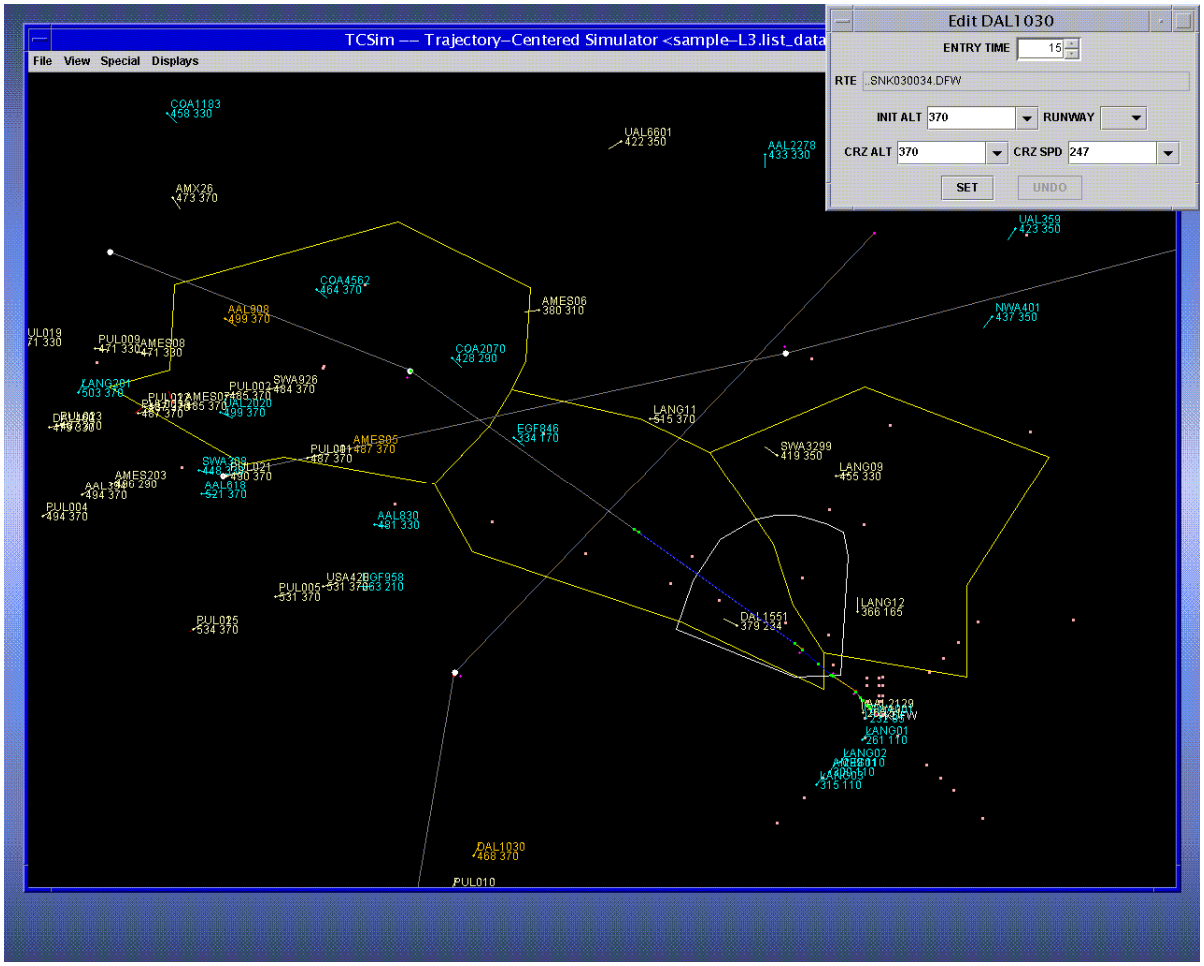


Figure 28. TCSim in scenario editing mode.

C. Data Analysis

1. *Automated data processing with DProc*

A Java-based tool called DProc was developed to visualize, integrate and transform the data collected from large-scale ATM simulations in the AOL.[34] Researchers may be interested in tracing event sequences, information flows, and operational contexts associated with certain outcomes of interest. This may entail identifying what other human subjects or automation agents are doing when one performs an action, and measuring relationships such as the time between various events or actions. DProc makes such analyses possible by creating a database of merged simulation data from available sources. The DProc interface enables researchers to replay simulated traffic and visualize recorded events together with aircraft states. Visualization data may be color-coded according to traffic characteristics (e.g., aircraft weight class, equipage, engaged autoflight modes), or filtered to highlight events associated with a particular controller, aircraft, or class of aircraft. In addition to replaying data, DProc is also capable of producing plots of aircraft tracks or event locations. DProc also produces batch output suitable for input to a spreadsheet or other analysis tool, such as a data mining application.

Data files for a particular simulation trial are specified in a configuration file. An analyst begins a DProc session by selecting the desired simulation trial or batch-processing mode. DProc then reads all the relevant data into its database and displays a window in which to visualize it. Figure 29 shows DProc replaying raw aircraft data, including aircraft trajectory data. The analyst can pan and zoom the airspace map, and drag the slider at the bottom to select data at a given time. Holding the mouse down on the slider enables continuous data replay. The Options window (upper left of Figure 29) allows the analyst to select which aircraft and controller(s) to view data for, and to switch between visualization modes. Figure 30 shows DProc in raw track data plot mode, in which selected aircraft tracks are color-coded by altitude. The lower portion of the Options window enables an analyst to select event types of interest. In Figure31, DProc is displaying events related to trial-planning for all aircraft and controllers. Also

visible at the bottom of the Options window in Figure 31 are buttons that enable analysts to save the currently displayed visualization in JPEG format, or dump selected event data to an Excel-readable file.

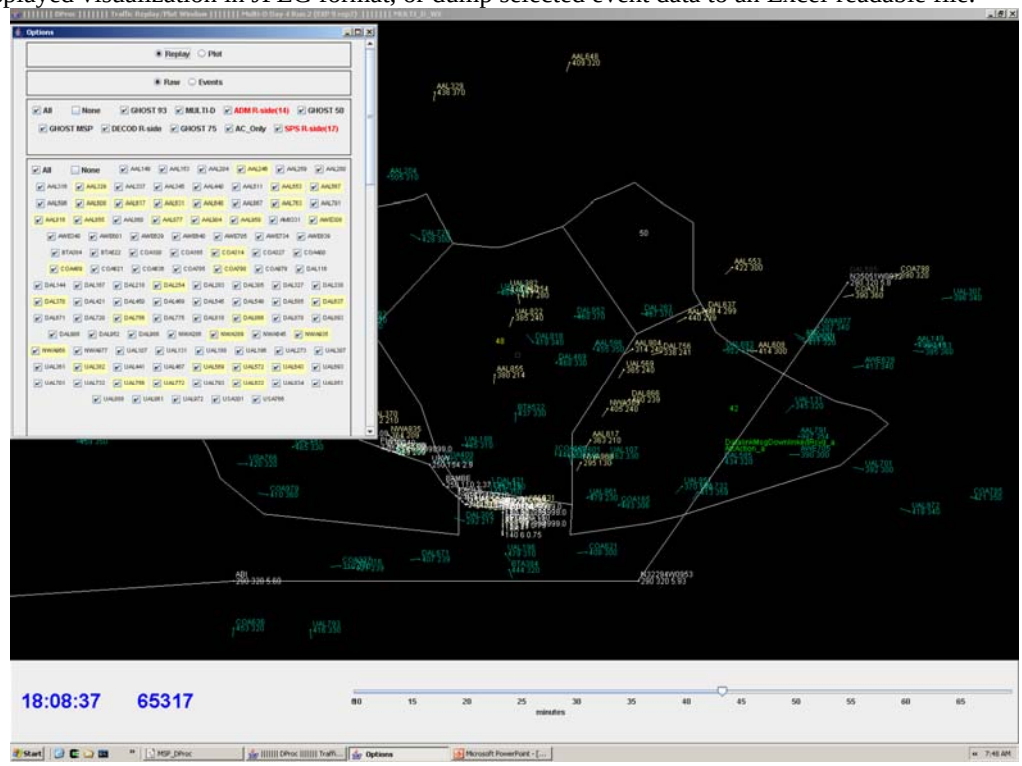


Figure 29. DProc interface showing raw data replay and Options window.

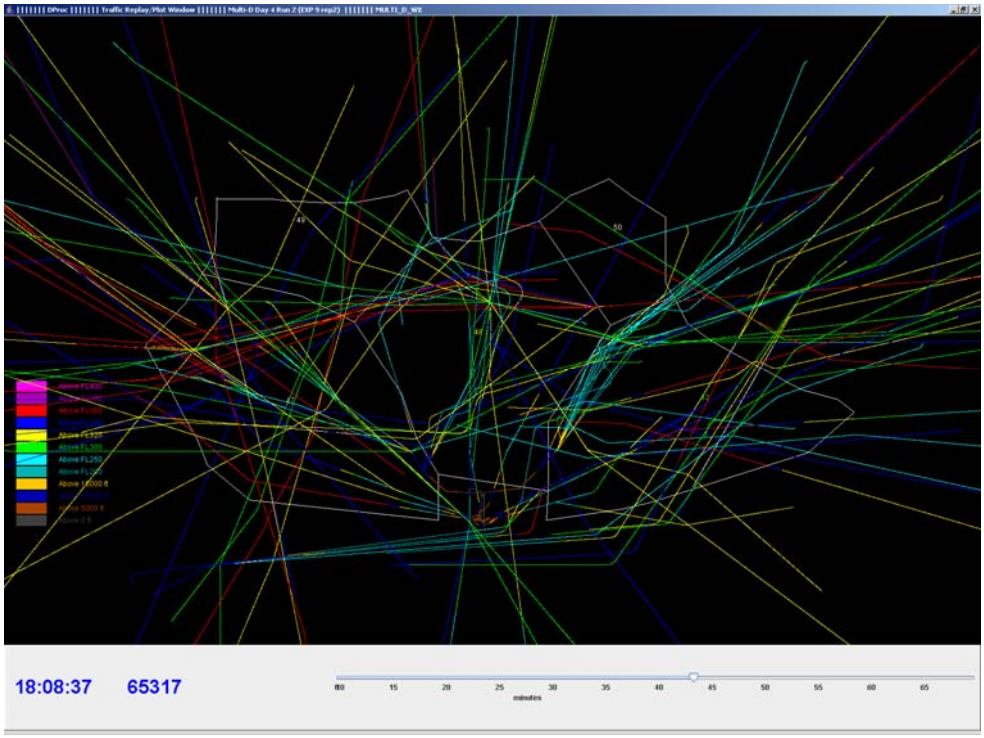


Figure 30. DProc aircraft track plot with altitude color-coding.

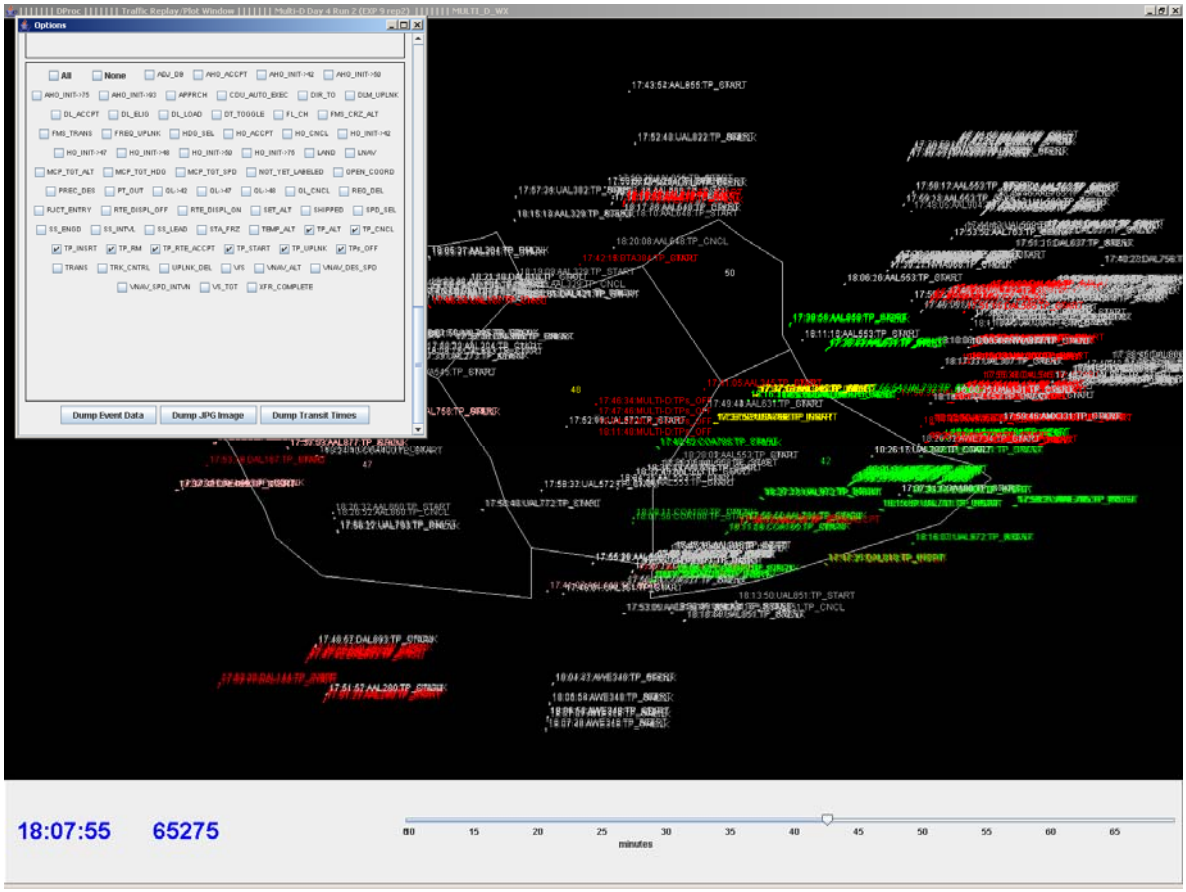


Figure 31. DProc event plot and Options Window showing event selection panel and output controls.

2. *Data processing with standard office software*

The MACS data collection system records data in a tab-delimited format that is easily viewed using e.g. Excel spreadsheet software. A significant portion of the system-generated data can be directly transferred to Excel and quickly converted into charts and graphs using normal Excel functions. The typical data collection process is a combination of both, using DProc for the preprocessing and Excel for additional analyses and graphs.

V. Projects in the AOL

The AOL has hosted a variety of simulation activities since 1996. This section gives an overview over some of the more recent activities that used the laboratory environment described above.

A. Distributed Air/Ground Traffic Management (DAG-TM) (2000-2004)

NASA's Airspace Systems program and its Advanced Air Transportation Technologies project funded research on Distributed Air Ground Management (DAG-TM) between 2000 and 2004. DAG-TM is an integrated operational concept in which flight deck (FD) crews, air traffic service providers (ATSP) and aeronautical operational control (AOC) personnel use distributed decision-making to enable user preferences and increase system capacity, while meeting air traffic management (ATM) requirements. The DAG-TM concept was formulated as a coherent set of solutions to a series of key ATM problems (or inefficiencies) in the gate-to-gate operations of the current NAS. For each problem, one or more solutions were identified that could potentially solve the problem by utilizing distributed decision-making between the user (FD and/or AOC) and the ATSP. These solutions, known as concept elements (CEs), would potentially enable greater accommodation of user preferences and increased system capacity. A

fundamental goal of the DAG-TM concept is the elimination of static restrictions, to the maximum extent possible. In this paradigm, users may plan and operate according to their preferences – as the rule rather than the exception – with deviations occurring only as dynamically necessary. Therefore, fourteen DAG-TM concept elements were originally formulated to mitigate the extent and impact of dynamic NAS constraints, while maximizing the flexibility of airspace operations.[3]

Four of the fourteen concept elements were selected for thorough investigation. We –the authors of this paper - were part of the core research team that investigated the following three concept elements:

- Concept Element 5: Free Maneuvering for user-preferred separation assurance and local traffic flow management (TFM) conformance.
- Concept Element 6: Trajectory Negotiation for user-preferred separation assurance and local TFM conformance
- Concept Element 11: Self-spacing for merging and in-trail separation

The simulation results can be summarized as follows: The *free maneuvering* concept element (CE5) mixing operations with airborne self-separating and controller-managed aircraft demonstrated a tremendous potential for increasing capacity, if the separation responsibility within a given airspace is split among multiple operators. However, airborne self-separation has raised safety concerns and requires substantial new automation in the air and on the ground.[35,36] The concept of *trajectory negotiation* (CE6) has been deemed a non-controversial concept for exchanging efficient 4D trajectories between the air and the ground and may provide substantial, but probably insufficient capacity increases if integrated into the current infrastructure[37]. *Airborne spacing* (CE11) has also been shown to be an acceptable and feasible concept; delegating well defined tasks to the flight crews. [38, 39, 40, 41]

Excerpts of the gathered results are reviewed in the next sections; see the referenced DAG-TM reports for more complete experimental descriptions and analyses.[35-41]

1. Free maneuvering: Mixed Operations with Airborne Self-Separation

A Joint NASA Ames/Langley simulation of mixed operations was conducted in June 2004.[35,36] During the simulation self-separating aircraft (also referred to as free maneuvering, or autonomous aircraft) shared en route and transition airspace with controller-managed aircraft. Flight crews of self separating aircraft had to separate themselves from all other traffic, while controllers were responsible for separating only the conventional aircraft from each other.

The analysis of aircraft counts and workload data across four sectors revealed that the sector controller's workload is primarily related to the number of aircraft he or she controls. Many more aircraft may be added to the same airspace if someone else is responsible for their separation. However, controllers reported that as the total number of aircraft increased, their available options for safely managing their traffic decreased. Figure 1 visualizes the relationship between the number of controller-managed flights, self-separating aircraft and controller workload for different traffic mixes (Conditions 1-4). In Condition 1 (C1) controllers managed trajectories and separation for all aircraft. In C2-C4 traffic mixes with an increasing number of self separating aircraft were simulated. Workload was measured during the simulations using workload assessment keypads that prompted controllers to rate their workload on a scale of 1 (lowest) to 7 (highest) every five minutes.

In the current day environment the Monitor Alert Parameters (MAP) for these sectors are set such that controllers control less than 20 aircraft at all times. During the simulations with ground automation for handoff and communication changes controllers handled more traffic than today. The workload appeared to be primarily related to the number of managed aircraft in each sector which was held constant, and not to the total sector count which was up to 3x current day traffic levels.

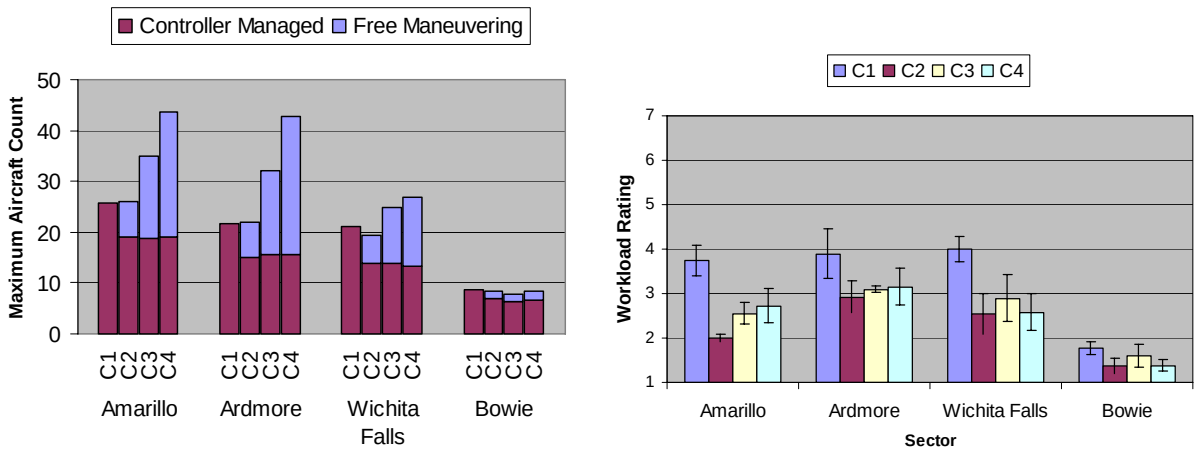


Figure 32. Maximum aircraft count and controller workload for 4 test sectors across 4 conditions (C1-C4) during DAG-TM simulations

The idea of air/ground distributed separation responsibility, however, has raised a number of safety concerns with the controllers - fueling sometimes passionate discussions about its acceptability and the required paradigm shift. The controllers' subjective safety ratings and comments reflect these concerns. Controllers rated mixed operations much less safe than managed operations[35,36]. However, this assessment was based on one particular concept implementation at an early technology readiness level. Therefore, these safety concerns should not be considered a show stopper for the concept of airborne self-separation, but they need to be taken very seriously. More research is required and significant adjustments to the concept of operations need to be made before mixed operations at the high traffic levels simulated during DAG-TM can be realized.

In addition to the safety concerns, airborne self-separation requires a highly developed infrastructure with extensive new air and ground equipage for self-separating and managed aircraft. This complex infrastructure was simulated in the AOL and is described in detail in [28]

It is our opinion that equipping for airborne self-separation should be optional for aircraft operators rather than an ATM requirement to increase capacity. It is therefore desirable to create an environment that can achieve the capacity increase without requiring airborne self-separation. The system should however be designed in a way that autonomous aircraft operations can be authorized and operators can take advantage of the increased flexibility and efficiency provided by new airborne avionics systems. An example for such an environment is described in [63]

2. Trajectory Negotiation: Data linking trajectories between ground-based DSTs and the FMS

The concept of trajectory negotiation was investigated in a number of studies including several simulations in the AOL. Frequently the notion of trajectory negotiation refers to a multi-stage process including requests, responses and potential modifications to trajectories. We take a broader view to the concept. By trajectory negotiation we mean the data link exchange of trajectories between the flight deck and the ground-side automation. Simple cases are downlinking the active aircraft trajectory from the FMS to the ground automation or uplinking a trajectory clearance from the controller workstation to the flight deck. The next level of negotiation is a route request initiated by the flight crew that is reviewed by the controller and responded to via data link. Negotiations designed to consist of several phases of requests and modifications were discussed with pilots and controllers, but were not considered to be necessary and therefore not included in any of the studies conducted at Ames.

Experiments on air/ground integration between 1997 and 2000 identified the feasibility and benefits of data linking trajectories from the ground automation into the FMS [42, 43, 44, 45]. DAG-TM research also made trajectory negotiation a central concept element. Two complimentary DAG-TM studies in 2002 and 2004 evaluated firstly the capacity and efficiency benefits of uplinking FMS loadable clearances from the controller to the flight deck and secondly the feasibility of flight crew initiated trajectory requests. Prevot et al. [46] reported reduced arrival spacing variability, increased flight efficiency and positive controller workload impacts. Lee et al. [47] documented the feasibility of downlink requests and trends in favor of data linking requests as opposed to voice requests.

The controller and flight crew interfaces underwent many improvements during the process. At the final DAG-TM simulations in 2004 the controller and pilot tools for modifying, evaluating and data link trajectory

modifications were seamlessly integrated with their workstations. Controllers and pilots preferred the concept of data linking trial planned trajectory changes between the ground and the air clearly over current day operations. Table 1 [18] summarizes some of the feedback of full performance level controllers gathered in post simulation questionnaires after the controllers had used a prototype DSR system that integrated CPDLC with advanced DSTs.

Clearly controllers were in favor of the advanced operations combining trajectory modifications with data link and trial planning tools. Details on the provided ground automation can be found in [28]. With this toolset and full aircraft equipage, vectoring was practically eliminated [29] and almost all flight path changes were conducted via trajectory modifications. It should be noted that this process of management by trajectory is also a central component of enabling mixed autonomous/managed operations. This concept allows aircraft to stay on trajectories almost exclusively, which makes them more predictable than if they were vectored. As a result airborne conflict detection and resolution (CD&R) logic can support flight crews more effectively, because the surrounding traffic (managed and self separating) provides stable trajectory intent information – a primary requirement for strategic CD&R.

Table 1: Controller responses to comparing trajectory-based clearances with CPDLC to current day operations

	Question	Range	Low Altitude	High Altitude #1	High Altitude #2	En route		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

Some findings have been very consistent throughout our trajectory negotiation research

- Uplinking FMS loadable trajectory clearances and downlinking the active FMS trajectory is desirable and beneficial and can improve delivery accuracy, predictability and eliminate excessive vectoring.

- Trajectory negotiation can be a simple process. Pilots and controllers had no problems with a simple task sequence that consisted of a request and a yes/no response. There is no evidence that a multi stage process is required. Therefore an initial implementation in the ground-based and airborne systems can be straightforward and still very powerful.
- It is very important that trajectory tools and data link is very responsive and properly integrated with the operator station to make the concept usable and useful in high traffic situations[20].

Based on the positive results trajectory management/negotiation should be a central component of any future airspace architecture. The ongoing work on Tailored Arrivals[22] is an important initial step into this direction by implementing trajectory exchange between the airborne FMS and the ground-based automation in the near term in a low density environment. In order to implement trajectory management effectively in high density airspace, controller and flight deck tools need to be well designed and integrated into their respective operator stations[28,].

3. Airborne Spacing

Airborne spacing has also been evaluated in simulations in a number of studies[38,39,40]. In this concept controllers can assign flight crews of properly equipped aircraft a lead aircraft and an interval specified in time or distance to maintain to this lead aircraft using ADS-B and airborne spacing tools. Airborne spacing does not change responsibilities but increases the role of the flight crew in the spacing task. Controllers –as today- remain responsible for safe separation between aircraft. The general consensus derived from the conducted studies is that airborne spacing is acceptable to pilots and controllers if proper procedures and spacing algorithms are in place. It can increase controller availability and relieve controllers from some monitoring and tactical control tasks. One of the primary advantages of airborne spacing is its ability to increase the precision of inter-arrival spacing between aircraft.

A DAG-TM study in the AOL investigated terminal area FMS arrivals with airborne spacing and merging. In the study two professional terminal area controller pairs interacted with 9 commercial pilots and additional confederate controllers and pseudo pilots to evaluate four different conditions:

- Air Tools'—seventy-five percent of aircraft assigned to the primary landing runway were equipped for airborne spacing and controllers could issue self-spacing commands,
- 'Air and Ground Tools'—controllers also had DSTs available to aid in issuing airborne spacing clearances and monitoring conformance,
- 'Ground Tools'—controllers had DSTs available, but no aircraft were equipped for airborne spacing;
- 'No Tools'—basic FMS TRACON operations;

In this study the AOL simulated two parallel "worlds", by conducting each run concurrently with two sets of pilots and controllers operating the same traffic scenario in parallel. This way the 80 runs required for the analysis could be conducted in half the time and controllers and pilots could interact with different groups throughout the study.

The results show that accuracy improves when aircraft are capable of airborne spacing in conditions 'with air tools.' The addition of controller DSTs in the Air and Ground Tools condition does not improve spacing accuracy beyond that obtained in the Air Tools condition. Ground Tools did, however, help controllers err on the conservative side relative to No Tools, suggesting an improved awareness of the required spacing that may help minimize go-arounds. While workload always remained within an acceptable range, clearance data indicate that airborne spacing works best when linked to en route concepts capable of delivering aircraft in coordinated flows.

The increased precision of airborne spacing is documented in the spacing error at the final approach fix. Figure 33 shows the spacing accuracy at the final approach fix to the primary landing runway for that study.

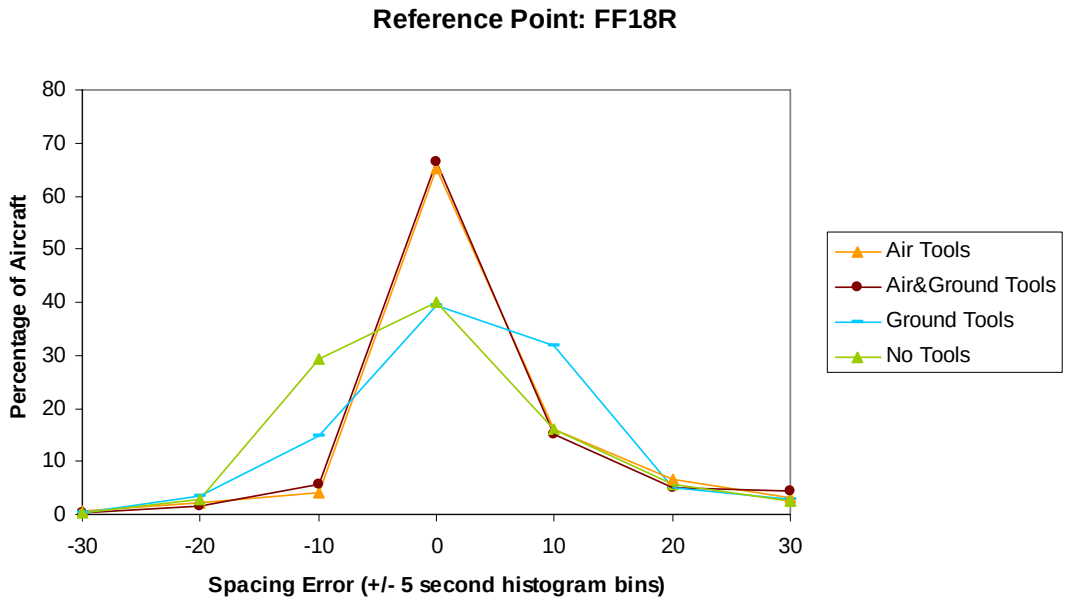


Figure 33. Spacing accuracy histogram measured at the Final Approach Fix during DAG-TM study conducted in 2004 at NASA Ames Research Center

The concept of airborne spacing has recently gained significant momentum. The US/European Requirements Focus Group is tasked to establish application definitions, safety and performance analyses, and interoperability requirements for airborne spacing in order to prepare a widespread implementation. Airborne spacing should be considered a powerful tool for future air traffic management that can be applied to all phases of flight and requires only moderate equipage upgrades on the flight deck and the ground-side.

B. Multi Sector Planner (MSP) (2006)

Air traffic control in the en route airspace environment in the United States has traditionally been performed by a team configuration. This team divides duties so that one controller (the radar-controller) has primary responsibility for observing the radar screen (DSR) and exercising control by communicating with the flight crew by voice-radio contact. The second controller (data-controller or radar-associate) on the team has primary responsibility to manage flight progress strips and to serve as a "strategic" aid to the radar controller. Several developments in the technology supporting air traffic management, digital data communication among controllers and between controllers and aircraft, improved positioning accuracy for flight operations, conflict prediction, and sector complexity assessment, have enabled consideration of the continued efficacy of the standard team concept. New organizational and functional operations are being considered. These configurations are responses to increased traffic demand while the controller workforce transitions to more decision support and automation aiding. They are also, in part responsive to FAA initiatives in response to controller work force initiatives. [47,48]

In an FAA sponsored study conducted in the AOL in 2006, the standard controller team configuration was modified to include a "multi-sector planner" (MSP) position. This MSP position has been investigated in several research and field studies [49,50,51,52, 52, 54, 55]. The concept provides a spectrum of redistributed roles and responsibilities among the air traffic management team members. The feasibility and effectiveness of two of these concepts were investigated in the study.

One concept, termed "Multi-D", took the traditional role of a data-controller but provided these types of services to several radar controllers (three radar controllers were assigned to be the responsibility of the data-controller in our experiment). As in current operations, the Radar position had the responsibility for managing the sector operations for the individual sectors, including aircraft separation and traffic flows. The Multi-D position supported the R-side by managing traffic flows within the multi-sectors and providing medium-term conflict resolutions, as well as assuming normal data-controller duties with automation assistance. Multi-D was provided with a traffic situation display that spanned across three sectors, a conflict probe with 15-minute look-ahead time along the aircraft 4D

trajectory, route/altitude trial plan capability, ground/ground and ground/air data link, sector load graphs and table, electronic flight strips, and "quick look" capability.

In the second configuration, the MSP served functions often associated with "traffic flow" management, coordinating with external MSP areas and attempting to manage sector traffic levels in a proactive process balancing loads among the three sectors in their area of responsibility as well as with external areas. This function was termed "area flow manager". In this MSP role, the Area Flow was meant to be a bridge between TMU and R-side controllers. Since the role focused on strategic flow issues and did not involve tactical control of operations, the Area Flow was not co-located with the R-side controllers in the study. Unlike Multi-D, Area Flow did not resolve medium-term conflicts. Instead, s/he actively managed the sector loads across the three sectors by rerouting aircraft to keep the aircraft count below Monitor Alert Parameter (MAP). Except the conflict probe and ground/air data link capability, the Area Flow position had the same tools as Multi-D.

The experiment consisted of a pair of one-week human-in-the-loop studies, in which each MSP concept (i.e. Multi-D and Area Flow) was tested separately with a different team, each consisting of five participants. The MSP position provided services for three radar-controllers in a modified Forth Worth center airspace. A "ghost MSP" position was staffed by one of the participants to act as an adjacent MSP so that coordination activities between MSPs could be captured within the study. The participants were presented with two different types of scenarios, a high traffic scenario without weather and a moderate traffic scenario with weather, that were designed to exercise different facets of an MSP's roles and responsibilities. In addition to running one of two MSP conditions (i.e. Multi-D or Area Flow) in each week, a baseline condition – in which two of the three sectors were staffed with radar and data-controller pairs – was also run each week to provide data that were directly comparable to the corresponding MSP conditions. The Baseline condition assumed maintenance of the current day team concept of radar and data-controllers but with the presence of advanced decision support tools and automation, such as data link, conflict probe, and 4D trajectory trial planning capability. With an equivalent set of advanced tools in both MSP and the Baseline conditions, significant differences in the results would indicate the impact of the shift in roles and responsibilities that resulted from the MSP concepts.

The analyses of the results showed interesting differences between the Multi-D and the Area Flow concept that resulted from the slight differentiation of their roles and responsibilities. For example, since the area flow planner (but not Multi-D) was actively balancing the aircraft count below Monitor Alert Parameters, the aircraft count shows a significant reduction below MAP for Area Flow but not Multi-D (see Figure 1). This result suggest that the Area flow planner was able to use the sector load graphs and table effectively to manage the aircraft count. The subjective feedback supports this idea, as the Area Flow planners rated sector load graph and table to be highly useful (M = 5 out of 5 for both) and usable (M = 5 and 4.5 for load graph and table, respectively).

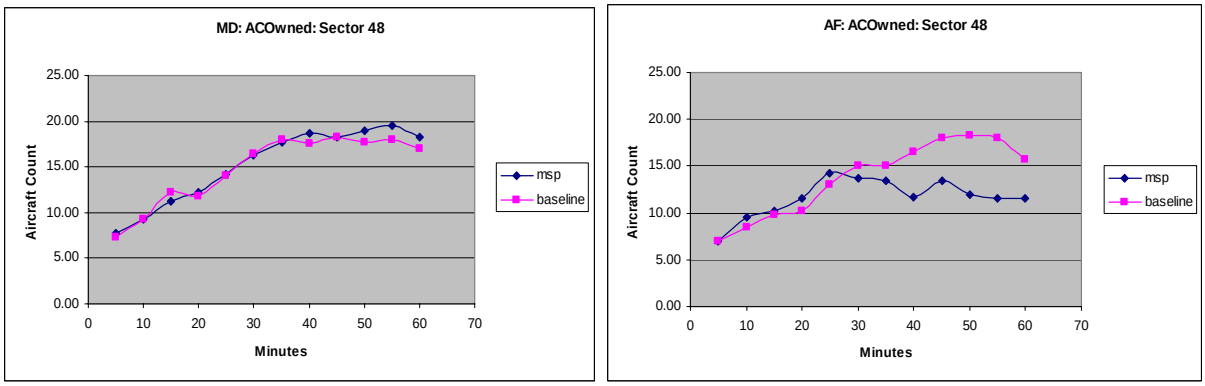


Figure 34. Aircraft count for baseline (purple line) vs. MSP (blue line) during Multi-D (MD) and Area Flow (AF) evaluations. Graphs depict aircraft count in sector 48 (Ardmore).

The overall analyses revealed that the two types of scenarios – high traffic without weather and moderate traffic with weather – provided interesting insights into how potential benefits of each MSP concept may vary for the weather and non-weather scenarios. For example, both Multi-D and area flow planner managed the traffic more strategically compared to baseline but each did it in its own way. Since Multi-D resolved medium-term conflicts, fewer conflicts were resolved late compared to the baseline. However, this result only held true for the high traffic/no weather condition, suggesting that medium-term 4D trajectory conflict probes were less effective during weather scenarios. Since the area flow planner did not resolve conflicts, the concept showed little benefit with respect to conflict resolution. In contrast, the area flow planner generally focused on the weather problem and

managed to reroute aircraft completely around the weather, resulting in a significant reduction in the number of tactical maneuvers in the weather scenarios. Figure 35 shows the number of altitude and vectors issued by voice at the last minute. The cumulative number of verbal clearances across three sectors (ADM, DECOD, and SPS) in the weather condition shows a significant decrease in the MSP condition compared to baseline. In contrast, Multi-D did not show a similar decrease in tactical maneuvers (not shown).

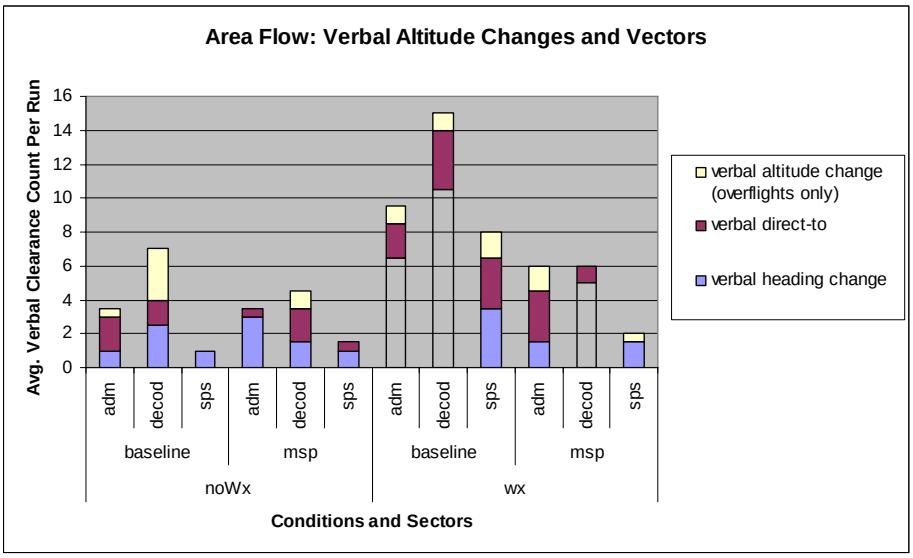


Figure 35. Verbal Altitude/Heading Change and Direct-to for Area Flow Operations.

Both Multi-D and Area Flow seemed to help the R-side controllers to maneuver effectively around the weather. The number of aircraft that penetrated the weather cells was significantly less during the MSP conditions (see Table 3), suggesting that both Multi-D and Area Flow aided R-side controllers to strategically maneuver around weather cells.

Table 2: Weather Penetrations for Ardmore Sector: Multi-D vs. Area Flow

Condition	MSP Concepts	
	Multi-D	Area Flow
Baseline	62	13
MSP	41	4

The analyses of the participant workload suggested that in the Multi-D condition, the radar-controllers' workload was relatively unaffected by the conditions (i.e. Multi-D vs. Baseline), suggesting that a Multi-D was equally effective in aiding the radar-controllers as were the two data-controllers in the Baseline condition. However, they achieve this goal in different ways, as the Multi-D helped radar-controllers mostly by reducing traffic complexity in the sectors with traffic flow initiatives, while Baseline data-controllers helped their respective radar-controllers via point-outs, handoffs, etc. There was expected tension between the radar controllers and Multi-D with respect to who has the final authority in a sector. Multi-Ds thought that they have a greater authority to re-direct aircraft based on a larger picture of the traffic situation while the radar-controllers thought that, as a data-controller, Multi-D should maintain a similar level of authority as current day data-controllers.

In the Area Flow condition, the MSP was only able to reduce the radar-controllers' workload slightly for the sector that did not have a data-controller in the Baseline condition. The Area Flow manager coordinated with the adjacent Area Flow manager to manage the traffic flow far away from the impacted sectors, resulting in frequent verbal coordination between them but only few verbal coordination activities with the radar-controllers. The acceptability of the Area Flow concept seemed to predicate on having proper tools to assess and execute traffic flow initiatives, such as accurate departure information, shortcut functions to re-route multiple aircraft along a similar

route, and better traffic complexity indicators. Overall, the study shows feasibility of both concepts. However, the study also suggests that the Multi-D position needs to be re-defined since a simple mapping of its roles and responsibilities to current day data-controllers seems to be misaligned with the tasks that the Multi-D can perform.

C. Oceanic Tailored Arrivals Trials (ongoing)

1. Tailored Arrivals

For the past several years, the Boeing Company has led an international effort to develop and test a new arrival procedure called the Tailored Arrival[1]. The procedure uses an FMS-loadable route clearance, with along-path altitude and speed constraints, to construct a 4-D trajectory that extends from cruise altitude to the runway threshold. The resulting trajectory is designed to be a continuous, low-power descent that, with the proper ground tools, can be "tailored" for individual aircraft performance characteristics, airline preferences, and local traffic conditions. The Tailored Arrival permits the aircraft to remain at cruise altitude longer than conventional step-down arrival procedures used today, leading to reductions in community noise impact, flight time, and fuel consumption.

A data link trial of the Tailored Arrival was conducted in Australia in 2004 by a team that included Boeing, Qantas Airways, Air Services Australia and Air Traffic Alliance. During the trials, pre-defined data link clearances were sent to FANS 1/A equipped aircraft arriving in Sydney during low traffic periods. These clearances began before the top-of-descent, descended through a series of altitude and speed restrictions, then connected to a published STAR. The trials demonstrated the feasibility of sending an arrival clearance with multiple constraints to an arriving aircraft by controller-pilot data link in a non-congested environment, as well as a potential for greatly reducing pilot-controller voice communications.[56,67]

In early 2006 a second study was conducted at Schipol Airport in Amsterdam. This study involved Boeing; the Dutch ATC organization, LVNL; Eurocontrol's Maastricht Upper Area Control Centre; and the airlines Transavia and Martinair. The Schipol trials also used a set of predefined clearances, this time issued by voice, to take the aircraft from cruise altitude to the runway. One feature of the Schipol study was use of a series of altitude constraint windows (e.g., cross WPT at or above FL220 and below FL240), bounding a set of descent paths that could accommodate different aircraft types. Results from these trials will be presented at the ATIO conference in September 2006[58].

In August 2006, a third trial began in the San Francisco Bay Area, supported by United Airlines, Oakland Center (ZOA), Northern California TRACON (NCT), San Francisco Airport's Noise Office, Lockheed Martin, Boeing, and NASA.[59] The Bay Area trials use the data link equipped ATOP system[24] installed at Oakland Center, to send the Tailored Arrival clearances to inbound international flights arriving during low traffic hours. Since ATOP is only used for the Oakland Center Oceanic sectors, only oceanic arrivals are candidates for these "Oceanic Tailored Arrival" (OTA) trials. Figure 1 displays the nominal events for an inbound OTA flight from Honolulu.

This is the first test of Tailored Arrivals in the U.S. Another unique feature of these trials is the use of an automated ground tool, NASA's En Route Descent Advisor (EDA), to modify components of the uplinked clearance for some of the flights in order to manipulate their arrival time at an 11,000' metering waypoint.

1. Nightly coordination is completed before flight arrives in Oceanic sector.
2. At least 60 minutes prior to top of descent, flight crew downlinks "RQST SFO TRIAL".
3. Controller uplinks OTA route clearance.
4. If acceptable, crew executes OTA uplink and downlinks "wilco".
5. After the aircraft sequences the "At" position (e.g., COSTS), speeds may be uplinked for EDA test option.
6. Aircraft leaves oceanic airspace and loses controller-pilot data link.
7. Controller issues pilot's discretion descent.
8. TRACON clears aircraft to continue descent and provides approach clearance.

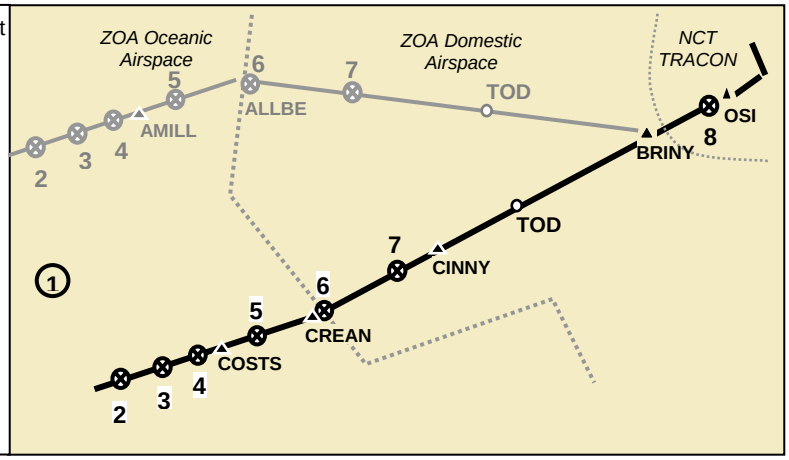


Figure 36. Some of the nominal events for an inbound OTA flight on "Track C" from Honolulu for SFO.

2. Simulation of Oceanic Tailored Arrival (OTA)

In preparation for the field evaluation, AOL software was adapted to support simulation of OTA operations that would be used during the trials. These changes and their purpose are described briefly below.

The OTA is a clearance issued while an aircraft is about two hundred miles off-shore that ends at the runway threshold. It travels through three types of airspace: Oceanic en route, domestic en route, and TRACON (Figure 1). In order to simulate all of the controller operations, controller-to-pilot interactions and controller-to-controller coordination that would occur during the OTA, a new oceanic controller interface was needed. ATOP user manuals and training material were used as a model for designing a complete, high fidelity ATOP emulation in MACS that included a data link interface, traffic display, and interactive flight strips. During the field trial preparations the MACS ATOP display has been used both to support the simulation of controller operations and as a researchers' tool for viewing live and recorded traffic along the oceanic tracks that the test flights will use.

Other AOL enhancements to support OTA trial preparations included modification of the ADRS software to accept a live "ASDI" data feed, and adding a data base adaptation for Oakland Center's oceanic airspace.

In contrast to the studies described in earlier sections, the AOL's OTA simulations were conducted to support the development and testing of procedures for a near-term application that would be used in field operations. Between September 2005 and July 2006, simulation sessions were used to introduce the concept to ATC facility representatives, evaluate air-ground procedures, assess facility-to-facility coordination requirements, develop controller and pilot training material, and conduct a final walkthrough review before the trials began. Two examples of the value of these simulations are described next.

Representatives of the two ATC facilities that needed to support the OTA trials, Oakland Center and Northern California TRACON, were invited to meetings at NASA Ames in fall 2005. These meetings included briefings and paper-based walkthroughs of the OTA procedures, along with a simulation in the AOL of a representative flight traveling through the oceanic, domestic and TRACON sectors. The simulation greatly enhanced the controllers' understanding of the proposed new operations. By seeing the OTA events and procedures play out as the flight traveled across the three displays, controllers could immediately identify similarities and differences between OTA operations and their current practice. The result was recognition of how few changes were needed to implement the OTA, and strong support from both facilities to help make it happen.

A final simulation, conducted in July, supported a continuous end-to-end walkthrough of the OTA procedures in real time. The simulation started with the flight approaching the region where coordination between flight crew and ATC would begin, with each air-ground exchange, controller action and pilot action being completed in real-time as the flight progressed. Two problems rapidly became apparent: (1) that air ground coordination needed to begin earlier than planned, and (2) that the controller tasks for composing the OTA route clearance needed to be streamlined. As a result of the simulation, the procedure was modified to begin OTA activities 30 minutes sooner, allowing ample time for data link exchanges to be completed before the aircraft entered domestic airspace (and lost the controller-pilot data link connection). To address the second problem, a procedure was developed to insure that OTA clearance components for that night's flight were composed and saved in advance in a readily accessed file on the controller's workstation. This preparatory activity could be performed off line, reducing the time pressure on the controller and the opportunity for input errors when the OTA route clearance was composed and sent. In short, the simulations provided a uniquely effective resource in preparing to conduct the OTA trials.

D. Trajectory Oriented Operations with Limited Delegation (TOOWiLD) (ongoing)

The AATT-sponsored CE-5 and CE-6 simulations explored the use of 4-D trajectory based operations in the en route airspace. CE-11 simulations tested delegation of self-spacing responsibility to the flight crew from the TRACON boundary to the runway threshold. While conducting the en route studies, it became apparent that meter fix throughput could be improved, and controller and pilot workload reduced, if trajectory operations were combined with limited delegation clearances as aircraft converged. A concept for integrating "trajectory oriented" and "limited delegation" operations, TOOWiLD, was first presented by Prevot in 2004[60]. This concept is similar that presented by Graham, et al. (2002)[61].

The TOOWiLD concept has three main features. It uses (1) time-based flow management to regulate traffic density; (2) trajectory-based operations to create efficient, nominally conflict-free trajectories that conform to traffic management constraints; and (3) it maintains local spacing between aircraft with airborne separation assistance. A schematic illustration of the basic TOOWiLD scenario is shown in Figure 37.

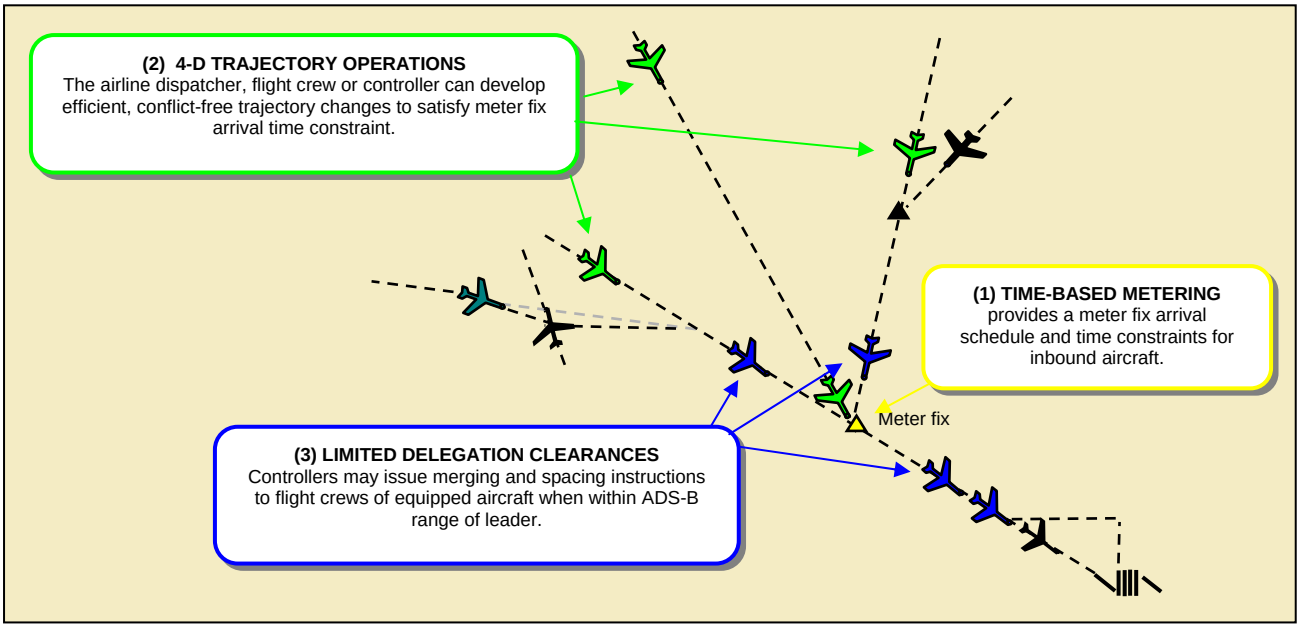


Figure 37. Basic TOOWiLD scenario.

3. *Merging and Spacing Operations at Louisville*

The TOOWiLD research plan included development and testing of "site-specific" variations of the TOOWiLD concept. An adaptation for UPS hub operations at Louisville's Standiford Airport (SDF) has been developed, in collaboration with the FAA-sponsored Merging & Spacing (M&S) development group.

The M&S group is pursuing the phased development and deployment of a concept for integrating the continuous descent approach (CDA) with airborne spacing. A detailed description of the M&S effort is beyond the scope of this paper, but a high level overview will be provided as background for the TOOWiLD implementation.

UPS has a fleet of Boeing 757 and 767 aircraft that arrive from the west each night at SDF. These aircraft are the last to arrive for the nightly "sort", and the efficiency of UPS hub operations is highly dependent on timely arrival of these aircraft. This group is equipped with advanced automation (CDTI and ADS-B), and a set of CDAs have been developed for their arrival routes. The first phase of the M&S effort has the UPS dispatcher provide speeds to these aircraft while they are en route in order to regulate their arrival at an en route merge fix, preparing them to receive clearances for uninterrupted CDA descents [62]. The second phase will combine this pre-conditioning with an airborne spacing capability that can be engaged when an aircraft is within ADS-B range of its leader. As with the speeds used for pre-conditioning the flow, lead aircraft and spacing interval are assigned through ACARS uplinks from the UPS dispatcher. Figure 38 depicts the airspace and operations described for en route preconditioning arrivals via CDAs.

The air traffic controller's role in this concept is to issue the CDA clearances and monitor separation. They are informed that UPS arrivals from the west may conduct airborne spacing, but have no new responsibilities towards the self-spacing flights. Any ATC clearances that conflict with the conditions required for self-spacing (e.g., speed clearances, vectors or route changes) automatically override and cancel self-spacing.

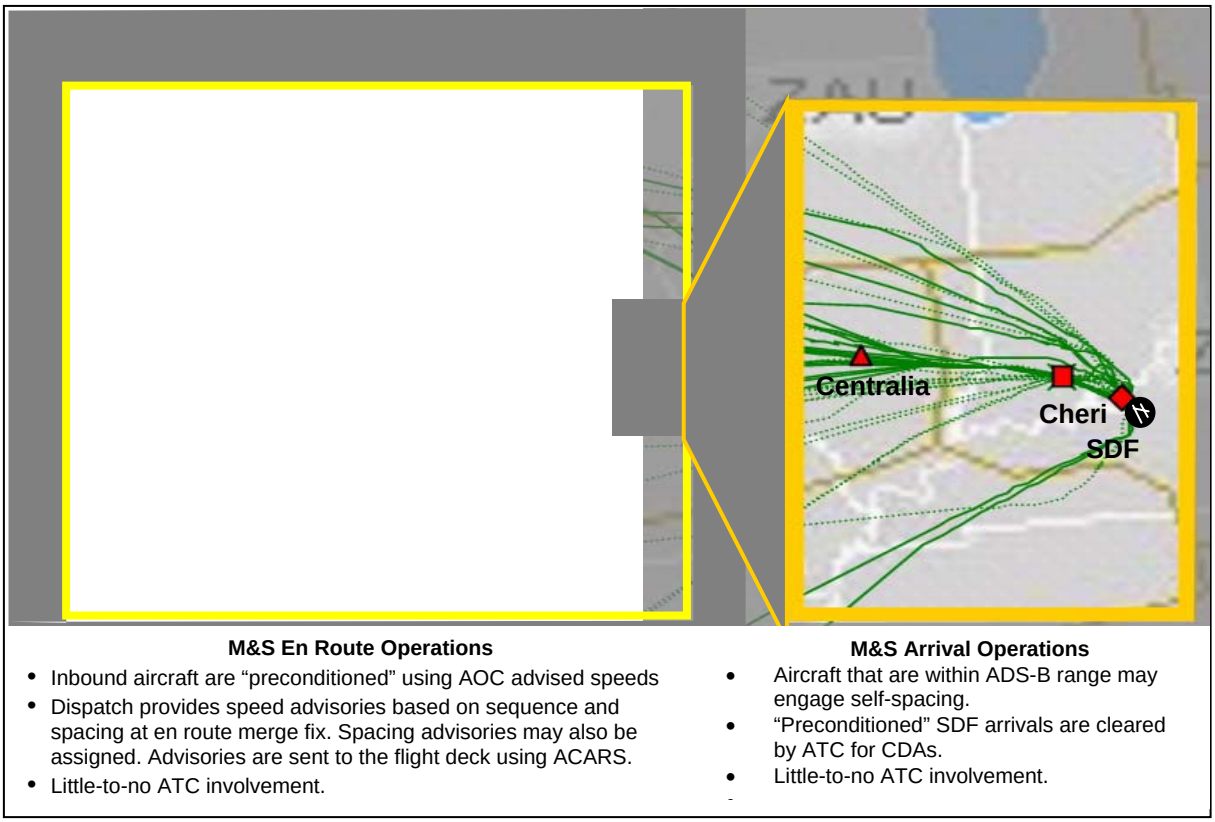


Figure 38. M&S concept for en route and arrival operations.

4. TOOWiLD "site-specific" implementation

There are several common elements between the M&S concepts and TOOWiLD, including the use of time-based metering to coordinate the arrival of inbound aircraft, engagement of relative spacing when aircraft are within ADS-B range. In fact, the M&S idea for en route pre-conditioning grew out of an early TOOWiLD demonstration

The TOOWiLD research has also benefited from this sharing of ideas: a "site-specific" implementation of the concept, prototyped in the AOL, assumes as its operational context the fleet capabilities, air-ground procedures, traffic patterns and airline-centric arrival flow management that are being developed by the M&S group.

The most advanced Louisville TOOWiLD version has the following features, illustrated in Figure 39:

(1) Time-based metering: All arrival aircraft are scheduled to the runway threshold. This master schedule is shared between ATC and the dispatcher of the airport's dominant carrier.

(2) 4-D trajectory-based operations: The airline dispatcher has sophisticated planning tools that enable pre-conditioning of the arrival flow based on the common schedule. En route and TRACON controllers also have tools to monitor the inbound runway flow, and can use them to develop speed or route advisories to integrate aircraft from other airlines, or unequipped aircraft into the arrival sequence. All arriving aircraft are candidates for CDA clearances, which enable improved, trajectory-based arrival time predictions.

(3) Airborne spacing operations: The airline dispatcher can use the planning tools to assign properly equipped flights a lead aircraft and spacing interval as appropriate. The flight crew (or airborne automation) determines when it is appropriate to engage or disengage self-spacing.

5. TOOWiLD experiment:

A simulation experiment will be conducted in the AOL in September, 2006, with the implementation described above. Six conditions will be presented using a 3 x 2 test matrix: 3 levels of controller automation, and presence or absence of airborne spacing operations. The controller automation levels that will be tested include (1) current day (a "no tools" condition), (2) metering and trial planning tools, and (3) metering and trial planning tools with controller-pilot data link. In all three cases the dispatcher has a schedule, and advanced tools to pre-condition the arrival stream using speed advisories.

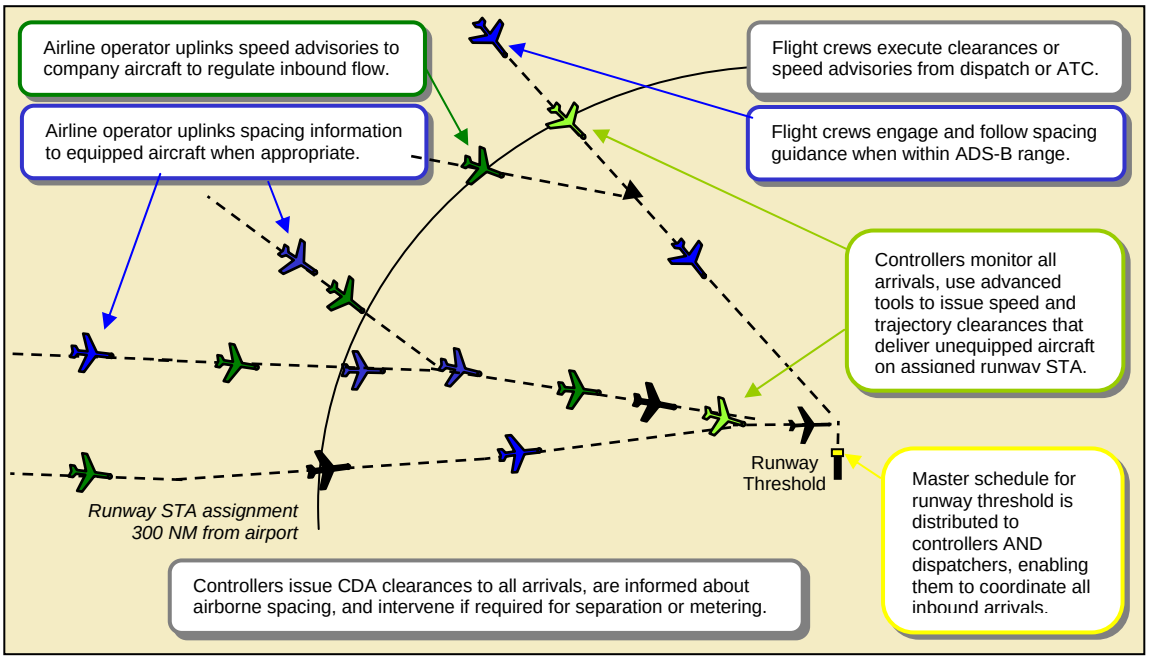


Figure 39. "Site-specific" Louisville version of TOOWiLD concept.

A 3-day shakedown of the TOOWiLD experiment was conducted with retired controllers working the three sequential en route sectors and single TRACON position. Results from this shakedown indicate that an airline-centered approach to arrival flow management may be feasible. In an airport like Louisville, which has one dominant carrier, this may even be possible without the introduction of new controller tools.

Whether the trends observed during the shakedown hold up can only be stated when the data of the planned simulation in September 2006 will have been analyzed.

VI. Concluding Remarks

The Airspace Operations Laboratory at NASA Ames Research Center hosts a powerful air traffic simulation environment. The many capabilities that are already integrated and the expandable rapid prototyping environment make it an excellent test bed for visionary NGATS concepts as well as transitional near- and medium term operations. The research conducted in the AOL to date has demonstrated that research questions can be successfully addressed in this AOL.

Acknowledgments

Trajectory-Oriented Operations with Limited Delegation (TOOWiLD) is funded under the Airspace Systems project. The MSP study was funded by the Federal Aviation Administration and was led by Principal Investigator Dr. Kevin Corker of the San Jose State University. DAG-TM research was funded by the Airspace Systems program as part of the Advanced Air Transportation Technologies Project (AATT). DAG-TM Simulation results used for this paper were generated with the help of many dedicated individuals at the AATT project office, the NASA Ames Flight Deck Display Research Laboratory, the NASA Ames Airspace Operations Laboratory, Crew Vehicle Systems Research Facility, and the NASA Langley Air Traffic Operations Laboratory. This work could not have taken place without the active support of the Air Line Pilots Association, the National Air Traffic Controllers Association, and

the Air Traffic Services Office of the Federal Aviation Administration. The authors deeply appreciate their interest in and support of our research.

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