Integrated Air/Ground System: Trajectory-Oriented Air Traffic Operations, Data Link Communication, and Airborne Separation Assistance

Thomas Prevot, Vernol Battiste, Todd J. Callantine, Parimal H. Kopardekar, Paul U. Lee, Joey S. Mercer, Everett A. Palmer, and Nancy M. Smith

Trajectory-oriented, time-based air traffic operations, data link communication, and airborne separation assistance systems (ASAS) can play an important role in the transformation of the airspace system. This article reviews several years of research conducted primarily at NASA Ames Research Center. The research promotes an integrated air/ground system combining trajectory-orientation, data link communication, and airborne separation assistance as complementary components of a modernized airspace system, rather than viewing them as competing approaches to modernization. The integrated air/ground system promises capacity, efficiency,

---

Thomas Prevot, Todd J. Callantine, Paul U. Lee, and Joey S. Mercer are with San Jose State University/NASA Ames Research Center, Moffett Field, CA. Vernol Battiste, Parimal H. Kopardekar, Everett A. Palmer, and Nancy M. Smith are with NASA Ames Research Center, Moffett Field, CA.

Received July 28, 2004; accepted March 17, 2005.

Air Traffic Control Quarterly, Vol. 13(2) 201–229 (2005)
 CCC 1064-3818/95/030163-20

and security benefits through trajectory-oriented air traffic management and control. It uses data link to communicate aircraft states and trajectories between pilots and controllers, and it utilizes airborne separation assistance to improve throughput at traffic bottlenecks. This paper highlights benefits of this approach and provides recommendations and guidelines for controller tool and data link implementation as well as a near term concept of ASAS integration. **Funding for this work was provided by the Advanced Air Transportation Technologies (AATT) project and the NextNAS project of NASA's Airspace Systems Program.**

INTRODUCTION

In light of anticipated future traffic demand, a number of concepts aimed at improving air traffic efficiency and safety have been proposed and investigated over the past decades. Reduced vertical separation minima (RVSM) are implemented in many regions throughout the world, which significantly increase the available en route airspace. However, the increase in available airspace can only be utilized if the number of aircraft does not exceed the maximum that can safely be handled by the controllers. Increasing en route and transition capacity becomes even more important when measures to expand approach and landing capacity are implemented, such as adding more runways, utilizing secondary airports, and optimizing wake vortex spacing requirements. Controller workload, in particular, limits en route and transition airspace capacity. In terminal areas controller workload and excess spacing between aircraft are being viewed as contributors to suboptimal throughput.

Frequently, *absolute* 4D trajectory-based air traffic management and control and *relative* aircraft-to-aircraft-based spacing concepts are viewed as alternative pathways to addressing both problems. Absolute operations focus on strategic time-based air traffic management and control, and require substantial improvements to ground automation and communication infrastructure, as well as integration with the aircraft's flight management system [e.g. EUROCONTROL, 1999; Haraldsdottir et al., 2003; Wichman et al., 2004]. Relative operations target improvements in managing local dense airspace areas by delegating the spacing task to flight crews. Relative operations also require flight deck automation that incorporates ASAS and data link capabilities [e.g. Grimauld et al., 2004; Callantine et al., 2005; Lohr et al., 2003].

Any concept of future airspace operations will require significant investments by air traffic authorities and/or aircraft operators. In the authors' opinion, new investments in modernization may render disappointing returns, if the ground systems, the airborne systems, and the communication infrastructure are not compatible with a common concept of operations. Activities related to the Next Generation Air

Transportation System Integrated Plan formulated by the Joint Planning and Development Office [JPDO, 2004] in the U.S. and the ATM Master Plan development in Europe acknowledge the importance of synchronization of air and ground development.

Traditionally, flight decks are far more advanced than ground systems. Today, for example, this mismatch prevents air traffic service providers (ATSP) from allowing flight crews and airlines to utilize their systems to their maximum effectiveness. Twenty years after many aircraft have been equipped with flight management systems, these systems can rarely be used in dense airspace areas where their precise path tracking capabilities could be most advantageous for controlling aircraft.

Research conducted during the past decade indicates a number of air-ground integration steps that can be taken to provide an integrated air traffic environment that utilizes ground-based and airborne systems more effectively. A well integrated air/ground system promises benefits without drastically changing the current distribution of roles and responsibilities. Future air traffic concepts represent a variety of options, from near-term limited delegation concepts such as "Co-Space" [EUROCONTROL, 2004] to far-term approaches such as the highly automated Advanced Airspace Concept (AAC) [Erzberger, 2004], or autonomous airborne operations such as the Distributed Air-/Ground Traffic Management (DAG-TM) [AATT, 1999] concept of free maneuvering. Some far term concepts potentially provide higher capacity gains than the concept proposed in this paper, but they also require significant paradigm shifts and extensive additional research and development before implementation. By contrast, the proposed concept of comprehensive air/ground integration is evolutionary and can be implemented now to lay the groundwork for moving towards more advanced concepts. The idea of "Co-Operative Air Traffic Management" under exploration at NASA Ames [Prevot et al., 2005b] provides a scalable framework to phase in the integrated air ground system, considering transitional concerns such as mixed equipage, controller training, and inhomogeneous ATM environments. Estimated capacity gains from this approach should be sufficient to handle the projected traffic growth over the next ten to fifteen years. Once the air and ground systems are properly integrated on a conceptual, procedural, and technological level, more advanced concepts that now appear revolutionary may become just another evolutionary step.

The first part of this paper describes the proposed integrated air/ground system on different levels. The subsequent sections discuss simulation results and implementation recommendations for the three components—trajectory-orientation, data link, and ASAS—with respect to the integrated air/ground system.

INTEGRATED AIR/GROUND SYSTEM

This section describes the proposed integrated air/ground system on a conceptual, procedural and technological level. The conceptual level explains the functional interaction of the main components. The procedural level describes the distribution of roles and responsibilities between the stakeholders. The technological level addresses requirements for airside equipment, ground-side equipment and communication infrastructure.

Conceptual Level

The proposed concept is a combination of absolute and relative operations [Graham et al., 2003; Prevot et al., 2003a; 2003b; 2003c] and is in line with research findings and analyses of the air traffic system conducted in Europe and the US. Graham et al. [2003] discuss the layers and loops of the air traffic management system and postulate that a combination of trajectory-based absolute operations and relative operations is desirable. Based on these recommendations and further analyses, a concept for an integrated air/ground approach to trajectory-oriented operations with limited delegation [Prevot et al., 2004] can be formulated:

(1) Use time-based flow management to regulate traffic density,
(2) Use trajectory-based operations to create efficient, nominally conflict-free trajectories that conform to traffic management constraints, and,
(3) Maintain local spacing between aircraft with airborne separation assistance.

This concept can be explained using the simplified functional diagram shown in Figure 1 [Prevot et al., 2003c].

The system is trajectory-oriented with time-based traffic flow management (TFM) and a tactical layer for local spacing in the flight execution phase. If necessary, TFM generates a set of time constraints assuring that local airspace areas are not overloaded at any given time. Conflict free 4D trajectories are generated that comply with all or at least the upcoming subset of these constraints. In this concept, 4D trajectories are defined in terms of routing and altitude profile. They may include either a speed profile and time estimates or time constraints, depending on TFM requirements and aircraft equipage. If a trajectory that meets the requirements cannot be generated, the preferred trajectory is fed back to TFM to identify a new set of time constraints that the trajectory planning phase can accommodate. Once a 4D trajectory has been generated, an aircraft will fly the 4D trajectory unless there is a local spacing/separation requirement

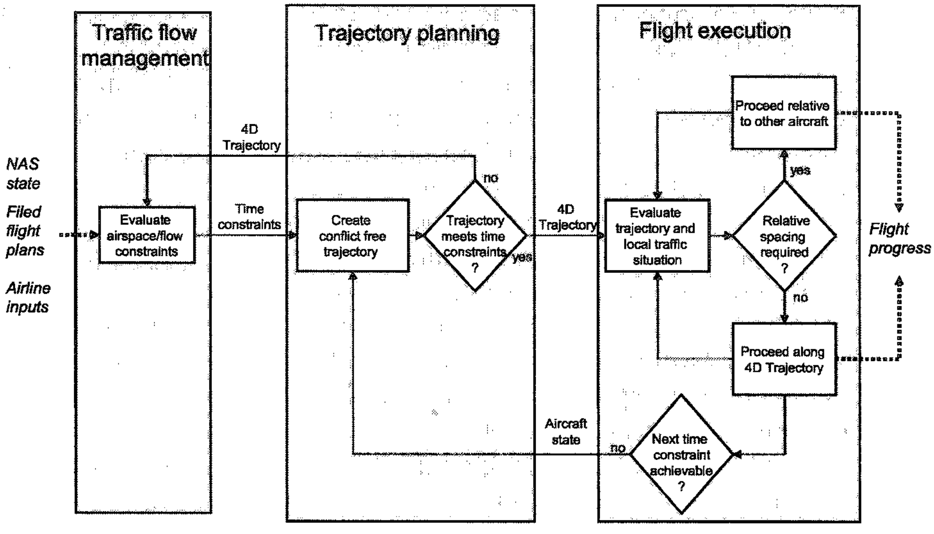

Figure 1. Conceptual description of the proposed system: tactical relative spacing augments, time-based traffic flow management, and trajectory-orientation.

with another aircraft. In that case, the local situation will be resolved relative to the other aircraft, which may result in a deviation from the 4D trajectory. When the local problem is resolved, the aircraft returns to its trajectory and tries to meet the next time constraint. If the next time constraint cannot be achieved, a new trajectory is created that meets the TFM constraints.

The general functional flow does not make assumptions about task allocation between traffic managers, controllers and flight crews. While roles and responsibilities and technologies can evolve, this paper is focused on a medium-term operational environment that the research findings presented in the subsequent sections of this article suggest can provide significant benefits.

Procedural Level

The target time frame for implementation of this system is 2010 to 2020. It is based on

- ground-based traffic flow management coordinated between airlines and air traffic service providers
- strategic trajectory planning, trajectory de-confliction and schedule implementation by the controllers and flight crews
- precise execution of strategic clearances such as trajectory changes, or spacing operations by the flight crews

There are no significant changes in responsibilities, but some shifts from current day operations in the roles of pilots and controllers. The controllers' role moves from tactical control of aircraft headings, speeds and altitudes towards strategic local airspace management. The flight crews perform local spacing operations and implement complex clearances and instructions from the controllers. Table 1 compares the roles of TFM, air traffic controllers, and flight crews, today and in an integrated air/ground system.

The primary difference between today's system and the proposed system is that strategic tasks are handled primarily via changes to the 4D trajectories. These trajectories represent a detailed description of the intended flight path and are suitable for coordinating a specific flight between different specialties, facilities, and stakeholders. For security purposes, the filed flight plan, with controller-initiated amendments, can be compared against the data linked aircraft trajectory. If properly equipped, flight crews can request advantageous trajectory modifications and communicate complex flight path requests via data link to the controllers for approval.

Tactical operations that would result in major flight path changes should rarely be necessary. Small speed and/or route adjustments can be conducted with airborne separation assistance compatible with the ASAS Category 2 of spacing operations [FAA/EUROCONTROL, 2001], which retains responsibility for separation with the controller. While controllers manage the overall traffic flow, flight crews would be assigned specific tasks, such as spacing or merging relative to only one aircraft at a time. In this way, controllers and pilots can gain experience in conducting novel, but well-defined tasks. Based on operational experience it may be desirable later to delegate the separation responsibility for a given problem to the flight crew using airborne separation (ASAS Category3) as for example described in Simons et al. [2004].

Technological Level

Conceptual and procedural considerations dictate changing the primary mode of interaction between controllers and flight crews from voice to data link. Frequent single task instructions from the controllers to the flight crews are replaced with infrequent trajectory adjustments or spacing clearances. In order to accomplish this trajectory management task effectively, both controllers and the ground automation need to be informed about aircraft current strategic flight intent and preferences.

The main components are depicted in Figure 2:

- Air traffic service providers equipped with decision support tools for scheduling and trajectory planning.
- Aircraft equipped with Flight Management Systems (FMS)

Table 1. Role Comparison

	Current Day			Integrated Air/Ground System		
	TFM/AOC	Controller	Flight Crew	TFM/AOC	Controller	Flight Crew
Traffic flow management	Miles-in-trail-constraints			Time-constraints		
Flight planning	Filed flight plan	Flight plan amendments		4-D Trajectory	Trajectory changes	
Schedule management	Meter list	Sequencing and delay absorption with 1 minute tolerance		Scheduled times of arrival (STA)	Meet STA with 15 seconds tolerance	
Strategic conflict prevention		Route/altitude segregation			Trajectory deconfliction	
Delay absorption techniques		Holding, vectoring			Holding, Trajectory changes, Required Time of Arrival (RTA) to aircraft	RTA compliance
Separation management		Vectoring			Vectoring, Delegation of spacing to flight crew	Monitoring or executing spacing
Flight path management		Off route vectoring, back to route via known waypoints	Simple route change requests		Trajectory changes	Complex trajectory requests possible
Primary flight mode in congested airspace			Tactical, autopilot			FMS engaged
In-trail-spacing and merging		Speed commands				ASAS spacing

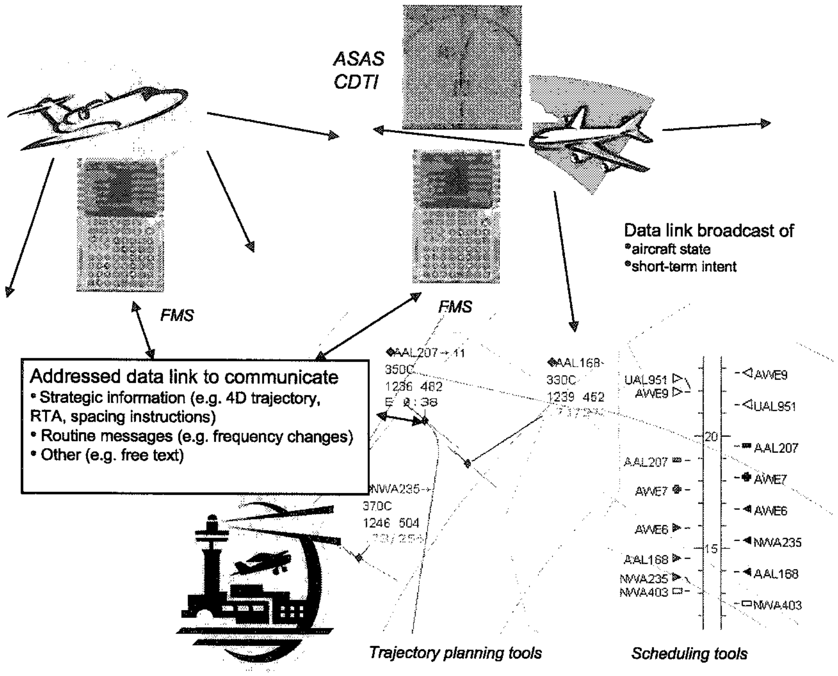

Figure 2. Technologies for the integrated air/ground system.

- Addressed data link communication between ground-based decision support tools and FMSs to exchange strategic information and routine messages between controllers and pilots
- Data link broadcast from the aircraft to provide up-to date state and short term-intent information to the ground and other aircraft
- Airborne separation assistance systems (ASAS) and cockpit displays of traffic information (CDTI) on the flight deck

Instantiations of these components are currently either already operational, have been initially field tested, or are planned to be in place within the next decade [FAA, 2004]. However, many of the technologies are not well-integrated with each other, as required for the air/ground system discussed here.

Data link technologies are a prime example for incomplete integration: The future air navigation system (FANS) is to date the only data link technology that interfaces directly with the Flight Management System [Smith et al., 2001]. FANS and VHF data link mode 2 (VDL-2) is used routinely in some European airspace regions (Upper Area Control Centre Maastricht), but is not used in domestic US airspace for a variety of reasons, including latency and unreliability concerns. Additionally, FANS ground systems do not directly interface with the ground automation, requiring controllers to operate from separate stations for FANS communication. NEXCOM (VDL-2 and higher) is the only field tested controller pilot data link communication (CPDLC) in the continental USA. It is integrated into the controller's workstation, but is not integrated with the FMS or the controller's decision support tools. Automatic dependent surveillance broadcast (ADS-B) has a number of limitations, including bandwidth, which makes it an appropriate medium for state information and flight control system targets, but less adequate for communicating detailed and complete 4-D trajectories. As long as security questions resulting from the fact that ADS-B is not an independent means of surveillance are not sufficiently addressed, this concept intends to use ADS-B data in addition to radar data to improve automatic decision support and compliance monitoring functions and not as a sole means of surveillance in radar-covered airspace.

Clearly, integrating and interfacing of aviation technologies involves a number of costly harmonization and certification issues. On the other hand, the simple addition of side by side technologies without a concept for integration and use may be even more costly, and no significant improvements over today's very robust and safe air traffic system will be achieved with clumsy automation and procedures.

SIMULATION RESULTS

This section discusses the research that was instrumental in developing the concept of an integrated approach to trajectory-orientation, data link, and ASAS. Research findings gathered at NASA Ames Research Center over the past seven years in several series of simulations are presented. Some simulations were part of joint work between Ames and Langley Research Centers on CTAS/FMS integration within the Terminal Area Productivity program (TAP), while others were part of DAG-TM work on trajectory negotiation, free maneuvering, and in-trail spacing and self-merging. (DAG-TM research has been jointly conducted at NASA Ames, Langley, and Glenn Research Centers.)

The CTAS/FMS integration simulations conducted between 1997 and 2001 demonstrated the feasibility of flying FMS arrivals into terminal areas and the acceptability of CPDLC for communicating FMS trajectory changes from the ground to the aircraft in en route and approach control airspace. For details see [Crane et al.,1999; Palmer et al., 1999; Oseguera-Lohr and Williams, 2003; and Callantine et al., 2001.

The next paragraphs trace the evolutionary path of the recent research highlighting the following simulation results:

1. Compared with current day tactical operations, trajectory-based operations increase efficiency and metering accuracy, and shift workload from downstream to upstream sectors. While these are

substantial benefits, a system that only partially integrates trajectory-based DSTs with data link will likely show only minor en route capacity or traffic throughput benefits. The details are laid out in the section below entitled: *Comparison of current day tactical ATC metering and 4D trajectory-based operations with partially integrated system.*

2. The full integration of trajectory-based operations and data link with highly responsive DSTs can likely increase en route capacity to 150% or more of the current day values. It can almost completely eliminate the need for tactical vectoring of aircraft, and therefore increase flight predictability and security. This point is discussed in the section below entitled *Effects of full integration of trajectory-orientation and data link on operations in en route and transition airspace*
3. In order to optimize relative aircraft-to-aircraft spacing and increase throughput at traffic bottlenecks, future research will integrate airborne spacing with trajectory-based operations and data link. The section *Integration of airborne spacing* discusses initial observations from simulations of self-spacing operations in the TRACON, and benefits anticipated from this integration.

Comparison of Current Day Tactical ATC Metering and 4D Trajectory-Based Operations with Partially Integrated System

The airspace operations laboratory (AOL), the flight deck display research laboratories (FDDRL) and the crew vehicle systems research facility (CVSRF) at NASA Ames Research Center teamed up in September 2002 to conduct DAG-TM experiments. These experiments included comparing trajectory-oriented time-based arrival operations with current day arrival operations. The simulation architecture is described in detail in Prevot et al. [2002]. Details on various other aspects of the experiment including autonomous operations, trajectory negotiation, and self spacing are reported in Lee et al. [2003]. The experiments highlight some interesting differences between ATC-controlled 4D operations and current day metering.

Conditions, Scenario, and Participants. The conditions of interest for the purpose of this section are a current day metering control condition and one experimental condition based on Concept Element 6 (CE6) "En route Trajectory Negotiation" in the DAG-TM framework [AATT, 1999].

The control condition was designed to reflect current day operations at Ft. Worth Center (ZFW), which has been using the CTAS Traffic Management Advisor (TMA) for a number of years. In the experimental condition, controllers were given decision support tools (DSTs) to visualize and modify the aircraft 4D trajectories as required to meet the scheduled time of arrival (STA) at the metering fix. The controllers' DSTs were CTAS-based and included a timeline display, a cruise/descent speed advisory function, a trial planning function for route modifications, and a Controller-Pilot Data Link Communication (CPDLC) function. The CTAS conflict probe was used to monitor active and provisional trajectories for potential separation losses. Controllers could also use a new precision descent procedure clearance that instructed flight crews to fly their descent coupled to the FMS that was configured with assigned cruise and descent speeds. Some aircraft were additionally equipped with an experimental Required Time of Arrival (RTA) capability.

The air traffic scenario was modeled after current peak arrival traffic within and adjacent to the northwestern area at ZFW. About 90 aircraft, half of which were arrivals and half overflights or departures, were managed in and out of one en route high altitude sector in Albuquerque Center (ZAB), two high altitude sectors in ZFW, and one ZFW low altitude sector. All four test sectors were staffed with Full Performance Level (FPL) controllers from different facilities in the United States not including ZFW. Two sectors of the Dallas-Ft. Worth (DFW) Terminal Radar Approach Control (TRACON) were also simulated. Whereas previous studies used data-link equipage level mixtures, this experiment assumed 100% data link equipage for all conditions and runs. Data were collected for three variations of the same basic scenario per condition. The conditions were alternated. Each scenario lasted for about 75 minutes with traffic density and complexity peaking between 30 and 50 minutes.

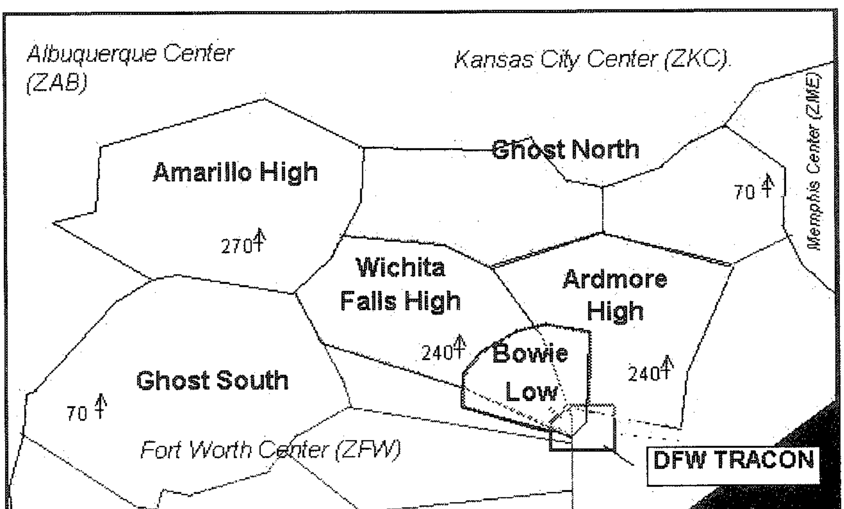

Figure 3. Airspace layout and test sectors.

The pilot participants flying the full mission simulator and the desktop-based single pilot stations were all airline pilots with glass cockpit experience. The pilots of the multi aircraft control stations were private pilots who had participated in a number of experiments and simulations and were well trained to handle the remaining traffic.

Results. The comprehensive data collection included all controller and pilot inputs to the automation, frequent state information, workload measurements recorded during and after the runs, observations at each subject position, and questionnaires. Most performance measures were analyzed to reflect the measures suggested and used by the FAA Free Flight Office [FAA, 1999].

The data analysis shows amplification of the trends that were noticed in a number of previous experiments. Three individual results are presented as examples for the potential capacity, efficiency, and workload impact. The inter-arrival spacing at the meter fix is an example of increased delivery accuracy at a time constraint. The mean altitude of the arriving aircraft is an example of the potential gain in flight efficiency. Finally, sector workload was reduced at the busiest low altitude sector and unchanged at the feeding high altitude sectors, where the controllers performed additional tasks to solve downstream problems. As expected with future airspace operational concepts, there are problems that accompany the associated benefits, some of which are addressed and discussed at the end of this section.

Inter-Arrival Spacing at the Meter Fix: The CTAS TMA was configured to schedule aircraft 7 nmi in trail at the meter fix creating delays that averaged about two minutes, with a maximum of five minutes. Given the winds used and a crossing restriction of 11,000 feet and 250 Knots, the in-trail restriction is equivalent to 82 seconds spacing. Fifteen seconds tolerance was assumed adequate for traffic management purposes in the TRACON. Aircraft less than 58 seconds apart had less than 5 nmi lateral separation and were therefore delivered at different altitudes to avoid the separation loss. The samples used for Figure 4 were created using all metered jet aircraft pairs from the three control condition runs and the three CE6 experimental runs.

The 4D trajectory-based operations resulted in a significant reduction in variance of the inter-arrival spacing at the metering fix, demonstrating that aircraft were delivered more consistently.

There was also a marginal reduction of the inter-arrival spacing itself, bringing the mean within 1.5 seconds of the target spacing of 82 seconds. In the current day condition, 10 aircraft were delivered

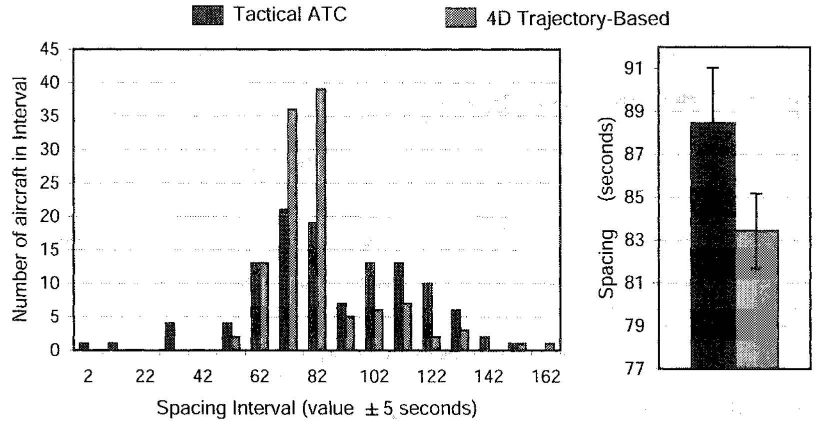

Figure 4. Inter-arrival spacing. Histogram (left) and mean and standard error (right). (see also Table 2)

vertically spaced with less than 5 nmi lateral spacing, as opposed to only two aircraft in the experimental condition. Overall, the trajectory-based approach promises improvements for the consistency of the traffic flow with a moderate potential for improving throughput at traffic bottlenecks like a metering fix.

Mean Altitude of Arriving Aircraft: Figure 5 shows the mean altitude of the arriving aircraft at different ranges from the meter fix. Means and standard errors are shown for 115 aircraft in each condition that started between flight level 290 and 370 averaging flight level 350. In the experimental condition aircraft remained at cruise altitude longer than in the baseline condition. Controllers in the current day condition started descending aircraft from their cruise altitude before the top of descent point, indicated by the lower altitude at the 120 nmi range. They also felt more comfortable issuing precision descent clearances in the trajectory-based condition than pilot's discretion clearances in the control condition, thus permitting more aircraft to fly their FMS-computed idle descent path.

Controller Workload: Figure 6 represents subjective workload ratings on a modified NASA TLX scale that were obtained from the controllers after each run. Workload ratings were also obtained dur-

Table 2. Summary of the Data Samples for Meter Fix Inter-arrival Spacing Depicted in Figure 4

Sample	Count	Mean Spacing	Variance	Std. Error	Std. Dev.
Tactical ATC	115	88.44	772.69	2.59	27.80
4D Trajectory-based	115	83.43	351.67	1.75	18.75

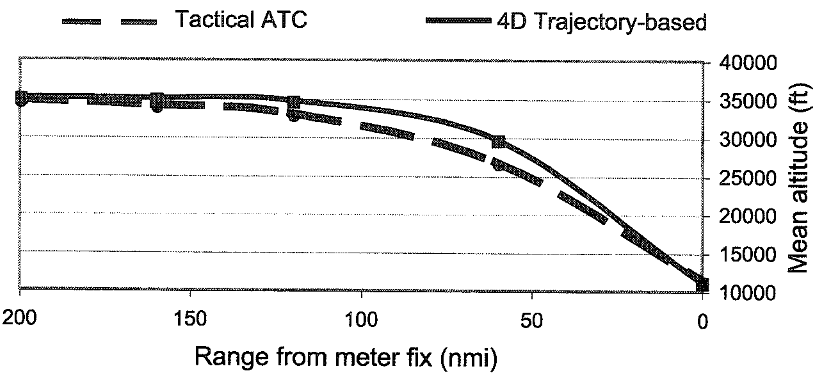

Figure 5. Mean altitude of arrivals.

ing the runs using Workload Assessment Keyboards (WAK) that prompt the operators periodically to assess their workload on a scale from 1 (lowest) to 7 (highest). These ratings were consistent with the post-run ratings and are not presented here. The sector names can be located on the airspace map in Figure 3. The main workload impact is in the low altitude sector (Bowie). The controller at this sector benefited most from the trajectory-based approach, because the high altitude sectors set up the trajectories for the downstream sector. The controller reported less mental demand, effort, and frustration required to achieve a higher level of performance. At the same time, workload for the high altitude sectors was not increased, and the controllers felt that they were performing better than in the tactical ATC condition.

Discussion. The 2002 simulations demonstrated concept feasibility and benefits in terms of delivery accuracy, flight efficiency, and a workload reduction at the low altitude sector. However, controller workload at the high altitude sectors was still very high and equivalent to current day operations. Therefore, high altitude controllers could work the same number of aircraft that they control today more efficiently, but not more aircraft. A shortcoming of the concept was reflected in the small improvement of throughput over the metering fix due to the necessary tolerance of ±15 seconds between scheduled and estimated time of arrival. This tolerance still requires excessive spacing buffers between aircraft.

Further analysis revealed that the high workload in the en route sectors was partially due to:

1. Tool usability: The generic controller interface was considered to be too slow and too clumsy to use. The trial planning tool especially was considered only marginally usable.

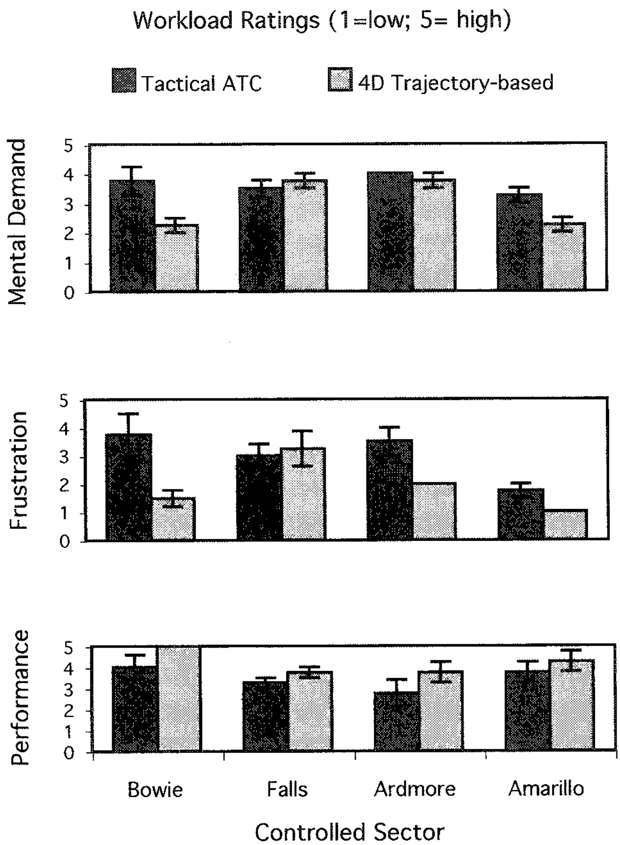

Figure 6. Subjective controller workload ratings of mental demand, frustration, and performance (mean and standard error).

2. Data Link integration: Use of CPDLC was limited to route and speed uplinks. All transfers of communication had to be done by voice. Trajectory downlinks from the aircraft were only partially used by the ground automation. Therefore estimates were sometimes inaccurate, causing erroneous time information, erroneous advisories, and false and missed alerts.

Effects of Full Integration of Trajectory-Orientation and Data Link on Operations in En Route and Transition Airspace

The tool usability and integration lessons learned from the simulations described above were used to implement the recommended toolset into a high fidelity controller workstation prototype. The flight deck simulation environments were redesigned to provide full FMS functionality and air/ground data exchange capabilities [Prevot et al., 2002a; 2002 b; 2003; 2004]. Several more DAG-TM simulations were conducted between November 2003 and August 2004 to evaluate the feasibility of trajectory negotiation, mixed autonomous/managed operations, and self spacing and merging during terminal approaches. Each of these simulations focused on different aspects of DAG-TM concepts and used the integrated air/ground system described here as a baseline. Many results regarding the research focus of these simulations are reported in several other publications [Smith et al., 2004; Lee et al., 2004]. This section highlights effects that were newly observed when simulating a system that fully integrated controller DSTs, flight deck capabilities and data link without changing roles and responsibilities. The aspects discussed below were noted mainly as side-effects during baseline runs of the final simulations of DAG-TM Concept Element 5: free maneuvering operations. These simulations were conducted jointly between NASA Ames and Langley Research Centers and involved four full performance level controllers, 22 airline pilots, and about 20 confederate pilots and controllers.

En Route Sector Capacity. While the partial integration presented previously did not demonstrate potential en route sector capacity benefits, the fully integrated air/ground system enabled IFR operations at about 150 % of current day operations without creating excessive workload at any sector, and with only one controller managing each position and one "tracker/supervisor" to monitor multiple stations. Figure 7 shows the sector loads worked in the four test sectors with only IFR traffic during a 30 minute period from 20 minutes to 50 minutes into each data collection run. A nominal Monitor Alert Parameter (MAP) is also indicated for reference based on FAA regulation 7210.3 [FAA, 2004]. This figure shows that the controller

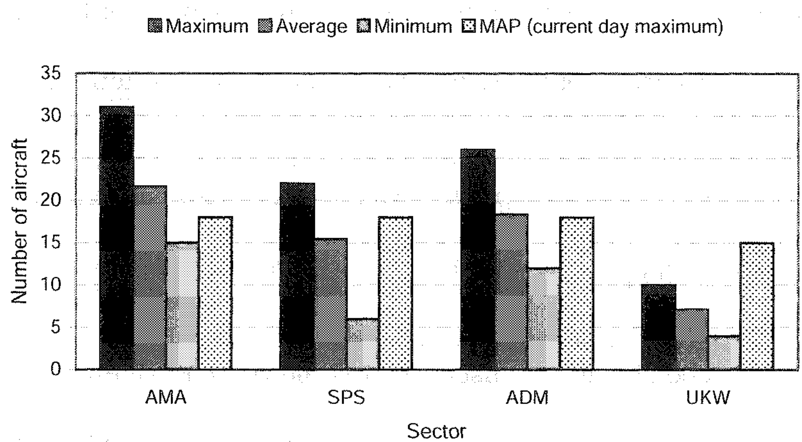

Figure 7. Sector count during IFR operations in 2004 DAG-TM simulations from 20 to 50 minutes runtime.

in the pure en route sector (AMA) had track control over 22 aircraft on average, peaking up to 31. The transition sector (SPS) that had the majority of arrival traffic and a significant amount of overflights handled 15 aircraft on average with a maximum of 22. The other transition sector (ADM) handling an equal combination of departures, overflights and arrivals controlled 18 aircraft on average with a maximum of 26. The low altitude sector only handled 7 aircraft on average, because both high altitude sector controllers absorbed most of the delay, so that the low altitude sector controllers' task basically involved taking and giving the handoffs and fine-tuning the aircraft merge at the metering fix.

These examples show that en route and transition sector controllers were able to handle as many aircraft or more than the current day maximum for a significant period of time, and peaking at a maximum of about 150% of the current day sector capacity. The relationship between sector count and workload provides further evidence to the potential capacity increase.

Figure 8 illustrates the average workload ratings as reported with the workload assessment keyboards (WAK) by the controllers during runtime in relationship to the average number of aircraft the con-

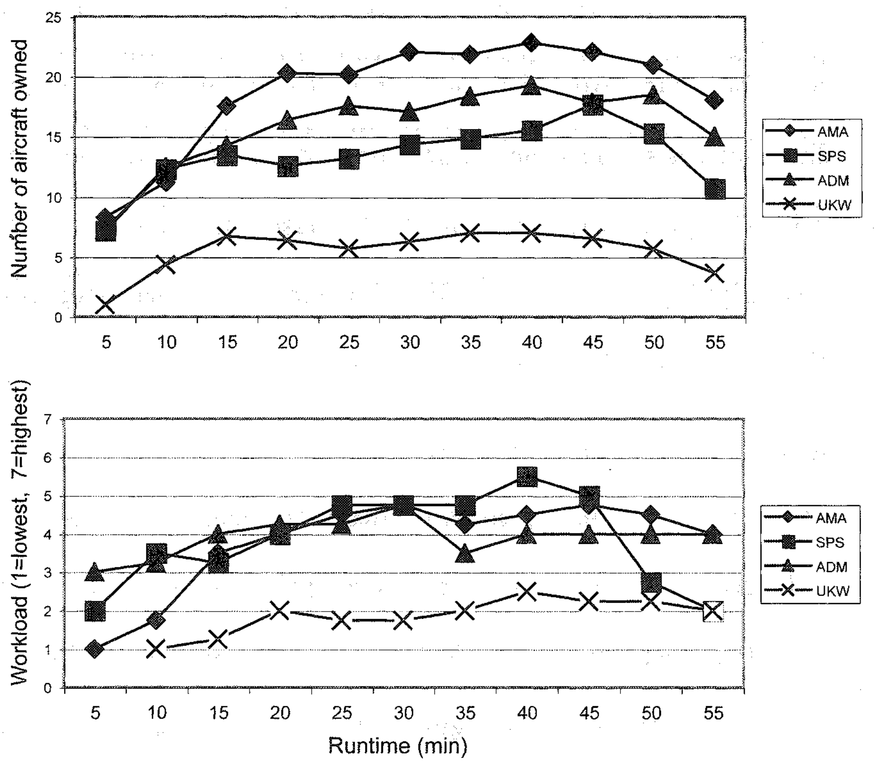

Figure 8. Sector count (top) and controller workload (bottom). Averages from four IFR data collection runs with complex traffic scenarios.

troller owned. The low altitude sector (UKW) controller reported very low workload throughout the run. All three en route sector controllers reported similar workloads.

Vectoring vs. Trajectory Changes. The fully integrated air/ground system practically eliminated vectoring, instead relying on trajectory changes, which were delivered via datalink. Therefore, all aircraft were flying along FMS trajectories, which were data linked to the ground system. This observation is of significance since prior research has indicated that manual trial planning is unsuitable for arrival metering in high traffic loads [MacNally et al.,1999; 2001; Prevot et al., 2003; Green et al., 2001]. In debriefing discussions, the controllers stated that the highly responsive trial planning tool integrated with data link allowed them to perform almost all adjustments via trajectory changes, and this procedure would be clearly preferable to issuing tactical radar vectors. In the rare cases that controllers issued vectors, aircraft had to leave their FMS trajectories only for short periods of time and the controllers had no problems issuing efficient instructions or trajectory changes to resume the flight along a 4D trajectory.

This elimination of vectoring can also have very positive security implications because air traffic security is tightly coupled to flight path predictability. If the ground controllers and the ground system receive information directly and automatically from the aircraft about their future state and flight path, comparisons with independent data sources such as radar and host flight plan amendments can immediately identify aircraft that are out of compliance, which should be a major security benefit. As discussed in previous sections of this paper, in today's environment aircraft do not data link their predicted flight path to the ATSP, and dense airspace operations typically require controllers to issue tactical instructions (radar vectors) that take aircraft off their flight paths.

Integration of Airborne Spacing

The integration of airborne spacing into a trajectory-oriented environment with full data link capabilities is currently in its prototyping stages. EUROCONTROL research focuses primarily on the integration of airborne spacing into the current day environment. Grimaud et al. [2004] report a reduction in late vectoring, a workload reduction, and a more regular spacing as a result of ASAS operations.

DAG-TM research has investigated airborne spacing and merging in the approach environment and simulations were conducted at NASA Ames Research Center, and simulations and flight tests at

NASA Langley Research Center [Lohr et al., 2003]. A simulation in August 2004 at NASA Ames of TRACON self-spacing and merging with pilots and controllers working across four different conditions without CPDLC and trajectory modification tools yielded some interesting observations and comments, summarized below.

Initial Observations for Spacing Usage in Mixed Equipage Approach Environment without CPDLC and Trajectory Tools. The concept of airborne spacing and merging in TRACON was considered feasible and potentially beneficial, if some areas of concern can be addressed. The airborne spacing algorithms should be sophisticated enough to provide smooth mostly monotonic speed control to be acceptable to the pilots and controllers. Excessive speed variations of a self spacing aircraft caused difficulties for controllers in assigning appropriate speeds to a trailing unequipped aircraft. Controllers also commented on problems monitoring compliance with assigned time-based spacing intervals without decision support tools on the ground. Pilots preferred receiving spacing or merging instructions early and not too close to or even on final approach. However, some portions of the traffic scenarios required several early and late route changes that interfered with controllers issuing spacing instructions suitably early.

Anticipated Benefits of Integrating ASAS with Data Link and Trajectory Tools. The full integration of ASAS with data link and trajectory tools can potentially address a number of the problems discussed above. Excess spacing required for safe meter fix or runway scheduling can be reduced, if flight crews can maintain a spacing interval slightly above the minimum separation requirement. An additional safety layer and an electronic VFR like environment are created when the flight crew monitors spacing to the next aircraft. The use of trajectory-based operations and CPDLC has indicated capacity, efficiency and security benefits. If applied to the TRACON spacing and merging situation, controllers could preplan the TRACON routing, data link it to the aircraft, and then issue the spacing and merging instruction based on a known flight path.

PROTOTYPE IMPLEMENTATION OF THE INTEGRATED AIR/GROUND SYSTEM

This section gives recommendations about the controller tools, flight deck capabilities and data link communication based on lessons learned from the simulations described above.

Ground-Side Automation

One of the key features of the integrated air/ground system is the integration of trajectory-oriented tools with data link into the controller's workstation. An initial set of recommendations for the required toolset was presented in Prevot et al. [2003]. A prototype of this toolset was implemented into a high fidelity controller display emulation created at NASA Ames Research Center as part of the Multi Aircraft Control System (MACS) [Prevot, 2002] according to these recommendations.

Display Design. The current set of ground tools has been designed as mostly subtle, but powerful additions to the state of the art controller radar displays in the National Airspace System (NAS). The center controller tools have been integrated into an accurate emulation of the Display System Replacement (DSR) controller workstation, and the TRACON controller tools augment the standard STARS functionality. Both displays combine essentially the same capabilities with the currently prototyped DSR toolset focusing more on the integration of trajectory-tools and CPDLC, and the STARS prototype on the integration of ASAS.

Both display prototypes have the capability to display timelines for various scheduling points like meter fixes, runways, etc. The interactive timelines are modeled after the CTAS TMA timelines and integrated into the specific display scheme. Figure 9 shows a timeline on a DSR prototype integrated with early/late feedback in the data tag. In the integrated air/ground system the STAs can be retrieved from the CTAS TMA. The ETAs are received from the downlinked FMS trajectory for aircraft that are on their route and downlink their trajectory. If not, timeline ETAs are determined by a simple trajectory prediction based on a direct routing to the metering fix or standard route to the runway.

All trajectory changes can be planned with highly responsive route and altitude trial planning tools accessible via the data tag or keyboard inputs. The data tag is modified to present conflict and data link status feedback in the first line and speed or spacing advisories as well as delay feedback in the fourth line. Details about the particular data tag modifications can be found in Prevot et al., 2005.

Usability and Usefulness. During the 2004 DAG-TM simulations controllers used the new DSR prototype toolset and afterwards rated its usefulness and usability on a scale of 1 (not very useable/useful) to 5 (extremely usable/useful) as shown in Figure 10.

The general DSR emulation was considered very usable and useful. All added tools received high marks, with the trial planning tool rated highest. Whereas an earlier version of the trial planning tool

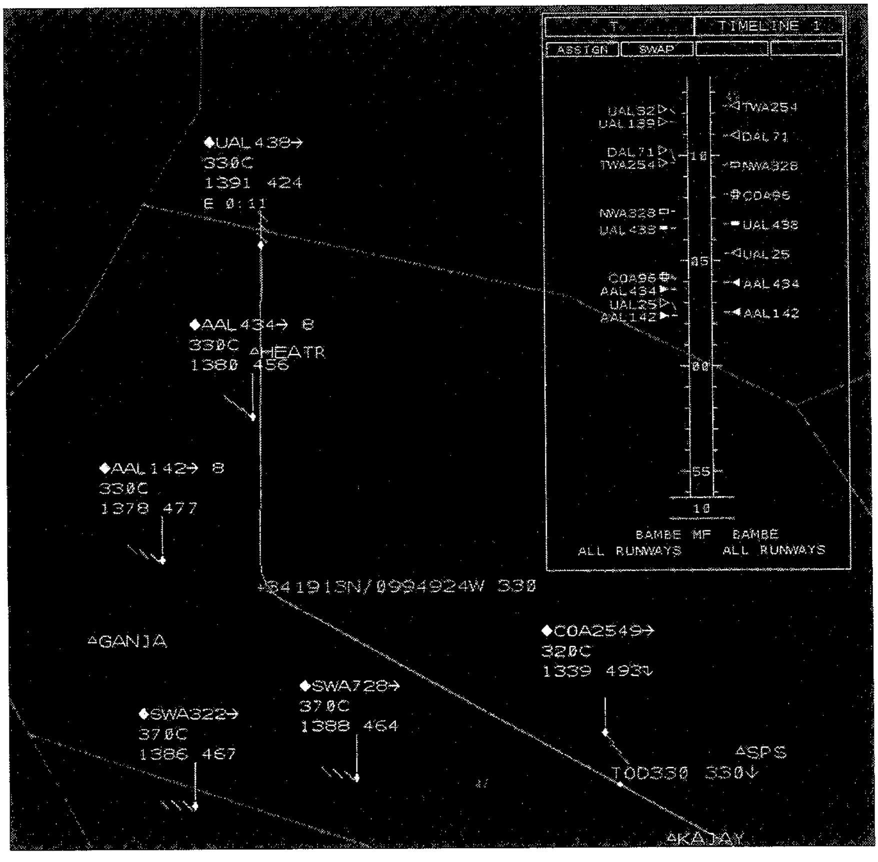

Figure 9. Timeline and early/late information in the data tag during trial planning of UAL438. AAL434 and AAL142 are on schedule, but have a predicted conflict in eight minutes.

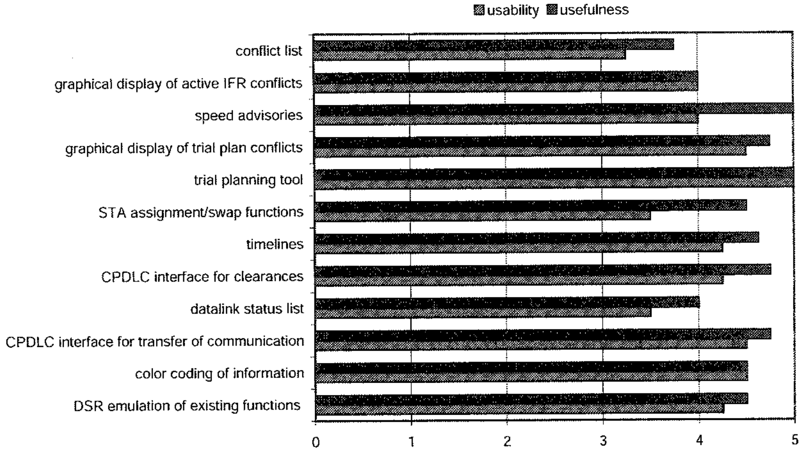

Figure 10. Usability and usefulness of the DSR prototype providing trajectory tools and data link.

had previously been considered a major problem [Prevot et al., 2003], the redesigned highly responsive trial-planning tool integrated with the R-Side display to provide immediate conflict feedback and full CPDLC integration was largely preferred by the controllers to issuing vectoring instructions.

Graphical displays accessible via and integrated with the data tag were generally preferred over lists on the display. The CPDLC interface that allowed a one command uplink of route, speed or altitude trajectory changes was considered very useful and usable.

Data Link

Automatic Downlink of Information from the Aircraft. The two types of information that are required from the aircraft for the integrated air/ground system are up-to date state information and trajectory information. The state information should be distributed periodically and frequently. While a high update rate (e.g. 1 second) might be desirable the main benefit for the ground system lies in the precision of position and velocity information and, therefore, lower update rates within the regular radar cycles might be sufficient. The trajectory intent should be available to the ground system whenever it changes significantly, i.e. the routing, altitude or speed profile, or arrival time estimate has changed noticeably compared with the last transmission. One main point of discussion is whether the commanded trajectory or the planned trajectory should be reported. The commanded trajectory reflects the path of the aircraft if pilots make no further input, whereas the planned trajectory represents the trajectory that the FMS has computed and that will be flown if the pilots engage FMS managed modes and set the altitude limit according to the FMS restrictions. The argument for the commanded trajectory revolves around the integrity of conflict probing functions. One argument against it is that it is not readily available from the aircraft and would require major additional cost and effort to retrieve.

A rarely mentioned argument for reporting the planned trajectory is that the planned FMS trajectory is much more useful to the ground-based scheduling and planning functions. The basic idea of trajectory-oriented operations is to plan conflict free trajectories ahead of time and allow the pilots to use their FMS to fly these trajectories. The ground system can use the data linked FMS trajectory for precisely determining ETAs, conflict probing, and calibrating the ground-based trajectory synthesizer used for trial planning in an FMS-compatible fashion. If the system works, the aircraft will end up following the planned FMS trajectory, providing the highest level of integrity for conflict probing. The question about diversions from the FMS trajectory becomes a question of compliance monitoring. Compliance monitoring can be improved by broadcasting the actual mode settings and target values for managed vs. manual modes, altitude, heading and speed from the aircraft. One promising approach to this in light of ADS-B bandwidth limitations is to broadcast state and target values with ADS-B and the FMS planned trajectory with addressed data link. Most of the infrastructure for this is already in place or planned. However, the reliability and latency of the addressed data link needs to be improved to provide the information in a timely manner. The ADS-B information would be sufficient for initial airborne merging and spacing information. When trajectory information is needed by the airborne systems, they could use the addressed data link to retrieve it from the ground system.

Controller Pilot Data Link Communication. It is extremely important that CPDLC is integrated with the FMS and the ground-based DSTs. Only this integration allows controllers and pilots to exchange complex trajectory information without causing unacceptable workload and delays. In order to phase-in this capability, a separate controller position that integrates CPDLC with advanced DSTs could be installed in air traffic control facilities handling the equipped aircraft as proposed in Prevot et al. [2005b].

During the air/ground integration simulations described before, the following messages were used and appeared sufficient for covering all relevant cases. More details can be found in Prevot et al. [2005a]

- Transfer of communication (TOC)
- Route uplink
- Cruise altitude uplink
- Climb/Cruise/Descent speed uplink
- RTA uplink
- Spacing instruction uplink
- Free text uplink
- Downlink of new route request

The ground side prototype data link implementation has been modeled after the Miami Center implementation of CPDLC. All new messages have been added using a compatible scheme. For most messages the typical controller procedure is to start a trial plan manually or review a system advisory presented in the fourth line of the data tag and then use the "UC" command to uplink the clearance. When the clearance is uplinked the data link status indicator and the trial planning portal change to an up-arrow until the response is received. When a downlinked request is received the trial planning portal changes to a down arrow and clicking on it opens the request. The pilot procedure involves noticing the message when being cued to its arrival and loading the new values into the FMS. Upon review of the resulting trajectory, the flight crew accepts or rejects the message and executes or erases the modified FMS route, respectively. Whenever the flight crew executes a new FMS route the new FMS trajectory is automatically downlinked to the ground system, which then uses this up-to-date trajectory as its reference. These general procedures were considered acceptable and straightforward by pilots and controllers.

Air-Side Automation

Initially the most important airborne system required to participate in the basic integrated air/ground environment is the FMS integrated with data link. The FMS needs basic lateral and vertical navigation capabilities. RTA capability is not required if controllers have speed advisory tools. If an aircraft is equipped with a sufficiently precise RTA function controllers can assign the RTA instead of speeds and let the flight crew manage their arrival time. In simulations in 2003 [Lee et al., 2004] controllers and pilots found RTA assignments acceptable and useful.

A CDTI is required to conduct ASAS operations. For the initial implementation and as long as it cannot be ensured that the aircraft receives sufficient trajectory information from other aircraft, a state-based merging and spacing algorithm should be sufficient. As stated in the previous section however, the algorithm needs to provide smooth and predictable speed control logic to be acceptable by the controllers and pilots.

The CDTI can also serve as a graphical interface to the FMS and be used to review uplinked trajectories within the general traffic content, therefore providing additional traffic awareness and an additional layer of safety. Furthermore, the CDTI can be used to generate trajectory requests to be downlinked to the controllers. For more information on the pilot requests within the integrated air/ground system see Lee et al. [2004].

Figure 11 shows a CDTI prototype with spacing information [DAG-TM, 2004].

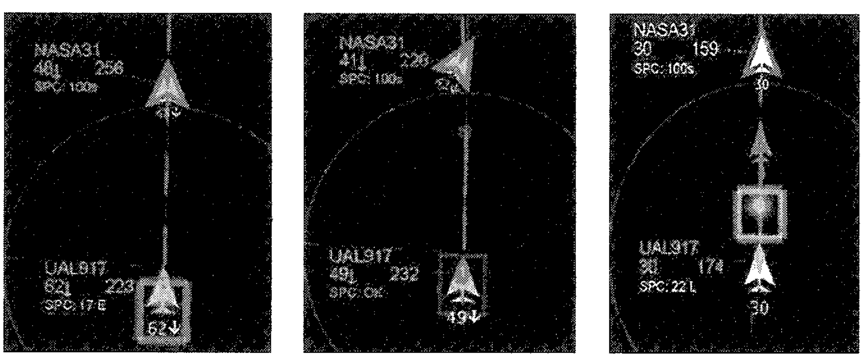

Figure 11. CDTI with airborne spacing support.

FUTURE RESEARCH

Research on the concept of trajectory orientation with limited delegation at NASA Ames will be conducted under NextNAS. It is currently planned to initially engage in several more rapid prototyping and refinement phases with controllers and pilots. The specific benefits and problem areas in only partially integrated air/ground environments and with different mixed equipage levels are being addressed in the ongoing development of the Co-Operative Air Traffic Management concept [Prevot et al. 2005b].

CONCLUDING REMARKS

Trajectory-oriented time-based arrival operations, data link, and spacing operations have shown potential benefits for capacity, security, efficiency, and controller workload. In order to achieve the maximum benefits, a well-designed set of air and ground automation tools integrated with data link are required, along with appropriate procedures. The integrated air/ground system described in this paper should provide the necessary flexibility to aid controllers in handling significantly more traffic than today in high-density air traffic control sectors and could be implemented within the next ten years. The architecture can be considered as a baseline, which can be built upon to support more advanced air traffic management concepts that might be required to handle the air traffic demand beyond 2020.

ACKNOWLEDGEMENTS

This research owes its success to many dedicated individuals at NASA Ames Research Center, including Walter Johnson and the flight deck research group, the AOL support staff, the MACS development team, and the ACFS support staff. Additional thanks go to the AATT project office, Paul Mafera of Booz-Allan Hamilton and Nicole Racine of Titan Systems and the rest of Raytheon's CT0-2 team. We greatly appreciate the support of the Air Line Pilots Association, the National Air Traffic Controllers Association, and the FAA's Air Traffic Services office.

ACRONYMS

AAC	Advanced Airspace Concept
ADS-A/B	Automatic Dependent Surveillance-Addressed/Broadcast
ASAS	Airborne Separation Assistance System

ATM	Air Traffic Management
ATSP	Air Traffic Service Providers
CDTI	Cockpit Display of Traffic Information
CPDLC	Controller Pilot Data Link Communication
CTAS	Center/TRACON Automation System
DAG-TM	Distributed Air Ground-Traffic Management
DSR	Display System Replacement
DST	Decision Support Tool
E/DA	Enroute and Descent Advisor
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FMS	Flight Management System
MACS	Multi Aircraft Control System
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
TLX	Task Load Index
TMA	Traffic Management Advisor
TRACON	Terminal RADAR Approach Control
RVSM	Reduced Vertical Separation Minima
RTA	Required Time of Arrival
STA	Scheduled Time of Arrival
STARS	Standard Terminal Automation Replacement System
WAK	Workload Assessment Keypad

REFERENCES

AATT (1999), *Concept Definition for Distributed Air/Ground Traffic Management (DAG-TM)*, Version 1.0, NASA AATT Project Office, NASA Ames Research Center, Moffett Field, CA.

Callantine, T., Prevot, T., Smith, N., and Palmer, E. (2001), *Simulation of CTAS/ FMS Air Traffic Management*, Proceedings of the 4th USA/Europe Air Traffic Management Research and Development Seminar, Air-Ground Cooperation Track, Santa Fe, NM.

Callantine, T., Lee, P., Mercer, J,, Prevot, T., and Palmer, E. (2005), *Air and Ground Simulation of Terminal Area FMS Arrivals with Airborne Spacing and Merging*, The Sixth International ATM R&D Seminar ATM-2005, Baltimore, MD, July 2005.

Crane, B., Prevot, T., and Palmer, E. (1999), *Flight Crew Factors for CTAS/FMS Integration in the Terminal Airspace*, NASA Technical Memorandum 2000-209607, NASA Ames Research Center, Moffett Field, CA.

DAG-TM (2004), *Final Terminal Area Self Merging and Spacing Human Factors Assessment for Distributed Air/Ground Traffic Management*, AATT Milestone report, Moffett Field, CA.

Davis, T.J., Erzberger, H., and Bergeron, H. (1989), *Design of a Final Approach Spacing Tool for TRACON Air Traffic Control*, NASA Technical Memorandum 102229, Ames Research Center, Moffett Field, CA.

Erzberger, H., Davis, T.J., and Green, S.M. (1993), *Design of Center-TRACON Automation System*, AGARD Meeting on Machine Intelligence in Air Traffic Management, Berlin, Germany, May, and http://ctas.arc.nasa.gov

Erzberger, H. and Paielli, R.A. (2002), *Concept for next generation air traffic control system*. Air Traffic Control Quarterly, Vol. 10(4), 355–378.

Erzberger, H. (2004), *Transforming the NAS: The next generation air traffic control system*, NASA Technical Paper-2004-212828, Moffett Field, CA.

EUROCONTROL (2003), *CoSpace Delegation of spacing tasks from air traffic controller to flight deck.* http://www.eurocontrol.fr/projects/freer

EUROCONTROL (1999), *PHARE Research Programme.* http://www.eurocontrol.int/phare

FAA (2004), *The Federal Aviation Administration, National Airspace System Architecture* 5, http://www.nas-archtecture.faa.gov/cats

FAA (2004), *Order 7210.3T Facility Operation and Administration*, available at http://www.faa.gov/ATpubs/FAC/INDEX.htm

FAA (1999), *Free Flight Phase 1 (FFP1) Metrics Plan*, Federal Aviation Administration: Free Flight Phase 1 Program Office, 1999, Washington, DC, http://ffp1.faa.gov/approach/approach_ben_met.asp.

FAA/EUROCONTROL (2001*), Action Plan 1 FAA/Eurocontrol Cooperative R&D, Principles of Operation for the Use of Airborne Separation Assurance Systems*, Version 7.1, 19 June 2001.

Green S.M. and Vivona, R. (2001), *En Route Descent Advisor Concept for Arrival Metering*, AIAA-2001-4114, AIAA and Exhibit, Montreal, Canada.

Green, S.M., Billimoria, K.D., and Ballin, M.G. (2001), "Distributed Air/Ground Traffic Management for En Route Flight Operations," *ATC Quarterly*, Vol. 9(4), pp 259–285.

Graham, R., Hoffmann, E., Pusch, C., and Zeghal, K. (2003), *Absolute versus Relative Navigation: Theoretical Considerations from an ATM Perspective*, 5th USA/Europe Air Traffic Management R&D Seminar, Budapest, Hungary.

Grimauld I., Hoffmann E., Rognin L., and Zeghal K. (2004), *Spacing instructions in approach: Benefits and limits from and air traffic controller perspective*, AIAA-2004-5105, AIAA Guidance, Navigation and Control Conference conference, Providence, RI.

Haraldsdottir, A., Schoernig, G., Schwab, R.W., Singleton, M.K., Sipe, A.L., and van Tulder, P.A (2003)*, Boeing Capacity-Increasing ATM Concept for 2020*, 5th USA/Europe Air Traffic Management Research and Development Seminar, Budapest.

Hoffmann E., Ivanescu, D., Shaw, C., and Zeghal, K. (2002), *Analysis of Spacing Guidance for Sequencing Aircraft on Merging Trajectories*, AIAA.

Johnson, W., Battiste, V., and Bochow, S. (1999), *A cockpit display designed to enable limited flight deck separation responsibility*, SAE Technical Paper 1999-01-5567, SAE International, Warrendale, PA.

Lee, P., Mercer, J., Prevot, T., Smith, N., Battiste, V., Johnson, W., Mogford, R., and Palmer, E. (2003), *Free Maneuvering, Trajectory Negotiation, and Self-Spacing Concepts in Distributed Air-Ground Traffic Management*, ATM2003, FAA/Eurocontrol R&D Seminar, Budapest, Hungary.

Lee, P.U., D'Arcy, J.F., Mafera, P., Smith, N., Battiste, V., Johnson, W., Mercer, J., Palmer, E.A., Prevot, T. (2004),. Trajectory Negotiation via Data Link: Evaluation of Human-in-the-loop Simulation.*HCI-Aero 2004: International Conference on Human-Computer Interaction in Aeronautics,* Toulouse, France.

Leiden, K.J. and Green. S.M. (2000), *Trajectory Orientation: A Technology-Enabled Concept Requiring a Shift in Controller Roles and Responsibilities.* 3rd USA/Europe ATM R&D seminar, Napoli, Italy, June.

Lohr G., Oseguera-Lohr R., and Abbott, T. (2003), *Flight Evaluation of a Time-based Airborne Inter-arrival Spacing Tool*, ATM2003, FAA/Eurocontrol R&D Seminar, Budapest, Hungary

McNally D., Erzberger, H., Bach, R., and Chan, W. (1999), *Controller Tools for Transition Airspace*, AIAA-99–4298, AIAA GNC Conference, Portland OR.

McNally, D., Engelland, S., Bach, R., Chan, W., and Erzberger, H. (2001), *Opera-*

tional Evaluation of the Direct-To Controller Tool, 4th USA/Europe Air Traffic Management R&D Seminar, Santa Fe, NM.

Oseguera-Lohr, R.M. and Williams, D.H. (2003), "Evaluation of Trajectory Errors in an Automated Terminal-Area Environment," NASA/TM-2003-212174, NASA Ames Research Center, Moffett Field, CA.

Palmer, E. A., Williams, D., Prevot, T., Romahn, S., Goka, T., Smith, N., and Crane, B. (1999), "An operational concept for flying FMS trajectories in Center and TRACON airspace," *Proceedings of the 10th International Symposium on Aviation Psychology*, Columbus, OH.

Prevôt, T., Palmer, E., Smith, N., and Callantine, T. (2002), *A multi-fidelity simulation environment for human-in-the-loop studies of distributed air ground traffic management* AIAA-2002-4679, Reston, VA.

Prevôt, T. (2002), *Exploring the many perspectives of distributed air traffic management: The Multi Aircraft Control System MACS*, In S. Chatty, J. Hansman, and G. Boy (Eds.), Proceedings of the HCI-Aero 2002, AAAI Press, Menlo Park, CA, pp. 149–154

Prevot T., Lee, P., Callantine, T., Smith, N., and Palmer, E. (2003a), *Trajectory-Oriented Time-Based Arrival Operations: Results and Recommendations*, ATM2003, FAA/Eurocontrol R&D Seminar, Budapest, Hungary.

Prevôt, T., Battiste, V., Palmer, E., and Shelden, S. (2003b), *Air Traffic Concept Utilizing 4D Trajectories and Airborne Separation Assistance*, AIAA-2003-5770, Reston, VA.

Prevot, T., Shelden, S., Mercer, J., Kopardekar, P., Palmer, E., and Battiste, V. (2003c),: *ATM concept integrating trajectory-orientation and airborne separation assistance in the presence of time-based traffic flow management*, Proceedings of the 22nd Digital Avionics Systems Conference, AIAA-2003-197. Indianapolis, IN.

Prevôt, T., Shelden, S., Palmer, E., Johnson W., Battiste V., Smith N., Callantine T., Lee P. and Mercer J. (2003d),: *Distributed air/ground traffic management simulation: results, progress and plans* AIAA-2003-5602, Reston, VA.

Prevot, T., Callantine, T., Kopardekar, P,, Smith, N., Palmer, E., and Battiste, V. (2004), *Trajectory-Oriented Operations with Limited Delegation: An Evolutionary Path to NAS Modernization*, AIAA-2004-6449, AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum, Chicago, IL.

Prevot, T., Lee, P, Smith, N., and Palmer, E. (2005a), *ATC Technologies for Controller-Managed and Autonomous Flight Operations*, AIAA-2005–6043, AIAA Guidance Navigation and Control Conference, San Francisco, CA.

Prevot, T., Callantine, T., Lee, P., Mercer, J., Battiste, V., Johnson, W., Smith, N., and Palmer, E. (2005b), *Co-Operative Air Traffic Management: Concept and Transition*. AIAA-2005-6045, AIAA Guidance Navigation and Control Conference, San Francisco, CA.

Simons, E., Hawkins, P., Zeitlin, A., and DeSenti, C. (2004), *Controller Assigned Airborne Separation (CAAS) Concept Exploration*, AIAA-2004-6390, AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum, Chicago.

Smith, N., Polson, P., Brown, J.A., Moses, J. (2001), *An Assessment of Flight Crew Experiences with FANS-1 Controller-Pilot Data Link Communication in the South Pacific*, Proceedings of the 4th USA/Europe Air Traffic Management Research and Development Seminar, Air-Ground Cooperation Track, Santa Fe, NM.

Smith, N., Lee, P., Prevot, T., Palmer, E, Battiste, V., and Johnson, W. (2004), *A Human-in-the-Loop Evaluation of Air-Ground Trajectory Negotiation*, AIAA-2004-6260, AIAA 4th ATIO, Chicago, IL.

Wichman, K., Lindberg, L., Kilchert, L., and Bleeker, O. (2004), Four-Dimensional trajectory Based Air Traffic Management, AIAA-2004-5413, AIAA Guidance, Navigation, and Control Conference and Exhibit, Providence, RI.

BIOGRAPHIES

Thomas Prevot is an employee of the San Jose State University conducting collaborative research at the NASA Ames Research Center. His research and development activities are centered on advanced ground-based and airborne capabilities and air/ground integration. He holds a doctorate in Aerospace Engineering from the Munich University of the German Armed Forces for his prior research on intelligent flight crew assistance and advanced flight management functions.

Vernol Battiste is a human factors engineer and a principal investigator for the flight deck display research group at NASA Ames Research Center. He holds a Master's degree in Research Psychology from San Jose State University.

Todd J. Callantine earned his Ph.D. from the Georgia Institute of Technology in Industrial and Systems Engineering and has conducted ATM research at NASA Ames Research Center for the past nine years.

Parimal Kopardekar works as a Project Manager at NASA Ames Research Center. He holds Ph.D. and M.S. degrees in Industrial Engineering and Bachelor of Engineering in Production Engineering.

Paul U. Lee is a NASA Ames human factors researcher who earned his Ph.D. in Cognitive Psychology from Stanford University.

Joey Mercer works in the NASA Ames human factors division and is completing his M.S. degree at San Jose State University.

Everett Palmer is a Principal Investigator for the air ground integration research group at NASA Ames. He earned B.S., M.S. and Ph.D. degrees in Electrical and Industrial Engineering from Stanford University.

Nancy Smith is a Research Psychologist and Project Manager at NASA Ames Research Center. She holds a Master's degree in Human Factors Engineering from San Jose State University.