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Trajectory-Oriented Operations with Limited Delegation: An Evolutionary Path to NAS Modernization

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This paper presents a concept named Trajectory Oriented Operations with Limited Delegation. The concept provides a framework for transforming NAS operations in line with global modernization trends. It enables the evolutionary introduction of trajectory oriented air traffic tools and airborne separation assistance systems. Specific implementation examples for several evolutionary phases are presented. The tools and procedures prototyping this concept will be further developed and tested in simulations at NASA Ames Research Center as part of the NextNAS project.

Nomenclature

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 (Center Controller Workstation in the NAS)
DST = Decision Support Tool
E/DA = Enroute and Descent Advisor
FAA = Federal Aviation Administration
FMS = Flight Management System
NASA = National Aeronautics and Space Administration
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)

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I. Introduction

Air traffic demand is anticipated to grow substantially in the coming decades[1]. Improvements are being put in place to provide the airport and en route capacity required to keep up with the increased demand over the next 10 years. Reduced vertical separation minima (RVSM) will increase the available en route airspace, time-based metering can control the flow in and out of airports and more runways add landing capacity to some airports[2]. As these changes can instantiate parts of the infrastructure to enable more operations, the number of operations in a given airspace is primarily limited to the number of aircraft that can safely be handled by the air traffic controller team overseeing that airspace.

A primary objective in many ATM research initiatives is therefore to reduce controller workload. Some far-term concepts re-distribute the separation assurance task for some or all aircraft from the air-traffic controller to flight crews or advanced automation. Research on the DAG-TM[3,4] concept element 5 “free maneuvering” investigates the feasibility and potential capacity and safety impact of allowing flight crews of properly equipped aircraft to freely maneuver as long as they separate themselves from all other traffic and comply with ATM constraints. This approach requires that ground-based and airborne systems have sufficient knowledge of other aircrafts state and intent, which is achieved by data link. Large scale simulations have been conducted and the data is currently being compiled.

A different approach proposed as the Advanced Airspace Concept postulates that a reduction in controller workload “can be accomplished by automating the monitoring and control of separation and by using air-ground data-link to send trajectories directly between ground-based and airborne computers” [5]. In this approach the separation assurance task is assigned to the ground-based computer system instead of the air traffic controller. At the present time the AAC exists only as a concept and the development of research prototypes, and human in the loop simulations will be necessary to investigate the actual implications of this approach and refine the design.

Both these far-term concept examples pursued in the USA target the problem of doubling or tripling airspace capacity. Both concepts are controversial because they require fundamental changes to the roles and responsibilities of air traffic controllers, flight crews, ground-based and/or airborne automation. At the present time it is unclear whether any one of these, a mixture of both, or a completely different approach will represent the air traffic system of the future. As different as the approaches appear they also have many commonalities: They assume time-based traffic flow management and rely on the accurate and timely availability of four-dimensional (4D) trajectories for all aircraft. Traffic planning occurs on a strategic level with respect to these trajectories instead of pre-dominantly tactical maneuvering as required in the current system.

Near-term concepts for the evolutionary introduction of airborne separation assistance systems (ASAS)[6] are being pursued as a potential means to reduce controller workload and provide better spacing between aircraft. Eurocontrol research[7,8] is investigating the use of ASAS spacing in the extended terminal area and the terminal area in the framework of current day operations. DAG-TM concept element 11 has investigated airborne merging and spacing in TRACON airspace[9]. These concepts pursue the limited delegation of spacing tasks from the controller to the flight crew in order to achieve a more optimal spacing between aircraft without increasing controller workload. Simulation results indicate a possible controller workload shift from the monitoring to the planning phase and the potential for more optimal spacing between aircraft. They also indicate higher traffic awareness by flight crews actively monitoring the traffic, which is a potential safety benefit. Capacity gains from spacing applications can likely occur at traffic bottlenecks like final approaches, merge points, or in any other situation in which the available airspace is very limited like in bad weather conditions. En route capacity gains in regular operations are probably rather moderate. Therefore, ASAS spacing can be viewed as additional tool to be used at controllers’ discretion for particular situations to increase throughput at traffic bottlenecks, but will not solve all the capacity problems of the future.

This paper proposes to combine the common near- and medium-term components of the various far-term trajectory-based approaches and the near-term ASAS application into one common concept of operations. The concept of trajectory-oriented operations with limited delegation takes advantage of the benefits of the individual concept components to improve capacity, safety, security, throughput, and flight efficiency. The proper integration of the individual components is expected to provide bigger benefits than the sum of its parts and lays out an evolutionary path to phase in new capabilities and moderately changing the roles and responsibilities of controllers, flight crews and the automation. The next section explains the concept in detail.

II. Trajectory-Oriented Operations with Limited Delegation

A. Concept

The proposed concept is in line with research findings and analyses of the air traffic system conducted in Europe and the US proposing the combination of absolute and relative operations[11,12,13]. Graham et al. [11] 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 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 [11]. 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 trajectories are generated that comply with all or at least the upcoming subset of these constraints. 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 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.

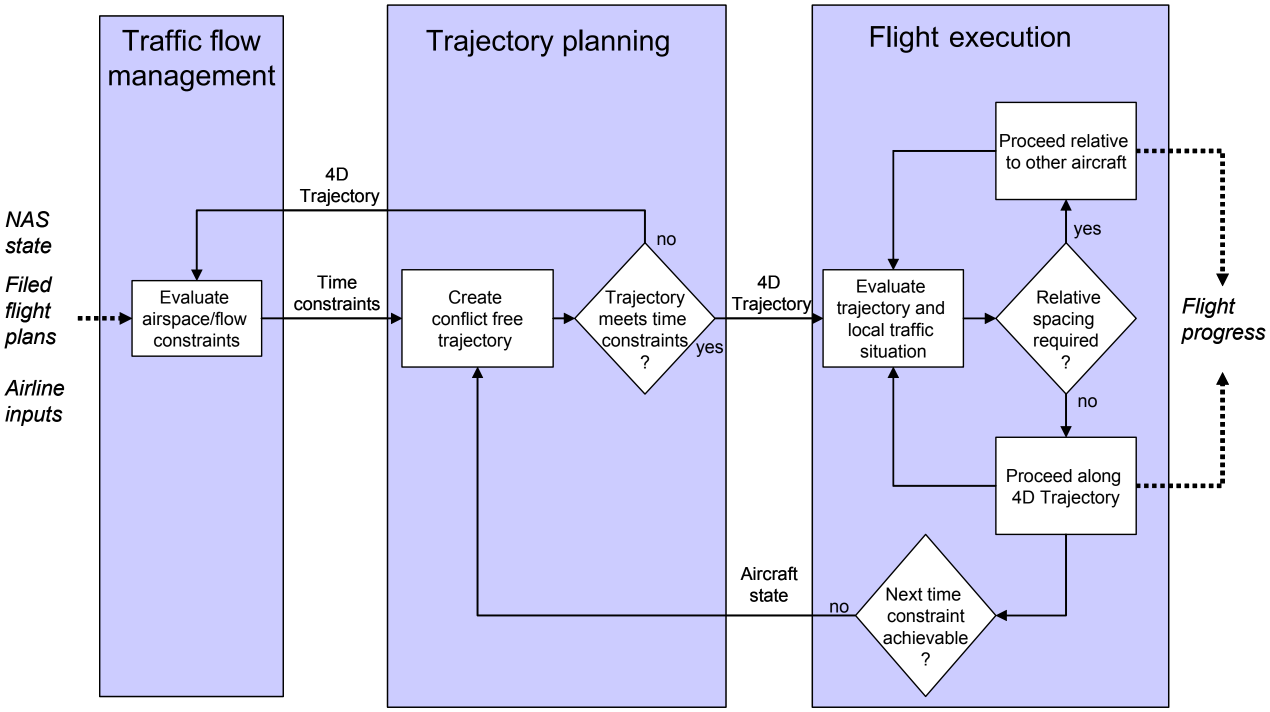


Figure 1. Proposed system: time-based traffic flow management and trajectory-orientation are augmented by a tactical relative spacing loop

The general functional flow does not make assumptions about task allocation between traffic managers, controllers and flight crews. The roles and responsibilities and technologies can evolve and additional benefits can be gained. An overview over the roles and responsibilities is given in the subsequent section. The main part of the paper outlines three different implementation phases with regard to procedures, technologies and roles and responsibilities. All presented prototypes in these sections build on current NAS technologies. Similar prototypes can be integrated into other display concepts using their particular design philosophy.

B. Roles and Responsibilities

The integration of advanced air/ground automation can enable applying the operational concept throughout the airspace. There are no significant changes in responsibilities but some shifts in the roles of pilots and controllers from current day operations. The controllers' role moves from tactical micromanagement 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. The following table compares the roles of TFM, air traffic controllers and flight crews today and in a fully integrated air/ground system.

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 de-confliction,	
Delay absorption techniques		Holding, vectoring			Holding, Trajectory changes, 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			Trajectory changes	Trajectory requests possible
Primary flight mode in congested airspace			Tactical, autopilot			FMS engaged
In-trail-spacing and merging		Speed commands				ASAS spacing

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. The filed flight plan with the controller initiated amendments can be compared against the current aircraft trajectory for security purposes. If properly equipped, flight crews can request advantageous trajectory modifications and communicate those 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. While controllers manage the overall traffic flow, flight crews would be assigned specific tasks like spacing or merging relative to only one aircraft at a time. This way controllers and pilots can gain experience in conducting novel, but well-defined tasks.

C. Evolutionary Path

Three evolutionary phases are analyzed with regard to roles and responsibilities, technologies and procedures. The near-term phase highlights the procedural integration of different concept elements and technologies that could be in place by 2010. The medium-term phase discusses a fully integrated air/ground system with all technologies properly integrated with each other, but little changes in roles and responsibilities as it could be in place by 2020. The far-term phase speculates about how this integrated air/ground system could be used to implement concepts that require a substantial paradigm shift. Obviously the transition from one phase to the next is not discrete and the introduction of new procedures and technologies will be incremental and not occur at the same pace in all airspace areas.

III. Near-term phase: Procedural integration of near-term technologies

A. Technologies

The near term application of the concept is based on the FAA's current modernization plan up to the year 2010[13]. By this time it is anticipated that controller workstations will have access to largely improved surveillance data provided by ADS-B and improved radar sources. CPDLC will also be available from the DSR R- and D-Sides for some initial functions like transfer of communication. Controller stations will have access to time-based metering and conflict probe information. Some aircraft will be equipped with cockpit displays of traffic information (CDTI) based upon ADS-B and TIS-B data. The majority of aircraft will be equipped with flight management systems; some may be equipped with airborne spacing functions.

B. Introducing the concept

The initial implementation of the concept is based on

- ground-based traffic flow management coordinated between airlines and air traffic service providers
- definition of FMS procedures for air/ground coordination
- schedule management with FMS compatible procedures by the controllers
- delegation of spacing operations to flight crews of properly equipped aircraft
- precise management of spacing using improved surveillance data and DSTs by controllers for unequipped aircraft

In this initial phase controllers get familiar with the concepts of trajectory-orientation, precise time-based metering and managing aircraft spacing based on precise position and speed information. Flight crews will be able to utilize their FMS throughout more phases of flight, become aware of their local traffic situation, and/or are responsible for managing their spacing to another aircraft.

C. FMS Procedures

FMS procedures pre-define the flight path of an aircraft in terms of routing, altitude, and speed and are a means of coordinating trajectories between the air and the ground suitable for radio communication. The 4D trajectory of an aircraft following an FMS procedure is highly predictable in its lateral dimension, because the FMS has a very precise lateral path-tracking capability. The FMS altitude profile is well predictable if crossing restrictions are defined and the speed schedule (Climb, Cruise, and Descend Speed) and the aircraft weight are known. With these values the times of arrival at downstream waypoints can also very accurately be estimated. In order to retrieve these values in a near-term environment, charted FMS procedures and FMS compatible clearances can be used. Additionally, the aircraft weight could be communicated via ADS-B.

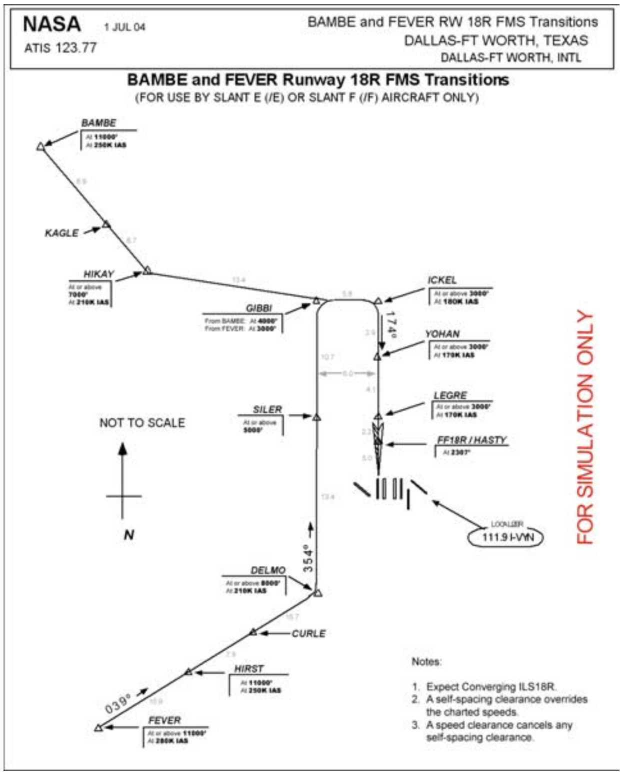


Figure 2. Charted FMS procedure example

Charted FMS procedures can span several sectors and facilities. Figure 3 shows an example FMS procedure defining TRACON routings into Dallas Ft. Worth. By clearing an aircraft for an FMS procedure controllers can accommodate a number of altitude, route and speed clearances in one step and clear the aircraft through downstream sectors.

In addition to charted FMS procedures, FMS compatible clearances can be defined and used for radio communication. Such clearances were used extensively for CTAS/FMS integration[14, 15] and DAG-TM experiments[16] with good acceptance by pilots and controllers. For example a precision descent clearance enables controllers to clear flight crews to descend at their FMS computed Top of Descend point with or without a predefined speed schedule and meet downstream crossing restrictions. For example assume AAA123 is flying at cruise altitude with a speed of Mach .82 along an FMS arrival procedure that has a first restriction of 250 knots and 11000 feet at waypoint XYZ. The clearance "AAA123 cleared for the precision descent at 310 knots" combines the following atc instructions. "Maintain Mach .82; descend in managed mode (VNAV, PROF) at the FMS computed Top of Descent; Maintain 310 knots when able; cross waypoint XYZ at 250 knots and 11000 feet." The flight crew procedure to handle such a clearance can be published in a flight manual bulletin and requires some, but not excessive training.

Without FMS-integrated data link, modifications to FMS routings are limited to items that can be communicated verbally between controllers and pilots and can manually be entered into the FMS by the flight crew. Therefore, named waypoints, especially if they are already part of the aircraft's current FMS route are suitable while latitude/longitudes defining random locations in the airspace are unsuitable for near-term applications.

D. Precise time-based metering

The improved predictability of 4D trajectories for aircraft following FMS procedures can be utilized to increase the precision of time-based metering over the current system. The DSTs available to the air traffic controllers can be augmented with some very well defined tools. Air traffic controllers participating in human-in-the-loop studies at NASA Ames Research Center have consistently ranked a timeline display on the R-Side as one of the most useful and usable tools[11,17]. Timelines are a graphical depiction of estimated and scheduled times of arrival at certain waypoints like metering fixes or runways. Timelines are used frequently and successfully for traffic management with the CTAS TMA[18]. In the current system alphanumeric meter lists and delay numbers are presented to the controllers to support time-based metering that provide little situation awareness. Timelines allow controllers to evaluate the situation of the aircraft that they are responsible for in reference to the remaining merging traffic flows. Figure 3 shows an example in which AAL142 and AAL434 are scheduled to follow each other, while UAL438 will have to be delayed further to allow UAL25 to cross the meter fix ahead.

While timelines present the overall picture of the traffic situation at the metering fix, additional support for on schedule delivery can be integrated into the data tag to reduce the need for traffic scan interruptions. Figure 3 shows speed advisories in the fourth line of the data tags for UAL438 and AAL434. These advisories represent the speed schedule the aircraft should fly to arrive at the metering fix on time. If the controller determines that this is the appropriate means to absorb the delay he or she can communicate it by voice to the flight deck or data link it to the aircraft. In both cases a controller action can mark the speeds as assigned, so that the ground system can use the revised speed schedule for its predictions from now on. The flight crew needs to configure the FMS with the new speeds.

Simulation evaluations and field tests have shown that this type of speed advisory-based metering can deliver aircraft within 15 seconds of their scheduled time. Instead of communicating a speed schedule, properly equipped aircraft can also receive the scheduled time of arrival from the controllers as required time of arrival and configure their FMS to meet this time. This procedure seemed equally acceptable to controllers and pilots when initially tested in simulations in 2003[19]

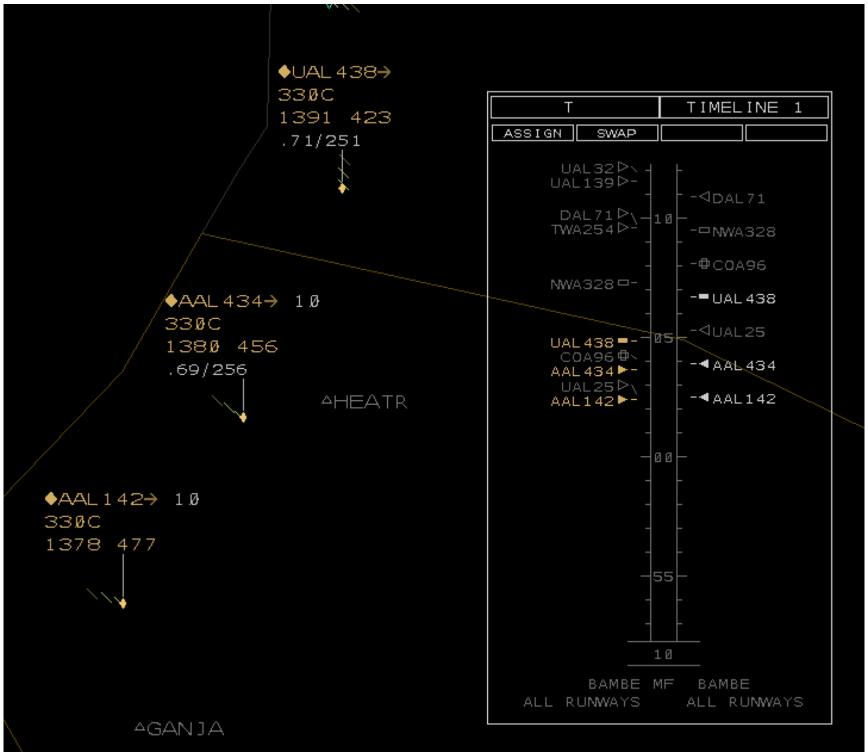


Figure 3. Timeline and speed advisories

Ongoing work on the CTAS En route/Descent Advisor (EDA) is focusing on presenting advisories to the controllers that provide conflict free route, altitude and speed changes that deliver aircraft on time and can be executed in a voice environment[23,24]. The problem of FMS compatibility of these advisories has been recognized and the tool has not yet been tested in realistic high density traffic operations. Therefore, in the near-term a concept of highly responsive trial planning capabilities and delay feedback for vectoring operations might be used instead.

E. Trial Planning

Manual trial planning allows controllers to construct and review trajectory changes before communicating them to the flight deck or entering them into the host computer. Trial planning tools are part of many advanced ATSP automation tools. Some of these tools easily blend into the proposed FMS-compatible near-term concept. Shortcuts to downstream waypoints or cruise altitude changes can easily be implemented and executed, because they can be communicated by voice and entered into the FMS. These changes are most common in the en route environment, in which time pressure is low to moderate. However, several field tests and simulations in the past have concluded that manual trial planning is inappropriate for a high workload arrival metering environment.[20,16] Controllers reported problems with slow response times of the trial planning tools and difficulties in vectoring aircraft along the trial planned path.

For DAG-TM simulations conducted in 2003 and 2004 a new trial planning prototype was created and integrated into a high fidelity DSR emulation that is part of the Multi Aircraft Control System (MACS) [21,22]. This tool is implemented to be highly responsive providing immediate conflict and delay feedback and is fully integrated with the DSR CHI and data link capabilities. Unlike previous trial planning tools, this very responsive tool was used almost exclusively for all route and cruise altitude changes in very dense arrival airspace and received the highest marks of all controller tools[17]. Moreover, tactical vectoring of aircraft was practically eliminated. The tool allows for rapid creation of routes along fly-by-waypoints defined as latitudes and longitudes that can directly be data linked into the airborne FMS.

1. Route trial planning

In the current MACS/DSR prototype route trial planning to a downstream waypoint can be accessed from the keyboard by typing a "TR <waypoint> <callsign or cid> command or graphically by clicking on the portal in the data tag next to the callsign (modeled after the CTAS Direct-To prototype). Waypoints can be graphically removed by entering or picking them. New waypoints can be inserted by clicking on the trial plan trajectory and scrolling the waypoint to the desired location. All trial plans are automatically and immediately compared to other trajectories for conflicts. Conflicts are displayed with filled J-rings around the aircraft target symbol and the conflict location is indicated graphically.

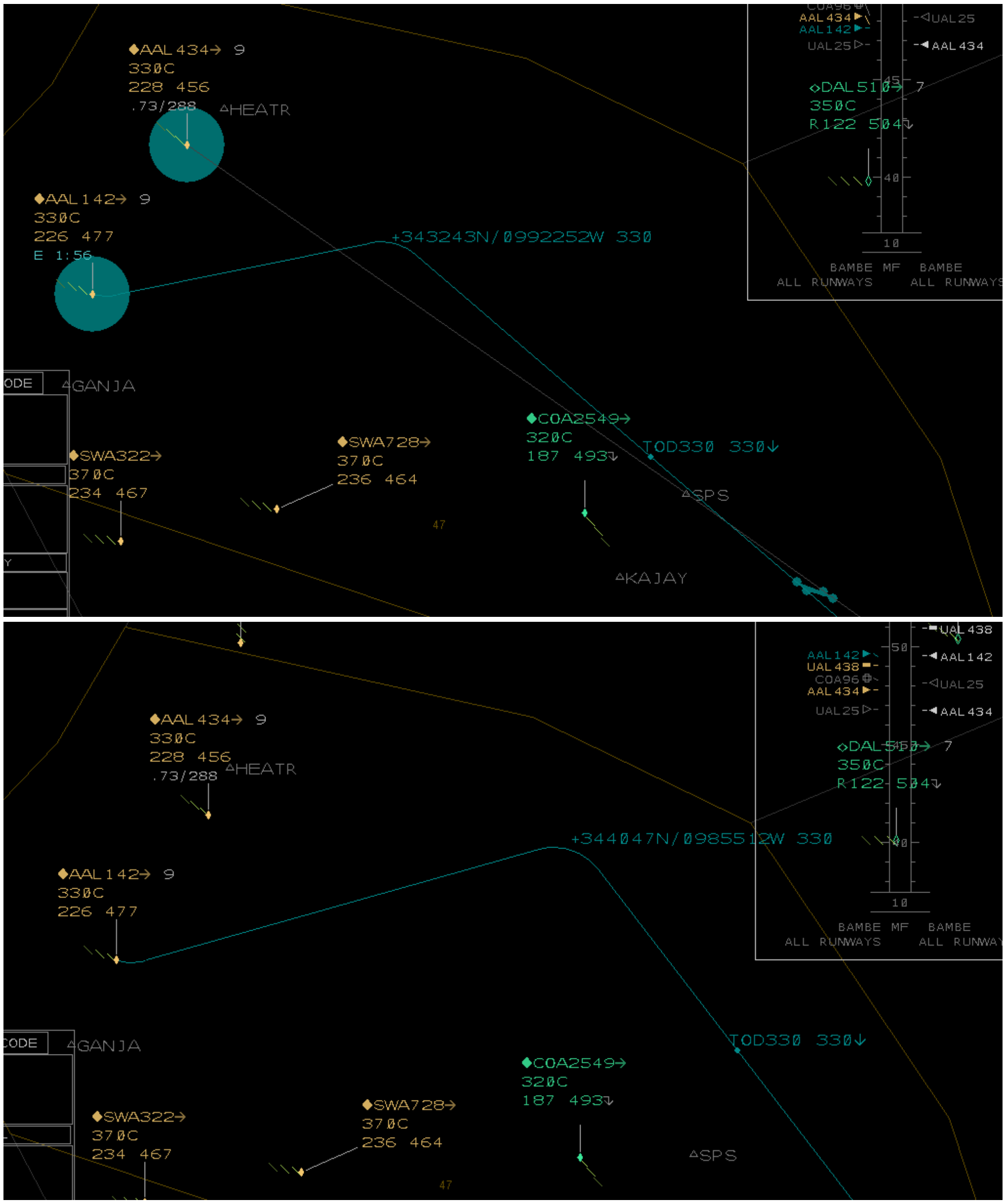


Figure 4. Trial planning tool. While a new waypoint is dragged the trajectory is continuously re-computed and compared to all other trajectories in the area. The new STA/ ETA difference is indicated in the data tag as long as it is outside a pre-defined tolerance.

Figure 4 shows an example trial planning sequence. The controller is dragging the newly inserted waypoint. The trajectory is continuously re-computed and provides feedback about potential conflicts. The amount of delay to be absorbed in addition to the new route is indicated in the data tag and on the timeline. Once the trial plan is conflict free, the filled circles around the conflict aircraft disappear. Once the trial plan absorbs all the delay, the delay indication in the data tag disappears. Therefore, a controller can use this tool by dragging the newly inserted waypoint(s) into the preferred area for absorbing the delay until all trial plan indications except for the trajectory disappear.

This route trial planning tool can be implemented in the near-term. However, it becomes most effective when integrated with data link, so that the trajectory can be sent to the aircraft's flight management system as envisioned for the medium-term phase of the concept. Near-term route trial planning can be enabled for sending aircraft direct to downstream waypoints, or along named waypoints. Free rerouting without data link might be possible in low to medium traffic density, using some of the concepts proposed for the CTAS Direct-To or E/DA tools[20, 23, 24]. Workload permitting controllers can experiment with a near-term version of the tool at their discretion to provide input for improvement of the implementation before integrating it with data link.

2. Altitude trial planning

Altitude trial planning can be accommodated within the DSR framework as depicted in figure 5. In this example the controller wants to determine the impact of changing the cruise altitude from FL330 to FL310. He or she can access the altitude trial planning function from the keyboard by typing a "TA <altitude> <callsign or cid>" command or graphically as follows: Clicking on the altitude field brings up the regular DSR altitude pop-up menu. A "trackball pick" on the desired altitude creates a new trial plan trajectory. The new altitude is displayed as modified assigned altitude in trial planning color in the data tag. The new trajectory with the computed bottom or top of descent is displayed graphically. The fourth line of the data tag indicates the delay estimate for the new trajectory (in this case the aircraft is estimated to arrive 42 seconds late). The new altitude can be communicated by voice and manually entered into the FMS by the flight crew. Therefore, altitude trial planning is an appropriate near-term application.

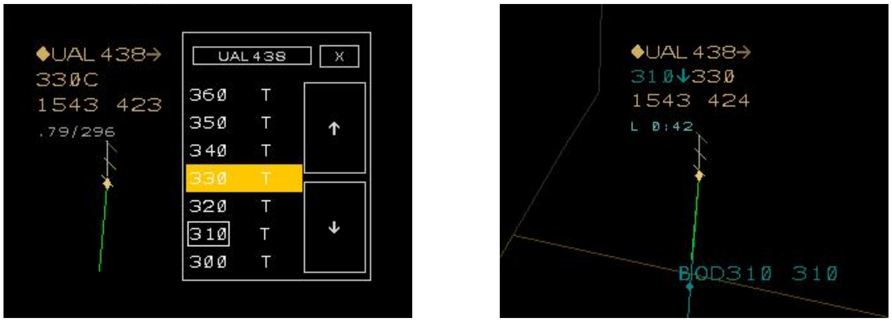


Figure 5. Altitude trial planning is accessed via picking an altitude from the altitude menu, entering an altitude assigns it.

F. Spacing operations

Near-term spacing operations can make use of the more precise surveillance information on the ground and the flight deck. The type of airborne separation assistance that can be enabled in the near-term belong to ASAS categories 1 (situation awareness) and 2 (spacing). Eurocontrol research focuses primarily on the integration of airborne spacing into the current day environment. Grimaud et al.[8] 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 Centers and simulations and flight tests at NASA Langley Research Center. In a recent simulation in August 2004 at NASA Ames of TRACON self-spacing and merging pilots and controllers worked across four near-term conditions with and without airborne and ground-based spacing tools.

The ground-based spacing tools are depicted in Figure 6 as a prototype implementation of a TRACON (STARS) display:

Figure 6. Spacing advisories and feedback on a STARS prototype

The third line of COA110 displays a recommended lead aircraft, the recommended spacing and the current spacing automatically as long as the spacing has not been assigned. When the controller assigns a spacing clearance the advisory disappears and a Spacing Designator is turned white (see BAW601). At any time the controller can dwell over an aircraft and get the spacing information including a circle depicting the history position of the lead aircraft 80 seconds ago in the case of COA538.

Ground-based spacing tools like those depicted in figure 6 can be used to monitor spacing operations that were delegated to an equipped aircraft or to fine-tune the spacing for unequipped aircraft with appropriate speed and route clearances. In order to delegate spacing operations to the flight crew, aircraft need to be equipped with ASAS automation. A CDTI developed by the flight deck display research group at NASA Ames Research Center combining situation awareness and spacing support for the flight crew is depicted in figure 7[23, 24].

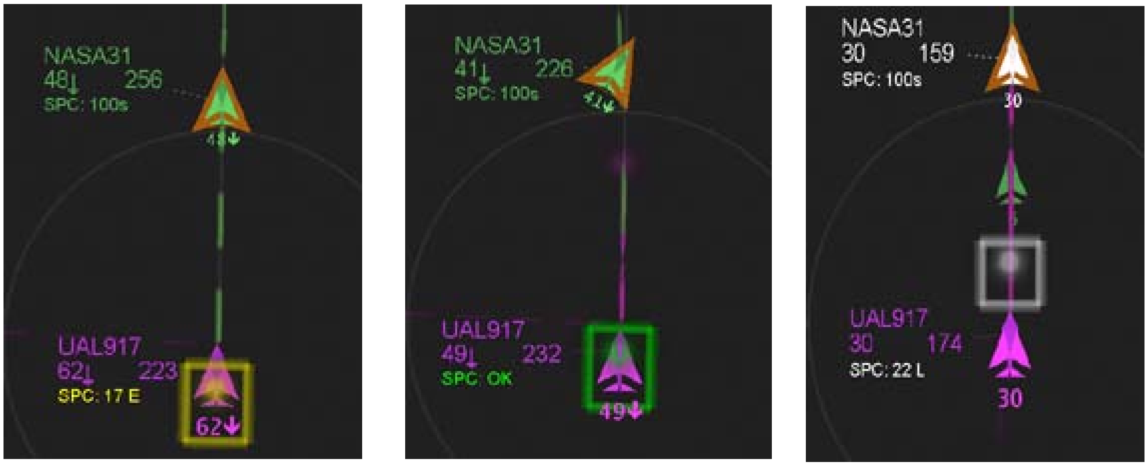


Figure 7. CDTI with airborne spacing support

G. Objectives and expected benefits of the near-term implementation

One of the objectives of the near-term implementation is to phase in the concepts of time-based trajectory-oriented operations and aircraft-to-aircraft relative spacing in a safe operational environment. Pilots and controllers can gain experience with these concepts at their discretion and help refine operational procedures for the future. No major changes in the roles and responsibilities are required. Another objective is to advance the ground-side automation to be an equivalent to the currently much more advanced flight deck automation. While the flight deck automation should also evolve, it is the ground-side automation that currently lacks a number of the capabilities necessary to support controllers in moving from tactical sector-oriented operations to strategic trajectory-oriented operations.

These objectives are intended to pave the way for more advanced concepts. However, research has demonstrated that even the near term implementation can provide some immediate benefits: Delivery accuracy at metering fixes can be significantly improved[16, 24]. Flight efficiency can be improved by allowing aircraft to fly longer at cruise altitude and avoiding excessive delay vectoring[16]. Workload at downstream sectors that handle merging of traffic streams into terminal areas or final approaches can be reduced. In conjunction with improved spacing tools this workload reduction can allow controllers to provide a more efficiently spaced traffic flow into very dense airspace areas. It is unlikely however, that the near-term implementation will be able to provide the amount of en route sector capacity or throughput benefits required in the long term.

IV. Medium-term phase: Technological integration of advanced air/ground automation

A. Technologies

While the near-term phase focuses on the procedural integration the medium-term phase needs to focus on the technological integration of advanced air/ground automation. Conceptual and procedural considerations eventually require 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 controllers and the ground automation need to be informed about the current strategic flight intent and preferences of the aircraft.

The main technologies of a fully integrated air/ground system are depicted in figure 8:

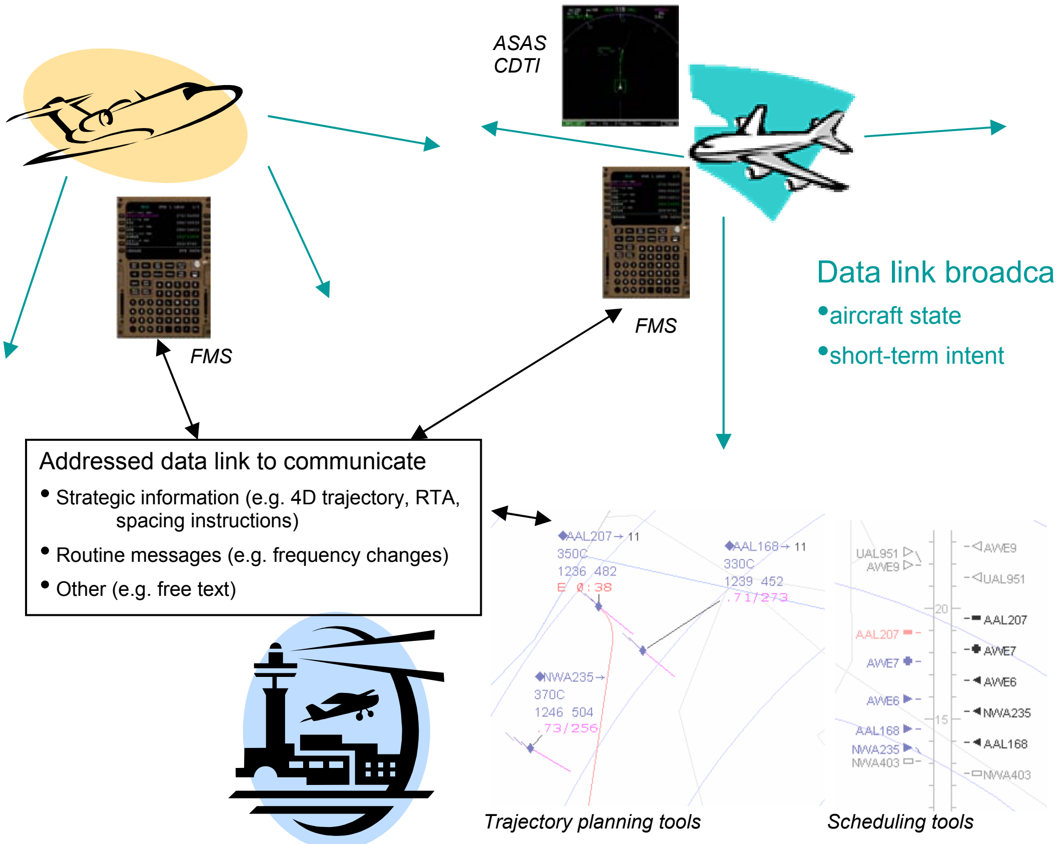


Figure 8. Technologies for comprehensive air/ground integration

- Air traffic service providers equipped with decision support tools for scheduling and trajectory planning.
- Aircraft equipped with Flight Management Systems
- Addressed data link communication between ground-based decision support tools and FMS 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 with trajectory planning tools

B. Data Link

Specifying the appropriate data link technologies for air/ground integration has been a recurring problem. The future air navigation system (FANS) is to date the only data link technology that interfaces directly with the Flight Management System[25]. For a variety of reasons including latency and unreliability FANS is only used in the oceanic environment. Additionally, FANS ground systems do not directly interface with the ground automation, requiring controllers to operate from separate stations for FANS communication. NEXCOM (VHF data link mode 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 up-to-date state information and flight control system targets, but inadequate for communicating detailed and complete 4-D trajectories.

1. 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 at about a 1 second update rate and provide precise position and velocity information. The trajectory intent should be available to the ground system whenever it changes significantly. One main point of discussion is the question about 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 distributing 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 distributing 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 distribute 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.

2. Controller Pilot Data Link Communication

It is extremely important that CPDLC is integrated with the FMS and the ground-based DSTs to support the full spectrum of trajectory-oriented operations. Only this integration allows controllers and pilots to exchange complex trajectory information without causing unacceptable workload and delays. During DAG-TM air/ground integration simulations the following messages were used and appeared sufficient for covering all relevant cases.

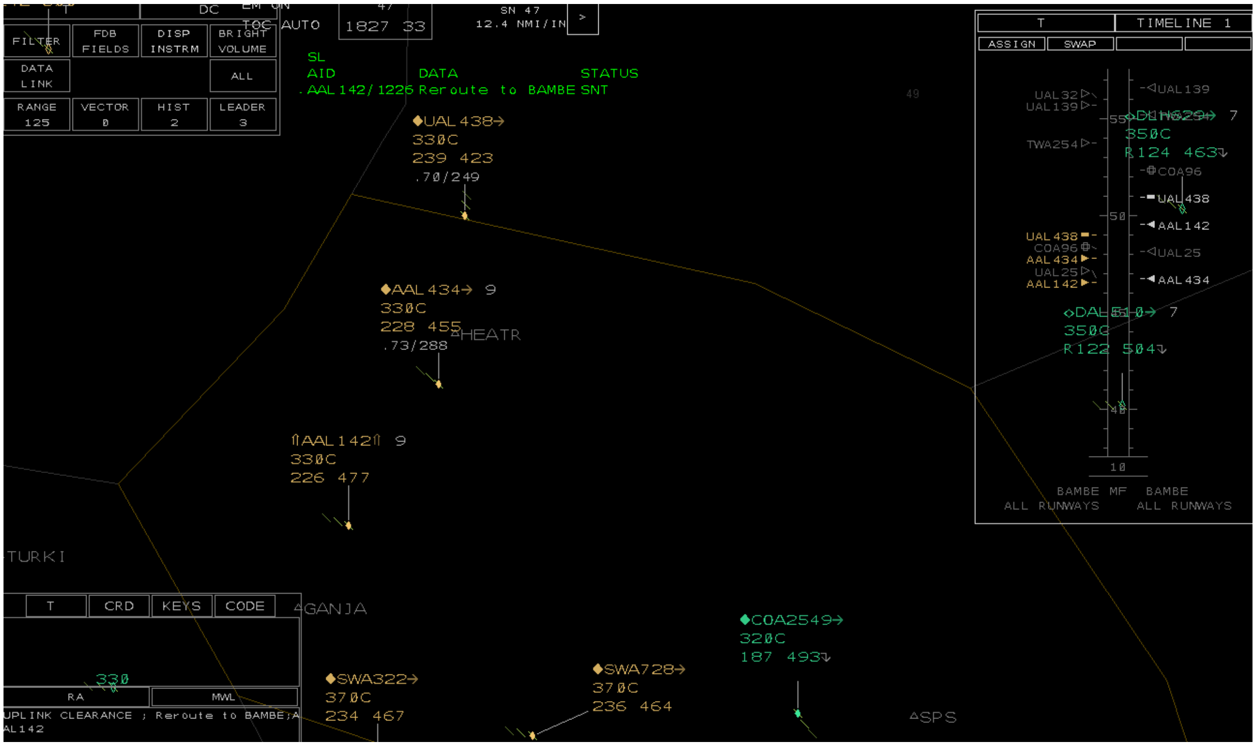
Table 2 .Messages for Controller Pilot Data link Communication (CPDLC)

Message Type	**Message Text**	**Loadable content**	**Controller procedure**	**Flight Crew procedure**
Transfer of Communication (TOC)	CONTACT / MONITOR <frequency>	None required	If TOC Auto selected, occurs automatically when handoff accepted by next sector, or use command "UF"	Accept message, Select new frequency, contact or monitor new frequency
Route uplink	REROUTE TO <waypoint>	Location of new points (named or latitude/longitude) , and /or altitude/speed restrictions	Create route trial plan then use command "UC"	Load message content, review uplinked route, accept or reject message, Execute
Cruise Altitude uplink	CLIMB/ DESCEND AND MAINTAIN <flightlevel>	Cruise altitude	Create altitude trial plan, then use command "UC"	Load new cruise altitude, review new trajectory, accept or reject message, Execute or Erase
Cruise/Descend Speed Uplink	DESCEND AT <mach/cas>	Cruise mach or cas and descent cas	When speed advisory appears in fourth line, use command "UC"	Load new cruise/descend speed, review new trajectory, accept or reject message, Execute or Erase

Message Type	Message Text	Loadable content	Controller procedure	Flight Crew procedure
RTA uplink	RTA AT <waypoint> : <UTC time>	RTA waypoint, RTA (UTC)	When "UPLK RTA" appears in fourth line, use "UC", use "UR" anytime RTA has been assigned	Load new RTA, review new trajectory, accept or reject message, Execute or Erase
Spacing uplink	e.g. FOLLOW <callsign> AT <time> Seconds	Lead aircraft, spacing interval	When spacing advisory appears in fourth line, use "UC", use "US" anytime lead and time have been assigned	Select target on CDTI, select interval, review acceptability, accept or reject, engage or de-select target
Free Text Uplink	e.g. CHECK STUCK MIKE	None	Use command "UT" and type text or select from predefined Menu Text options	Read message and deal with it
Downlink of new route request	REQUEST REROUTE TO <waypoint>	New trajectory	See pending request in portal, click on portal to open request in trial planner, accept or reject request with "UY" or "UN"	Create route on CDTI or FMS downlink request, wait for response, execute or erase modified FMS route

C. Ground-side integration of DSTs and data link

The ground side data link implementation in the MACS/DSR prototype 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 changes to an up-arrow until the response is received. Figure 9 shows how the trial plan depicted in figure 4 can be communicated to the flight crew with data link.



SL
AID DATA STATUS
.AAL142/1226 Reroute to BAMBE SNT

UPLINK CLEARANCE ; Reroute to BAMBE;AAL142

Figure 9. The trial plan created in figure 4 is uplinked to AAL142 using the "UC" command.

After the flight crew accepts and executes the route modification, the data link status indicator in the data tag changes back to the regular indication and the message disappears from the data link status list after an adapted timeout period. Since the trial plan modification in this example resolves the conflict and absorbs all required metering delay, the conflict indication in the first line of the data tag and the highlighted metering indication in the fourth line disappear. The controller can incorporate this CHI concept into his or her regular scan with the simple rule: Only aircraft that have additional information highlighted in the data tag require special attention.

Figure 10 shows the controllers display after the flight crew acceptance and FMS downlink of the new trajectory. In this case the controller reviews the new FMS trajectory by clicking on the aircraft callsign. In this particular display setup the aircrafts indicated air speed or MACH is displayed in the fourth line, whenever the controller dwells on a data tag (.76 for AAL142).

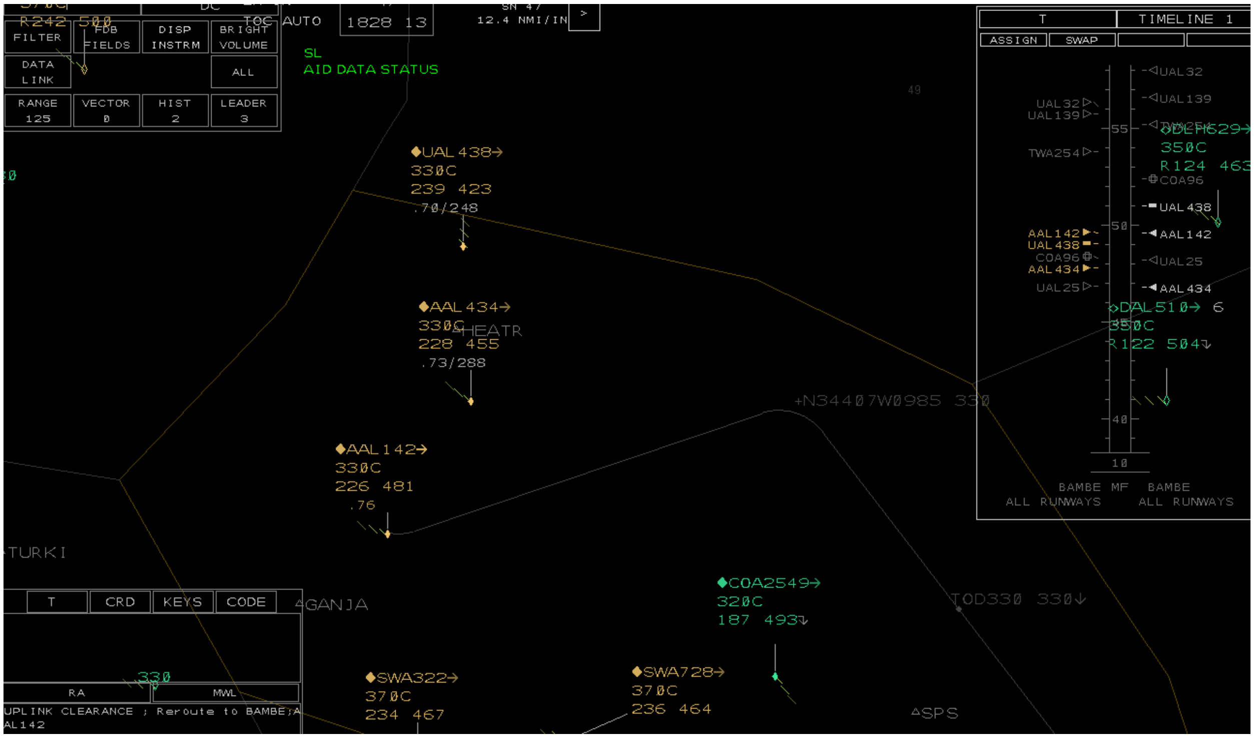


Figure 10. Display of FMS trajectory after the trial plan has been uplinked and executed by the flight crew.

Downlinked request can be integrated into this concept in a similar fashion. When the request is received the trial planning portal and the data link status indicators change to a down arrow and clicking on the portal opens the request and checks it for conflicts with the other trajectories.

D. Airborne integration of FMS and CDTI with data link

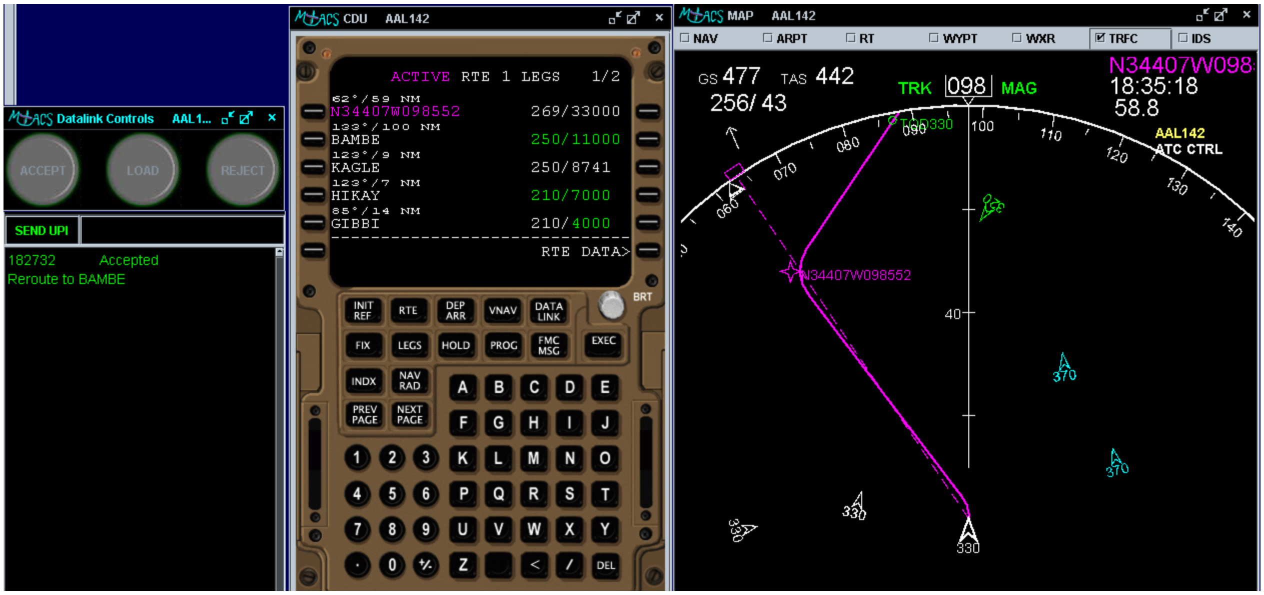
The pilot procedure to deal with uplinked messages involves noticing the message when being cued to its arrival and loading the new values into the FMS. Upon review of the resulting trajectory the flight crew accepts or rejects the message and executes or erases the modified FMS route, respectively. 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. Figure 11 shows the uplinked trial plan displayed in figures 4, 9, and 10 from the perspective of a current day flight deck with a simple traffic depiction on the MAP display.

```
182732          Loaded
Reroute to BAMBE
```

```
      MOD     RTE 1 LEGS    1/2
63°/60 NM
N34407W098552          269/33000
133°/100 NM
BAMBE                  250/11000
123°/9 NM
KAGLE                  250/8741
123°/7 NM
HIKAY                  210/7000
85°/14 NM
GIBBI                  210/4000
--------------------------------
<ERASE                 RTE DATA>
```

Figure 11. After loading the uplinked trajectory into the FMS the flight crew can review the new flight path on the Control and Display Unit and the MAP display. (Generic MACS integrated flight deck simulator.)

Figure 12 shows the flight path change after the flight crew has executed and accepted the message:



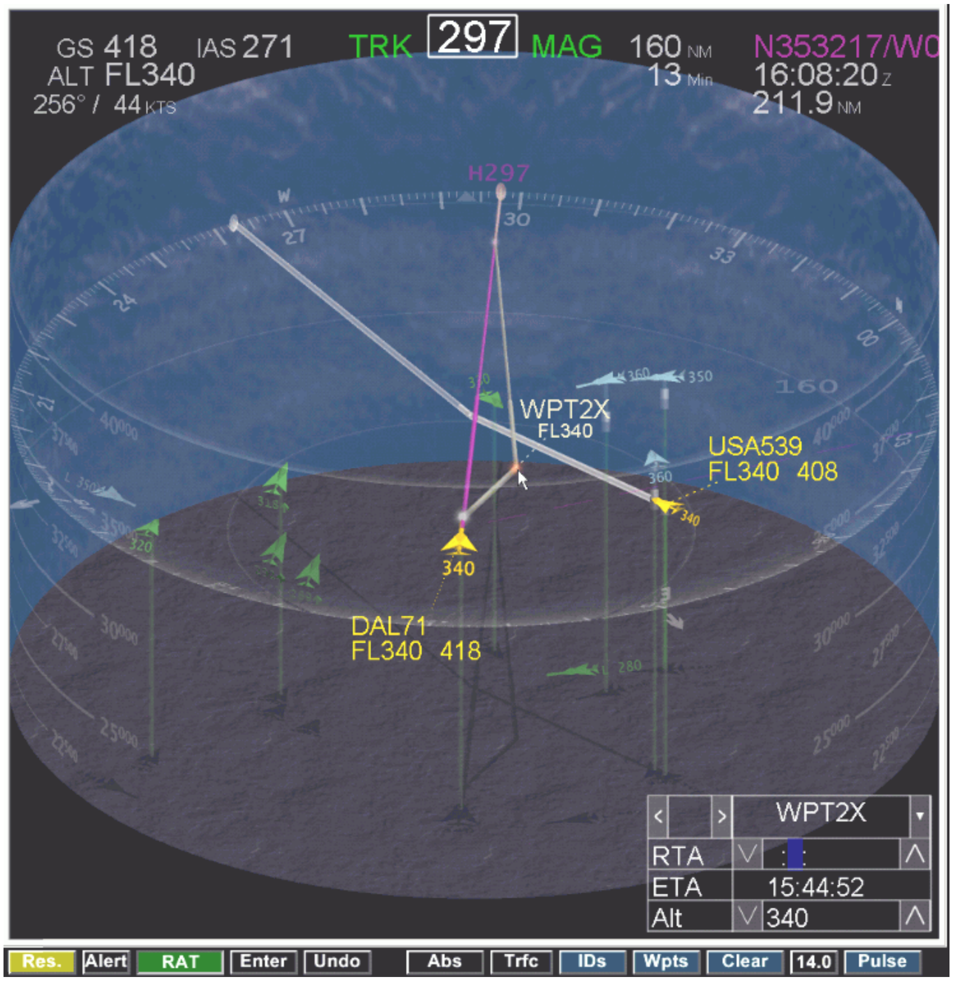
```
182732          Accepted
Reroute to BAMBE
```

```
    ACTIVE RTE 1 LEGS       1/2
62°/59 NM
N34407W098552          269/33000
133°/100 NM
BAMBE                  250/11000
123°/9 NM
KAGLE                  250/8741
123°/7 NM
HIKAY                  210/7000
85°/14 NM
GIBBI                  210/4000
--------------------------------
                       RTE DATA>
```

Figure 12. When the trajectory modification is executed the new flight path will be automatically flown by the flight management system.

The flight deck automation depicted in figures 11 and 12 basically represents current day technology. Only the data link connection needs to be properly integrated to ensure the timely delivery and handling of uplinked route modifications and the immediate downlink of the new FMS trajectory to the ground. To provide an additional safety layer and increase the flight crews' situation awareness it would be desirable to have an advanced CDTI. This would allow flight crews to review the trajectory change in the context of the traffic situation. If the trajectories of the surrounding traffic are made available to the flight deck automation, flight crews can create conflict free trajectories for example for weather avoidance and downlink informed requests to the ground controllers for approval. This type of trajectory negotiation has been evaluated in simulations at NASA Ames Research Center in 2003[19].

A prototype CDTI providing this type of functionality is depicted in figure 12:



< >	WPT2X
RTA	:
ETA	15:44:52
Alt	340

Figure 12. Prototype CDTI in optional 3D representation[25].

The CDTI depicted in figure 12 was developed by the Flight Deck Display Research (FDDRL) group at NASA Ames Research Center [24]. Flight crews can create route modifications in all dimensions - route, altitude and speed- and review the resulting trajectories in planar and three-dimensional representations relative to the trajectories of the surrounding traffic. The same CDTI was shown in figure 5 supporting the spacing task.

H. Objectives and expected benefits of the medium-term implementation

The medium term implementation of the concept focuses on the full procedural and technological integration of advanced ground-based and airborne automation. At the end of this phase pilots and controllers have access to relevant trajectory and traffic information and powerful tools to modify and communicate trajectories from the controller position to the flight deck and vice versa. This environment is essential for implementing strategic flight path changes that comply with air traffic management constraints. Pilots and controllers can also access a suite of tools to fine-tune relative aircraft-to-aircraft spacing and have gained experience with distributing this task between the air and the ground.

While this is the foundation for implementing far-term concepts as discussed below, this integrated air/ground system already provides a number of significant benefits. Simulations within the DAG-TM framework using the trajectory-oriented system discussed here as a baseline have demonstrated en route sector capacity gains of at least 50 % over the current system. The need for aircraft vectoring was practically eliminated and all aircraft were flying along FMS trajectories for almost the entire flight time. This largely improves flight path predictability and is a major security benefit.

The following table summarizes some of the feedback of full performance level controllers gathered in post simulation questionnaires after the controllers had used the prototype system for two weeks.

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

V. Far-term: Advanced concepts with paradigm changes?

Once the air and ground are comprehensively integrated on a conceptual, procedural and technological level, moving towards more advanced far-term concepts like autonomous operations or the advanced airspace concept may become an evolutionary progression of the integrated air/ground system. Depending on gained experience and achieved benefits the system can evolve into different directions. Three examples are laid out in this section that can seamlessly be integrated into the overall architecture. Most likely the far-term system will be a combination of various approaches.

A. Refining the medium-term concept with increased pilot involvement and additional automation

The medium-term concept may prove effective enough to support traffic demands even beyond the next twenty years without large paradigm shifts. In that case flight crews may be increasingly involved in trajectory negotiation tasks by requesting trajectory changes more frequently. Traffic management would remain on the ground. The ground-based and airborne automation can be improved to provide very reliable conflict feedback and more accurate trajectory predictions. Controllers would still have to maintain the global traffic picture and monitor all aircraft in their airspace for proper separation. However the task delegation to the flight deck could allow for additional degrees of freedom in terms of altitude and route tolerances. Advanced automation in the air and on the ground can support the operators by alerting them to potential separation or traffic management problems.

B. Advanced Airspace Concept

The advanced airspace concept[6] uses the same infrastructure as described in the previous section and as the ground-based automation becomes more powerful and reliable, it may be able to relieve the controller of some of the separation management tasks. For this to be acceptable controllers would have to gain trust into the automation first. This trust can be achieved in earlier concept implementation phases. One of the main differences between the concept of trajectory-oriented operations with limited delegation and the advanced airspace concept remains the role of the flight crew in the separation management task. The advanced airspace concept proposes to assure local separation at all times through the ground-based Tactical Separation Assured Flight Environment (TSAFE). TSAFE is designed as a backup system to detect imminent separation losses if the strategic trajectory de-confliction fails for whatever reason. A short-term conflict resolution would automatically be data linked to the aircraft to be implemented by the flight crew. While this procedure can be enabled via the fully integrated air/ground system it remains to be seen whether this approach is superior to the approach of limited delegation. If the flight crew becomes responsible for a particular spacing task, it will be aware of its local traffic situation and can act as the redundant system. Ultimately, both approaches can probably co-exist and provide not just one, but two additional safety layers.

C. Autonomous Operations

The delegation of limited spacing or separation tasks to the flight crew can also be expanded into fully autonomous operations like the DAG-TM concept of free maneuvering. Again, the integrated air/ground system that enables the full exchange of up-to-date state and trajectory information is the enabling technology. Flight crews can change their flight paths without controller approval as long as they don’t create any near-term conflicts and comply with traffic management restrictions like time-constraints. Controllers are responsible for managing the lesser-equipped IFR traffic. Ground and airborne automation needs to monitor the trajectories of all aircraft to alert the operators, controllers and pilots to potential conflicts. A tactical trajectory-independent component to provide redundancy for the separation management task is also required.

During the evolutionary near- and medium-term phases described before the limited delegation of spacing tasks from controllers to flight crews can provide for initial experience with new roles. Controllers can gain trust in flight crews performing air traffic control tasks and flight crews gain experience in managing their aircraft relative to other traffic. Possibly, the step of assigning the complete separation responsibility to a flight crew of a properly equipped aircraft may not seem as radical as it seems today.

VI. 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 during the evolutionary phases and with different mixed equipage levels will be addressed.

VII. 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 concept of trajectory orientation with limited delegation can be applied to the different phases of an evolutionary path to advanced far-term concepts. The medium-term full integration of air and ground systems 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 to fifteen years. The architecture can be considered as a baseline, which can be build upon to support more advanced air traffic management concepts that might be required to handle the air traffic demand beyond 2020.

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