A FAST-TIME SIMULATION ENVIRONMENT
FOR AIRBORNE MERGING AND SPACING RESEARCH

Frank J.L. Bussink, National Institute of Aerospace, Hampton, VA
Nathan A. Doble, Titan Corporation, Hampton, VA
Bryan E. Barmore, NASA Langley Research Center, Hampton, VA
Sharon Singer, Rice University, Houston, TX

Abstract

As part of NASA's Distributed Air/Ground Traffic Management (DAG-TM) effort, NASA Langley Research Center is developing concepts and algorithms for merging multiple aircraft arrival streams and precisely spacing aircraft over the runway threshold. An airborne tool has been created for this purpose, called Airborne Merging and Spacing for Terminal Arrivals (AMSTAR).

To evaluate the performance of AMSTAR and complement human-in-the-loop experiments, a simulation environment has been developed that enables fast-time studies of AMSTAR operations. The environment is based on TMX, a multiple-aircraft desktop simulation program created by the Netherlands National Aerospace Laboratory (NLR). This paper reviews the AMSTAR concept, discusses the integration of the AMSTAR algorithm into TMX and the enhancements added to TMX to support fast-time AMSTAR studies, and presents initial simulation results.

Introduction

After a short reprieve, demand for air travel is once again rising to levels that will strain the National Airspace System (NAS) and exacerbate passenger delays [1]. Several major airports are already in need of capacity enhancements to meet current demand [2]. While more runways could alleviate some of these demand pressures, new runway construction is often a time-consuming and uncertain process due to local economic, political, and environmental concerns.
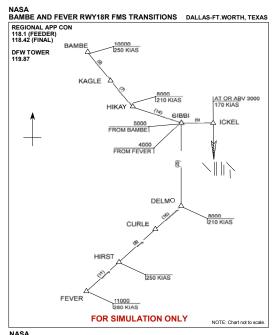
An alternative means of increasing airport capacity is to apply new technology and operating procedures to the arrival and departure processes. For arrival operations, airport capacities are governed by runway configurations, runway occupancy times, and wake turbulence separation requirements. Due to the limitations of ground-based surveillance and uncertainties about how control instructions will be followed, Air Traffic Control (ATC) often incorporates additional spacing buffers between arriving aircraft to ensure that separation standards are not violated. By reducing uncertainties in the arrival process and precisely spacing aircraft over the runway threshold, the need for such buffers may be lessened. This could effectively increase airport arrival capacities even without altering in-trail separation minima [3].

As part of NASA's Distributed Air/Ground Traffic Management (DAG-TM) effort, under the Advanced Air Transportation Technologies (AATT) project, NASA Langley Research Center has developed airborne tools to precisely space arrival aircraft and increase arrival throughput. An initial concept was called Advanced Terminal Area Approach Spacing (ATAAS). Under this concept, time-based spacing intervals were maintained between successive in-trail arrival aircraft using onboard speed guidance [4]. Other features of the ATAAS guidance included smooth transitioning to a stabilized final approach, compensation for dissimilar final approach speeds and wake turbulence classes, and adherence to aircraft configuration speed limits. This concept was evaluated using both high-fidelity flight simulator experiments and flight tests [5,6].

An extension to ATAAS is NASA Langley's Airborne Merging and Spacing for Terminal Arrivals (AMSTAR) concept [7]. AMSTAR also uses onboard speed guidance to achieve precise interarrival times. However, a key capability of AMSTAR is that aircraft are no longer required to be in-trail. This supports the frequent situation in which multiple arrival routes are flown to a

common runway. In such instances, AMSTAR ensures safe airborne-managed merging and spacing among multiple arrival streams.

AMSTAR Concept of Operations

Under the AMSTAR concept of operations, equipped aircraft enter the Terminal Radar Approach Control (TRACON) airspace on a charted arrival route containing lateral and vertical constraints plus a nominal speed profile (Figure 1). ATC then issues a precision spacing clearance consisting of the callsign of the preceding traffic (the "lead aircraft," which may be on a different arrival route) and a time-based spacing interval. The pilot enters this data into the AMSTAR avionics via the flight management system (FMS). Using Automatic Dependent Surveillance-Broadcast (ADS-B) data from the lead aircraft, AMSTAR generates speed guidance that is presented to the pilot on the aircraft's primary flight display and navigation display. The pilot follows the AMSTAR speed guidance with either manual throttle control or a new autothrottle mode called Paired-Dependent Speed (PDS). Following the speed guidance then results in the aircraft crossing the runway threshold at the assigned spacing interval.

Figure 1. Prototype Merging AMSTAR Arrival Routes For DFW Runway 18R

Fast-Time Simulation Goals

Human-in-the-loop simulation and flight testing is necessary to evaluate many aspects of the AMSTAR system, such as flight crew acceptability, ATC acceptability, and operator workload. However, other experiments can be conducted more appropriately, and more efficiently, by means of fast-time simulation. NASA's fast-time AMSTAR simulations are designed to complement human-in-the-loop experiments by studying such factors as wind prediction inaccuracies, mixed aircraft classes in the arrival stream, data broadcast range limitations, and TRACON entry time errors. These results will then be used to identify the range of conditions under which AMSTAR can operate and to tune the performance of the AMSTAR speed guidance algorithms.

TMX Traffic Manager

The TMX traffic manager has been developed by the National Aerospace Laboratory (NLR) of the Netherlands, in cooperation with NASA Langley, and serves as a key element for air traffic management research at both facilities. It was originally designed in 1996 on a 486 PC to study the interactions of multiple aircraft operating in a Free Flight environment with airborne separation assurance [8]. Since then, it has been ported to Windows and continually enhanced for use in a wide range of simulation projects, including runway incursion research. As TMX has evolved, a constant emphasis has been placed on computational efficiency, allowing TMX to simulate up to 1000 aircraft simultaneously. This capability is particularly useful for studies of high-density traffic situations [9].

In order to realistically simulate traffic operating under a variety of air traffic management concepts, TMX contains the following features:

- *Aircraft Performance Models:* over 200 different 6 degree of freedom models, including fuel consumption, using the Eurocontrol Base of Aircraft Data (BADA) [10].
- *Autoflight Model*: basic altitude, heading, and speed modes, plus FMS-coupled LNAV and VNAV modes with autothrottles

- *Airborne Separation Assurance Systems (ASAS)*: conflict detection, resolution, and prevention systems selectable among 10 variants
- *Gate to Gate Operations:* includes ILS approach and taxi control
- *Pilot Model*: includes parameters for reaction time and scheduling effects
- *ADS-B Model*
- *Wind Model*: 3-D truth and predicted wind fields
- *Weather Model*: includes moving weather cells

Used as a stand-alone air traffic simulator, TMX can operate in real-time or fast-time, accepting user input both from predefined scenario files (which contain time-stamped commands to create, control, and delete aircraft throughout a scenario) and a graphical user interface. The user interface, shown in Figure 2, contains a radar-like traffic window with zoom/pan functionality, a command/message window, and a flight strip window.

Figure 2. TMX User Interface

TMX can also be operated as part of an on-line traffic simulation, in which TMX provides a realistic air traffic environment for one or more piloted flight simulators. In this configuration, TMX also acts as an experiment manager station, controlling simulation modes (start/stop/pause) and dynamically allocating aircraft among external simulators. To enable this functionality, TMX

contains interfaces for DirectX (using Microsoft Direct Play to connect over the internet), TCP/IP, and High Level Architecture (HLA). With these capabilities, TMX has been used in distributed simulations at both NLR and NASA Langley. In addition, TMX can interface with the commercial flight simulator X-Plane.

Figure 3 shows the overall TMX architecture. Aside from the primary traffic state update loop, TMX employs an event-driven architecture with a command stack populated from scenario files, from user interface input, and from externally connected flight simulators. Scenarios are recorded for playback and for use as new initial conditions, and a data-logging module records information for post-experiment analysis.
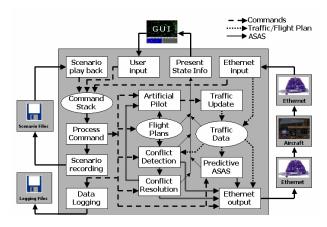

Figure 3. TMX Architecture

AMSTAR-TMX Integration

AMSTAR is integrated into the TMX autothrottle module, incorporating PDS as an additional speed guidance mode (Figure 4). The autothrottle module is itself a subset of the LNAV/VNAV module, which chooses speeds based on waypoint restrictions in the FMS route. As such, PDS can only be engaged when a TMX aircraft is flying fully coupled to its FMS route (when uncoupled, TMX uses a procedural speed mode, based on the aircraft type, configuration, and altitude). This is a limitation in that certain nonstandard procedures cannot be simulated (e.g., following the AMSTAR approach path in heading-select and vertical speed-select autoflight modes). However, such procedures are not intended to be examined in the AMSTAR fast-time simulations.
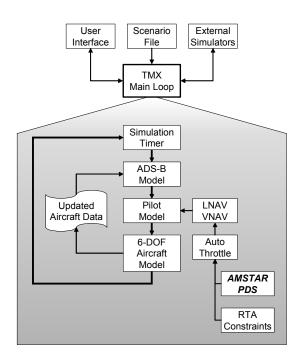
Figure 4. AMSTAR-TMX Integration

The AMSTAR code base in TMX is identical to that used in NASA Langley's higher-fidelity flight simulators [11]. However, the AMSTAR interface, which was originally designed for a single aircraft, has been modified to allow up to 50 simultaneous AMSTAR arrivals in TMX.

The AMSTAR module input information consists of:

- *Command Data:* lead aircraft and spacing interval
- *Traffic Data:* state, route, final approach speed, weight class
- *Ownship Data:* state, route, final approach speed, weight class
- *Environment Data:* airport elevation, approach winds
- *Time Data:* current time and increment

Whereas the command data would normally be input by the pilot based on ATC clearances, this data is input via user interface commands, scenario file commands, or default values in TMX. Per the TMX ADS-B model, traffic data is available in 1 Hz updates. Because ownship data is internally calculated by each aircraft, the most recently calculated ownship data is always available. This

data is directly passed to AMSTAR, along with the environment and time data.

Because AMSTAR is essentially a control law, it requires a minimum update rate of 4 Hz. This has required TMX to bypass some of its internal schedule routines, which were designed based on computational efficiency. For example, the TMX autothrottle module previously updated speed guidance at 1 Hz. When AMSTAR is active, TMX now automatically modifies its scheduling parameters to ensure a minimum speed guidance update rate of 4 Hz.

TMX Enhancements for AMSTAR Simulations

Improved Aircraft Performance Models

The BADA aircraft performance models used by TMX define coefficients for 5 flight phases: takeoff, initial climb, cruise, approach, and landing. To increase the fidelity of the models, additional logic has been included in TMX to determine phase of flight, aircraft configuration and, consequently, aircraft performance. This logic is based on current airspeed, target airspeed, current altitude, target altitude, and vertical speed. In addition, drag coefficient data has been expanded in the approach and landing phases, resulting in enhanced flight characteristics in high-lift/high-drag configurations and more accurate final approach speeds.

Improved ADS-B Model

A more realistic ADS-B message reception model has been added to TMX in order to support studies of ADS-B range limitations on AMSTAR performance. Previously, TMX used a deterministic ADS-B reception model with a single maximum distance parameter. For two aircraft within this maximum distance, ADS-B messages were always received. For two aircraft outside this maximum distance, messages were never received.

The improved TMX ADS-B model more accurately depicts message reception behavior near the range limit. Two distance parameters are specified, between which the probability of message reception varies according to the following function:

$$P_{reception} = \begin{cases} 1 & r \le r_1 \\ \exp\left[-4.5\left(\dfrac{r - r_1}{r_2 - r_1}\right)^2\right] & r_1 < r < r_2 \\ 0 & r \ge r_2 \end{cases}$$

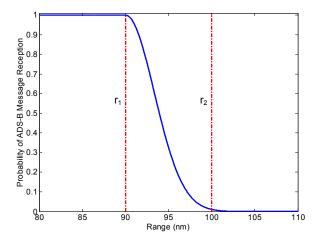Figure 5 shows the ADS-B message reception function for $r_1 = 90$ nm and $r_2 = 100$ nm.

Figure 5. TMX ADS-B Reception Model

The TMX ADS-B interface has also been enhanced to process messages with varying update rates. Previously, TMX processed all ADS-B data at 1 Hz, the frequency of aircraft state messages. However, AMSTAR makes use of both state messages and a new TRACON message (sent every 30 sec.). The TRACON message, which conforms to the ADS-B on-condition message format, includes additional information necessary for AMSTAR operations. TMX is now able to process both of these ADS-B message types. In addition, ADS-B buffers have been added to store historical ADS-B data, which is used by AMSTAR when ADS-B updates are unavailable.

Arrival Sequencer/Scheduler

An arrival sequencer/scheduler has been added to TMX to properly assign lead aircraft and spacing intervals to AMSTAR arrivals. In addition, the sequencer/scheduler issues a TRACON entry time to each aircraft. This Required Time of Arrival (RTA) is part of the NASA DAG-TM concept for transitioning from en-route to terminal area airspace. Under this concept, an aircraft manages its own flight path to arrive at an ATC-assigned TRACON entry point (the "meter fix") at an ATC-specified and flight crew accepted RTA [12,13]. Initially movable, the RTA is fixed once an aircraft is within a certain distance (the "freeze horizon") from the meter fix. As currently implemented in TMX, each freeze horizon is approximately 160 nm from its associated meter fix, well before top of descent for a typical transport category aircraft.

The RTA-issuing capability of the sequencer/scheduler will be used to examine the effects of TRACON entry time errors on AMSTAR performance. The RTAs output by the sequencer/scheduler are directly based upon the AMSTAR spacing intervals issued by the sequencer/scheduler. As such, an aircraft that meets its RTA should already be near the correct spacing interval as it crosses the meter fix. By incorporating errors into the meter fix crossing times, it will be possible to determine the sensitivity of AMSTAR to the amount of time that needs to be "made up" or "lost" throughout the duration of an arrival.

The sequencer/scheduler is designed to operate only using data available in the TMX ADS-B model. This data includes current state information (position and velocity) plus up to 4 Trajectory Change Points (TCPs) from the aircraft's intent trajectory. Exceptions to this rule include data stored within the scheduler, such as a database of arrival routes, a prediction of winds along the arrival routes, and a matrix of required separations according to aircraft wake turbulence class. Also, while an operationally-deployed sequencer/scheduler—as part of a ground-based decision support tool suite—would likely determine arrival routes and landing runways based upon optimal runway balancing criteria, the TMX sequencer/scheduler uses arrival routes and runways that are assigned a priori through the TMX scenario files. This was done for several reasons: Because NASA Langley is primarily focusing on the airborne components of the AMSTAR concept, a more complex sequencer/scheduler was deemed unnecessary. More importantly, by explicitly assigning arrival routes and runways in advance, there is more control over the scenarios used for AMSTAR fast-time simulations. Figure 6 shows the inputs and outputs used by the TMX sequencer/scheduler.
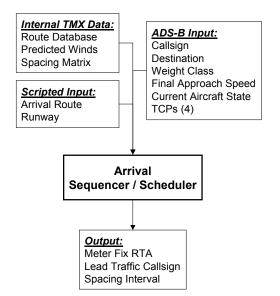
Figure 6. Inputs And Outputs For TMX Arrival Sequencer / Scheduler

Aircraft sequences are based upon Estimated Times of Arrival (ETAs) at the runway threshold. For each aircraft, the meter fix ETA is first calculated using ADS-B data. If the meter fix is contained in the aircraft's TCP reports, this ETA is used. Otherwise, the meter fix ETA is extrapolated from the last TCP ETA. If no TCP data is available, a direct course from the current aircraft position to the meter fix is assumed. Then, after accessing a database of arrival routes and predicted winds, the sequencer uses a trajectory synthesizer to generate runway threshold ETAs. To ensure compatibility between the arrival schedules and the AMSTAR speed guidance, the TMX scheduler uses the same trajectory synthesizer as AMSTAR.

Once landing sequences are determined, the TMX arrival scheduler uses a matrix of pair-wise, weight class-based (small, large, heavy, B757) wake turbulence separation minima to calculate AMSTAR spacing intervals and runway threshold RTAs, from which meter fix RTAs can be found. If an aircraft has crossed the freeze horizon, the sequencer/scheduler then assigns its meter fix RTA, lead aircraft, and spacing interval. Otherwise the aircraft is returned to the sequencer/scheduler along with updated ADS-B data, if available. Figure 7 depicts the operation of the sequencer/scheduler in flowchart form.
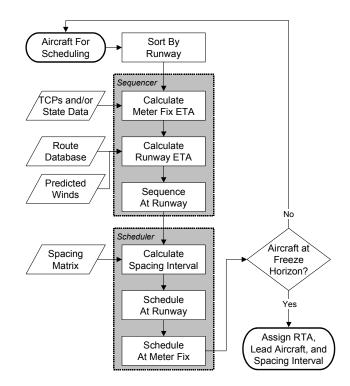

Figure 7. TMX Arrival Sequencer / Scheduler Flowchart

Capability to Meet Waypoint RTAs

In order to meet meter fix RTAs issued by the arrival scheduler, an additional speed mode has been added to TMX. For aircraft with an RTA-constrained waypoint, this speed mode computes an indicated airspeed (IAS) for the autothrottle to follow. This improves the realism of TMX arrival operations, as it allows aircraft to meet RTAs while performing constant-speed descents.

To compute the required IAS, the aircraft flight plan is first passed to a routine that generates TCPs (flight plan waypoints, top-of-descent points, speed change points, etc.). ETAs are then calculated for each TCP, using the predicted wind model. If an RTA-constrained waypoint exists, the groundspeed required to meet the RTA is calculated. This is converted into a constant IAS, which is then used to update any top/bottom-of-descent points on the RTA-constrained route leg. Given a reasonable RTA (i.e., within the performance limits of the aircraft), the computed IAS will result in the aircraft meeting the RTA within 10 sec.

TRACON Operations Automation

To simulate AMSTAR pilot procedures in the TRACON (e.g., selecting a lead aircraft, engaging PDS autothrottles, exiting the runway after landing), automation has been added to the TMX pilot model. Upon entering the TRACON with an assigned lead aircraft and spacing interval, this data is automatically entered into AMSTAR. Once lead aircraft ADS-B data is available, PDS autothrottles are automatically engaged. After landing, aircraft are automatically deleted from the scenario. These automated functions can also be overridden with scenario file commands or commands input via the TMX user interface. This allows for the simulation of irregular operations such as amended lead aircraft assignments, amended spacing intervals, and go-arounds.

Initial Simulation Results

To demonstrate the enhancements to TMX discussed above, this section presents a simulation of multiple AMSTAR arrivals flying multiple routes to a single runway. In particular, this serves to highlight the TMX sequencer/scheduler, the capability to meet waypoint RTAs, and the merging and spacing performance of AMSTAR.

In this scenario, a total of six aircraft are flying arrivals to DFW. Three aircraft are following the BAMBE FMS Transition to runway 18R, and three aircraft are following the FEVER FMS Transition to the same runway, with the two streams merging on their base legs (see Figure 1 for a prototype approach plate). The aircraft are initialized prior to top of descent, approximately 120 nm from their meter fixes. Also, an altitude-varying wind profile is included that ranges from 10 kt at 180 deg at the surface to 50 kt at 250 deg at 40,000 ft. Figure 8 shows the initial aircraft positions on a portion of the TMX user interface (with colors reversed for clarity). Note that sequence numbers, shown in the aircraft data tags, and meter fix RTAs have already been assigned by the sequencer.

After receiving RTAs, TMX commands aircraft speeds that will allow the aircraft to cross their meter fixes at their assigned times. This will ensure that AMSTAR operations begin with a reasonable initial spacing. Figure 9 shows the aircraft staggered as they arrive at their meter fixes.

Table 1 shows the RTA accuracy for all six aircraft. Note that, due to path length differences between the two arrival routes, the meter fix RTAs do not necessarily increase according to landing sequence.
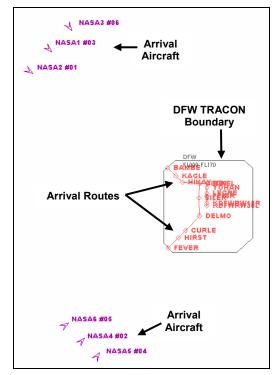

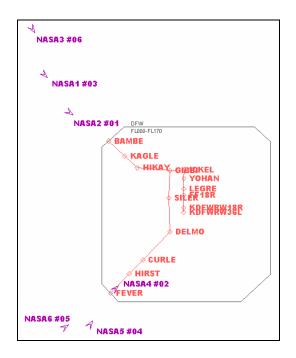**Figure 8. Initial Conditions of Arrival Scenario**

Figure 9. Aircraft Meeting Meter Fix RTAs

Table 1. TMX Actual Time of Arrival (ATA) vs. Assigned RTA at Meter Fix

Call Sign	Meter Fix	Meter Fix RTA (sec)	Meter Fix ATA (sec)	Error (sec)
NASA2	BAMBE	1155.7	1159.0	3.3
NASA4	FEVER	920.8	918.4	-2.4
NASA1	BAMBE	1425.7	1423.4	-2.3
NASA5	FEVER	1160.8	1158.5	-2.3
NASA6	FEVER	1310.8	1308.4	-2.4
NASA3	BAMBE	1770.7	1768.4	-2.3

Table 2. AMSTAR Spacing Performance at Runway Threshold

Call Sign	Weight Class	Threshold Crossing (sec)	Assigned Spacing (sec)	Spacing Error (sec)
NASA2	Heavy	1984.8	n/a	n/a
NASA4	B757	2130.6	150	-4.2
NASA1	B757	2250.2	120	-0.4
NASA5	Heavy	2369.0	120	-1.2
NASA6	Large	2518.0	150	-1.0
NASA3	Large	2597.7	75	4.7

Once each aircraft crosses its meter fix and enters the terminal area, TMX automatically engages PDS autothrottles, using the assigned lead aircraft and spacing interval output by the arrival scheduler. Figure 10 shows the aircraft actively spacing along their arrival paths. Table 2 shows the resulting performance of the AMSTAR speed guidance, measured by threshold crossing times relative to the assigned spacing intervals.
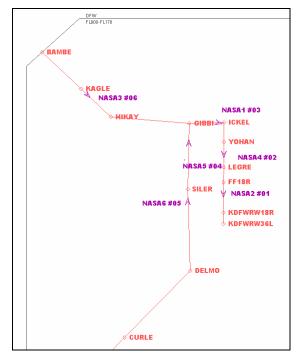

Figure 10. AMSTAR Approach Spacing Active

Concluding Remarks

This paper has presented a simulation environment used by the NASA Langley Research Center for fast-time studies of the AMSTAR airborne merging and spacing concept. This environment, TMX, contains an interface for the AMSTAR speed guidance as well as the necessary supporting elements of an arrival sequencer and scheduler, a capability to meet waypoint RTAs, a model of ADS-B communications, and realistic approach flight characteristics for a large set of aircraft types.

A sample AMSTAR arrival scenario has been presented that simulated six aircraft landing in sequence on a single runway, using two different arrival routes. In the presence of altitude-varying winds, TMX was able to deliver the aircraft within 3 sec. of their meter fix RTAs, and the AMSTAR speed guidance was able to deliver the aircraft within 5 sec. of their assigned runway threshold spacing intervals.

The integration of AMSTAR into TMX is a precursor to further fast-time simulation studies of the AMSTAR concept. This future work will concentrate on the effects of ADS-B range limitations, wind prediction inaccuracies, mixed aircraft classes in the arrival stream, and TRACON entry time errors.

References

[1] Stein, Mark A., "Flight Delays, Down After 9/11, Grow Worse Again", The New York Times, July 6, 2004

[2] Federal Aviation Administration, 2004, "Capacity Needs in the National Airspace System: An Analysis of Airport and Metropolitan Area Demand and Operational Capacity in the Future"

[3] Andrews, John W., John E. Robinson III, 2001, "Radar-Based Analysis of the Efficiency of Runway Use", 2001 AIAA Guidance, Navigation & Control Conference, Montreal, Canada.

[4] Abbott, T.S., 2002, "Speed Control Law for Precision Terminal Area In-Trail Self Spacing", NASA TM 2002-211742

[5] Oseguera-Lohr, Rosa M., Gary W. Lohr, Terence S. Abbott, Todd M. Eischeid, 2002, "Evaluation of Operational Procedures For Using A Time-Based Airborne Interarrival Spacing Tool", AIAA 2002-5824

[6] Lohr, Gary W., Rosa M. Oseguera-Lohr, Terence S. Abbott, William R. Capron, 2003, "Flight Evaluation of a Time-Based Airborne Interarrival Spacing Tool", 5th Eurocontrol/FAA ATM R&D Seminar, Budapest, Hungary

[7] Barmore, Bryan, Terence Abbott, Karthik Krishnamurthy, 2004, "Airborne-Managed Spacing in Multiple Arrival Streams", submitted to 24th International Congress of the Aeronautical Sciences, Yokohama, Japan.

[8] Hoekstra, J.M., 2001, "Designing For Safety: The Free Flight Air Traffic Management Concept", Doctoral Thesis, Delft University of Technology, ISBN 90-806343-2-8

[9] Hoekstra, J.M., R.C.J. Ruigrok, R.N.W.H. van Gent, 2000, "Free Flight in a Crowded Airspace?", 3rd Eurocontrol/FAA ATM R&D Seminar, Napoli, Italy

[10] Nuic, A., 2003, "User Manual for the Base of Aircraft Data (BADA) – Revision 3.5", Eurocontrol Experimental Centre, Bretigny, France http://www.eurocontrol.fr/public/reports/eecnotes/2003/11.pdf

[11] Palmer, Michael T., Bryan E. Barmore, Terence S. Abbott, 2004, "Integration of Paired-Dependent Speed Guidance into Current-Generation Glass-Cockpit Commercial Aircraft", submitted to 24th International Congress of the Aeronautical Sciences, Yokohama, Japan

[12] Advanced Air Transportation Technologies Project Office, 1999, "Concept Definition for Distributed Air/Ground Traffic Management (DAG-TM) Version 1.0", NASA Ames Research Center, Moffett Field, CA

[13] Advanced Air Transportation Technologies Project Office, 2004, "DAG-TM Concept Element 5 'En Route Free Maneuvering': Operational Concept Description, TRL 4", NASA Ames Research Center, Moffett Field, CA