

FACET: Future ATM Concepts Evaluation Tool

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Abstract

FACET (Future Air Traffic Management Concepts Evaluation Tool) is a simulation and analysis tool being developed at the NASA Ames Research Center. This paper introduces the design, architecture, functionalities and applications of FACET. The purpose of FACET is to provide a simulation environment for exploration, development and evaluation of advanced Air Traffic Management concepts. Examples of these concepts include new Air Traffic Management paradigms such as Distributed Air/Ground Traffic Management, advanced Traffic Flow Management, and new Decision Support Tools for controllers working within the operational procedures of the existing air traffic control system. FACET models system-wide en route airspace operations over the contiguous United States. The architecture of FACET strikes an appropriate balance between flexibility and fidelity. This feature enables FACET to model airspace operations at the U.S. national level, and process over 5,000 aircraft on a single desktop computer running on any of a wide variety of operating systems. FACET has been designed with a modular software architecture to facilitate rapid prototyping of diverse Air Traffic Management concepts. FACET has prototypes of several advanced Air Traffic Management concepts: airborne self-separation; a Decision Support Tool for direct routing; advanced Traffic Flow Management techniques utilizing dynamic density predictions for airspace redesign and aircraft rerouting; and, the integration of space launch vehicle operations into the U.S. National Airspace System.

Introduction

The global Air Traffic Management (ATM) system faces the challenge of increasing system capacity and flexibility to accommodate traffic growth and user preferences, while maintaining or improving the current level of safety. In order to achieve these goals, new ATM concepts must be explored and evaluated prior to field-testing and eventual deployment. Therefore, an ATM system model is necessary for simulation evaluations of new ATM concepts.

A variety of ATM system models have been developed by various organizations, many of them tailored to a specific set of applications. A NASA-sponsored comprehensive study on existing and required modeling capabilities for evaluating ATM systems and concepts is reported in [1]. It includes functional descriptions of several existing models such as RAMS, SIMMOD and TAAM.

FACET (Future ATM Concepts Evaluation Tool) was developed to meet anticipated requirements for advanced ATM concept development and evaluation activities under NASA's Advanced Air Transportation Technologies (AATT) Project. Based on these requirements, it was determined that there was a need for a flexible modeling environment that would facilitate: (1) Rapid prototyping of diverse ATM concepts; (2) Modeling of new vehicle classes such as space launch vehicles; and, (3) Collaborative research and development efforts with other organizations. It is believed that existing ATM models cannot provide the high level of flexibility necessary for realizing all of the above three capabilities.

This paper provides an introduction to FACET. It begins with an overview, and then presents details about the architecture and capabilities of FACET. Finally, the paper presents a description of several advanced ATM concepts that are currently at various stages of evaluation in FACET.

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Overview of FACET

FACET was designed to provide a flexible simulation environment for the exploration, development and evaluation of advanced ATM concepts. Evaluations of concept feasibility do not generally require a high level of simulation detail. Therefore, FACET's architecture strikes an appropriate balance between flexibility and fidelity, enabling it to model airspace operations at the U.S. national level, and process over 5,000 aircraft on a single desktop computer (e.g., Sun Ultra1, Pentium based PC, Macintosh G3) for a wide variety of operating systems. The core of FACET was designed to provide initially only those modeling features (e.g., airspace and trajectory models) that would be required for the evaluation of virtually any ATM concept application. Other modeling features would be added as required by individual ATM concept applications.

FACET models en route airspace over the entire contiguous United States. The airspace model includes geometric descriptions of Air Route Traffic Control Centers (ARTCCs or "Centers"), their sectors (low, high and super-high), Victor Airways and Jet Routes, as well as the locations of airports and fixes (navigation aids and airway intersections). FACET is hierarchically compatible with the Center-TRACON Automation System (CTAS) [2] in terms of scope and fidelity. The national-level flexible modeling capabilities of FACET will complement the Center-level high-fidelity modeling capabilities of CTAS. In addition to exploring future ATM concepts, FACET will also support the future development of CTAS by providing a simulation environment for preliminary testing and evaluation of new controller Decision Support Tools (DSTs).

FACET models four-dimensional (4D) aircraft trajectories in the presence of winds using round-earth kinematic equations. Aircraft can be flown along flight plan routes or direct (great circle) routes as they climb, cruise and descend according to their individual aircraft-type performance models. Performance parameters (e.g., climb/descent rates and speeds, cruise speeds) are obtained from data table lookups. Heading and airspeed dynamics are also modeled. FACET can predict the future locations of aircraft; these data can be supplied to application modules implementing advanced traffic flow management concepts. It also has graphic capabilities for data analysis and visualization.

FACET utilizes oblique stereographic projection (and its inverse) for displaying airspace features and air traffic movement on a menu-driven Graphical User Interface (GUI). It can be operated in real-time, fast-time or slow-time, with various options described later in the following section.

FACET Architecture and Functionalities

This section first describes the system architecture of FACET, and then details its various functionalities, including trajectory, weather and airspace modeling; system operating modes; and Graphical User Interface.

System Architecture

The FACET software integrates two distinct components: (1) Data computation using the "C" programming language; and, (2) Display of information through a GUI written in the "Java" programming language. This feature has enabled the portability of FACET software to computers running on several operating systems: Unix, Windows NT, MacOS and Linux.

FACET was designed with a modular architecture to facilitate rapid prototyping of advanced ATM concepts. Each ATM concept application is implemented as an individual module linked to the core structure of FACET. This core provides modeling features (e.g., airspace and 4D trajectories) required for the evaluation of almost any ATM concept.

A conceptual representation of FACET's core architecture is presented in Fig. 1. Details of the various databases and modules are provided in the following three subsections on Trajectory Modeling, Weather Modeling and Airspace Modeling. Data inputs to FACET include an airspace database, a weather database, an aircraft performance database, and air traffic (track, flight plan and schedule) data from an appropriate source such as the Enhanced Traffic Management System (ETMS).

FACET can be run in either playback mode or simulation mode. In the playback mode, track data are sent to the GUI for display. In the simulation mode, a 4D trajectory is synthesized from a set of initial conditions (that may either be derived from real track data or custom designed for a specific application) using various routing and navigation options, as described below.

Trajectory Modeling

In the simulation mode, 4D aircraft trajectories are determined from a set of initial states, using either the Direct (great circle) Routing option or the Flight Plan Routing option, as specified by the user. The Direct Routing (DR) module extracts the destination airport identifier from the flight plan and then determines the latitude and longitude of the destination point from the Airspace Database. The Flight Plan Routing (FPR) module ingests the entire flight plan, which contains route information expressed in terms of the names of fixes (navigational aids and airway intersections), Fix Radial Distance (FRD), and special waypoint coordinates. The names of fixes are converted into positions using the Airspace Database. The FRD

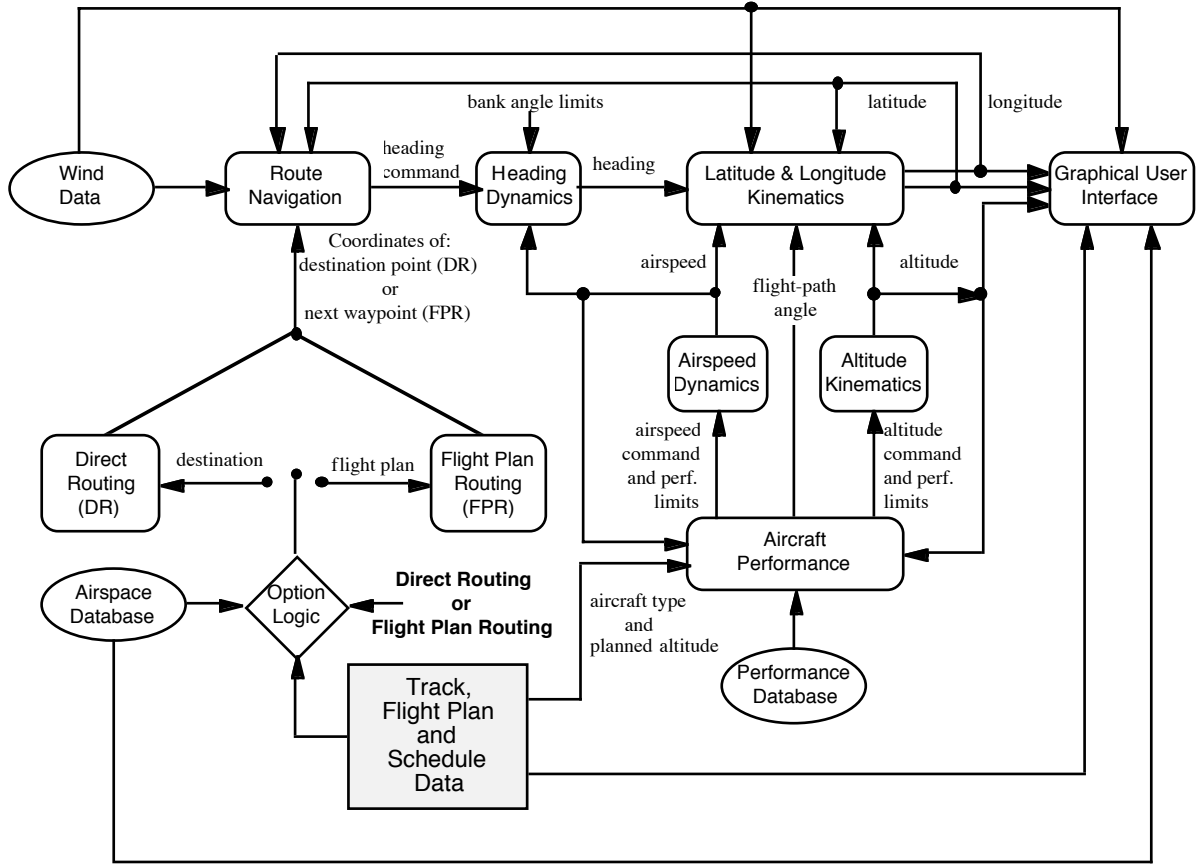


Fig. 1: Conceptual Representation of Core FACET Architecture

specifies a location in terms of distance and bearing from a fix; thus, using the location of the fix from the Airspace Database, the location specified by the FRD is obtained. Finally, the Flight Plan Routing module employs a flight plan parsing algorithm that reads the flight plan information and creates an ordered sequence of latitudes and longitudes that specify the locations of all waypoints defining the route of flight.

Based on the user-selected routing option, the coordinates of either the destination point (airport) or the next waypoint on the flight plan route are computed by the appropriate routing module (DR or FPR). These coordinates are then sent to the Route Navigation module which uses great circle navigation to determine the course angle to the next navigation point; an option for rhumb line (constant course angle) navigation is also available. It is noted that a direct route is flown as a single great circle, while a flight plan route is flown as a series of individual great circles (or, optionally, rhumb lines) connecting the waypoints. Using the current latitude-longitude coordinates (λ, τ) of the aircraft and the latitude-longitude coordinates (λ^*, τ^*) of the appropriate navigation point (destination point for DR option or next waypoint for FPR option), the course angle χ_{GC} for great circle navigation (or χ_{RL} for rhumb line navigation) can be calculated. For example, the great circle navigation law [3] is given by

$$\chi_{GC} = \tan^{-1} \left\{ \frac{\sin(\tau^* - \tau) \cos \lambda^*}{\sin \lambda^* \cos \lambda - \sin \lambda \cos \lambda^* \cos(\tau^* - \tau)} \right\} \quad (1)$$

The Route Navigation Module finally computes the heading angle command, χ_{com} , by adding a wind correction angle to the great circle (or rhumb line) course angle. The aircraft heading angle, χ , is then obtained from the Heading Dynamics module as the response of a first-order system with proportional feedback, subject to bank angle limits.

FACET's Performance Database contains performance models for 66 different aircraft types; it also contains an equivalence list that maps over 500 aircraft types recognized by the Federal Aviation Administration (FAA) to these 66 performance models. For climbs/descents, the airspeed and altitude-rate are derived from the calibrated airspeed (CAS) and Mach schedules for the particular aircraft type. For cruise flight, the airspeed is derived from cruise schedules for the particular aircraft type.

The pressure altitude h resulting from an altitude command, h_{com} (e.g., cruise altitude), is obtained from the Altitude Kinematics module as the response of a first-order system with proportional feedback, subject to

altitude-rate limits obtained from the Performance Database.

Using information on altitude and altitude-rate, the Aircraft Performance module determines the airspeed command, V_{com} , from a performance table lookup for the appropriate aircraft type. The airspeed, V , is then obtained from the Airspeed Dynamics module as the response of a first-order system with proportional feedback, subject to acceleration limits derived from the Performance Database.

The Latitude & Longitude Kinematics module integrates the round-earth equations of motion given by

$$\dot{\lambda} = \frac{1}{R} (V \cos \gamma \cos \chi + W_N) \quad (2)$$

$$\dot{t} = \frac{1}{R \cos \lambda} (V \cos \gamma \sin \chi + W_E) \quad (3)$$

where the flight-path angle, γ , is approximated by

$$\gamma \approx \sin^{-1}(\dot{h} / V) \quad (4)$$

In Eqs. (2) and (3) above, W_N and W_E are the north and east components of the wind speed, and $R = R_e + h_g$, where R_e is the mean radius of the earth and h_g is the geometric altitude. However, since $h_g \ll R_e$ for atmospheric flight, the approximation $R \approx R_e + h$ is used, where h is the pressure altitude.

Weather Modeling

FACET utilizes weather data generated by the Rapid Update Cycle version 2 (RUC-2), available on an hourly basis from the National Center for Environmental Prediction [4]. RUC-2 provides short-range forecasts of wind and temperature profiles (along with other atmospheric and surface parameters) over various time intervals ranging from 1 hr to 12 hrs. The horizontal resolution of the RUC-2 grid is 40 km, and the vertical resolution includes 37 isobaric levels corresponding to pressure altitudes ranging approximately from sea level to 53,000 ft.

Airspace Modeling

A general description of airspace features can be found in [5]. FACET contains a comprehensive Airspace Database that represents the geometry and structure of the airspace in the 20 ARTCCs covering the contiguous United States. It defines the horizontal boundaries of all 20 ARTCCs as well as the horizontal and vertical boundaries of all sectors (low altitude, high altitude, and super-high altitude) within each ARTCC.

Representations of airways (both Victor Airways and Jet Routes) are available in terms of the fixes (navigation aids and airway intersections) that define them. Position data for each fix are available within the

Airspace Database. The locations of over 13,000 U.S. airports are also available.

System Operating Modes

FACET can operate in either simulation mode or playback mode, as selected by the user. In simulation mode, FACET generates trajectories using initial conditions obtained from track and flight plan data. This mode is appropriate for the testing and evaluation of new ATM concepts implemented in FACET. In playback mode, FACET replays track data from a recorded data file. This mode is appropriate for data visualization applications.

Both of the above modes can be operated in a synchronous or asynchronous manner. Synchronous operation is recommended if the user wishes to maintain a fixed correlation (in fast-time, real-time or slow-time) between trajectory update display and clock time; this is accomplished by introducing an appropriate time delay between computation and display of results. During synchronous operation, there is a linear proportional relationship between trajectory time stamps and clock time (the constant of proportionality is called the time-scale factor), and the display is updated at regular time intervals. This is the default operational state for both simulation and playback modes.

Asynchronous operation is recommended if the user wishes to move through the simulation/playback as quickly as possible; this is accomplished by displaying results as soon as computations are completed. During asynchronous operation, there is a nonlinear monotonic relationship between trajectory time stamps and clock time, and the display is updated at irregular time intervals.

Graphical User Interface

The control and display of all information in FACET is achieved through a Graphical User Interface. The GUI is written using “Swing” and the Abstract Window Toolkit, which is available with the Java Development Kit. The motivation for developing the GUI in “Java” was to facilitate the transfer of FACET software to various computer platforms. Architecturally, FACET has been designed so that all of the data computations are performed in the “C” programming language, and the information display graphics are done in the “Java” programming language. The integration of the Java-based GUI with the underlying C-code data computation is accomplished through the use of the Java Native Interface.

Fig. 2 shows an example Graphical User Interface, which consists of a display canvas, a menu bar, and a status bar. The canvas is primarily used to display the selected airspace boundaries, aircraft locations, flight plans, track histories, and aircraft Flight Data Blocks.

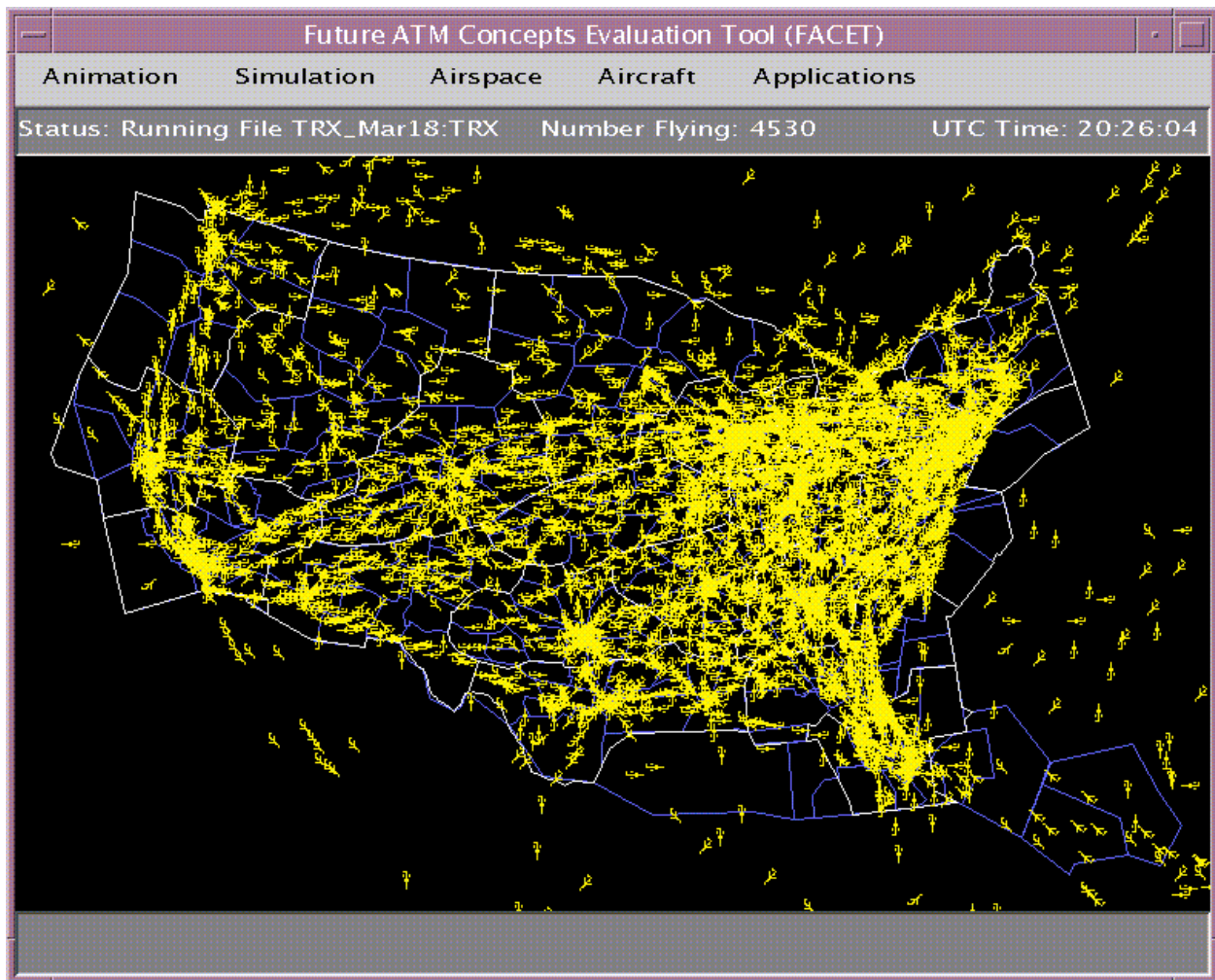


Fig. 2: FACET Graphical User Interface

FACET is menu-driven, and the main menu bar contains the following options: Animation, Simulation, Airspace, Aircraft, and Applications (see Fig. 2). From the Animation Menu, the user can pause, resume, restart, or terminate the current operational mode.

The Simulation Menu is used for selecting an input file to run FACET in Playback Mode, or Simulation Mode with either Direct (great circle) Routing or Flight Plan Routing. This menu also provides the option to run FACET in either synchronous or asynchronous operation mode. Additionally, the Simulation menu provides the capabilities for manually adding aircraft to a simulation and for recording aircraft track data (actual or predicted) over a user-selected ARTCC.

The Airspace Menu controls the display of various airspace features. For example, the 20 ARTCCs over the contiguous United States can be displayed along with their sector (low, high, and super-high) boundaries. Other airspace features include navigational aids / fixes, Jet Routes, and Victor Airways. The user can zoom in and out of the displayed area and translate across the airspace. This menu also provides the user with options for displaying specific waypoints and airways. When

the user clicks on any of the displayed waypoints, the name and coordinates of the waypoint appear in the status bar at the bottom of the GUI. The Airspace menu also provides access to the airspace redesign capabilities of FACET (described in the next section). Using this capability, the user can modify sector boundaries or load a previously saved airspace design in real-time.

By interacting with the Aircraft Menu, the user controls the amount of information displayed for selected (or all) aircraft in an active simulation. This menu provides options for specifying the contents of the aircraft Flight Data Block, modifying an aircraft's flight plan, toggling the display of both flight plans and track histories, and placing size-selectable range-rings around aircraft. In addition to displaying information for specific aircraft, the user can also filter the displayed aircraft based on user-specified combinations of altitude strata, airline, and aircraft type.

The last element of the menu bar is the Applications Menu. This menu allows the user to access application modules for advanced ATM concepts that are currently being implemented in FACET. Some of them are described in the following section.

Advanced ATM Concepts in FACET

This section describes some advanced ATM concepts that are currently at various stages of implementation and evaluation in FACET. These descriptions are not intended to be comprehensive treatments of the individual ATM concepts; the objective is to highlight some of the possible applications of FACET.

Aircraft Self-Separation

Distributed Air/Ground Traffic Management (DAG-TM) is an advanced ATM concept for mature Free Flight operations [6]. In the current air traffic control system, the decision-making authority for air traffic separation is centralized, and resides with the ground-based air traffic controllers. DAG-TM corresponds to a decentralized paradigm of air traffic operations, featuring distributed decision-making between three entities: flight deck, air traffic service provider (ATSP), and aeronautical/airline operational control (AOC). In the DAG-TM paradigm, ATSP personnel may delegate separation responsibility to the pilots of appropriately equipped aircraft under certain operational conditions. Airborne conflict detection and resolution (CD&R) capability is a key requirement for this “Free Maneuvering” aspect of DAG-TM.

Two qualitatively different aircraft-centered CD&R algorithms have been implemented in FACET to conduct studies on Free Maneuvering. One CD&R scheme utilizes a modified potential-field approach [7, 8] to compute conflict avoidance commands that are updated at each cycle, which generally results in continuous path modification. In a multiple conflict situation, an aircraft uses an avoidance command equal to the vector sum of the avoidance commands for all its individual conflicts.

The other CD&R scheme resolves conflicts using a geometric optimization approach [9] that attempts to minimize deviations from the nominal path. Although

conflict avoidance commands are updated at each cycle, this approach nominally resolves a conflict by commanding a single discrete path change; upon completion of the conflict avoidance maneuver, an additional command returns the aircraft to its preferred path. In a multiple conflict situation, an aircraft sequentially resolves the most immediate conflict. Fig. 3a shows a challenging test scenario featuring an eight-aircraft encounter that results in multiple conflicts (without CD&R). Fig. 3b shows the same test scenario with the Geometric Optimization CD&R scheme engaged; all conflicts were resolved.

A realistic free (great circle) flight traffic scenario has been developed in FACET for the Denver Center airspace, using initial conditions from a set of actual (ETMS) air traffic data. This scenario was used as a test environment to evaluate the feasibility of airborne separation assurance for Free Flight. It was found that the impact of self-separation on air traffic operations, as measured by the performance metrics of path-length and flight-time changes, was relatively low [10].

Benefits Study of the CTAS Direct-To Tool

Several studies have shown that airlines can realize significant time/fuel savings and other benefits by flying user-preferred direct routes instead of the current ATC-preferred routes. The CTAS Direct-To Tool [11] belongs to the CTAS family of controller DSTs. It searches through all aircraft within an ARTCC airspace, and identifies aircraft that could save flight time by flying a direct route instead of following the flight plan route. The CTAS Direct-To Tool has been extensively tested using actual traffic data from the Fort Worth Center.

A direct-routing algorithm has been implemented in FACET. Air traffic data from the Fort Worth Center were used to calibrate the FACET Direct-To implementation relative to the CTAS Direct-To implementation. The FACET Direct-To simulation was

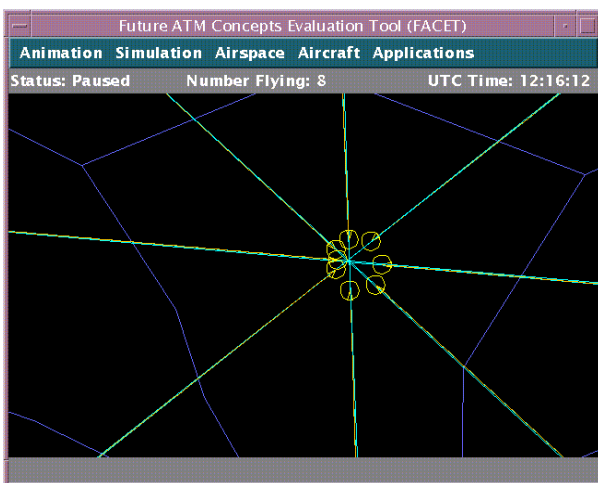


Fig. 3a: Test Scenario without CD&R

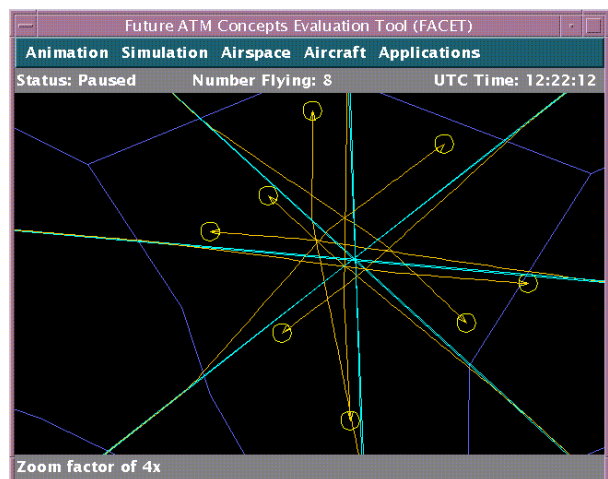


Fig. 3b: Test Scenario with CD&R using Geometric Optimization

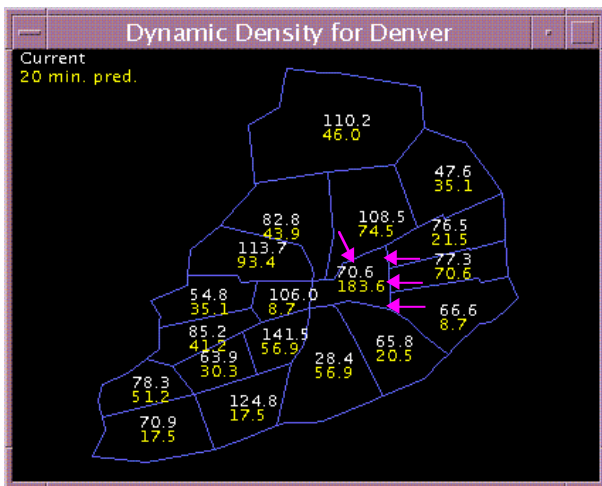


Fig. 4a: Dynamic Density Distributions Before Resectorization

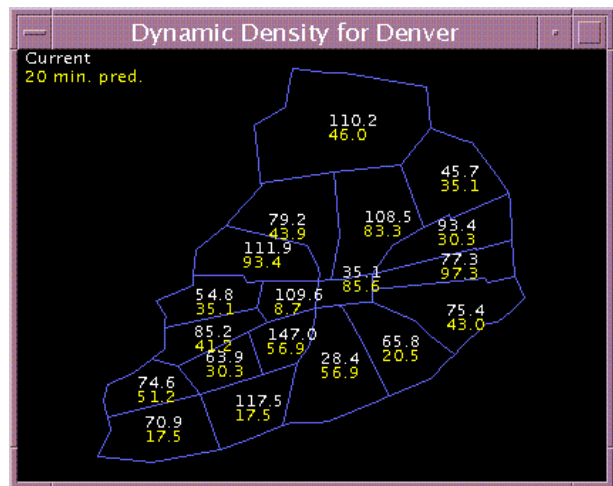


Fig. 4b: Dynamic Density Distributions After Resectorization

run using ETMS data to estimate benefits for 20 ARTCCs in the U.S. National Airspace System (NAS). Initial results indicate NAS-wide savings of up to \$200M per year using the Direct-To Tool [12]. The impact of Direct-To Tool utilization on traffic patterns in the Fort Worth Center was also studied; preliminary results indicate that the Direct-To Tool’s implementation does not significantly change the number or location of conflicts.

Advanced Traffic Flow Management

Predicted growth in air traffic, and the desire for more user-preferred routes in the National Airspace System will require advanced techniques and tools to efficiently manage the flow of air traffic. There will be times when the projected traffic load in a local region of airspace will exceed the abilities of the human controllers to safely and efficiently handle the traffic flow. This load can be balanced by reconfiguring local airspace (sector) boundaries, or by rerouting aircraft to change the pattern of traffic flow.

There is a need to understand the effect of changing airspace configurations and traffic flow patterns on the workload of air traffic controllers. This complex relationship is referred to as “Airspace Complexity.” Research indicates that “Dynamic Density” is a good measure of airspace complexity. Dynamic Density is a function of the number of aircraft and their changing geometries in a given airspace. In order to utilize Dynamic Density in a Traffic Flow Management (TFM) tool, it is necessary to project its behavior over the planning time horizon.

A Dynamic Density measure that was derived from actual controller workload and air traffic data [13] has been implemented in FACET. Using the trajectory prediction capabilities of FACET (based on flight plans and aircraft performance models), the aircraft states can be calculated at various times along the planning horizon. These predicted aircraft positions and speeds

are then used to calculate the Dynamic Density at the corresponding times, up to 30 minutes in advance. The prediction time horizon is limited primarily by the accuracy of departure time estimates [14].

An example of Dynamic Density distributions is shown in Fig. 4a. In this particular example, both the current and 20-minute predicted Dynamic Density values for all of the high-altitude sectors in the Denver Center are displayed. It can be seen that the Dynamic Density in the central sector, currently at 70.6, is predicted to increase to 183.6 after 20 minutes. For illustrative purposes, the boundaries of this sector were manually reconfigured (as shown by the arrows in Fig. 4a) in an attempt to reduce the build-up of Dynamic Density over the next 20 minutes. Fig. 4b shows the resulting changes in the distribution of dynamic densities. It can be seen that the 20-minute prediction of Dynamic Density in the central sector has decreased to 85.6, at the expense of increased dynamic densities in neighboring sectors, especially the sectors to the east of the central sector. The airspace reconfiguration obtained in this illustrative example may be acceptable if the values of predicted Dynamic Density in the neighboring sectors are within acceptable limits.

Tools for automated airspace redesign and aircraft rerouting are under development in FACET. These Traffic Flow Management tools will make it possible to easily modify airspace configurations and traffic flows at the sector (or even ARTCC) level, and evaluate their impact on air traffic operations by utilizing proven guidelines for airspace complexity and controller workload measures.

Space Launch Vehicle Operations in the NAS

Due to the increasing emphasis on affordable access to space, the number of Space Launch Vehicle operations is expected to increase significantly over the next decade [15, 16]. These vehicles operate within the National Airspace System during a portion of their

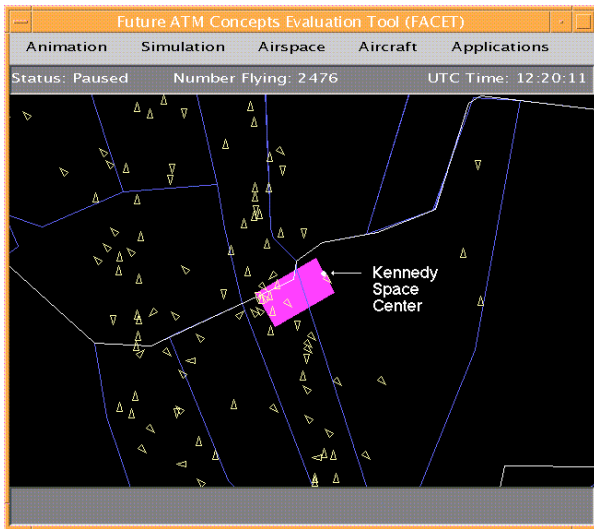


Fig. 5a: Example of RLV Airspace Corridor

ascent to orbital (or suborbital) altitude; Reusable Launch Vehicles (RLVs) also operate within the NAS during a portion of their descent and fly-back to a spaceport. The amount of time spent in the NAS during ascent is of the order of 90 seconds; the amount of time spent in the NAS during RLV descent is of the order of 300 seconds.

In order to assure safe separation between all user classes, the ATM system currently treats space launch vehicle operations as special events and reserves large volumes of airspace, referred to as Special Use Airspace (SUA), for these activities by removing them from airspace available for use by commercial and general aviation aircraft. These SUA envelopes are very large because in addition to a safety buffer around the nominal trajectory, they must also include very conservative estimates of airspace allocation for off-nominal operations and emergency situations (e.g., launch abort go-around trajectories for RLVs). As the number of space launch vehicle operations increases, the corresponding growth of SUA may adversely affect operations of other airspace users. This provides the motivation to model space launch vehicle operations and study their interaction with other vehicle classes in the NAS to optimize the use of airspace for both conventional and special users.

Work is underway to model space launch vehicle trajectories in FACET. As an illustrative example, Fig. 5a shows a possible airspace corridor for a RLV returning to a spaceport. Fig. 5b shows the corresponding number of aircraft that may be affected by the activation of this RLV airspace corridor, as a function of time. A current research objective is to study the interactions of space launch vehicle traffic with air traffic, and to investigate the feasibility of dynamic allocation of space access corridors to optimize airspace usage.

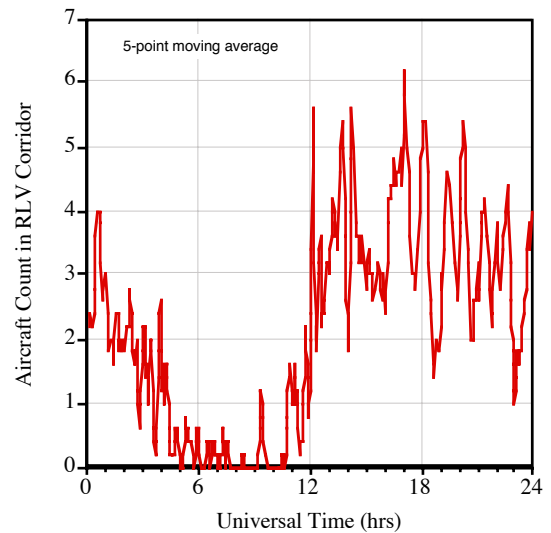


Fig. 5b: Aircraft Count in RLV Corridor

Conclusion

The design, architecture, and functionalities of the Future ATM Concepts Evaluation Tool have been presented. FACET's core capabilities include system-wide modeling of airspace and 4D trajectories. Its modular architecture facilitates rapid prototyping and evaluation of advanced ATM concepts. Several of these concepts have been summarized.

FACET capabilities are being expanded to meet the needs of NASA and the FAA in the area of air and space vehicle operations. Some of these activities will support evaluations of the Distributed Air/Ground Traffic Management concept of operations. Other activities will focus on the development of advanced techniques and tools for system-level Traffic Flow Management.

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References

1. *Existing and Required Modeling Capabilities for Evaluating ATM Systems and Concepts*, Final Report to the NASA Advanced Air Transportation Technology (AATT) Project by the International Center for Air Transportation, Massachusetts Institute of Technology, March 1997. Also available at the following website:
<http://web.mit.edu/aeroastro/www/labs/AATT/index.html>.

2. Erzberger, H., Davis, T.J. and Green, S.M., "Design of Center-TRACON Automation System," *Proceedings of the AGARD Guidance and Control Symposium on Machine Intelligence in Air Traffic Management*, Berlin, Germany, May 1993.
3. Chatterji, G., Sridhar, B., and Bilimoria, K.D., "En-route Trajectory Prediction for Conflict Avoidance and Traffic Management," *Paper No. 96-3766, AIAA Guidance, Navigation and Control Conference*, July 1996.
4. Benjamin, S.G., Brown, J.M., Brundage, K.J., Schwartz, B., Smirnova, T., and Smith, T.L., "The Operational RUC-2," *Proceedings of the American Meteorology Society 16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, 1998, pp. 249-252.
5. Nolan, M. S., *Fundamentals of Air Traffic Control*, Wadsworth Publishing Company, Belmont, CA 1994.
6. Green, S.M., Bilimoria, K.D., and Ballin, M.G., "Distributed Air/Ground Traffic Management for En route Flight Operations," *Paper No. 2000-4064, AIAA Guidance, Navigation and Control Conference*, August 2000.
7. Eby, M.S., "A Self-Organizational Approach for Resolving Air Traffic Conflicts," *Lincoln Laboratory Journal*, Vol. 7, No. 2, 1994.
8. Eby, M.S., and Kelly, W.E., "Free Flight Separation Assurance Using Distributed Algorithms," *Proceedings of the IEEE Aerospace Conference*, March 1999.
9. Bilimoria, K.D., "A Geometric Optimization Approach to Aircraft Conflict Resolution," *Paper No. 2000-4265, AIAA Guidance, Navigation and Control Conference*, August 2000.
10. Bilimoria, K.D., Sheth, K.S., Lee, H.Q., and Grabbe, S.R., "Performance Evaluation of Airborne Separation Assurance for Free Flight," *Paper No. 2000-4269, AIAA Guidance, Navigation and Control Conference*, August 2000.
11. Erzberger, H., McNally, D., and Foster, M., "Direct-To Tool for En Route Controllers," *ATM'99: IEEE Workshop on Advanced Technologies and their Impact on ATM*, Capri, Italy, September 1999.
12. Sridhar, B., Chatterji, G., and Grabbe, S., "Benefits of Direct-To Tool in National Airspace System," *AIAA Guidance, Navigation and Control Conference*, August 2000.
13. Laudeman, I.V., Shelden, S.G., Branstrom, R., and Brasil, C.L., "Dynamic Density: An Air Traffic Management Metric," *NASA-TM-1998-112226*, April 1998.
14. Sridhar, B., Sheth, K.S., and Grabbe, S. "Airspace Complexity and its Application in Air Traffic Management," *2nd USA/Europe Air Traffic Management R&D Seminar*, Orlando, Florida, December 1998.
15. *Commercial Space Transportation: Concept of Operations in the National Airspace System in 2005, version 1.0*, Federal Aviation Administration, February 1999.
16. *Commercial Spacecraft Mission Model Update*, Report of the Commercial Space Transportation Advisory Committee (COMSTAC) Technology and Innovation Working Group, Federal Aviation Administration, May 1998.