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NATIONAL AIRSPACE SYSTEM SIMULATION CAPTURING THE INTERACTIONS OF AIR TRAFFIC MANAGEMENT AND FLIGHT TRAJECTORIES

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Abstract

The Airspace Concepts Evaluation System (ACES) is a large-scale, fast-time computer simulation of flights through the National Airspace System multi-sector, multi-airport network. The simulation accounts for terminal gate pushback and arrival, taxi, runway system takeoff and landing, local approach and departure, climb and descent transition, and cruise operations. ACES employs a multi-trajectory based modeling approach that currently models Traffic Flow Management, Air Traffic Control and Flight operations, en route winds, and airport operating conditions. Future versions of ACES will model Airline Operational Control operations and Communication, Navigation, and Surveillance technologies, and weather. The ACES tool applies a continual feedback, hierarchical modeling process to capture actions and responses among scheduling and trajectory planning, flight deck trajectory management, Traffic Flow Management strategic trajectory planning, and Air Traffic Control tactical trajectory management operations. The intent is to quantitatively describe air traffic movement resulting from the interaction of the operational and technological constructs. By this process, Traffic Flow Management modeling agents in ACES assess projected demand over planning horizons, develop traffic flow plans and issue traffic restrictions to Air Traffic Control agents. ACES simulates the propagation of Traffic Flow Management constraints through the National Airspace System. ATC agents manage tactical flight movement by applying standard operating procedures subject to the Traffic Flow Management restrictions. An advanced four-degree of freedom trajectory modeling emulates the movement of each aircraft along a four-dimension trajectory in conformance with its current flight plan and clearance. ACES implements agent-based modeling using the High Level Architecture structure for inter-computer communications. Trial results of ACES show conformance with actual National Airspace System data and demonstrate its ability to estimate and distinguish quantitatively flight time data aggregated at the nation-wide level for different operational circumstances. ACES is under development by the National Aeronautics and Space Administration, and will be used to evaluate proposed system upgrades such as those intended to reduce delay, increase capacity, and support the dramatically increased traffic levels forecasted in the coming decades.

Introduction

The National Aeronautics and Space Administration (NASA) has established the Virtual Airspace Modeling and Simulation (VAMS) Project to examine proposed operational concepts for increasing the capacity of National Airspace System (NAS). As part of this effort, VAMS is developing the Airspace Concepts Evaluation System (ACES) to simulate NAS operations. ACES is a fast-time, computer simulation of local, regional and nationwide factors covering aircraft flight from gate departure to arrival.

ACES' overarching objective is to provide a flexible NAS simulation and modeling environment that can assess the impact of new NAS tools, concepts, and architectures, including those that represent a significant departure from the existing NAS operational paradigm. To meet this objective, ACES utilizes the High Level Architecture (HLA) and an agent-based modeling paradigm to create the large scale, distributed simulation framework necessary to support NAS-wide simulations. HLA is a set of processes, tools and middleware software, developed by the Department of Defense, to support "plug-and-play" assembly of independently developed simulations. For ease in integration and efficient runtime execution of the simulation, the ACES simulation framework employs agent-based modeling. The ACES agent-based processes simulate airspace and aircraft operations.[1,2]

The ACES architecture is designed to accommodate models of each operational component of the NAS.

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ACES currently is in an early state of development. The current state models: Air Traffic Management (ATM), encompassing Air Traffic Control (ATC) and Traffic Flow Management (TFM) operations; aircraft dynamics; and en route winds. The current modeling accounts for airspace and airport designs and procedures, including airport visual flight rules (VFR) and instrument flight rules (IFR). Agents represent present-day NAS operations and include Air Traffic Control System Command Center (ATCSCC), the en route Air Route Traffic Control Center (ARTCC), Terminal Radar Approach Control (TRACON), Airport Traffic Control Tower (ATCT), and aircraft entities.

The fully-developed ACES will have simulation constructs describing a comprehensive set of NAS components. These include those incorporated in the current ACES as well as aeronautical/airline operational control (AOC) and ramp management operational components. Other constructs describe additional infrastructure and environmental components. These include models and databases that further describe: airspace structures, airport locations and layouts, meteorological conditions and forecasts, Communication, Navigation, and Surveillance (CNS), human behavior, flight planning, flight management system (FMS), and more.

ACES Modeling Concept

The current ACES is a subset of the fully-evolved concept, both adhering to a common agent-based, trajectory-based modeling design. This modeling concept is discussed in the following paragraphs in the abstract context of a full-featured application.

The agents are autonomous entities, each simulating operations according to algorithmic and data processing logic defined by its model based on information exchanged with other agents and supporting constructs. In the ACES modeling concept, the unifying factor is the aircraft trajectory. Each of the basic NAS agents performs modeling functions that operate on flight trajectories. AOC agents conduct pre-takeoff flight planning to define four-dimensional (4-D) desired/requested trajectories, post-takeoff flight following to coordinate trajectory flight plan revisions, and flight schedule revisions based on delay, diversion and cancellation assessments. The TFM agents conduct local, regional and nationwide flow constraint assessments and determinations based on flight plan, traffic surveillance, meteorological and airspace and airport status and constraint information. The ATC agents conduct trajectory intervention assessments and resolutions based on traffic situation surveillance, procedures, separation rules and TFM constraints, trajectory state and intent, meteorological and aircraft performance information. The aircraft trajectory simulations are based on trajectory state estimate and intent, planned trajectory, ATC clearance, aircraft performance and meteorological information.

Each agent has information describing a trajectory and performs action on the trajectory based on this information. But each agent does not necessarily have the same information as another, and none may know the true trajectory state of a flight. The ACES design enables each agent to maintain separate or different trajectory data and trajectory management logic, hence implementing a multi-trajectory modeling concept. ACES also maintains a model of trajectory truth for each flight. Hence ACES would have the ability to model effects of trajectory estimation errors concurrently with the modeling of agent operational processes. The degree of accuracy and fidelity with which the agents operate on trajectories depends on the technologies and functional capabilities of the NAS operational concept being simulated. In ACES these are represented by the logic encoded into each agent and associated modeling parameters.

The information exchange process fits into a hierarchical structure in which TFM strategies define traffic constraint plans which guide ATC operations (see Figure 1). The simulation process is driven by input data describing the arrival and departure schedule by airport and flight plan for each flight. TFM models in ACES examine the flight schedule, develop traffic flow plans and issue traffic restrictions and advisories to each other and ATC agents. ATC models in ACES manage flight movement and apply standard operating procedures subject to satisfaction of the TFM traffic restrictions. Resulting flight trajectory revisions are fed-back through flight schedule modifications to support TFM planning updates.

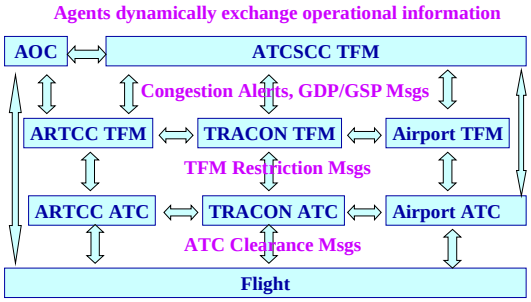


Figure 1 ACES Agent-Based Modeling Concept Example. NAS operations are simulated modularly. Information exchange is simulated by agent message transactions.

Overview of Current ACES

The ACES design supports the evaluation of a wide range of NAS operational concepts. These evaluations may not require modeling all NAS components, or modeling each component to the same level of fidelity. But models of basic NAS components would be included, and, in fact, are part of the currently-developed ACES. The remainder of this paper describes the current ACES modeling logic and parameters to provide an understanding of NAS operational concept assessment capabilities and potential.

ACES is being developed as series of builds. ACES Build 1.1[3] was completed in February 28, 2003, and Build 2 is scheduled for completion on September 30, 2003. The remainder of this paper describes Build 1.1 and on going Build 2 development. Build 2 incorporates features described for Build 1.1.

ACES Build 1.1 simulates NAS domestic operations covering the conterminous US. The coverage includes all domestic ARTCCs and en route sectors, a nationwide network of airports, and flights between any airport pair. Each simulated flight trajectory is generated using a four-degree of freedom (4-DOF) aircraft dynamics model. Figure 2 summarizes the current modeling scope of ACES.

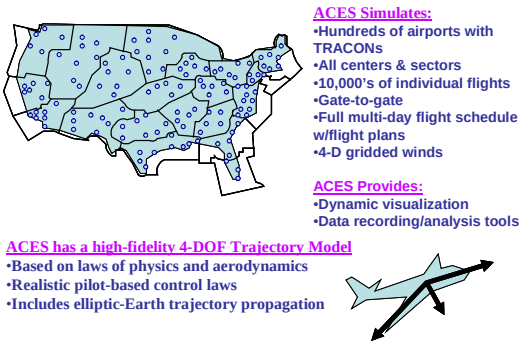


Figure 2 ACES Scope. ACES models tens of thousands of daily flights among hundreds of airports.

ACES Build 1.1 implements software models to describe ATM and AOC agent operations, flight trajectories and wind conditions. ACES ATM agents are defined to distinguish ATC and TFM functions:

TFM	ATC
Airport	Airport
TRACON	TRACON
ARTCC	ARTCC
ATCSCC	

As used in today's ACES, the term "TRACON" refers to generic radar and non-radar terminal airspace operations. Future ACES development will enable representations of actual terminal area designs.

Each agent is an instantiation of its corresponding model. An Airport agent is constructed for each airport in the simulation, a TRACON agent is constructed to represent the terminal airspace of each Airport agent, an ARTCC TFM and an ARTCC ATC agent is constructed for each of the 20 domestic en route centers, and one ATCSCC agent is constructed. A flight agent for each flight, AOC and wind models are also constructed. Modeling input parameter values are adjusted to describe the operational characteristics unique among instantiated agents (e.g., runway system operating parameters distinguish the traffic handling capabilities of different airports; traffic sector capacity parameters define different limits on traffic acceptance capabilities among en route sectors). ACES uses an agent message-passing communication construct and a distributed architecture using the HLA-based structure shown in Figure 3. All coding is in Java. Agents are organized into HLA federates (i.e., collections of models). In addition to coordinating models of NAS operations, the HLA federate structure provides an interface with traffic situation visualization, data collection and simulation control functions.

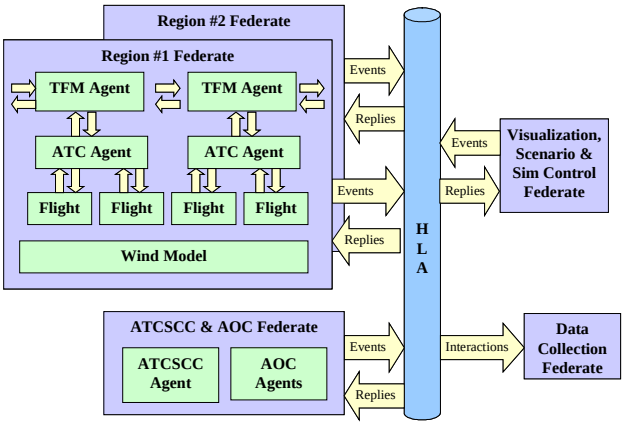


Figure 3 ACES Agents in the HLA Structure. HLA manages message transactions on a distributed computer system, processing event and reply messages among federates. Agents within a federate exchange event and reply messages directly between each other.

ATM Modeling in Current ACES

ACES Build 1.1 performs a gate-to-gate simulation of each flight. Flight movement is modeled from the departure airport terminal gate, through the departure airport surface taxi system to and through the takeoff

runway system, through the terminal airspace to a departure fix, through a series of en route ARTCCs and their sectors to an arrival fix on a terminal airspace boundary, through the terminal airspace to and through the landing runway system, and through the arrival airport surface taxi system to the arrival airport terminal gate. The corresponding ACES agents that handle the flight are shown in Figure 4.

ACES Build 1.1 provides various levels of modeling fidelity. En route operations currently are simulated with higher fidelity than terminal. A 4-D aircraft trajectory model is used to simulate detailed, time-stepped flight dynamics in en route airspace, whereas node-to-node transit times are used to simulate terminal flight movement. The boundaries of the 20 domestic ARTCCs and all en route sectors are encoded in ACES databases. Each terminal operation is defined by nodes representing the terminal gate system, runway system and arrival and departure fixes (see Figure 5). These fixes demarcate the terminal-en route airspace boundary.

ACES currently applies a generic terminal area design to represent the TRACON. This generic design assigns four arrival and four departure fixes to each TRACON where the fixes are evenly spaced on a 40-nautical mile (nmi) circle centered on the airport, aligned and interleaved as shown in Figure 5. The arrival fixes are assigned only to flights landing at the airport and departure fixes are assigned only to flights taking-off from the airport. One TRACON is associated with each airport. ACES currently models 250 airports.

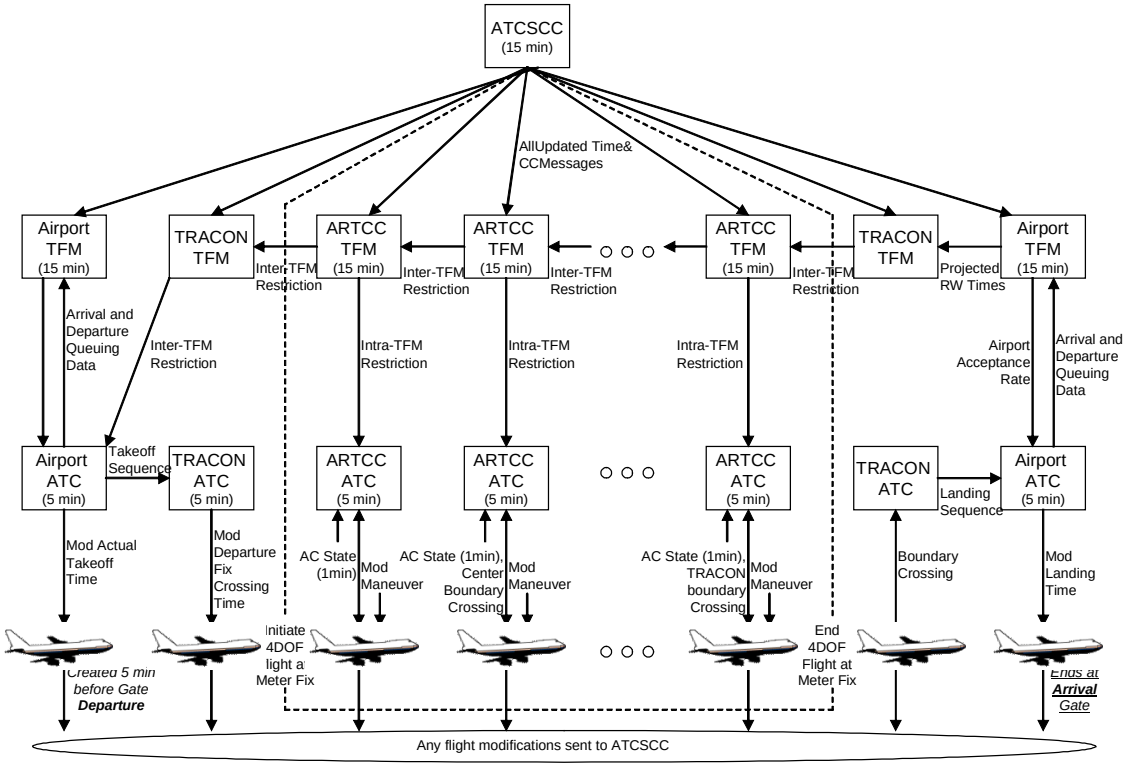


Figure 4 Gate-to-Gate Modeling. ATM agents manage the trajectory through each flight phase.

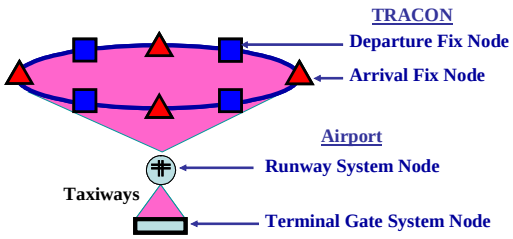


Figure 5 Generic Terminal Modeling Structure. ACES accounts for terminal gate, surface, runway system and terminal airspace operations.

The ACES modeling of terminal operations across the NAS is illustrated in Figure 6. This network generates the simulated flights that are processed by the Airport, TRACON and ARTCC TFM and ATC agents.

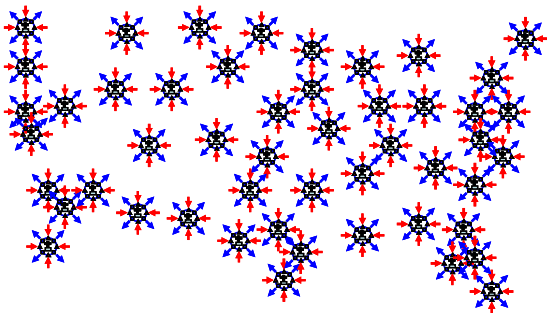


Figure 6 NAS-wide Airport Network Modeling Schematic. ACES currently models 250 airports.

Airport TFM Model

ACES Build 1.1 treats the runway system node as the critical factor in modeling each terminal operation. In this modeling structure, each Airport TFM agent invokes its model to examine projected takeoff and landing traffic loading at the runway system based on the flight schedule (see Figure 7). This model sets runway system arrival and departure acceptance rates over a TFM planning horizon based on airport capacity descriptors. The acceptance rates vary over time depending on arrival versus departure mix and airport operating conditions where VFR procedures generally provide higher rates than IFR procedures. Concurrently, the Airport TFM model also determines planned landing times, which include any delays needed to meet the acceptance rates. The Airport TFM agent transmits the planned acceptance rates to its Airport ATC agent, and transmits planned landing time to its TRACON TFM agent. The Airport TFM agent also relays to its Airport ATC agent any planned flight takeoff time restriction received from its TRACON TFM agent. Such a restriction is due to an en route constraint at a departure fix set by an ARTCC TFM agent.

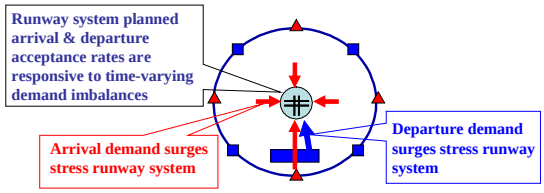


Figure 7 Airport TFM Operations Modeling. Airport TFM sets runway system arrival and departure acceptance rates over a TFM planning horizon in response to traffic demand schedule.

Airport ATC Model

Each Airport ATC agent in ACES Build 1.1 simulates the management of actual flight operations through the surface and runway systems (see Figure 8). The Airport ATC model generates each flight's actual departure time from the terminal gate system based on the schedule. The Airport ATC model constructs a takeoff schedule of flights based on the terminal gate system departure times and originally scheduled (un-delayed) taxi-out time. Concurrently, the Airport ATC model constructs a landing time schedule of flights based on projections received from the TRACON ATC agent. The Airport ATC model assigns actual takeoff and landing times based on comparative analyses of the flight schedule versus the arrival and departure acceptance rates. The model spaces successive takeoffs and successive landings to conform to the arrival and departure acceptance rates. The actual takeoff and landing times include delays induced by the acceptance rate-based traffic overloads, which result in runway system departure queues on the airport surface and airborne arrival delays. The Airport ATC model assigns each flight's terminal gate arrival time based on its actual landing time and originally scheduled (un-delayed) taxi-in time. The Airport ATC model transmits the actual takeoff times to its TRACON ATC agent and the ATCSCC agent.

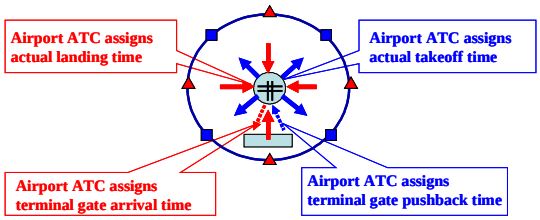


Figure 8 Airport ATC Operations Modeling. Airport ATC manages runway system and surface actual operations in conformance with TFM arrival and departure acceptance rates.

TRACON TFM Model

In Build 1.1, each TRACON TFM agent relays traffic restrictions, subject to local adjustments, between its Airport TFM agent and its adjoining ARTCC TFM agents. The TRACON TFM model determines flight restrictions to be applied at each arrival fix over the TFM planning horizon in conformance with the runway system planned acceptance rates. The TRACON TFM model processes planned landing times received from the Airport TFM model, applies originally scheduled (un-delayed) terminal airspace inbound transit times, and assigns planned arrival fix crossing times. The TRACON TFM model also determines flight restrictions to be applied to airport departure flights over the TFM planning horizon in conformance with constraints imposed by ARTCC agents. The TRACON TFM model processes planned departure fix crossing times received from an ARTCC TFM agent, applies originally scheduled (un-delayed) terminal airspace outbound transit times, and assigns planned takeoff times. The TRACON TFM agent transmits the inbound planned crossing time at each arrival fix to the ARTCC TFM agent handling that fix, and transmits planned takeoff time restrictions to its Airport TFM agent.

TRACON ATC Model

Each TRACON ATC agent in ACES Build 1.1 simulates management of actual flight operations through the terminal airspace. The TRACON ATC model determines a scheduled departure fix crossing time based on the actual takeoff time and originally scheduled (un-delayed) terminal airspace outbound transit time. The TRACON ATC model assigns actual departure fix crossing times based on comparative analyses of the flight schedule versus pair wise aircraft separation procedures (see Figure 9). The model spaces successive crossings at each fix in altitude-separated traffic streams (i.e., representing turbojet, turboprop and piston-powered aircraft) to conform to minimum separation requirements. Concurrently, the TRACON ATC model constructs a projected landing time schedule of flights based on actual times of arrival fix crossings received from the ARTCC ATC agent and the originally scheduled (un-delayed) terminal airspace inbound transit time. The TRACON ATC agent transmits the projected landing times to its Airport ATC agent, and the actual crossing times at each departure fix to the ARTCC agent handling that fix and the ATCSCC agent.

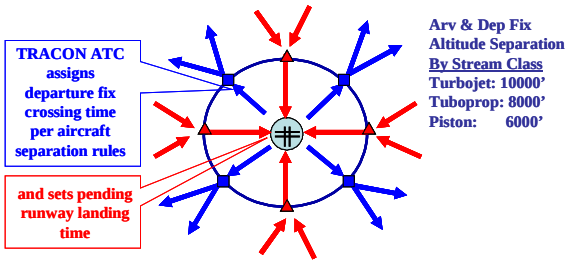


Figure 9 TRACON ATC Operations Modeling. TRACON ATC manages actual operations in terminal airspace.

ARTCC TFM Model

The ARTCC TFM agents generate and propagate TFM traffic restrictions through the en route network. Each ARTCC agent plans traffic restrictions for its multi-sector airspace. The ARTCC TFM model in Build 1.1 receives planned exit boundary crossing time requirements from adjacent TFM agents (e.g., ARTCC or TRACON TFM agents) and relays the exit time requirement to its ARTCC ATC agent. The ARTCC TFM model examines its capability to absorb delays and adjusts planned flight times accordingly to delay flights in its own airspace, to the extent possible, to meet TFM exit time requirements. Otherwise, planned delays are propagated upstream by assigning planned ARTCC entry time requirements for delayed flights. The ARTCC TFM model sets a plan (see Figure 10) for flights requiring outbound delay that either adsorbs the delay, transposes the delay upstream, or a combination thereof. Hence, all or part of a planned arrival delay due to runway system acceptance rate may be absorbed en route (in one or more ARTCCs) or propagated to the origin airport and absorbed prior to takeoff.

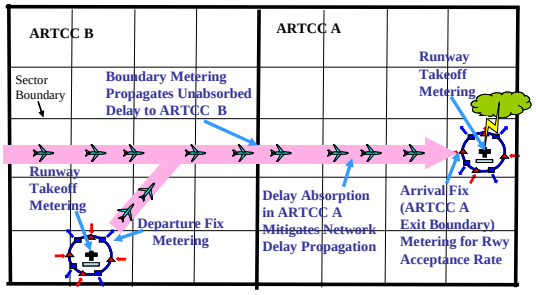


Figure 10 ARTCC TFM Operations Modeling. En Route TFM restrictions are dynamically defined and systematically propagated over a look-ahead span.

In Build 2, the ARTCC TFM model also receives Monitor Alert-based projected sector overload advisories from the ATCSCC TFM agent (see Figure

11). In response to a Monitor Alert advisory, the ARTCC TFM agent independently assesses that sector's projected traffic loading, determines the existence and severity of a projected overload (by comparing projected instantaneous aircraft counts and prescribed capacity), and assigns delay to selected flights to resolve the overload. ACES propagates these delays upstream by specifying planned crossing time requirements at the ARTCC entry boundary. The determination of delay due to sector overload is integrated with the determination of the exit boundary constraint resolution described in the preceding paragraph.

The ARTCC TFM agent transmits planned entry boundary crossings time restriction messages to adjacent TFM agents whether generated by exit boundary constraints or sector traffic overloads or both. These messages prescribe exit boundary crossing time restrictions for assessment and resolution by the adjacent TFM agents.

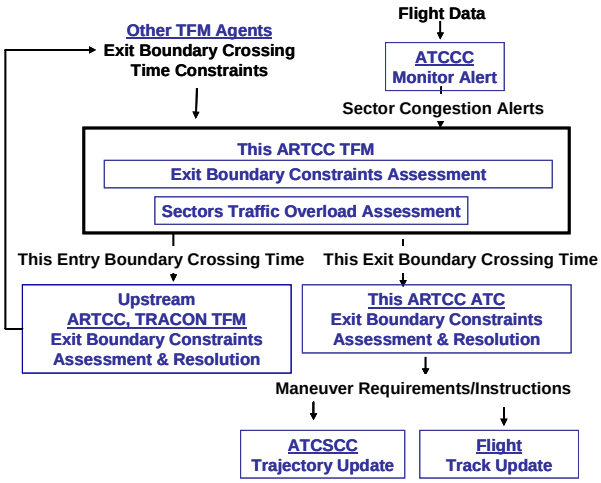


Figure 11 En Route Congestion Management Process. TFM agents propagate traffic restrictions through the NAS. ATC agents implement delay requirements.

ARTCC ATC Model

The ARTCC ATC model in ACES Build 1.1 manages traffic to maintain compliance with the TFM restrictions. The ARTCC ATC model maintains a list of all aircraft within the airspace and it receives TFM restriction messages specifying which aircraft are to be delayed and their required ARTCC exit boundary crossing time. For these TFM restrictions, the ARTCC ATC agent implements path stretching by turning the aircraft off-route temporarily to fly one or more dogleg turns about its nominal route. It rejoins the nominal route approximately as it exits the ARTCC. The dogleg turn model is an approximate solution. It uses a local flat-earth reference frame and accounts for wind and finite turn rates.

The ARTCC ATC model is being enhanced in ACES Build 2 to resolve potential violations of separation minima. After delaying all aircraft with TFM restrictions, the ARTCC ATC model next performs a tactical conflict detection and resolution (CD&R) computation for all aircraft pairs. It projects all aircraft into the future along their current state vectors to determine if there are any predicted conflicts. The default time window in which conflicts are checked for is two to ten minutes. For predicted separation loss, the ARTCC ATC model maneuvers the aircraft in an attempt to achieve at least minimum separation at the point of closest approach. We restrict the resolution maneuver to only one of the two aircraft to minimize controller workload. Furthermore, the resolution maneuver is limited to two turns, the first to resolve the conflict and the second to return to the flight plan. The resolution maneuver is determined by approximating the separation at the point of closest approach using a two-dimensional, second-order Taylor series expansion in the velocity vector components of each aircraft. This evaluation of all the options accurately and efficiently. The aircraft that requires the minimum maneuver is selected.

The ARTCC ATC model derives maneuver instructions to resolve any TFM restrictions, potential conflict, or both. This generally results in a series of vectors to be transmitted to the ATCSCC agent and each Flight agent at specific times.

ATCSCC TFM Model

An ATCSCC TFM agent in ACES Build 1.1oversees gate-to-gate flight movement, receiving and passing traffic movement information from and to other agents. In ACES Build 2, The ATCSCC TFM model simulates a Monitor Alert function by examining the predicted trajectories of all aircraft and computing sector traffic loadings. The sector traffic loadings are compared to the sector capacity to identify predicted overloaded sectors. The ATCSCC TFM agent transmits sector congestion alert messages to ARTCC TFMs.

Non-ATM Modeling in Current ACES

AOC Model

An AOC agent is used in ACES Build 1.1 to implement a traffic demand model. This model assigns flight plans for all flights for the given ACES simulation run. The output of the traffic demand model is a set of flights, where each flight is defined

by a city pair, planned departure and arrival times, aircraft type, and route details. In ACES Build 2, an AOC model is being developing to perform run-time analysis of flight irregularities and actively delay or cancel flights to meet schedule objectives.

Flight Model

The ACES Build 1.1 Flight model flies the aircraft forward in time to generate a four dimensional (4D) trajectory. The model uses a 4-DOF dynamics model [4] including the aircraft roll angle for realistic turn maneuver modeling in the en route airspace (i.e., between the departure and arrival meter fixes). It uses airframe and propulsion models to construct a free body diagram and solve the aircraft equations of motion. For guidance it uses route following and route capture logic for the horizontal plane maneuvers, and realistic energy-management logic for capturing a speed-altitude state. A lower fidelity approach is applied in terminal using transit time input data. Here, nominal (un-delayed) flight times specific to the stream class (i.e., jet, turbojet, piston) of the aircraft are assigned to define terminal airspace transit times. Similarly, nominal (un-delayed) inbound and outbound surface taxi times are assigned by airport. The TRACON TFM may apply delay to these un-delayed flight times.

Wind Model

ACES Build 1.1 uses the Rapid Update Cycle (RUC) nationwide hourly wind estimates to model wind as a two horizontal vector components in the north-south and east-west directions, respectively, at the aircraft location. These data appear in the equations of motion of flight which are used to propagate the aircraft trajectories. Wind forecast error is not currently modeled. The RUC data are interpolated to the aircraft position and time for all aircraft. This four-dimensional interpolation (three spatial coordinates and one temporal coordinate) is done using a sequence of four one-dimensional interpolation steps.

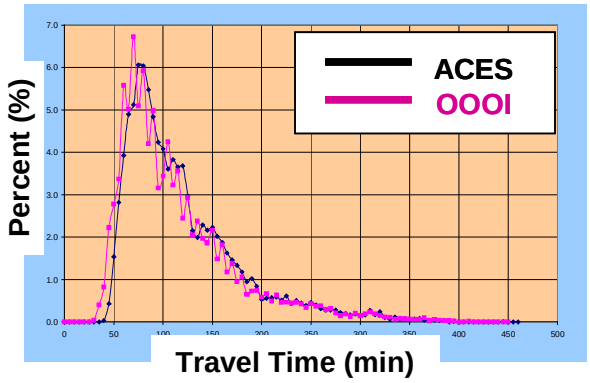
Results

Trial Application

Given its current early state of development, application of ACES to elaborate real-world problems would be premature. Issues first need to be addressed concerning the fundamental viability of the ACES design as a tool to evaluate NAS operations. For this purpose, the current HLA-based ACES Build 1.1 software was tested on a personal computer system of ten Windows machines to simulate the following NAS environment:

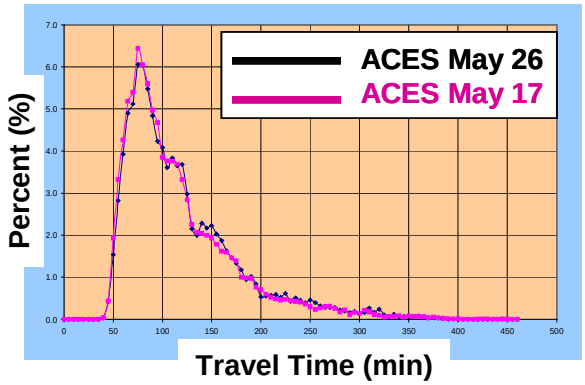
- 20 pairs of ARTCC TFM and ATC agents, one pair for each domestic ARTCC (with airspace boundaries defined for each ARTCC and each en route sector, and with a sector capacity defined for each sector as a maximum instantaneous aircraft count).
- 250 sets of Airport TFM and ATC and TRACON TFM and ATC agents, where a set of these four agents is constructed for each of 250 airports (with runway system maximum arrival, departure and total acceptance rates defined uniquely for each airport).
- Scenarios defining changing VFR and IFR procedures by airport.
- One ATCSCC TFM agent.
- At least one AOC agents, representing one or more generic airline/aircraft operator (trial exercises runs have instantiated 18 agents).
- 25,000 domestic flights over a 24-hour simulation period (the aircraft dynamics model, parameterized for different aircraft types, was used to construct trajectories individually for each flight).

Example results are shown in Figure 12 and Figure 13 using the gate-to-gate flight time distributions for NAS–wide traffic over 24-hour periods. ACES was run using input flight plan data derived from the Enhanced Traffic Management System (ETMS) for the sample days identified in the figures. Figure 12 compares ACES results with trajectory times derived from gate-Out, runway-Off, runway-On, gate-In (OOOI) statistics collected from actual airline operations on the same day that was modeled. These results indicate ACES results correspond reasonably well to actual operations. Figure 13 shows ACES results for NAS traffic loadings on two different days, indicating its ability to model different operations and quantitatively assess relative differences or similarities in performance. Similar modeling results have been applied[5] previously to evaluate ATM system alternatives.



ETMS and OOOI Source: Metron Aviation

Figure 12 Gate-to-Gate Flight Time Distribution: ACES vs. Actual, May 26, 2002.



ETMS Source: Metron Aviation

Figure 13 ACES Gate-to-Gate Flight Time Distribution: May 17 vs. May26, 2002.

Overall System Performance

All messages are sent in a reliable mode, guaranteeing delivery. Time critical messages are time-stamped to arrive in the next second of simulation time. The simulation clock is discrete, currently set with a minimum one-second time step. Early trial runs of ACES Build 1.1 took 24 hours to complete. System improvements have reduced the run time to approximately eight hours. The ACES Build 2 is estimated to simulate 25,000 flights (3000 peak count) through 250 airports and 20 centers in five to six hours. We anticipate more efficient message handling, algorithmic design and data processing will significantly improve performance. This capability to improve performance is important because the ACES modeling concept and architecture is intended to simulate many-hundreds of thousands of flights and many-hundreds of terminal areas for future operational concepts.

Conclusions

Finding

The key finding: it works. ACES processed the 25,000 daily flights, handling over 3000 flights simultaneously at peak periods. It generated trajectories, assessed runway system traffic demand versus throughput limitations for each and all airports, calculated runway system acceptance rates based on arrival versus departure traffic loading, propagated airport-based TFM restrictions through terminal and en route airspace, adjusted TFM restrictions to account jointly for airport overloads, further propagated TFM restrictions through the airspace to departure airports if required, and conducted ATC traffic assessments and resolutions to implement TFM restrictions. ACES generated computer graphics visualization of each run and collected statistics describing individual trajectories and general traffic activity.

Near-Term Enhancements Beyond Build 2

Some enhancements to ACES capabilities to emulate NAS operations include simulation upgrades that enable provision of multiple airport TRACONs, complex runway system configuration and sectorization alternative, flexible route and fix structures for extended terminal airspace, and rerouting, TFM functions that apply ground delay and stop programs and distinguish miles in trial and time-based metering, maturation of conflict detection and resolution functions (e.g., short term conflict avoidance), and stochastic perturbations.

Acknowledgement

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While selected references are sited, we emphasize that this effort reflects the common knowledge and expertise accumulated over 30 years of collective work in airspace, airport, flight dynamics, traffic demand and computer modeling conducted by many, many individuals and organizations, far too many to identify one-by-one. Much of this previous work has been sponsored by FAA, NASA, DOD and various other public and private members of the aviation and computer science communities.

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