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Design and Implementation of a Scenario Development Process for a 2040 Trajectory-Based Operations Simulation

Bill K. Buck, Terique L. Barney, Matthew C. Underwood, and Ryan C. Chartrand
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October 2020

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List of Acronyms

ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-C	Automatic Dependent Surveillance – Contract
ANSP	Air Navigation Service Provider
AOP	Autonomous Operations Planner
ARTCC	Air Route Traffic Control Center
ASTOR	Aircraft Simulations for Traffic Operations Research
ATC	Air Traffic Control
ATM	Air Traffic Management
ATOL	Air Traffic Operations Lab
ATOS	Air Traffic Operations Simulation
BS1	Batch Study 1
CIFP	Coded Instrument Flight Procedures
CPDLC	Controller-Pilot Data Link Communications
Data Comm	Data Communications
EoATMS	Exploration of Air Traffic Management Services
EPP	Extended Projected Profile
FAA	Federal Aviation Administration
FIS-B	Flight Information Service - Broadcast
FL	Flight Level
FMS	Flight Management System
HITL	Human-in-the-Loop
HLA	High Level Architecture
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
RAP	Rapid Refresh Product
RPFMS	Research Prototype Flight Management System
RTA	Required Time of Arrival
SUA	Special Use Airspace
SWIM	System Wide Information Management
TAP	Traffic Aware Planner
TASAR	Traffic Aware Strategic Aircrew Requests
TBO	Trajectory-Based Operations
TMX	Traffic Manager
WYPT	Waypoint
ZOB	Cleveland Air Route Traffic Control Center

Abstract

The National Aeronautics and Space Administration (NASA) is supporting research to transition from a legacy, air traffic management system to Trajectory-Based Operations environment targeting the 2035-2045 timeframe by creating simulation scenarios for current and future studies. Trajectory-Based Operations in the National Airspace System focuses on modernizing the current operating paradigm to increase efficiency, predictability, resilience, and flexibility while migrating toward greater operational autonomy across the airspace. These simulation scenarios offer a wide dissemination and use of system-level constraints and aircraft state/intent data, routine use of data communications to request complex trajectory modifications and to receive clearances, and aircraft that are flying on 4-D trajectories with flexibility when desired, but structure where required. This report describes the end-to-end development of scenarios for the NASA Langley Research Center simulation environment to represent a 2040 Trajectory-Based Operations airspace for air transport operations research.

1. Introduction

A key research area of air traffic management (ATM) in the National Airspace System (NAS) is Trajectory-Based Operations (TBO), which focuses on modernizing the current operating paradigm to increase efficiency, predictability, resilience, and flexibility while migrating toward greater operational autonomy across the airspace. Research conducted at the National Aeronautics and Space Administration (NASA) supports the transition from legacy ATM operations to TBO targeting the 2035-2045 timeframe. To support this research effort, there is a need to create simulation scenarios for current and future studies that demonstrate a representative TBO environment in that timeframe. Furthermore, a documented development methodology for simulation scenarios can be used to create additional scenarios for future studies or research applications in this operational environment.

This report describes characteristics and assumptions of a 2035-2045 TBO operational environment, describes NASA Langley Research Center air traffic operations research simulation capabilities, discusses a methodology and processes for creating simulation scenarios that represent this operational environment, and presents a discussion of the impact of the scenario development process on potential future research applications. Reference [1] applies the development methodology described in this report to study a representative TBO environment in a 2040 simulation use case.

2. Background

NASA is exploring a future service-based airspace system that enables increasingly diverse operations in dense, controlled airspace [2]. New entrants such as supersonic flights over land, space launch and re-entry vehicles, high-altitude long endurance aircraft, Unmanned Aircraft Systems, Urban Air Mobility systems, and drones are expected to introduce the greatest diversity as their demand for entering controlled airspace increases. However, it is just as important to ensure that the future airspace system accommodates traditional users such as commercial passenger and cargo airlines, business jets, and general aviation, while maintaining or improving current-day levels of safety and security.

The use of a service-oriented paradigm to provide equitable, safe, and secure access to the airspace for all users, vehicles, and missions has been identified as a goal of the proposed airspace system. The philosophical tenets of this new airspace system include:

1. Scalability for increased demand across users and missions;
2. Flexibility whenever possible and structure only when necessary;
3. Collaboration through integrated information exchange;
4. Resilience to uncertainty, degradation, and disruptions through local empowerment of decision making; and
5. Increased availability and use of user and third party services.

Current research activities at the NASA Langley Research Center are defining airspace services for the 2035-2045 timeframe that aim to improve efficiency and predictability for traditional users, and that could prepare the system for increased diversity from new entrants. These services leverage existing or soon-to-come technologies built on the principles of information sharing, traffic flow management, and time-based scheduling. In the 2035-2045 timeframe, it is envisioned that these services will be fully integrated with each other and used for gate-to-gate TBO for all airspace users. To understand this future service-based airspace system, simulations representative of the operational environment must occur.

3. 2040 Trajectory-Based Operations Simulation Environment Definition

The investigation of this service-based airspace system requires the simulation of a representative TBO environment containing anticipated characteristics for the target timeframe. The following subsections describe the TBO characteristics identified to be important to the research, the selected airspace of interest for the simulation, and the accompanying airspace traffic. Environmental factors considered in the simulation scenario development are also discussed.

3.1 TBO Characteristics

The service-based TBO environment for the target timeframe is expected to exhibit a number of unique characteristics not inherent to the airspace environment of today. Information related to these characteristics, the context of their applicability, and rationale behind their existence and implementation were identified and discussed with air traffic management subject matter experts throughout a series of research forums. Key TBO characteristics and attributes with a high likelihood of relevance to airspace environments in the 2035-2045 timeframe were selected for representation within scenarios.

Information such as aircraft state and intent data, and airspace system-level constraints, will be widely disseminated throughout the system and used for decision making by various stakeholders. Digital Data Communication, or “Data Comm” [3, 4], between airspace users and the air navigation service provider will be routinely used to request complex trajectory modifications and to receive clearances during all phases of flight. Aircraft are expected to fly closed-loop, four-dimensional (4-D) trajectories, which will include consideration of time of arrival constraints, lateral route constraints, altitude constraints, and speed constraints [5-8].

The 2035-2045 TBO environment will also allow for services that increase airspace user flexibility where desired (e.g., en route flights in Class A, center airspace where user-preferred trajectory negotiations are expected to be most frequent and effective) [9-13]. Airspace structure in this timeframe is expected only where it is required (e.g., terminal airspace where flow-management constraints are expected to be most prevalent). The implementation of technologies across the NAS as part of the Federal Aviation Administration (FAA)’s NextGen program [14] will increase the use of time-based flow management [15] and improve upon how existing system capacity is utilized. These technologies, which serve as the foundation of this future airspace system, are anticipated to increase the predictability of the NAS, as well as system and user efficiency in the future TBO environment.

3.2 Airspace of Interest

The center airspace structure [16] of today is expected to carry on into the 2040 TBO environment, albeit with an increase to air traffic densities to align with projections for annual traffic increases [17]. Class A airspace is also expected to have the most frequent en route trajectory negotiation activities in the target TBO environment [18]. Furthermore, Class A airspace avoids the coordination and traffic flow management complexities of terminal traffic at altitudes below 18,000 feet. As such, it is the focus of this activity and will be the airspace of interest.

Cleveland Air Route Traffic Control Center (ARTCC), referred to as ZOB, Class A airspace was chosen as the airspace of interest for this activity. Figure 1 presents the lateral boundaries of ZOB, the surrounding control centers, and high altitude airways that transect ZOB. The ZOB airspace structure includes several high-density parallel routes and multi-axis merging geometries that enable a large volume of en route traffic. Throughout the course of a nominal day, traffic flows transition between predominantly east to west in the morning, a mixing of the flows during the midday period, and a west to east flow during the evening and overnight. ZOB is surrounded by busy traffic regions, including New York, Indianapolis, and Chicago ARTCC controlled airspace, each feeding a large amount of traffic into ZOB. These characteristics make ZOB a suitable candidate for the simulated TBO environment.

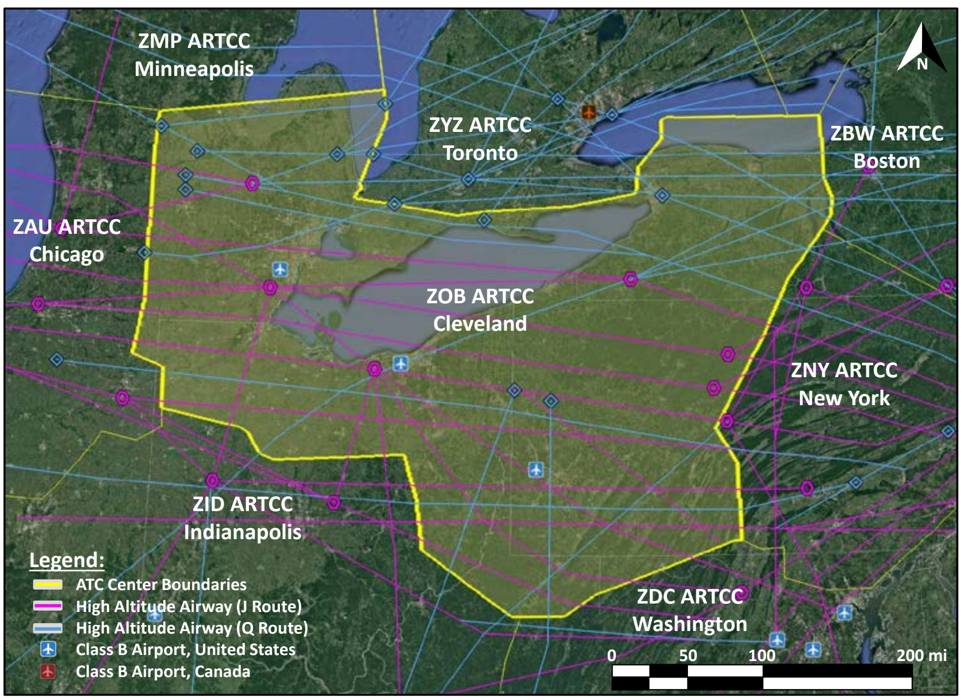

Figure 1: Airspace of Interest for 2040 TBO Simulation – Cleveland ARTCC

3.3 Airspace Traffic

To simulate a representative TBO environment containing anticipated characteristics for the target timeframe of 2040, airspace traffic data was collected for all aircraft traversing the ZOB control center on May 23, 2018, and May 24, 2018 from the FAA's System Wide Information Management (SWIM) system.

This enabled real-world routes to be depicted within the simulation. These dates were selected because the two days represented minimal convective weather impact days in the local region[1]. These traffic data were separated into various categories that are described in the following sections in further detail.

3.3.1 Traffic of Interest vs. Background Traffic

The first category for the aircraft within the simulation scenario is the designation of traffic of interest aircraft and background traffic. The traffic of interest group includes only subsonic jet transport aircraft (commercial airliners, business jets, and cargo aircraft) that flew above 18,000 feet during the entire ZOB portion of en route flight, initialize at least 10 minutes outside of ZOB airspace, and fly for at least 30 minutes within ZOB airspace. These aircraft are also equipped with the advanced airborne trajectory management technology, and are the primary focus during post analysis activities.

Aircraft that did not meet all of these criteria were placed into the background traffic group. Background traffic enabled airspace densities on the chosen traffic days to be increased to levels expected in the 2040 TBO environment. Background traffic commonly included turboprop aircraft, aircraft departing and arriving within ZOB, low altitude aircraft, and aircraft that traverse small sections along the edges of the approximate ZOB airspace.

3.3.2 Free Route vs. Fixed Route Aircraft

Another category for the aircraft within the simulation scenario is the designation of free route and fixed route aircraft. The target 2040 TBO airspace is assumed to consist of a combination of advanced airborne trajectory management service-equipped and non-equipped aircraft. Consultation with subject matter experts determined that aircraft in the simulation should be approximately 60% airborne trajectory management service-equipped traffic, and 40% non-equipped traffic. Conventional Flight Management System (FMS) capabilities on equipped aircraft are modified in the simulation to include the airborne trajectory management capability, which provides fuel-optimized trajectory modifications (i.e., "free routes"). Free route aircraft can only be simulated by the medium-fidelity aircraft simulator described in Section 4.2.

Fixed route aircraft maintain their original route flown from the recorded baseline traffic data and are not allowed implementation of any route modifications – regardless of if the aircraft is equipped with the advanced airborne trajectory management capability that generates optimized route modifications.

3.4 Environmental Factors

To represent the local airspace environment, several data sources were identified to be included in the scenarios to provide an additional level of realism. The aircraft chosen for the simulation commonly are affected by the weather (winds aloft, temperatures aloft, and convective activity), and areas of special use airspace. The following sections describe the use of real-world winds and temperature data gathered from the National Oceanic & Atmospheric Administration (NOAA), real-world convective weather activity considered, and real-world special use airspaces gathered from the FAA.

3.4.1 Winds and Temperature Data

To provide an increased level of realism and to match the recorded as-flown conditions of aircraft for the selected traffic days of interest, archived recordings of winds and temperature aloft were processed and

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[1] Minimal convective weather days were chosen to reduce the effects of weather disruptions in the NAS affecting the baseline scenarios. Subsequent TBO scenarios may consider incorporating various levels of convective weather activity to determine its impact on en route air traffic operations, and/or to investigate the ability of the service-based technologies evaluated in the simulation to operate in an environment with dynamic convective weather.

used within the simulation environment. The selected source of the wind and temperature data was the NOAA Rapid Refresh Product (RAP) [19]. The data within the RAP model is updated hourly, and the RAP model contains information for North America on a uniform 40-kilometer grid. The selected sub products in RAP are the north-south winds, east-west winds, and air temperature – with an altitude component in terms of pressure levels. Figure 2 presents an example of the gridded RAP wind product for the continental United States at a single altitude level.

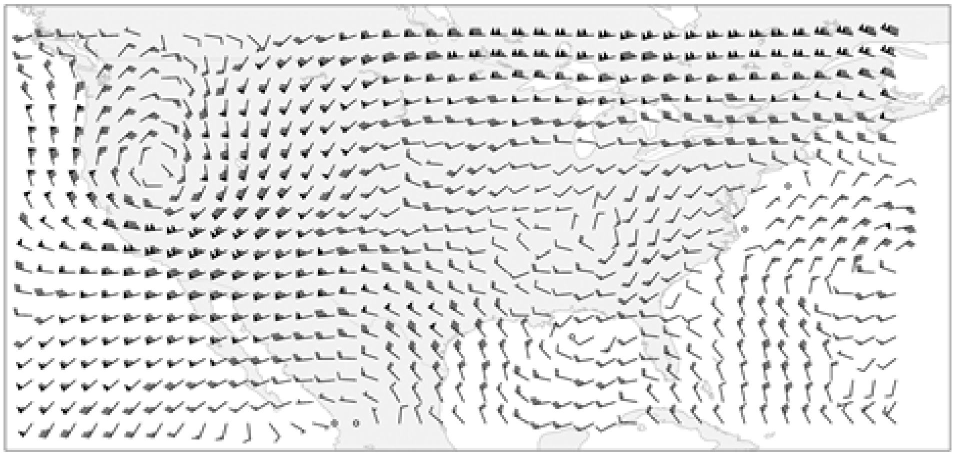


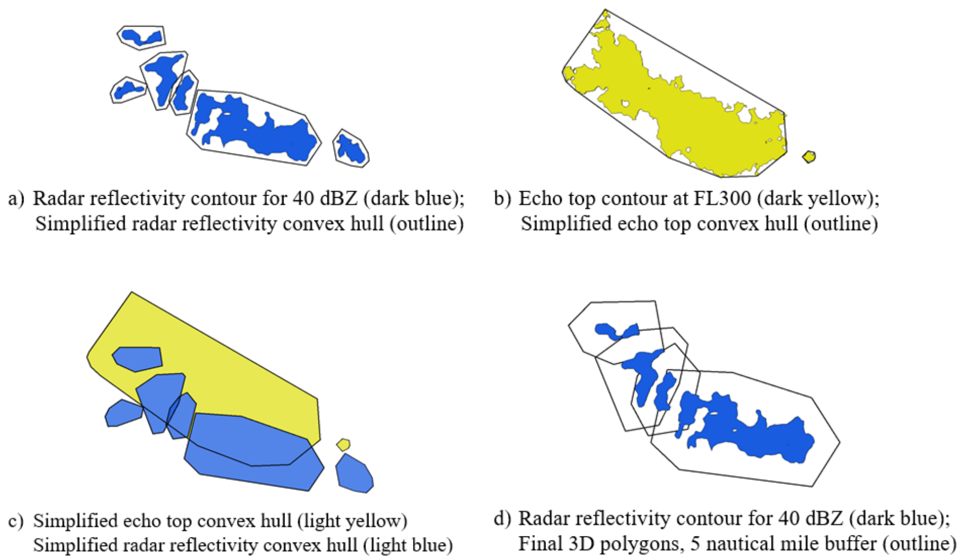
Figure 2: Example NOAA Rapid Refresh Product Gridded Wind Product

Wind and temperature data from NOAA are actively archived at NASA Langley Research Center for air traffic operations research [20]. The RAP data are processed and stored within individual data files for a specified time and date in a format that is compatible with the NASA Langley simulation environments. These files combine the horizontal wind components and temperature data into a 3-D reference data set used within the simulation scenarios.

3.4.2 Convective Weather Activity

The label "Convective Weather" can describe many types of weather phenomenon, but is generally associated with thunderstorms, weather fronts, and other forms of severe weather. Weather, its intensity and path, are a primary concern for air traffic operations when it comes to tactical and strategic planning of aircraft routes.

Current and forecast convective weather data are downloaded from an online weather service, processed, and archived at NASA Langley Research Center for air traffic operations research. The data are filtered, simplified, and a predetermined buffer distance is applied to the three-dimensional polygons (polytopes) and stored in a format that is compatible with the NASA Langley simulation environments (described further in [20]). This process is presented in Figure 3.



a) Radar reflectivity contour for 40 dBZ (dark blue); Simplified radar reflectivity convex hull (outline)

b) Echo top contour at FL300 (dark yellow); Simplified echo top convex hull (outline)

c) Simplified echo top convex hull (light yellow) Simplified radar reflectivity convex hull (light blue)

d) Radar reflectivity contour for 40 dBZ (dark blue); Final 3D polygons, 5 nautical mile buffer (outline)

Figure 3: Weather Avoid-Area Polygon Generation Process [20]

The resulting current (red) and forecast (yellow and green) three-dimensional polygons are presented in Figure 4. Although the ability to create reference convective weather for a simulation scenario exists at NASA Langley Research Center, the days selected for the basis of initial 2040 TBO scenarios had minimal weather, as specified in Section 3.3.

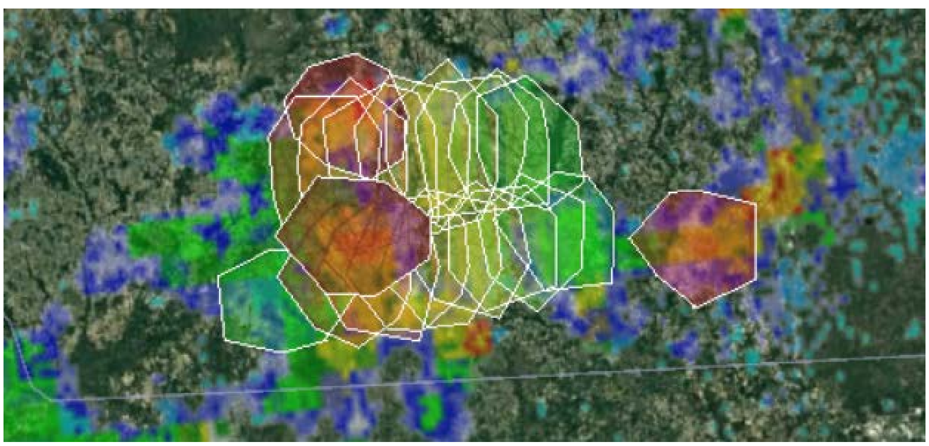


Figure 4: Notional Three-Dimensional Weather Avoid-Area Polygons

3.4.3 Special Use Airspace

Special Use Airspace (SUA) is a designated portion of the National Airspace System that is defined because of a specific need or use, either for select aircraft use or for a warning/alert area [16, 21, 22]. The shape of SUA is a defined set of dimensions containing an area above the earth's surface that may occupy varying vertical ranges. Each SUA also has a stated duration that defines if it is active (in effect) or inactive. SUAs may be designated as prohibited areas, restricted areas, warning areas, military operations areas, alert areas, controlled firing areas, or national security areas. SUAs that are included in the developed TBO scenarios for the planned airspace of interest are from the restricted category.

An example of SUA is presented in Figure 5. The dark yellow polytopes are part of a group of stacked SUA near the eastern seaboard of the United States. As shown in the figure, each SUA has varying vertical limits, allowing aircraft to fly above or below them.

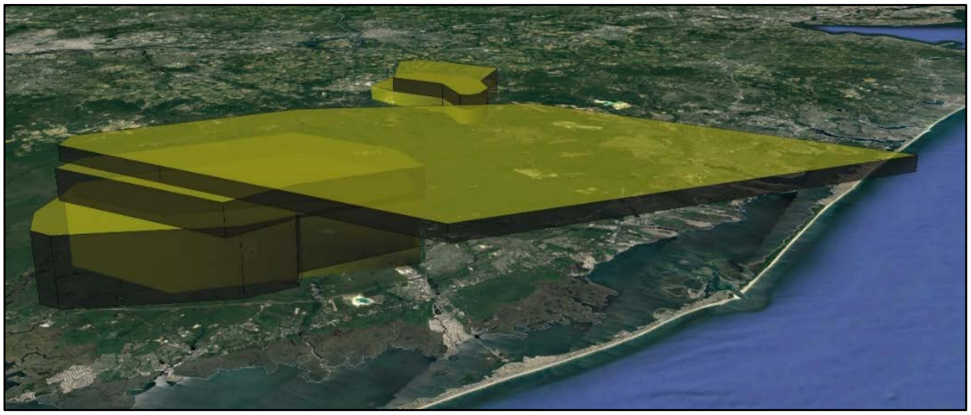


Figure 5: Special Use Airspace, Multiple Stacked Polytopes – Example

To create the information for the SUAs in the TBO environment scenarios, two separate data sources are merged together into a data format compatible with the simulation environment. The dimensional geometries of SUA are located within the FAA Coded Instrument Flight Procedures (CIFP) Navigation Database. The corresponding date cycle (1805) for the navigation database was matched to the timeframe of interest for the scenarios created. The second component of the information required is the activation/ deactivation schedule of the SUA. Both data sources are actively archived at NASA Langley Research Center for air traffic operations research.

4. Simulation Capabilities

The development of air traffic scenarios for a simulated 2040 TBO environment makes use of, and builds upon, several simulation capabilities at NASA Langley Research Center. The following sections describe these enabling and supporting environments for the development of the air traffic scenarios.

4.1 Air Traffic Operations Simulation

The NASA Langley Air Traffic Operations Simulation (ATOS) software provides an environment for exploring future airspace operations, including airspace modeling; realistic communication, navigation, and surveillance capabilities; prototype flight deck technologies; and advanced crew display interfaces. It serves as a platform for the development of advanced flight guidance, decision support systems, and operational procedures within research applications. ATOS is capable of simulating hundreds of aircraft using various aircraft performance models and connecting multiple simulation platforms. ATOS has been developed and extended for many years at NASA Langley to support experiments of multiple batch and piloted simulation studies [23, 24].

ATOS data collection can be completed in both batch and human-in-the-loop (HITL) modes, often within the Air Traffic Operations Lab (ATOL). A batch mode data run (batch study) is used for running one or more scenarios sequentially without the need for subject pilots or a human operator in an automated fashion. Within a batch study, individual aircraft are controlled according to a scenario file that acts like a script for actions of all simulation resources for the time span of the simulation. Individual aircraft are piloted by a software pilot model that senses and reacts to various events or command actions from the scenario based on a predetermined set of rules [24]. A HITL mode is used to integrate a mix of live subject pilots and controllers with automated aircraft in a single simulation environment. An ATOS data collection run gathers results, analyzes log files, and stores data collected during scenario runs for further analysis by researchers.

ATOS provides a simulated airspace environment, including a navigation database, SUAs, area hazards, weather radar model, and winds (actual and forecast). ATOS also includes a full set of communication, navigation, and surveillance equipage. Communication equipage in ATOS includes a voice channel that is supported during HITL studies and Controller-Pilot Data Link Communications (CPDLC) messaging. Navigation capabilities include Required Navigation Performance and Area Navigation [25, 26]. Surveillance capabilities are supported by Automatic Dependent Surveillance – Broadcast (ADS-B) [27-30] and Automatic Dependent Surveillance – Contract (ADS-C) [31].

ATOS has the ability to interoperate with other simulations to enable medium-fidelity simulation of airspace operations. ATOS uses a High Level Architecture (HLA) federation of networked medium-fidelity workstation-based aircraft, a simulation manager, air traffic generators, and network gateways to simulate a representative airspace of interest. Figure 6 presents a conceptual simulation architecture diagram of ATOS.

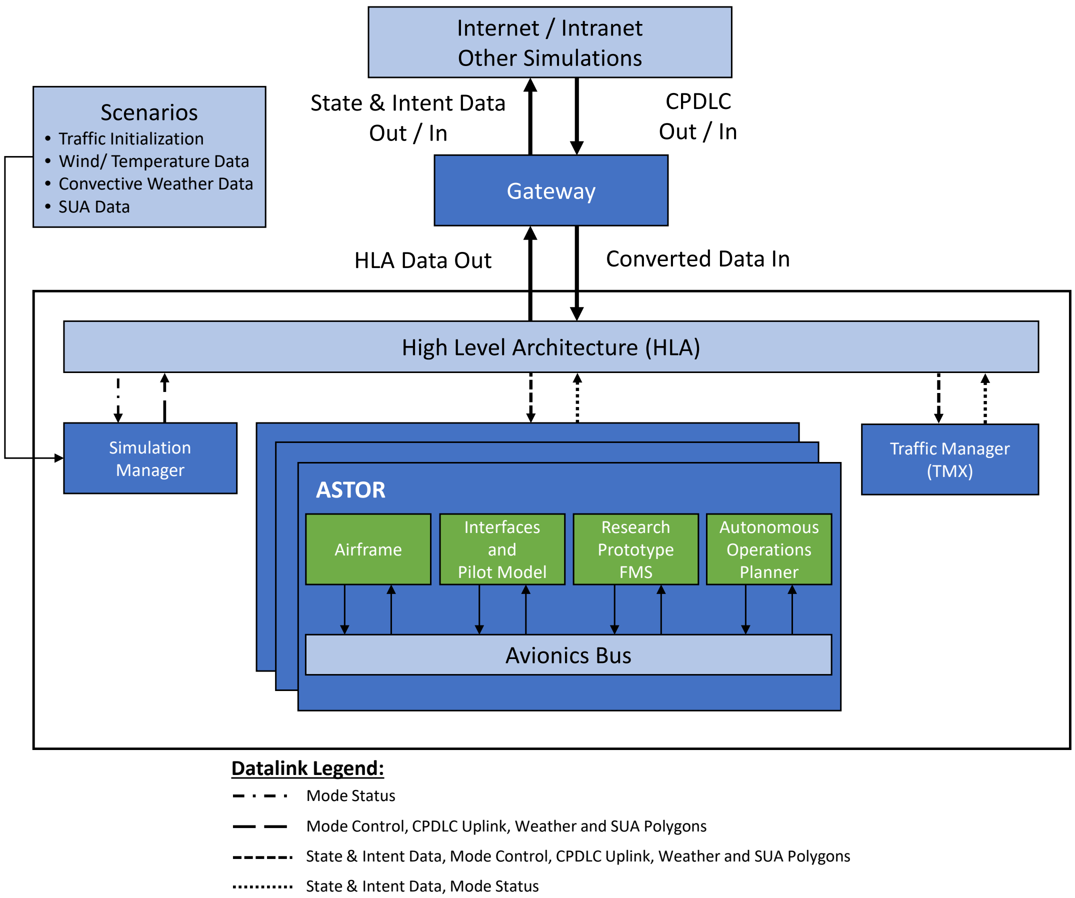


Figure 6: Conceptual ATOS Architecture Diagram

The HLA allows simulated aircraft from various platforms (e.g., Aircraft Simulation for Traffic Operations Research (ASTOR) described in Section 4.2 and Traffic Manager (TMX) described in Section 4.3) to operate in and communicate with one another in the same airspace environment. This capability enables a TBO airspace environment with significantly higher traffic density than is typically observed in modern-day traffic management operations to be simulated. The ATOS capability hosts ASTOR aircraft equipped with an advanced airborne trajectory management technology, the Autonomous Operations Planner (AOP), discussed in Section 4.2.4. The AOP technology enables en route trajectory optimization that creates the “free routes” discussed in Section 3.3.2, making AOP a critical component of the simulation.

4.2 Aircraft Simulations for Traffic Operations Research

The NASA Langley ASTOR is a medium-fidelity, networked, and interactive desktop simulation of a commercial transport aircraft and its flight deck systems [32, 33]. An ASTOR in simulation consists of multiple components, including a high-fidelity aircraft performance model, cockpit display and control panels, a customizable pilot model, a customizable FMS, environment sensors, and data communication emulation. The application of the ASTOR aircraft model types are discussed further in Section 4.2.1. Further information regarding ASTOR and supported applications is also provided in references [23, 24, 32, 34, 35].

The ASTOR was selected to represent the aircraft that required the use of capabilities that would not be supported by a more basic, medium-fidelity simulation (see Section 4.3). The following sections describe in further detail several of the components subsystems within an ASTOR that are used within the scenario development process to create a 2040 TBO environment.

4.2.1 Airframe

The ASTOR Airframe is the main aircraft simulation engine. It simulates aircraft mass properties, aerodynamics, propulsion systems, landing gear, primary controls (autopilot and auto-throttle), navigation, and air data systems. ASTOR Airframe uses a number of kinetic mathematical models based on manufacturer and experimental data to provide realistic forces and moments to the six-degree-of-freedom equations of motion for an aircraft, which calculate the position, rates, and accelerations of the aircraft.

ASTOR Airframe is capable of simulating a number of aircraft types. The aircraft performance model used within an ASTOR is based on the NASA Langley Standard Real-time Simulation in C++, a high-fidelity vehicle simulation [36]. Non-dimensional aerodynamic coefficients, corrected thrust, and corrected fuel flow data are stored in tabular form to represent a particular aircraft. Table 1 summarizes key characteristics of the aircraft model types used within the scenarios. Each aircraft model represents a medium-fidelity desktop aircraft simulation of a civil transport vehicle that simulates the dynamic response of the aircraft and the performance and operational limits of the vehicle.

Table 1: Reference ASTOR Aircraft Performance Information

ATOS Model	Airplane Type	Service Ceiling (ft)	Maximum Takeoff Weight (lbs)	Operating Empty Weight (lbs)	Max Payload Weight (lbs)
NASA_HU25	Business/ Regional Jet	42,000	32,000	17,937	6,213
NB137_2E22	Narrow-body Short Range	37,000	137,000	72,540	33,960
NB172_2E27	Narrow-body Medium Range	41,000	172,500	91,000	45,000
NB250_2E40	Narrow-body Long Range	41,000	250,000	136,940	47,060
WB315_2E48	Wide-body Medium Range	41,000	315,000	176,650	73,350
WB535_2E77	Wide-body Long Range	43,100	535,000	297,250	122,750

The ATOS aircraft models and their characteristics are referenced within various NASA researcher developed scripts to prepare the TMX aircraft routes for conversion to an ASTOR route and for the formulation of the CPDLC messages for the free route aircraft present within the simulation.

4.2.2 Crew Interfaces and Pilot Model

The ASTOR provides a set of displays and interfaces that creates a virtual cockpit environment. The cockpit displays consist of the following (shown in Figure 7, with the bullet numbers corresponding to the numbers on the figure):

1. Glare Shield Wing Panel
2. Display Select Panel
3. Mode Control Panel
4. Electronic Flight Instrument System Control Panel
5. Clock and Simulation Mode Status
6. Primary Flight Display
7. Navigation Display
8. Engine Indication and Crew Alerting System
9. Multi-function Control and Display Unit
10. Auxiliary Control Panel
11. Radio Tuning and Audio Select Panel
12. Transponder Control Panel

Figure 7: ASTOR Cockpit Display Interfaces

The cockpit displays and controls are patterned after a typical glass cockpit. The pilot interface consists of multiple graphical user-interface panels for flight crew interaction via computer mouse clicks, or through an automated pilot model.

The ASTOR Pilot Model simulates the actions of a human pilot in executing a flight plan through climb, cruise, and descent phases to support batch mode simulations without human interactions. Pilot Model uses a set of programmed behaviors, sensors, rules, and actions that react to operational conditions, sense flight conditions, recognize alert and advisories and generate needed actions, and execute these actions respectively to maintain normal flight operations.

4.2.3 Research Prototype Flight Management System

Within an ASTOR, NASA Langley developed a Research Prototype Flight Management System (RPFMS) that can be modified and enhanced to provide specialized functions for NASA research and various project needs over time. The RPFMS includes the capabilities of a production FMS in addition to the research flexibility afforded by a software-based simulation. The RPFMS is capable of computing 4-D trajectories for an aircraft that comply with route and traffic flow management constraints, and providing execution guidance to the ASTOR auto-flight and auto-throttle systems. Furthermore, the RPFMS can host advanced technology that provides closed loop guidance to meet arrival time or interval spacing constraints and technology that can provide separation assurance functions. The RPFMS can send, receive, and act upon Data Comm messages, as well as generate simulated ADS-C Extended Projected Profile (EPP) messages, which provides a representation of the FMS-calculated 4-D flight trajectories for aircraft to ground-based automation platforms. Further information on the RPFMS can be found in [23, 24, 37-39]. The Multi-function Control and Display Unit, which is the human interface to the RPFMS, is depicted as item 9 in Figure 7.

4.2.4 Autonomous Operations Planner

In the early 2000s, NASA began development of a concept for airborne trajectory management based on the ability of a given aircraft to perform the traffic separation function autonomously[2] without reliance on ground-based air traffic control (ATC). As part of this research effort, NASA developed a prototype cockpit-based software tool called the Autonomous Operations Planner [34, 40-42]. Its purpose was to provide the trajectory management functions of conflict detection, resolution, and prevention; constraint compliance; and coordination with other vehicles. For more than a decade, AOP was refined and matured through multiple batch experiments and piloted simulations [43-48].

In 2012, NASA formulated Traffic Aware Strategic Aircrew Requests (TASAR) as an innovative strategy for triggering the long-term changes needed in cockpit technology and pilot culture to achieve airborne autonomy in the NAS [10]. To accomplish these changes, TASAR applies AOP's trajectory management algorithms in a cockpit-based system for trajectory optimization known as the Traffic Aware Planner, or TAP. The TAP technology shifted the focus of AOP away from conflict detection and resolution towards flight path optimization[3] as a viable first step to increase the level of user autonomy in the NAS.

The current implementation of AOP, AOP Version 2 (AOPv.2), merges the conflict detection and resolution capabilities of AOP with the trajectory optimization capabilities of TAP. The merger creates a single airborne tool that can be used for research and development of advanced trajectory management concepts. There are two main operating modes of AOPv.2: Conflict Avoidance and Optimization.

- <u>Conflict Avoidance</u>: This mode is entered if the active route is predicted to have an airspace conflict (e.g., traffic, weather, Special Use Airspace). The AOPv.2 technology provides the flight crew with trajectory modification guidance to resolve the conflict in the most efficient (e.g., least fuel or least time) manner.
- <u>Optimization</u>: This mode is entered if the active route is predicted to be de-conflicted. The AOPv.2 technology provides the flight crew with trajectory modification advisories to optimize the current flight path (e.g., minimize fuel burn, minimize flight time, and minimize trip cost) while respecting known airspace constraints and avoiding conflicts with known airspace hazards. Three types of trajectory modification solutions: Lateral, Vertical, and Combination Lateral plus Vertical (known as Combo) solutions.

The AOPv.2 technology prototype is implemented in the ATOS environment, and is fully integrated with the avionics and displays of the ASTOR aircraft simulation. Figure 8 shows the implemented AOPv.2

[2] Autonomy is defined within this context as a vehicle that can execute its mission without any outside governance.
[3] Note: Even though the focus of TASAR shifted from conflict detection and resolution to flight path optimization, trajectory modification recommendations provided by TAP are de-conflicted from known airspace hazards, including traffic, weather, and Special Use Airspace.

prototype in the optimization mode. A notification of an optimized solution is presented on the Engine Indicating and Crew Alerting System, and details of the solutions are presented on the Navigation Display and the RPFMS. The flight crew may select a solution to implement, and, if approved by ATC, can upload the solution to the RPFMS for execution.

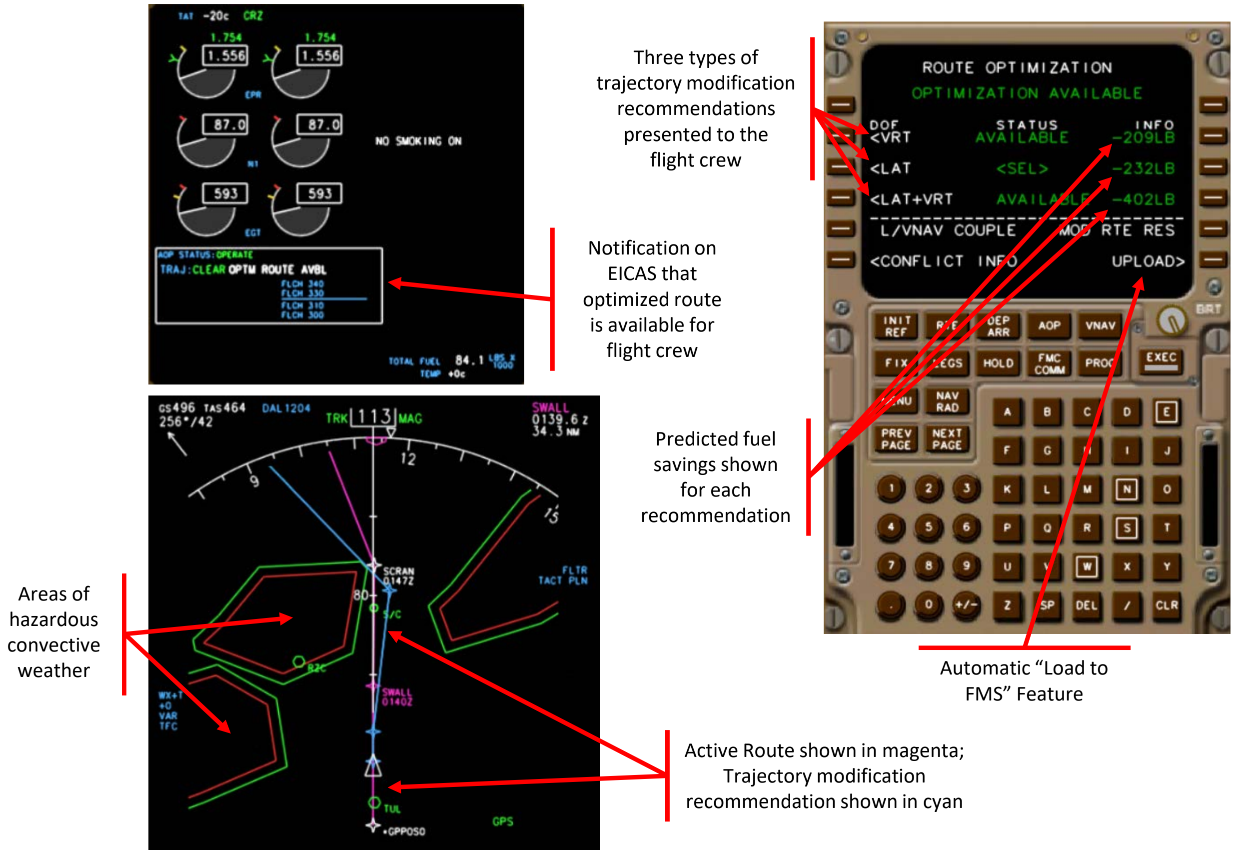


Figure 8: Autonomous Operations Planner, Version 2 Prototype (AOPv.2)

4.3 Traffic Manager

Traffic Manager (TMX) is a low-to-medium-fidelity simulation that has been jointly developed by National Aerospace Laboratory of the Netherlands and NASA Langley Research Center [49-51]. It is capable of simulating thousands of aircraft in a variety of operational environments. TMX can be used for several different simulation roles, including a rapid prototype development environment, a scenario generation tool, a traffic generator, a fast time simulation platform, and a real-time simulation platform that integrates with external simulations. TMX has many features that represent operational capabilities, which includes a pilot model, ATC model, ADS-B model, CPDLC model, 4-D wind model, and advanced airborne avionics. TMX has been used in multiple simulation studies for air traffic operations research and improvements for airborne merging and spacing [51, 52].

TMX was selected to support the scenarios for a TBO simulation environment to provide realistic high-density background traffic that minimized the overall simulation network and hardware infrastructure. TMX is able to simulate a large amount of aircraft on a single computer/network due to its comparatively lower level of fidelity. All TMX aircraft communicate with ATOS through a single connection in an HLA network. In contrast, each ASTOR instance needs its own individual HLA connection within an executed scenario. TMX is a valuable addition to the simulation use case given the need to simulate a large number of aircraft within a single network connection. Figure 9 presents the primary user interface for TMX. The airspace being simulated is the upper two-thirds of the display with aircraft shown as moving triangles. Other information for individual aircraft can be displayed alongside the aircraft icon with moving labels. Status display windows present selected configurations and error messages to the user.

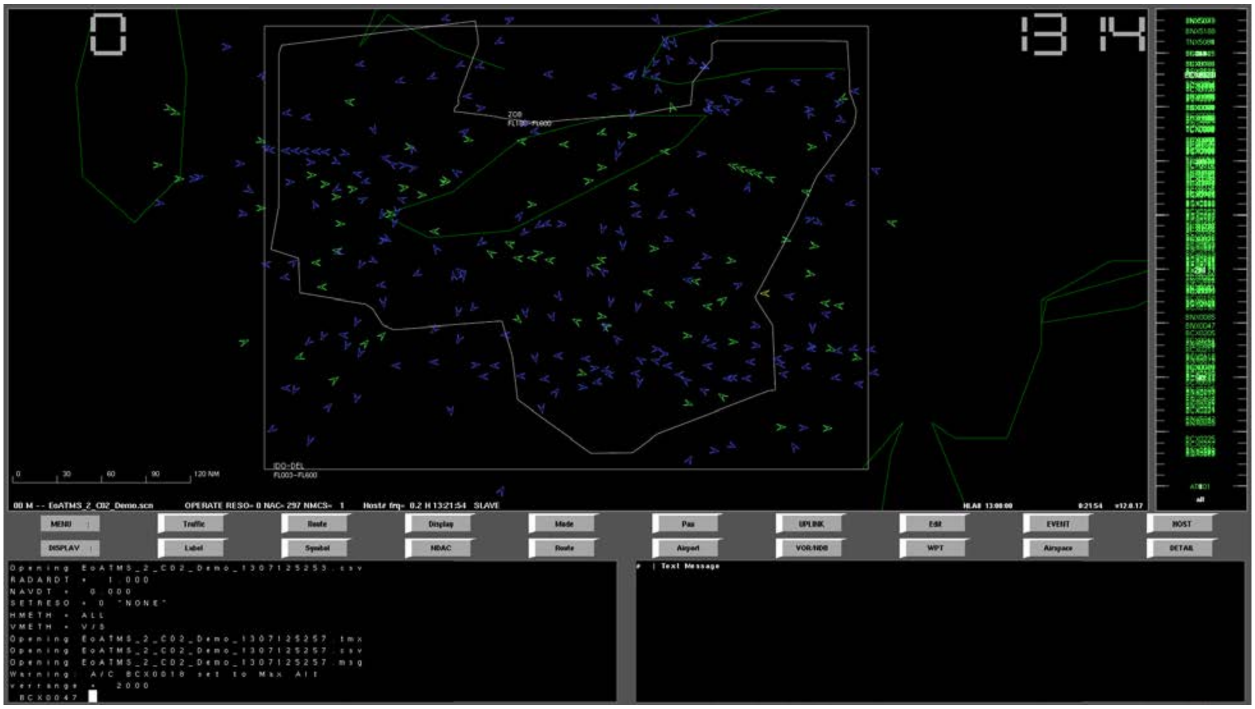


Figure 9: Traffic Manager Primary User Interface

5. Scenario Development Methodology

Simulation scenarios needed must provide a representative and realistic environment to evaluate service-based airspace operational concepts and technologies for the envisioned 2035-2045 TBO timeframe. The planned outcome of the scenario development process is the creation of 10 baseline TBO scenarios (two days with five time-periods each) that could be used in current and future ATM simulations. Two days were chosen to understand the variability between two nominal, minimal weather traffic days. Five time periods within a day were selected to cover the possible traffic fluctuations over the course of a typical day in the airspace of interest. The research team hypothesized that the variations between traffic days and traffic time-periods would exist; however, variability analyses determined there was no significant difference between scenarios for the two days selected. See Reference [1] for detailed information on the analyses conducted on the representative future TBO environment scenarios.

Following the methodology described herein, the scenarios were developed using a sequence of managed stages, automated scripts, and an iterative data collection process. The scenarios feature real-world traffic gathered from SWIM and archived at NASA Ames Research Center as a starting point, real-world convective weather data gathered from a weather service provider and archived at NASA Langley, real-world wind and temperature data gathered from NOAA and archived at NASA Langley, and real-world SUA data gathered from the FAA and archived at NASA Langley. All data are pre-processed to work with existing ATOS or TMX simulation capabilities.

The development of these scenarios was based on several requirements to be met or exceeded and to support potential follow-on activities. The four core requirements for the scenario development process are:

1. Real-world aircraft route data (SWIM) as a basis for traffic data
2. 4-D winds, special use airspace, and convective weather (planned for future research activities) will be considered for increased realism
3. Mixed equipage for services: 60% advanced-services equipped aircraft, 40% baseline equipage
4. High density airspace emulating 2040 traffic projections

The process by which the input base SWIM data were adjusted to fit into a form compatible with the ATOS environment was dictated by these requirements and checked at the end of each stage of processing before proceeding forward. The development processes and considerations in the scenario generation are described in the following sections.

5.1 Simulation Configuration

Adjustments were required to make the final scenario file for the time-periods of interest compatible with the ATOS environment. To achieve the TBO characteristics presented in Section 3.1, the following simulation configuration options were enabled.

- Wide dissemination and use of system-level constraints
    - Real-world wind data, properly formatted for use in ATOS, is used in the simulation.
    - Real-world convective weather and Significant Meteorological Information data, properly formatted for use in ATOS, is enabled in the simulation.
    - Real-world SUA data, properly formatted for use in ATOS, is used in the simulation.
    - Altitude and speed constraints during the arrival phase of flight are present on aircraft routes.
- Wide dissemination and use of aircraft state and intent
    - ATOS ADS-B Out model is used to broadcast aircraft state data.
    - ATOS ADS-B In model is used to receive aircraft state data from nearby traffic.
    - ATOS ADS-C EPP model is used to broadcast aircraft trajectory intent data.
- Routine use of Data Comm to request complex trajectory modifications and to receive clearances
    - ATOS Data Comm model is used to send route change clearances to aircraft.
- Aircraft always fly on 4-D trajectories
    - ASTOR RPFMS computes 4-D trajectories for all ASTOR aircraft.
    - ASTOR guidance, auto-flight, and auto-throttle systems are used to execute 4-D trajectories.
- Flexibility when desired, structure where required
    - The level of structure in the airspace is reduced by removing altitude constraints above FL180 to increase potential flexibility.
    - For equipped aircraft, AOPv.2 is used as a surrogate technology to provide flexible “free routes” that optimizes the route for fuel savings.
    - ATOS RPFMS capabilities that model standard terminal arrivals and approaches to known runways are used in the simulation.

ATOS is a complex simulation environment with a long history of development for multiple projects and programs. In addition to the aforementioned configuration options that enable the 2040 TBO environment, the following are just a few of the important ATOS/ASTOR specific configurations used during the research activity.

- Aircraft from recorded SWIM data are mapped to existing ATOS performance models.
- AOP is configured to provide lateral and/or combination lateral and vertical solutions. Vertical-only solutions are not permitted.
- ATOS Pilot Model will execute any received CPDLC message for a particular aircraft with a near perfect response time to the execution of commands from CPDLC messages.

5.2 Air Traffic in Simulation

To create baseline TBO scenarios for a future 2040 airspace environment, air traffic recorded in the FAA SWIM database is used as a starting point. Airspace traffic flows are expected to be dense and complex in 2040. Simulating future operations presents a difficult challenge: to accurately simulate realistic traffic routes that possess real-world complexities but are not contrived. Airspace sector loading and aircraft following routing structures with small variations in their flight paths are needed to match real-world flight conditions. Additionally, the air traffic in the simulation must match the operations within the presence of weather and SUA activation/deactivation schedules. The following subsections present the air traffic in the simulation in further detail.

5.2.1 FAA SWIM Data – Starting Point for Aircraft Routes

SWIM is an FAA information-sharing platform designated to facilitate an increased situational awareness and greater sharing of ATM system information [53]. SWIM is composed of multiple data sources with varying and unique purposes, accessible according to the end need of users. The NASA research team used the aircraft position and state data records within SWIM data as a starting point for the development of aircraft scenarios for the simulation used within the research activity. This air traffic data source provides the best source to simulate aircraft along realistic flight paths throughout a day instead of a contrived route. SWIM data are not a perfect recording of aircraft positional state data and considerable care must be taken in handling the original routes and putting them into an error free form for input into an ATOS scenario file format.

The following are some of the issues identified by the research team while working with the SWIM data.

- Only groundspeed is available in the SWIM data. Therefore, airspeed and/or Mach values may be computed using the groundspeed and corresponding wind, temperature, and pressure data.
- Aircraft weight information is not available within the SWIM data. Therefore, aircraft weight must be estimated based on the aircraft type, the fuel loading (which depends on the distance between the origin and destination airports), and the cargo/passenger loading.
- Aircraft call sign designations are routinely recycled throughout the day as presented in the SWIM data. Therefore, special care must be taken throughout the scenario development process to avoid duplication of information.
- Aircraft state data that define their as-flown routes in SWIM data are updated on a regular basis (up to once per second). Due to simulation constraints, the number of waypoints defining a route must be reduced.
- Incorrect or misaligned airports within the SWIM data can cause trajectory prediction errors for a TMX simulation. For example, if the origin or destination airport that is listed in the SWIM data is greater than an empirically derived distance and heading from the nearest waypoint in the data, the referenced airport will be removed from the scenario.
- Some airports identified in the SWIM data are incomplete in their 4-character designation. To solve this data issue, the research team must identify whether the airport in the data is a valid airport and just in need of its country code (e.g., “K” for airports in the United States). If the airport is valid,

the 3-character airport will be adjusted to 4-charcters with the inclusion of a “K” at the beginning of the origin or destination airport code.

5.2.2 Scenario Aircraft Call Sign Replacement Schema

Aircraft obtained from the SWIM data have their original commercial air traffic call sign (up to seven alphanumeric characters). One of the early steps of the scenario generation process is to replace the commercial call sign with a generic, but unique call sign. The replacement call sign schema allows tracking of the aircraft within the scenario based on its separation into one of six categories that represent the type of traffic that the aircraft is (i.e., background vs. traffic of interest, free route vs. fixed route). An additional designation for an aircraft beyond those discussed in Section 3.2 are “ASTOR Compatible,” which are aircraft that can be mapped to an ASTOR Airframe performance model, versus “ASTOR Non-Compatible,” which are aircraft that can only be modeled using TMX. “ASTOR Compatible” are able to receive free routes, since ASTORs interface with AOP.

These category abbreviations are used throughout the NASA researcher developed scripts and within the individual scenario files created for simulation. The replacement category abbreviations for the call signs in a scenario are presented in Table 2.

Table 2: Replacement Category Abbreviations for Call Signs

Aircraft Category	Abbreviation
Background Traffic	B
Traffic of Interest	T
ASTOR Compatible	C
ASTOR Non-Compatible	N
Fixed Route	X
Free Route	R

As aircraft are reassigned new call signs during the scenario development process, the original collection of aircraft can be subdivided into additional groups. Figure 10 provides a graphical example of how the categories in Table 2 are combined to define the aircraft (the first three characters of the call sign). The aircraft categories are represented by a tree branching equally until the final level at the bottom, describing the most detail about an individual aircraft’s new call sign. Note that two combinations are not possible due to the simulation: *BNR* and *TNR*. In these cases, it is not possible to simulate ASTOR Non-Compatible aircraft with free routes, since AOP only interfaces with ASTOR. In Figure 10, these aircraft types are represented with an 🛇 overlaid on the call sign letter designation.

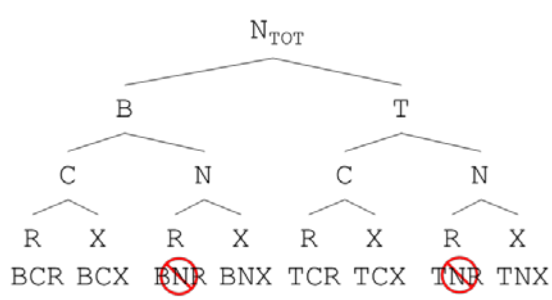


Figure 10: Scenario Aircraft Breakdown from SWIM Data

The replacement call signs are limited to a 7-character alphanumeric due to simulation constraints. Therefore, the final four characters of the call sign provide a numerical value incremented during the scenario development process. The following is the method in which the original call sign is modified for the scenario with examples.

- Original Call Sign → (*Background* or *Traffic of Interest*) (*ASTOR Compatible* or *ASTOR Non-Compatible*) (*Fixed Route* or *Free Route*) (up to 4 numeric values artificially incremented during replacement process)
- Example replaced call signs:
  - `UAL1234 → BCX0001`
  - `SWA9876 → TNX0224`
  - `DAL0918 → TCR2387`

Throughout the scenario development process, the same aircraft can have different category assignments in the evolution towards the final form of a scenario. In some cases, aircraft may revert to a previous category, using the updated letter designation for the new category. To maintain the original four-digit integer of that aircraft, the call sign number is incremented by a value of 5000 to maintain a point of reference. For example, consider an aircraft that has a modified original call sign of `TCX0746`, indicating that it is a fixed route, ASTOR compatible traffic of interest aircraft. Assume that aircraft is reassigned to a background traffic category – the new call sign will be `BCX5746`.

5.2.3 Development of High Density Traffic within Airspace Boundaries of Simulation

One of the goals of the scenario generation process was to take existing real-world traffic and use it as a basis to simulate traffic density in the year 2040. To reach this goal within the short developmental period of the research, it was postulated that the existing volume of traffic could be compressed in time by a specified factor and thereby significantly increasing the density of the traffic. The time compression factor is based on the following rationale:

- According to an FAA forecast [17], a 1.8% per year increase in traffic operations is expected. Therefore, targeting the year 2040 (midpoint of 2035 and 2045) from the start of this work equates to approximately a 40% increase.[4]
- NASA researchers made the decision to target an increase of 50% in air traffic density. The targeted increase is above the forecast value, but allows more simplified implementation for the simulation.
  - Current Day Operations + 50% Forecast Increase = 100% + 50% = 150% or 3/2 adjustment of current day operations

Therefore, time compression for the study has a factor of $66.\overline{6}$%, or 2/3, of the original time duration of the scenario. For example, a 4.5-hour scenario is compressed to 3 hours by multiplying 4.5 hours x $66.\overline{6}$%. The following is a list of key adjustments that are made within the initial scenario files:

- The start of the scenario file is the anchor point of the compression – it is unchanged.
- Command time stamps for all aircraft and their associated ATOS commands are adjusted linearly throughout the scenario file.
- Required Time of Arrival (RTA) values from SWIM data used by TMX are not compressed, but adjusted or slewed in time by the difference between the original command time and new

[4] Note, this projection was made prior to the COVID-19 global pandemic.

compressed command time. This keeps the original intended speed on target for the TMX aircraft.

- 3-D SUA polygons start and end times are adjusted within the compression routine. This includes their command times too.
- Weather Polygons, if they exist within the scenario, are adjusted similarly to the SUA polygons.
- ATOS 4-D reference wind files must be compressed to match the aircraft that flew through that airspace at that time. Compression routine does not directly adjust the values of the ATOS 4-D reference wind file, but the marked times in the ATOS 4-D reference wind file.

Figure 11 illustrates the time compression concept applied in the scenario development process to increase traffic density. Original simulation timeframe (uncompressed) will last 4 hours and 30 minutes (gray bar in the top timeline). The new simulation timeframe (compressed) will result in a total of 3 hours (gray bar in the second timeline). An example aircraft starts in the uncompressed simulation at the 1-hour mark and flies for 2.5 hours, ending at the 3.5-hour mark. Applying the time compression technique, the aircraft's start time is shifted towards the beginning of simulation at the 40-minute mark and flies for 2.5 hours as well, ending at the 3 hours and 10 minutes mark. Note that if the flight duration (RTA downstream values from SWIM data) was also compressed, the example flight would only last for 1 hour and 40 minutes total, requiring the simulated flight to fly faster than is operationally realistic for the given aircraft type.

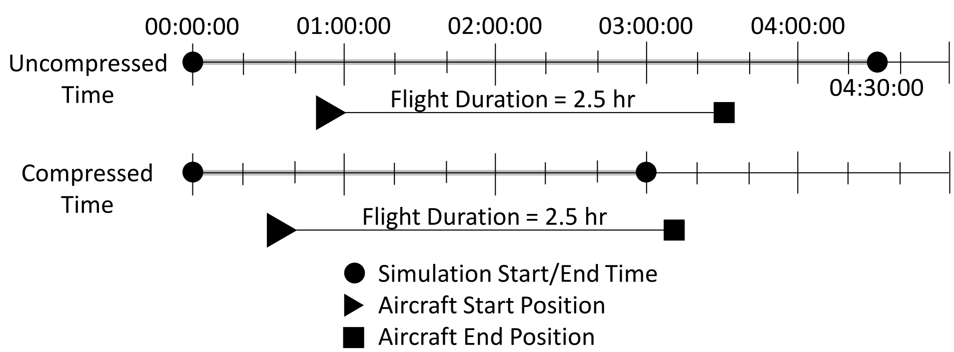


Figure 11: Time Compression Example

5.2.4 ASTOR/TMX Aircraft Exclusion Process

Throughout the scenario development processes, an aircraft may be either converted from an ASTOR Compatible designation back to a Non-Compatible TMX, or excluded from the simulation completely. The following list identifies, in general terms, a reason an aircraft may be excluded or changed to a non-compatible status and flown as a TMX aircraft.

Individual aircraft are excluded from the simulation if:

- The aircraft’s planned route is exclusively below FL180.
- The aircraft’s origin and destination airport are the same.
- The aircraft’s origin airport is empty or missing, which may occur due to the aircraft leaving the origin airport under Visual Flight Rules and transitioning to Instrument Flight Rules to continue its flight to the arrival airport.
- The estimated distance remaining between the aircraft initialization point to the destination airport is empty or less than 50 nautical miles.

Individual aircraft are returned to a non-compatible status if:

- The aircraft's origin and destination airports are empty or missing.
- The last waypoint in the aircraft's route from the SWIM data is not below FL180, signifying that the route data are incomplete to the destination airport.
- The aircraft's cruise altitude is determined to be less than or equal to 10,000 feet, or greater than FL400 (or altitude greater than FL370 for a 737-300 model type), which avoids the potential for bad trim conditions when the simulated aircraft initializes.
- The aircraft's route contains a turn that exceeds a preset radius limit that is unsolvable by automatic means.

5.3 Scenario Generation Process

The complexity of the scenarios required for the research activity necessitated the need to separate the scenario generation process into multiple stages. Each stage provided a meaningful milestone in the process of separating flights into the groups defined in Section 5.2.2, adding corrective measures to the aircraft's state and route, and selecting traffic for post-hoc data analyses. The scenario generation process was implemented for multiple scenarios simultaneously. Thus, any necessary stage repetitions were not applied piecewise to select scenarios, but rather to all scenarios to ensure uniformity in the end product. The four stages are presented below and more detail is provided in the following sections.

- **Stage 0:** Gather input data from SWIM and create a baseline TMX scenario with "Background" and "Traffic of Interest" groups.
- **Stage 1:** Prepare baseline TMX scenario from Stage 0 in ATOS format, accommodating winds, weather polygons (if present), and SUA polygons. Compress traffic to approach 2040 traffic density. Prepare TMX-only scenario files for a data collection run. Perform Stage 1 Data Collection activity.
- **Stage 2:** Assign aircraft to "ASTOR Compatible" and "ASTOR Non-Compatible" groups. Convert TMX aircraft routes to ASTOR aircraft routes for ASTOR Compatible aircraft, reducing the number of waypoints for the RPFMS to handle. Provide corrections to ASTOR Compatible aircraft, ensuring that they are able to initialize and fly the route properly. Prepare ASTOR-only scenario files for a data collection run. Perform Stage 2 Data Collection activities.
- **Stage 3:** Select 60% equipage for free route aircraft. Assign aircraft to "Free Route" and "Fixed Route" groups. Prepare combined TMX and ASTOR scenario files with replicates for a data collection run. Perform Stage 3 Data Collection activities.

To implement these stages, scripts were developed by NASA Langley research team members from October 2019 through February 2020. Scripts were developed and executed within the MATLAB R2019b coding language and were version controlled between research team members using the Git repository management by Atlassian Bitbucket. Ten primary researcher scripts were developed with multiple supporting scripts for scenario generation (e.g. looping functions). Approximately 10,000 lines of code (including comments and explanatory information) comprise the scripts used in the development of simulation scenarios of a 2040 TBO environment. The scripts were architected to reduce duplicate actions and use a common Route Database for tracking changes to an individual scenario throughout the staging process. A high-level summary of the scripts is presented in a table in Appendix A followed by a more detailed description in Appendix B.

Throughout the various Stages as described, input and intermediate files are used and created before the final simulation scenarios are generated. An input and output file naming convention was developed to keep track of the various components used in the process. The details of the file naming convention used in the scenario development and in the output files used in the subsequent data analysis is specified in Appendix C.

5.3.1 Stage 0 – Preparation

For Stage 0, the preparation of a traffic simulation scenario begins with three primary scripts and the TMX SWIM scenarios generated from the initial SWIM data source.

The initial step in the Stage 0 process is the generation of a baseline TMX scenario from SWIM data. SWIM data for the selected dates and times is acquired and converted with a series of tools and scripts to create a scenario file compatible with a basic TMX simulation. Figure 12 presents the airspace of ZOB and the criteria used to initialize and terminate aircraft within a simulation. Starting positions for aircraft within the scenario are selected to begin anywhere within the region of the ARTCC ZOB center (yellow line within Figure 12) and up to 10 minutes outside this boundary (approximated by the shaded green region of Figure 12). Aircraft selected for inclusion must meet a variety of researcher specified criteria and each aircraft's route is terminated at its destination (if within ZOB) or at a defined deletion boundary that is outside of ZOB (red line within Figure 12). The output baseline uncompressed TMX scenario is confirmed with a TMX simulation and the traffic movement data returned by the simulation is validated using engineering judgement. Details on the process to convert SWIM data to a TMX scenario are presented in Appendix D.

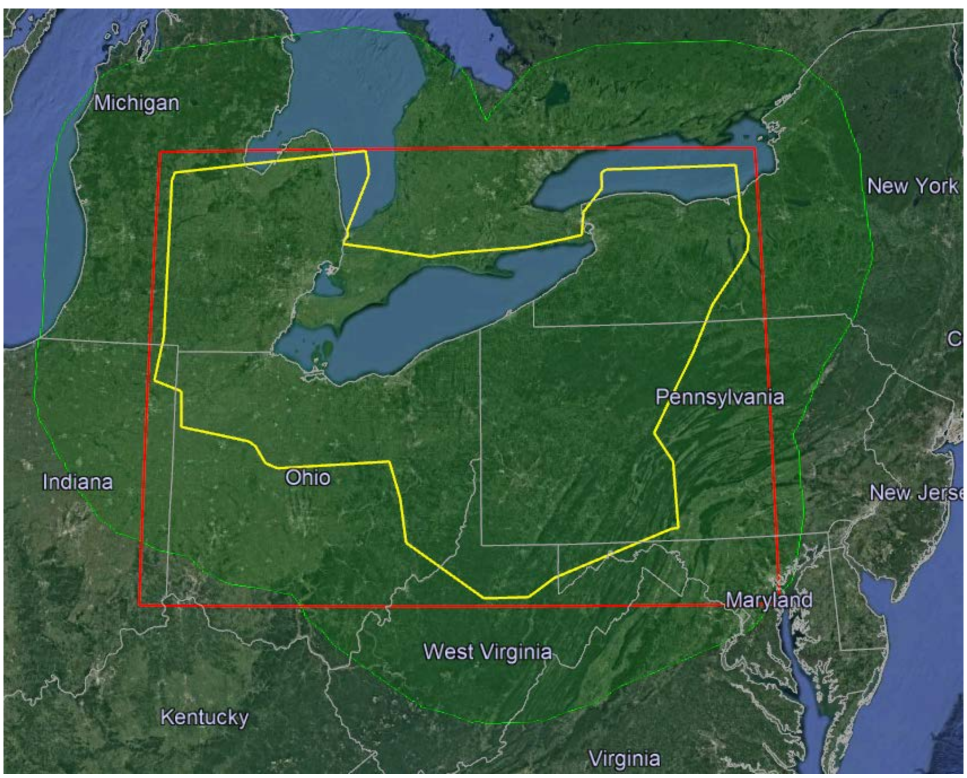


Figure 12: Airspace of Interest Creation and Deletion Boundaries

Following the development of the baseline TMX scenario from the initial SWIM data source, the first script prepares the ATOS 4-D Wind Reference data files (`S0_ATOS_4dwinds.m`) for a specified time and date range. This script combines multiple existing ATOS formatted wind data files into one file and adds the fourth dimension, a time component. An individual ATOS wind file contains North-South Winds, East-West Winds, and Temperature data. ATOS 4-D wind reference files for the specified time and data combination are exported from the process.

The next script parses the SUAs for the region of interest (`S0_SUA_Parser.m`) for the scenario in an ATOS compatible format that includes the activation schedule and geometry. The script accommodates a limitation in the ATOS required format for SUA polygon identifiers, a 200 vertex pair limit for the polygons, and polygon information is written in blocks of information separated at one second intervals to allow for repeated broadcast to new entrants into the simulation space. An ASCII (American Standard Code for Information Interchange) text file of the SUAs is exported from the process.

The third and final script of Stage 0 creates the baseline TMX scenarios (`S0_Baseline.m`) by combining SWIM data formatted as a TMX scenario file with 4-D Winds, SUA Polygons, and Weather Polygons, if present. A TMX only scenario that is the original time length of 4.5 hours (i.e., the scenario is uncompressed) is exported from the process.

The basic assumptions and rules applied within these scripts are:

- TMX scenario from SWIM data:
    - SWIM Data are present for all aircraft in the airspace of interest for the time period of interest.
    - SWIM data are accurate within reasonable basic ground tracking information, knowing that adjustments will be required.
    - SWIM TMX scenario files are split from a 24-hour SWIM time block into times of interest for each scenario (e.g. 4.5-hour blocks for this research activity).
    - To reach expected levels of aircraft density for targeted timeframe of 2035-2045, 4.5 hour blocks of current day traffic data will be compressed down to represent 3-hour blocks of future traffic data in Stage 1.
    - All aircraft are terminated upon exiting an established deletion boundary.
- ATOS 4-D Winds:
    - Data exist for times and dates selected for simulation within NASA Langley archives and is continuous (i.e. there is no missing data over the timeframe of interest).
- SUA Parser:
    - SUA activation schedule data exists for times and dates selected for simulation within NASA Langley archives and is continuous (i.e. there is no missing data over the timeframe of interest).
    - SUA polygon vertex point data have been already been extracted from corresponding FAA Navigation database.
    - Non-unique SUA names are combined together with a single activation and deactivation time.
- Baseline TMX scenario:
    - Data exist for times and dates selected for simulation and is continuous (i.e. there is no missing data over the timeframe of interest) for Wind and Temperature data, SUA activation schedule data, and input SWIM TMX scenario files.

The defined exit criteria for Stage 0 scripts is a TMX scenario file with as-flown aircraft routes (baseline simulation data set) for all selected times and dates for the simulation.

5.3.2 *Stage 1 – TMX Only Preparation*

For Stage 1, two primary scripts work with the data from the baseline information to form scenarios that will fully support a TMX simulation (both uncompressed and compressed time).

The first script is labeled Call Sign Replacement (`S1_CallSign_Replacement.m`) and its primary purpose is the renaming of the aircraft call signs from SWIM data to the specific categories for the TBO scenarios. Aircraft specified in the original scenario files generated in Stage 0 will have their call sign (up to seven alphanumeric characters) replaced to de-identify and allow tracking of the aircraft configuration within the scenario based on its separation into one of six categories, as discussed in Section 5.2.2. A TMX only scenario is exported from the process. Specifically, this script allocates aircraft to either the Traffic of Interest or Background Traffic groups, based on the criteria discussed in Section 3.3.1.

The second script, labeled Time Compression (`S1_Time_Compression.m`), applies a specified time compression ratio to scenario aircraft command time values, 4-D winds, SUAs, and weather polygons within individual aircraft routes. The script compresses the time stamps of all simulation commands for individual aircraft within the scenario, compresses the time stamps for activation and deactivation of SUAs and weather polygons if present, and compresses the reference times for the ATOS 4-D wind reference files. RTA time stamps are adjusted or slewed in time by the difference between the original command time and new compressed command time. A compressed time TMX only scenario and 4-D wind reference files are exported from the process.

The basic assumptions and rules applied within these scripts are:

- Call Sign Replacement:
    - Various aircraft types possible within the scenario and their possible mapping to an ASTOR airframe model are already identified in the aircraft-mapping file stored within the script directory.
    - Key Variable assumptions:
        - Minimum distance to go to end of a flight is 50 nautical miles.
        - Minimum altitude for the last waypoint in the route is 18,000 feet.
        - Constrained waypoint altitude is 18,000 feet.
- Time Compression:
    - No midnight crossover of command time values.
    - Command time values have already been shifted to zero to match the simulation clock.
    - Time compression ratio will be $66.\overline{6}$%, or 2/3. This will compress a 4.5-hour time block to 3.0 hours.

After the last script of the stage completes a data processing run, the resulting scenario (including SUAs and weather polygons if present) and matching ATOS 4-D wind reference files are ready for a data collection run within the ATOS simulation environment (Stage 1 Data Collection). The data are analyzed to ensure that all aircraft in the scenario fly their respective routes properly.

The defined exit criteria for Stage 1 scripts is a set of problem-, bug-, and issue-free TMX uncompressed and compressed scenarios with as-flown aircraft routes for all selected times and dates for the simulation.

5.3.3 *Stage 2 – ASTOR Only Preparation*

Stage 2 consists of four primary scripts that use the processed Stage 1 simulation scenarios to prepare scenarios (both uncompressed and compressed time) that are compatible with ASTOR aircraft performance models, AOP, and the higher fidelity resources of ATOS.

The first script applied is the TMX to ASTOR conversion (`S2_TMX2ASTOR.m`) and its primary purpose is to convert TMX aircraft to ASTOR aircraft for all compatible aircraft types and modify its route to be compatible with ASTOR RPFMS. ATOS and ASTOR specific commands are added to compatible aircraft types. Various initial conditions are estimated to enable TMX aircraft to fly now as ASTOR aircraft. Initial TMX positional routes are simplified with various fixes to SWIM routes for bad radii and vertical constraints. Information on the modification processes of the initialization state and the aircraft route data from SWIM data is presented in Appendix E. ASTOR aircraft in the scenario are equipped with AOPv.2, which generates free routes for those aircraft. A combined TMX and ASTOR scenario is exported from the process. The TMX to ASTOR conversion is followed by an ASTOR-only data collection activity (Stage 2 Data Collection 1), where all ASTOR aircraft are AOP equipped and run for 10 minutes within the 3- or 4.5-hour scenario.

The second script, labeled as Scenario Checkout (`S2_SCNcheckout.m`), is part one of a two part process to attempt a correction for initialization and route errors within the input as-flown route data from SWIM. Scenario Checkout identifies and attempts to fix errors encountered during Stage 2 Data Collection 1. If issues manifest, they are corrected through various means. If the attempted corrections are not able to solve the issues, the aircraft is sent back to non-compatible status as a TMX aircraft. A combined TMX and ASTOR scenario is exported from the process. The Scenario Checkout is followed by another ASTOR-only data collection activity (Stage 2 Data Collection 2), where all ASTOR aircraft are AOP equipped and run for 10 minutes within the 3- or 4.5-hour scenario.

The third script is the Scenario Confirmation (`S2_SCNconfirm.m`), which performs part two of the scenario correction process. Its purpose is to eliminate any remaining errors encountered during Stage 2 Data Collection 2. As before, all ASTOR aircraft are equipped with AOP and run for 10 minutes after initialization within the 3- or 4.5-hour scenario. If issues manifest, they are corrected through various means. If the corrective actions are not able to solve the issues, the aircraft is sent back to non-compatible status as a TMX aircraft. A combined TMX and ASTOR scenario to be used as a baseline run for Stage 3 data collection is exported from the process.

The last script within Stage 2 is the creation of free route ASTOR aircraft messages (`S2_FreeRoute_Conv.m`). The script creates CPDLC messages that define free routes for ASTORs from AOP logs generated during Stage 2 Data Collection 2. Additionally, ADS-B is turned on for all ASTOR aircraft. A combined TMX and ASTOR scenario with CPDLC messages for compatible aircraft to be used as an experiment replicate for Stage 3 is exported from the process.

The basic assumptions and rules applied within these scripts are:

- TMX to ASTOR:
    - Airspeed estimates are based on the 1976 U.S. Standard Atmosphere, adjusted for temperature for matching time and date within the 4-D ATOS wind reference file.
    - Original SWIM waypoints below 10,000 feet are removed.
    - The aircraft's as-flown route from SWIM data can be simplified and corrected if needed by one or more of the route simplification methods.
    - Non-monotonically decreasing or increasing vertical trajectories are corrected.
    - Key variable assumptions:
        - If a non-zero vertical speed is present at initialization, it is bound between +/- 500 ft/min.
        - Fuel reserve in the weight estimation is 60 minutes.
        - Payload weight estimation is 80% of maximum payload weight.

- Scenario Checkout:
    - Stage 2 Data Collection 1 has been completed successfully.
- Scenario Confirmation:
    - Stage 2 Data Collection 2 has been successfully completed.
- Free Route Conversion:
    - Stage 2 Data Collection 2 has been successfully completed.
    - AOP solutions are sorted for each candidate aircraft and the least-fuel consuming flyable option is selected.

The defined exit criteria for Stage 2 scripts is ATOS scenarios that contains free routing for all ASTOR compatible aircraft that had AOP solutions for all selected times and dates for the simulation.

5.3.4 Stage 3 – TMX and ASTOR Integration

Stage 3 involves running one script that uses the final form of the Stage 2 free route CPDLC messages for both uncompressed and compressed simulation scenarios. Information on the aircraft naming convention used in the Stage 3 description is described in Section 5.2.2.

The last script of the scenario development process is the TMX and ASTOR Integration (`S3_Integrated.m`). This script performs a 60/40 split on available free route aircraft for a scenario. To comprise 60% free route aircraft, all TCX aircraft that have free routes available to them are assigned their free routes (thus becoming TCR aircraft), and a variable percentage of BCX aircraft that have free routes available to them are randomly assigned their free routes (thus becoming BCR aircraft). Excess CPDLC messages are removed from the final form of the scenario file. A TMX and ASTOR scenario with these changes is exported from the process, including necessary replicates. Scenarios from Stage 3 processing are ready for final data collection in the Stage 3 ATOL ATOS Runs (TMX & ASTOR).

The basic assumptions and rules applied within the Stage 3 script are:

- TCR: 100% of Traffic of Interest are assigned their free routes.
- TCX: Traffic of Interest aircraft that do not have free routes available to them remain as traffic of interest on fixed routes.
- BCR: 60% of ASTOR-Compatible traffic (TC and BC aircraft) with free routes available to them minus all TCRs are randomly assigned their free routes; remainder fall back to BCX.
- BCXs - Remain as Background ASTORs.
- TNXs and BNXs - Remain unchanged as TMX aircraft.
- ADS-B Out/In is turned off for ASTORs to minimize computer network traffic.

The defined exit criteria for Stage 3 scripts form a set of ATOS Scenarios that match the criteria outlined in the Data Analysis and Collection Plan [1] for the research activity. Scenarios contain fixed route, background traffic for TMX simulation and fixed route, background and traffic of interest aircraft for ASTOR airframes, and free route ASTOR aircraft that have AOP solutions for all selected times and dates for the simulation.

6. Discussion

The following section discusses the results from the scenario development methodology described in this document. A summary of the result of the scenario development process for the selected date specified in Section 3.3 is presented with included figures and tabular data. Following this, the impacts to the NASA Langley simulation capabilities are discussed as well as the potential future research applications that this scenario development methodology can support. The work completed under and documented in this scenario development process represents several significant advancements in the state-of-the-art of NASA Langley's ATM simulation capability.

6.1 Scenario Development Process Summary

The TBO simulation scenarios created used Cleveland Center Class A airspace as the airspace of interest. Cleveland Center was chosen for three reasons: 1) there is a large volume of en route traffic, 2) the airspace structure features several high-density parallel routes and multi-axis merging geometries, and 3) the airspace has predominant east to west, west to east, and mixed traffic flows throughout the course of a nominal day. The scenarios use recorded SWIM air traffic, four-dimensional wind and temperature data, four-dimensional convective weather data, and SUA data from days/times of interest. The process for creating the scenarios was documented, and the research team developed and documented automated scripts to create these scenarios.

Ten distinct simulation scenarios were created using traffic from May 23-24, 2018, to support current and future research applications. Each scenario contains approximately 1500-2000 aircraft simulated in 3-hour time periods of compressed traffic density. Approximately 70% of the aircraft in each scenario are medium-high fidelity ASTOR simulated aircraft, and the remaining 30% are low-fidelity TMX simulated aircraft. Two versions, compressed and uncompressed, of each scenario were created, and additional replicates were created to test the variability of the simulation environments. Table 3 lists the individual scenario numbers and the associated date and time range used to create 3-hour compressed scenarios for the simulated TBO environment.

Table 3: Stage 3 Scenarios – Data and Time of Simulation

Scenario No.	May 23, 2018	May 24, 2018
1	1100-1530Z (0700-1130 EDT)	-
2	1300-1730Z (0900-1330 EDT)	-
3	1500-1930Z (1100-1530 EDT)	-
4	1700-2130Z (1300-1730 EDT)	-
5	1900-2330Z (1500-1930 EDT)	-
6	-	1100-1530Z (0700-1130 EDT)
7	-	1300-1730Z (0900-1330 EDT)
8	-	1500-1930Z (1100-1530 EDT)
9	-	1700-2130Z (1300-1730 EDT)
10	-	1900-2330Z (1500-1930 EDT)

To create a representative TBO environment, approximately 40% of flights in each scenario were provided with modified SWIM routes that fly a more business-optimal route. The goal of the TBO scenarios was to represent a mixed equipage of services – 60% advanced-services equipped aircraft and 40% conventional equipage. However, the outcome of the equipage split was affected by several issues. First, the limited availability of ASTOR performance models within ATOS comparable to the real-world aircraft within the SWIM data. Even with the mapping of multiple aircraft types to an individual ASTOR aircraft performance model (see Appendix E.1), many aircraft types within the traffic composition of the scenario that met the criteria of "Traffic of Interest" were still forced to be part of the "Background Traffic" group. Throughout the stages of the scenario development, aircraft that were part of the "ASTOR Compatible" group had their designation changed to the "ASTOR Non-Compatible" group generally because of invalid routes, diminishing the possible equipage of advanced services. Finally, the removal of aircraft from the scenario's airspace as presented in Section 5.2.4 further reduced the total count of possible “Free Route” aircraft in the TBO scenarios.

Figure 13 presents an overview of the flights within a 2040 TBO scenario overlaid over a satellite image map. Similar to Figure 12, ZOB airspace is illustrated by the heavy yellow line. Aircraft in the simulation are represented by the small blue aircraft icons with a portion of their trailing paths shown in yellow (ASTOR Compatible) or blue triangles with a trailing path shown in red (ASTOR Non-Compatible, or TMX aircraft). Larger Class B airports are noted by the blue airport symbol, and state outlines are in gray.

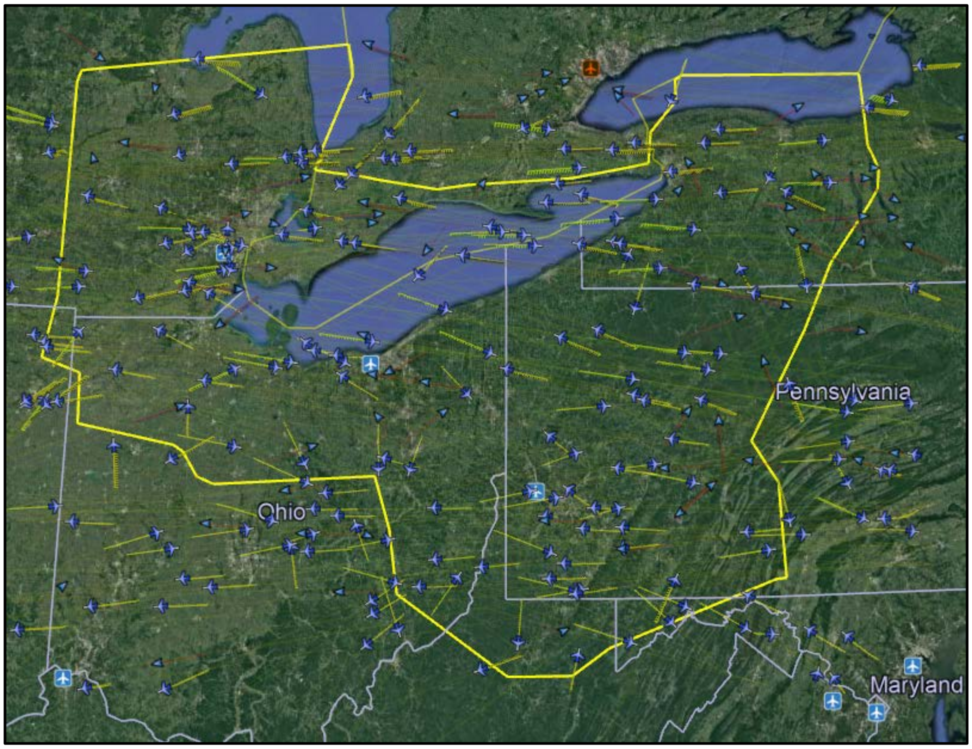


Figure 13: Overview of Flights within a TBO Scenario

The final version of the TBO environment scenarios are extremely complex and contain thousands of aircraft in the simulation. Figure 14 illustrates the complexity and density of a full 3-hour, compressed scenario from the SWIM data as a starting point to the final scenario product.

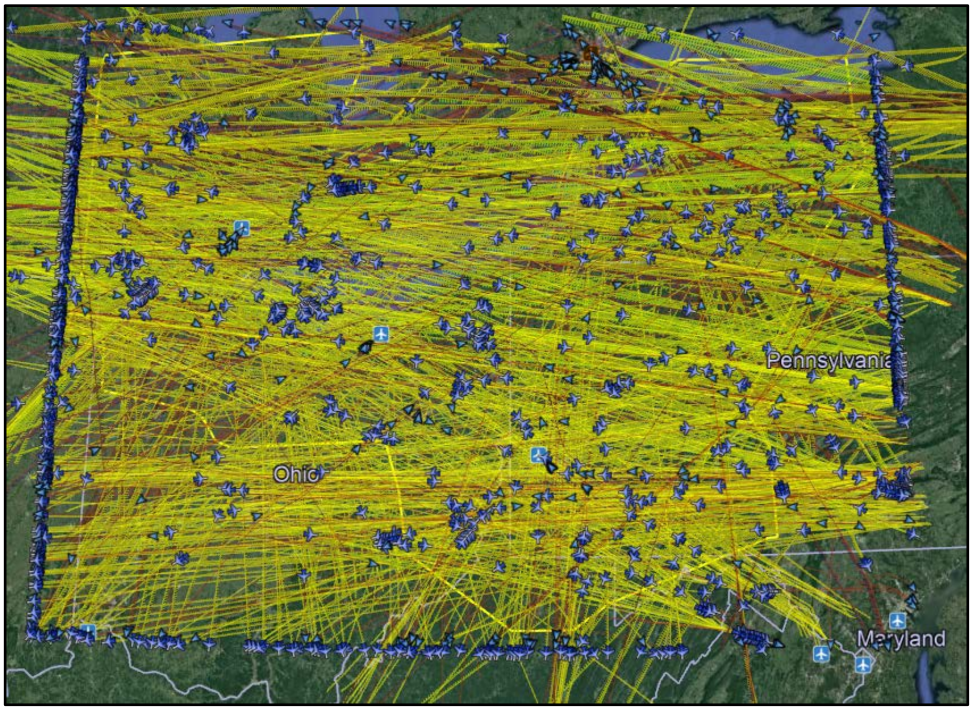


Figure 14: All Flight Paths for a 3-hour Compressed Scenario

Figure 15 presents an example of the more complex movements of aircraft within a scenario. The image is zoomed in near an airport within ZOB. It shows the dynamic flight paths and various flight path elevations (shown as drop lines from the aircraft's trailing path to the earth's surface) of aircraft within the simulation.

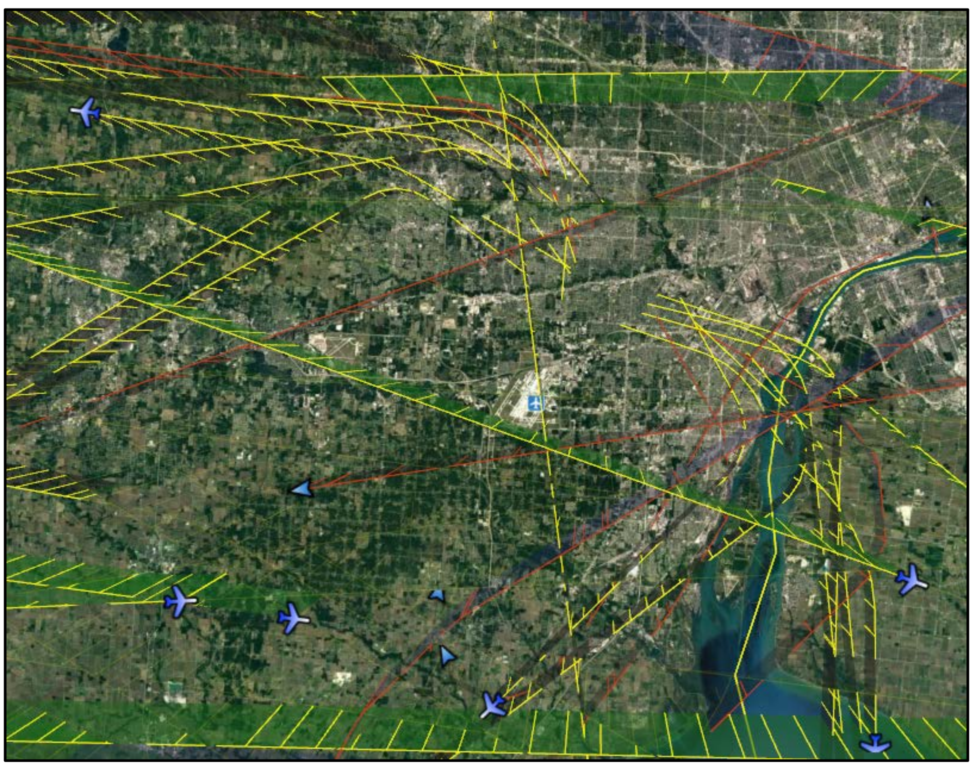


Figure 15: Example of Complexity of Aircraft Routes near an Airport

6.2 Results and Discussion

The following section presents results from the scenario development process for the ten TBO environment scenarios, first for the baseline, 3-hour compressed traffic density scenarios (no "Free Route" aircraft) and then for the integrated 3-hour compressed traffic density scenarios. Similar results occur for the 4.5-hour uncompressed traffic scenarios. A summary of the potential impacts to NASA simulation capabilities for ATM researchers is also presented.

The results that follow are focused on the scenarios that were generated from the development process prior to any subsequent data analysis that may have removed outlier aircraft from the scenario based on perceived erratic behavior caused by simulation artifacts[5]. Information in the following tables and figures uses notation that is explained in Section 5.2.2. An "Excluded" category has been added within the tables and figures to capture the aircraft that were removed from the initial input SWIM data as described in Section 5.2.4. As described in Section 5.3.4, replicates of each scenario were created for the data analysis and assessment process. Three replicates were generated for each integrated scenario in Stage 3; however, the following results are identical for all replicates created in Stage 3 because variability is only present after the simulation is executed in ATOS[6]. Finally, it is noted that a portion (less than 16 minutes, uncompressed time) of the input baseline SWIM data used to form the TBO scenarios is not present for the beginning of Scenario #1.

6.2.1 Stage 3 Baseline Scenarios

Tabular data for the Stage 3 baseline 3-hour compressed traffic density scenarios are presented in Table 4. Maximum values for each aircraft simulation category across the ten scenarios are highlighted with a gray fill. The difference between aircraft to be analyzed and aircraft in the scenarios is captured within the "Excluded" group. Unlike the Stage 3 integrated scenarios, aircraft sub-groups TCR and BCR are empty within the Stage 3 Baseline scenarios.

Table 4: Aircraft Count by Scenario – Stage 3 Baseline Scenario, 3-hour

Category	Scenario Number									
	1	2	3	4	5	6	7	8	9	10
Aircraft Analyzed	**2076**	**2337**	**2427**	**2659**	**2652**	**2274**	**2396**	**2549**	**2740**	**2776**
TCX	198	239	262	288	328	235	245	276	314	324
BCX	801	883	845	953	1016	878	871	861	885	893
TCR	0	0	0	0	0	0	0	0	0	0
BCR	0	0	0	0	0	0	0	0	0	0
TC & BC	**999**	**1122**	**1107**	**1241**	**1344**	**1113**	**1116**	**1137**	**1199**	**1217**
TNX	56	76	111	155	158	69	83	107	152	188
BNX	422	355	385	435	447	379	357	392	504	614
TN & BN	**478**	**431**	**496**	**590**	**605**	**448**	**440**	**499**	**656**	**802**
Excluded	**(599)**	**(784)**	**(824)**	**(828)**	**(703)**	**(713)**	**(840)**	**(913)**	**(885)**	**(757)**
Aircraft in Scenario	**1477**	**1553**	**1603**	**1831**	**1949**	**1561**	**1556**	**1636**	**1855**	**2019**

[5] Reference [1] provides an overview of the techniques used to validate aircraft performance in the simulation scenarios and the results of the validation activity.

[6] Reference [1] provides an analysis methodology and results for evaluating the variability within and between simulation scenarios.

A graphical representation of the data within Table 4 is presented in Figure 16. Individual aircraft simulation categories are shown as the grouped vertical bars using the primary (left) y-axis, where cumulative groups are shown as solid colored markers using the secondary (right) y-axis ("Aircraft Group Count"). Aircraft sub-groups TCR and BCR are empty within these scenarios and are not presented within the figure.

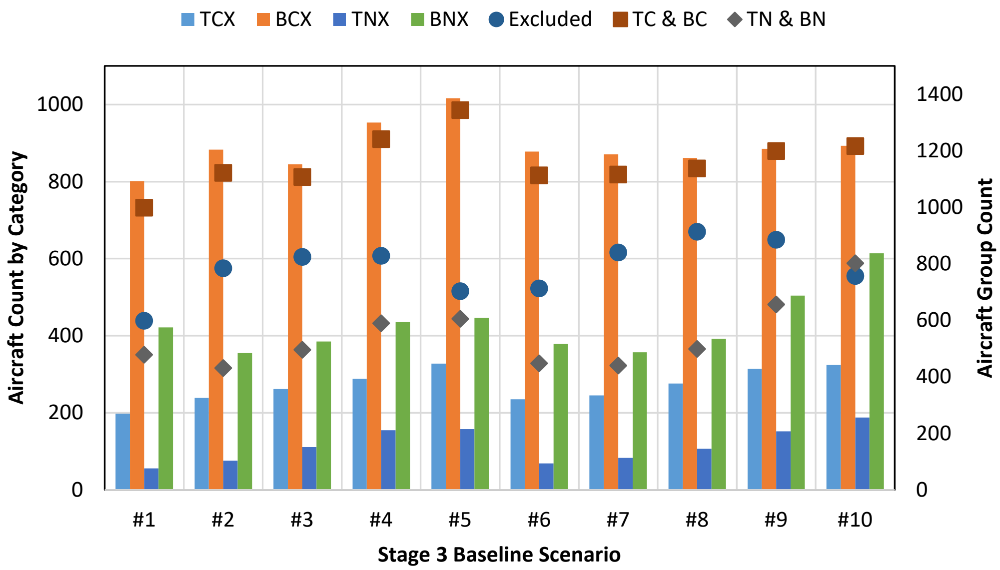


Figure 16: Aircraft Distribution by Scenario – Stage 3 Baseline Scenario, 3-hour

6.2.2 Stage 3 Integrated Scenarios

Tabular data for the Stage 3 integrated 3-hour compressed traffic density scenarios are presented in Table 5. Maximum values for each aircraft simulation category across the ten scenarios are highlighted with a gray fill. The difference between aircraft to be analyzed and aircraft in the scenarios is captured within the "Excluded" group.

Table 5: Aircraft Count by Scenario – Stage 3 Integrated Scenario, 3-hour

Category	Scenario									
	1	2	3	4	5	6	7	8	9	10
Aircraft Analyzed	**2076**	**2337**	**2427**	**2659**	**2652**	**2274**	**2396**	**2549**	**2740**	**2776**
TCX	51	62	76	77	75	61	65	94	101	87
BCX	349	387	367	420	463	385	382	361	379	400
TCR	147	177	186	211	253	174	180	182	213	237
BCR	452	496	478	533	553	493	489	500	506	493
TC & BC	**999**	**1122**	**1107**	**1241**	**1344**	**1113**	**1116**	**1137**	**1199**	**1217**
TNX	56	76	111	155	158	69	83	107	152	188
BNX	422	355	385	435	447	379	357	392	504	614
TN & BN	**478**	**431**	**496**	**590**	**605**	**448**	**440**	**499**	**656**	**802**
Excluded	**(599)**	**(784)**	**(824)**	**(828)**	**(703)**	**(713)**	**(840)**	**(913)**	**(885)**	**(757)**
Aircraft in Scenario	**1477**	**1553**	**1603**	**1831**	**1949**	**1561**	**1556**	**1636**	**1855**	**2019**

A graphical representation of the data within Table 5 is presented in Figure 17. Individual aircraft simulation categories are shown as the grouped vertical bars using the primary (left) y-axis, where cumulative groups are shown as solid colored markers using the secondary (right) y-axis ("Aircraft Group Count").

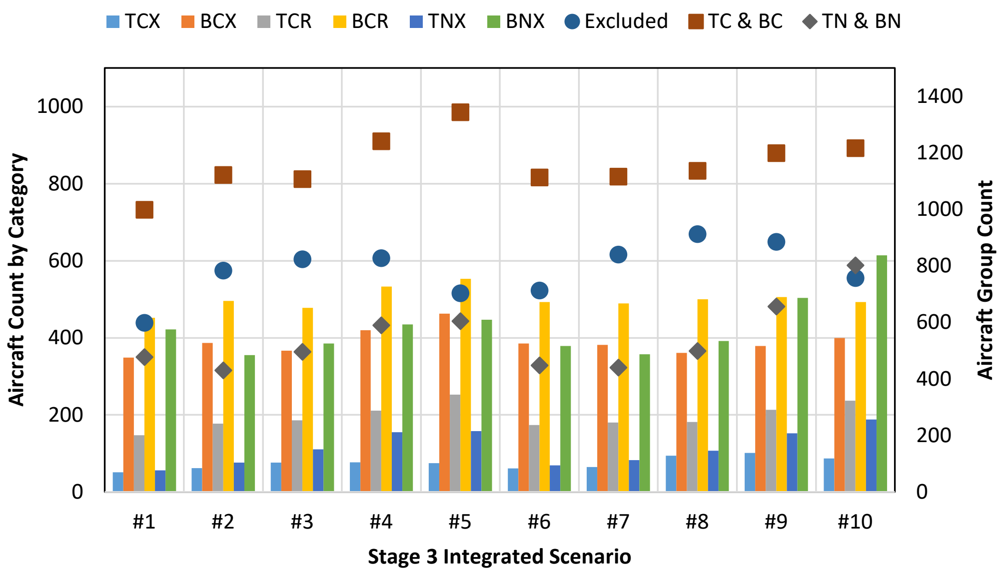


Figure 17: Aircraft Distribution by Scenario – Stage 3 Integrated Scenario, 3-hour

Common to both the Stage 3 integrated and baseline 3-hour compressed traffic density scenarios is the data presented in Table 6. In this table, aircraft are separated by aircraft performance model instead of aircraft group. Data includes aircraft simulated by both ASTOR and TMX simulation capabilities. The category of 'Other' represents aircraft types that exist within the simulation scenario, but are exclusive to the background traffic group and simulated within TMX.

Table 6: Aircraft Count by Performance Model by Stage 3 Integrated Scenario, 3-hour

ATOS Model	Scenario Number									
	1	2	3	4	5	6	7	8	9	10
NASA_HU25	523	602	601	669	692	590	616	619	628	582
NB137_2E22	21	22	17	22	25	26	24	23	21	20
NB172_2E27	386	425	419	467	536	430	411	415	461	522
NB250_2E40	33	33	26	31	38	31	25	26	33	38
WB315_2E48	24	26	24	29	31	21	22	30	30	32
WB535_2E77	12	14	20	23	22	15	18	24	26	23
Subtotal	**999**	**1122**	**1107**	**1241**	**1344**	**1113**	**1116**	**1137**	**1199**	**1217**
Other (TMX)	478	431	496	590	605	448	440	499	656	802
Aircraft in Scenario	**1477**	**1553**	**1603**	**1831**	**1949**	**1561**	**1556**	**1636**	**1855**	**2019**

Lastly, Figure 18 presents a generalized distribution of the aircraft within a simulation scenario over the various altitudes in the simulated airspace of ZOB. A goal of the scenario development was to capture aircraft operating at and above 18,000 feet for the majority of their time within the simulation. Data within this figure are representative of all the scenarios created by the processes outlined in this document.

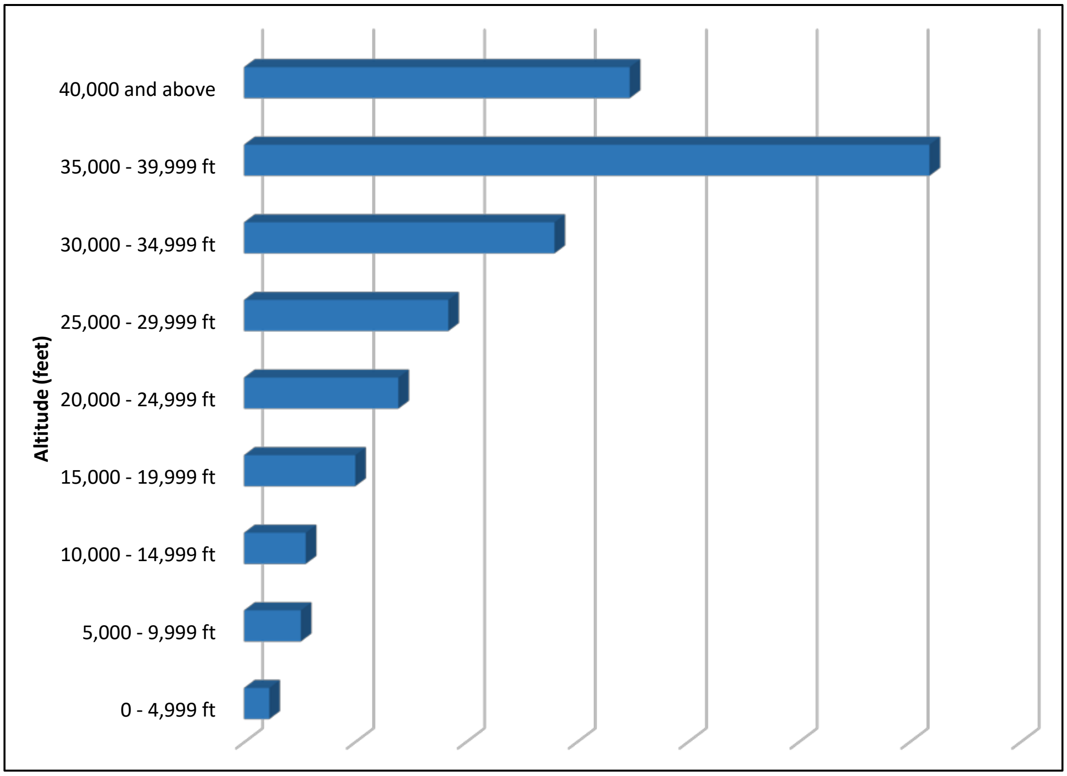


Figure 18: Generalized Distribution of Aircraft over Altitudes Throughout a 3-hour Scenario

6.2.3 Impacts to Simulation Capabilities

The scenario development methodology described in the report represents a significant advancement in the state-of-the-art of ATM simulation capabilities at NASA Langley Research Center. Before this effort, air traffic scenarios that replicated real-world conditions were created using a labor-intensive manual process and traffic scenarios that featured this quantity of ASTOR aircraft used contrived flight routes not based on real data. The process and automated scripts used to generate simulation scenarios represent a significant step forward in the state-of-the-art in scenario generation and air traffic simulation. ATM researchers at Langley Research Center can now simulate realistic, high-density flight operations for Class A airspace in a representative and configurable TBO environment.

Prior to this activity, the largest number of ASTOR aircraft in a single simulation scenario was 500. Development work conducted for this activity has increased the number of individual ASTOR aircraft in the simulation environment by 200-250%, as seen in the Subtotal row of Table 6. The prior limit for the number of simultaneous ASTOR aircraft running in an ATOS simulation was approximately 150, shown in Figure 19. This simulation used scenarios that initialized with approximately 150 ASTORs and the peak amount during one scenario was approximately 450 simultaneous operations – a 200% increase over the prior limit.

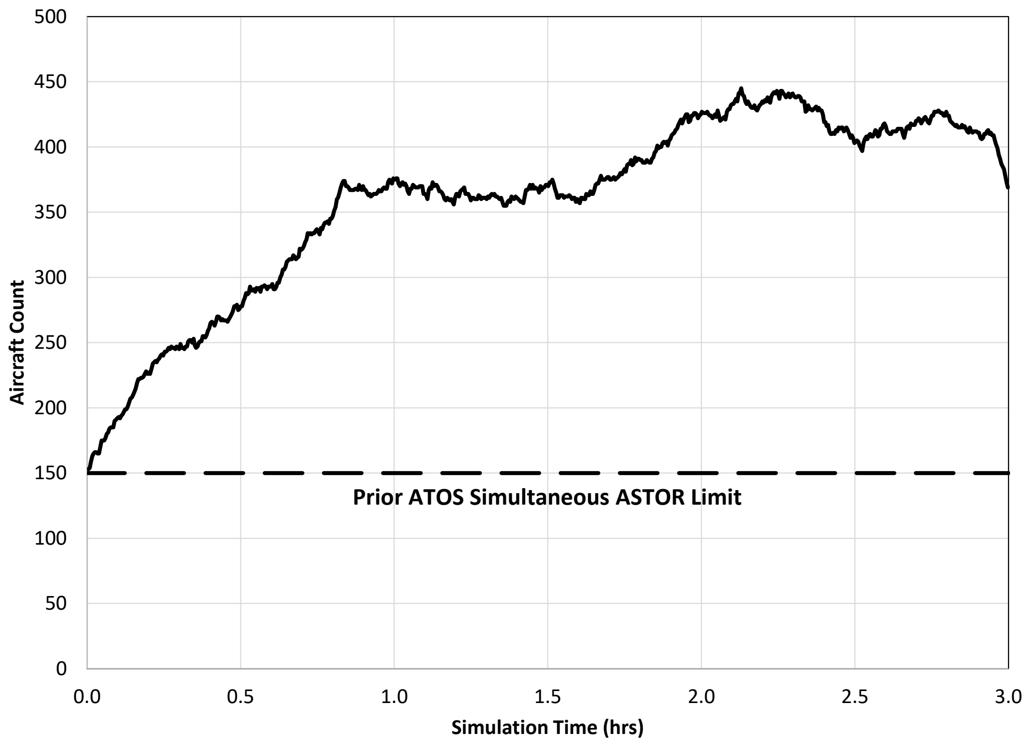


Figure 19: Simultaneous Active Aircraft – Example Stage 3 Integrated Scenario, 3-hour

6.3 Potential Future Research Applications

The scenario development methodology presented in this report has profound effects on the ability of Langley Research Center to conduct ATM research using realistic, high-density air traffic in its simulation scenarios. These scenarios can be used to conduct numerous types of research analyses, ranging from algorithmic performance studies using individual aircraft to fleet-scale benefit analyses.

For example, individual aircraft may be equipped with advanced airspace services to understand the algorithmic performance of a given service in the context of other aircraft and the ATM operation system. Dynamic weather polygons may be added to the simulation scenarios to evaluate the performance of an airspace service near convective weather conflicts. Fleets of aircraft (by aircraft type or by airline) may be equipped with one or more airspace services, and medium-high fidelity benefits analyses may be conducted to provide interested parties with information regarding operational improvements that airspace services may provide.

Furthermore, by using operationally realistic scenarios and select aircraft equipped with one or more airspace services in a HITL experiment, procedures and workload may also be evaluated. These scenarios allow flight crews and/or air traffic controllers to evaluate how the technology is used during operation, and may provide both quantitative and qualitative airspace service data.

Finally, by connecting the simulation capabilities used throughout this process with external simulations (a capability of ATOS discussed in Section 4.1), integrated air-ground simulation activities may occur. These types of activities present a unique opportunity to evaluate not only a given technology's performance or the procedures used to operate it, but can do so in the greater ATM operational context, using simulations or emulations of ground-based ATM technologies. Simulation activities like these provide a wealth of information regarding the expected operation once the technology matures to the point that an in-situ test (e.g., flight test) or an operational evaluation with a partner airline is possible.

7. Conclusion

To understand the future service-based airspace system proposed by NASA ATM researchers, simulations representative of the operational environment must occur. This report presented the characteristics and assumptions of a 2035-2045 TBO environment, described simulation capabilities for air traffic operations research at NASA Langley Research Center, discussed a methodology and processes for creating simulation scenarios that represent this operational environment in the year 2040, and discussed the impact of the scenario development process on potential future research applications.

The TBO simulation scenarios created used Cleveland Center Class A airspace as the airspace of interest. The simulation scenarios used recorded SWIM traffic data, four-dimensional wind and temperature data, four-dimensional convective weather data, and SUA data from days/times of interest. To create a representative TBO environment, approximately 40% of flights in each scenario were provided with modified SWIM routes that fly a more business optimal route. The process for creating the scenarios was documented, and the research team developed and documented automated scripts (~10,000 lines of code) to create these scenarios.

During this work, ten distinct simulation scenarios were created using traffic from May 23-24, 2018. Each scenario contains approximately 1500-2000 aircraft simulated in 3-hour time periods of compressed traffic density. Approximately 70% of the aircraft in each scenario are medium-high fidelity ASTOR simulated aircraft, and the remaining 30% are low-fidelity simulated aircraft. Furthermore, the variability between scenarios was minimal, which allows future research activities to utilize these scenarios without concern for effects due to the scenario chosen.

The work completed as part of this activity represents several significant advancements in the state-of-the-art of NASA Langley's ATM simulation capability. First, this research created a documented process and set of scripts that provide the ability to convert large quantities of real-world data into complex, high-density simulation scenarios. Prior to this activity, simulation scenarios that featured real-world traffic a) were very limited in size and scope, and b) required significant manual adjustments to work within the confines of the simulation platform. Additionally, previous simulation scenarios that used large amounts of traffic to simulate high-density operations featured contrived routes that may not be representative of actual flights in the NAS. Because of the capabilities developed during this research activity, ATM researchers at NASA Langley can now simulate high-density and realistic flight operations. Second, this development work has increased the number of federates in the simulation environment by 200-250%, and increased the number of simultaneous ASTOR operations by approximately 200% over the prior limit.

This scenario development methodology presented has profound effects on the ability of NASA Langley Research Center to conduct ATM research using realistic, high-density air traffic in its simulation scenarios. These scenarios can be used to conduct numerous types of research analyses, ranging from algorithmic performance studies using individual aircraft to fleet-scale benefit analyses. Furthermore, by using select aircraft equipped with one or more airspace services in a HITL mode, procedures and workload may be evaluated using operationally realistic scenarios. Finally, integrated air-ground simulation activities may be conducted using these scenarios; this presents a unique opportunity to evaluate not only a given technology's performance or the procedures used to operate it, but to do so in a more complete ATM operational context by including simulations or emulations of ground-based ATM technologies.

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Appendix A. Script Summary

The following table presents specific details on the input and output file naming used within the various NASA researcher developed scripts.

Appendix Table A-1: Script Summary for the Development of 2040 TBO Scenarios

Stage	MATLAB Script Name	Output Identifier	Example Filename	Input to Data Run	Input Identifier	Input Data Runs	10 min Terminate	ADS-B	AOP	TMX
0	`ATOS_4dWinds.m`	-	`BS1_ATOS_Wnd_20180523_13Z_18Z.wnd`	-	-	-	-	-	-	-
0	`SUA_Parser.m`	-	`BS1_ATOS_SUA_20180523_1300Z_1730Z.txt`	-	-	-	-	-	-	-
0	`Baseline.m`	S	`20180523_1300Z_1730Z_S.scn`	-	-	-	-	Off	-	Off
1	`Callsign_Replace.m`	U *or* T	`20180523_1300Z_1730Z_U.scn` `20180523_1300Z_1730Z_T.scn`	-	S	-	-	Off	-	Off

1	`Time_Compression.m`	C	`20180523_1300Z_1730Z_U_C66.scn`
			`20180523_1300Z_1730Z_T_C66.scn`
			`BS1_ATOS_Wnd_20180523_13Z_18Z_C66.wnd`
				S1 ATOL ATOS Run (**TMX only**)[1]	U *or* T	-	-	Off	-	Off

2	`TMX2ASTOR.m`	A	`20180523_1300Z_1730Z_A_C66.scn`	S2 GovCloud ATOS Test Run (**ASTOR only**)[2]	U *or* C	-	**On**	Off	CX	Off
2	`SCNCheckout.m`	Y	`20180523_1300Z_1730Z_Y_C66.scn`	S2 ATOL ATOS Run (**ASTOR only**)[2]	A	S2 GovCloud ATOS Test Run (**ASTOR only**)	**On**	Off	CX	Off
2	`SCNConfirm.m`	X	`20180523_1300Z_1730Z_X_C66.scn`	S3 ATOL ATOS Run (**TMX+ASTOR**)[1]	Y	S2 ATOL ATOS Run (**ASTOR only**)	Off	Off	Off	**On**
2	`FreeRoute_Conv.m`	R	`20180523_1300Z_1730Z_R_C66.scn`		X	S2 ATOL ATOS Run (**ASTOR only**)	Off	Off	TC, BC	**On**
3	`Integrated.m`	I	`EoATMS_1_C02_1_1.scn`	S3 ATOL ATOS Run (**TMX+ASTOR**)[1] • 3 Replicates per Iteration in specified random order	R	S3 ATOL ATOS Run (**TMX+ASTOR**)	Off	Off	TCR	**On**

[1] 3.0 hour QUIT for compressed scenarios; 4.5 hour QUIT for uncompressed scenarios
[2] 3.0 hour QUIT for compressed scenarios with 10 minute TERMINATE; 4.5 hour QUIT for uncompressed scenarios with 10 minute TERMINATE

Appendix B. Detailed Script Summaries

The following content presents details on the primary scripts (labeled by stage), multiple common functions supporting the primary scripts, and primary script looping functions. Each subsection describes the individual script, input and output data used, and cross-reference information. If a primary script is preceded by or followed by a data collection run, this is also called out in **bold text**. Several functions called by the scripts listed in this appendix are not presented for brevity and their purpose are of a general use to create the final scenario.

Appendix B.1 S0_ATOS_4dWinds.m

Purpose:

- Create 4-D Wind files for SCN files for specified Date and Time range

Description:

- Combines multiple existing ATOS formatted WND files into one file and adds the 4th dimension time component. Source of 4-D Wind data is the NOAA Rapid Refresh Product stored within the Langley data archives. ATOS Wind files contain North-South Winds, East-West Winds, and Temperature.

Input [I] / Output [O] Data:

- [I] Start Date and Start Time for time period of interest
- [I] Latitude / Longitude coordinates for region of interest
- [I] Pre-formatted ATOS WND files
- [O] Formatted ATOS WND file

Cross Reference Information:

- This Function Calls:
```
├─ EoATMS_BS1_S0_ATOS_4dWind_DeltaWND.m
├─ EoATMS_BS1_S0_ATOS_4dWind_GetRawData.m
├─ EoATMS_BS1_S0_ATOS_4dWind_ReadWND.m
│    └─ EoATMS_BS1_S0_ATOS_4dWind_Import_WND_file.m
└─ EoATMS_BS1_S0_ATOS_4dWind_WriteWND.m
```
- This Function is Called By:
    - *none*
- This Function is preceded by:
    - *none*
- This Function is followed by:
    - `S0_Baseline.m`

Appendix B.2 S0_SUA_Parser.m

Purpose:

- Create SUAs for SCN files in Flight Information Service - Broadcast (FIS-B) format from activation schedule & geometry

Description:

- Creates a listing of SUAs within an area of interest from the combination of the Ground Data Server that stores the SUA schedules from the FAA and the SUA geometry that is extracted from the FAA CIFP Navigation Database. The output format matches the ATOS FIS-B text format for SUA and Weather polygons. Considerations are in place for the ATOS 9-character limit for SUA polygon ids with no spaces, 200-vertex pair limit for the polygons, and polygon information is written in blocks of information separated at one-second intervals to allow for repeated broadcast to new entrants into the simulation space.

Input [I] / Output [O] Data:

- [I] Start Date and Start Time for time period of interest
- [I] Latitude / Longitude coordinates for region of interest
- [I] Navigation Database geometry data file prepared by supporting software development team
- [I] SUA activation schedule archived on D318 Reprisal Storage device
- [O] SUA geometry and activation/deactivation schedule for areas within the region and time period of interest formatted to ATOS FIS-B text format.

Cross Reference Information:

- This Function Calls:
```
├── EoATMS_BS1_S0_SUA_Parser_FormatSUAPolygons_ATOS.m
├── EoATMS_BS1_S0_SUA_Parser_GetRawData.m
├── EoATMS_BS1_S0_SUA_Parser_Interval.m
├── EoATMS_BS1_S0_SUA_Parser_ReadSUAGeometry.m
├── EoATMS_BS1_S0_SUA_Parser_ReadSUASchedules.m
├── EoATMS_BS1_S0_SUA_Parser_WriteFISB.m
└── EoATMS_BS1_S0_SUA_Parser_WriteKML.m
```
- This Function is Called By:
  - *none*
- This Function is preceded by:
  - *none*
- This Function is followed by:
  - `S0_Baseline.m`

Appendix B.3 S0_Baseline.m

Purpose:

- Combine formatted SWIM data with referenced 4-D Winds, SUA Polygons, and Weather Polygons

Description:

- Combine SWIM data formatted as a TMX scenario file with 4-D Winds, SUA Polygons, and Weather Polygons. Write each scenario to a file.

Input [I] / Output [O] Data:

- [I] Start Date and Start Time for time period of interest
- [I] Input SWIM route data formatted for as scenarios for TMX

- [I] SUA geometry and activation/deactivation schedule for areas within the region and time period of interest formatted to ATOS FIS-B text format
- [I] Weather polygons (if present) for areas within the region and time period of interested formatted to ATOS FIS-B text format.
- [O] Air traffic scenario for ATOS containing TMX aircraft types

Cross Reference Information:

- This Function Calls:

```
├─ EoATMS_BS1_S0_Baseline_UpdateSCN.m
├─ export_SCN_file.m
└─ import_SCN_file.m
```

- This Function is Called By:
  - *none*
- This Function is preceded by:
  - `S0_ATOS_4dWinds.m`
  - `S0_SUA_Parser.m`
- This Function is followed by:
  - `S1_Callsign_Replace.m`

Appendix B.4 S1_Callsign_Replace.m

Purpose:

- Renames aircraft call signs from SWIM data to specific categories

Description:

- Aircraft specified in the original scenario files generated in Stage 0 will have their (up to 7-alphanumeric characters) call sign replaced to de-identify and allow tracking of the aircraft configuration within the scenario based on its separation into 1 of 6 categories. A TMX only scenario is also exported.

Input [I] / Output [O] Data:

- [I] Airport Database file matched to the time period of interest for the scenario
- [O] Route Database containing air traffic scenario for ATOS
- [O] Air traffic scenario for ATOS containing TMX and marked for ASTOR aircraft types

Cross Reference Information:

- This Function Calls:

```
├─ EoATMS_BS1_S1_Callsign_Replace_AirportCheck.m
│    └─ import_AirportDAT.m
├─ EoATMS_BS1_S1_Callsign_Replace_Define_RouteDB.m
├─ EoATMS_BS1_S1_Callsign_Replace_NewCallsign.m
├─ EoATMS_BS1_S1_Callsign_Replace_ReadASTORMap.m
├─ EoATMS_BS1_S1_Callsign_Replace_UpdateSCN_file.m
│    └─ SCN_Totals.m
│         └─ SCN_Counts.m
├─ EoATMS_BS1_S1_Callsign_Replace_export_RouteDB.m
├─ EoATMS_BS1_S1_Callsign_Replace_export_TSA.m
│    └─ export_TSA_to_RouteDB
│         └─ SCN_Totals.m
│
```

```
│              └─ SCN_Counts.m
├─ EoATMS_BS1_S1_Callsign_Replace_find_ACType.m
│   └─ time_adder.m
├─ export_SCN_from_RouteDB.m
└─ import_SCN_file.m
```

- This Function is Called By:
  - *none*
- This Function is preceded by:
  - `S0_Baseline.m`
- This Function is followed by:
  - `S1_Time_Compression.m`

Appendix B.5 S1_Time_Compression.m

Purpose:

- Applies Time Compression ratio to scenario aircraft command time values, 4-D winds, SUAs, weather Polygons, and RTA time stamps (slewed) with individual aircraft routes

Description:

- Compresses the time stamps of all time values for aircraft within the scenario, compresses the time stamps for activation and deactivation of SUAs and weather polygons if present, and compresses the reference times for the ATOS 4-D wind reference files.

Input [I] / Output [O] Data:

- [I] Uncompressed air traffic scenario for ATOS and TMX containing SUAs and weather polygons.
- [I] Uncompressed 4-D ATOS Wind file containing wind speed, wind direction, and temperature.
- [I] Route Database containing air traffic scenario for ATOS
- [O] Updated Route Database containing air traffic scenario for ATOS
- [O] Time compressed air traffic scenario for ATOS and TMX
- [O] Time compressed 4-D ATOS Wind file containing wind speed, wind direction, and temperature.

Cross Reference Information:

- This Function Calls:

```
├─ EoATMS_BS1_S1_Time_Compression_SCN_Compress.m
│   ├─ EoATMS_BS1_S1_Time_Compression_Time_Compress.m
│   └─ EoATMS_BS1_S1_Time_Compression_Time_Delta.m
├─ EoATMS_BS1_S1_Time_Compression_Wnd_Compress.m
│   ├─ export_4dWND_file.m
│   └─ import_4dWND_file.m
├─ export_SCN_from_RouteDB.m
└─ export_to_RouteDB.m
    └─ SCN_Totals.m
        └─ SCN_Counts.m
```

- This Function is Called By:
  - *none*
- This Function is preceded by:
  - `S1_Callsign_Replace.m`

- This Function is followed by:
    - `S2_TMX2ASTOR.m`

Appendix B.6 S2_TMX2ASTOR.m

Purpose:

- Convert TMX aircraft to ASTOR aircraft for all Compatible aircraft types to generate an ATOS scenario

Description:

- Convert TMX aircraft to ASTOR aircraft for all Compatible aircraft types to generate an ATOS scenario. ATOS and ASTOR specific commands are added to compatible aircraft types. Various aircraft conditions are estimated to enable them as ASTOR aircraft. Initial TMX positional routes are simplified with various fixes to SWIM routes for bad radii and vertical constraints.

Input [I] / Output [O] Data:

- [I] Uncompressed or Compressed TMX traffic scenario
- [I] Airport Database file matched to the time period of interest for the scenario
- [I] Uncompressed or Compressed ATOS 4-D Wind file containing wind speed, wind direction, and temperature
- [I] Route Database containing air traffic scenario for ATOS
- [O] Updated Route Database containing air traffic scenario for ATOS
- [O] Air traffic scenario for ATOS containing ASTOR and TMX aircraft types

Cross Reference Information:

- This Function Calls:

```
├─ EoATMS_BS1_S2_TMX2ASTOR_CMDXchg.m
│    ├─ EoATMS_BS1_S2_TMX2ASTOR_findWndSpdLoad_ATOS_WND.m
│    │    └─ Import_WND_file.m
│    ├─ estimate_airspeed
│    │    ├─ TAStoCAS.m
│    │    ├─ airdensity.m
│    │    ├─ airpressure.m
│    │    ├─ crossover_altitude.m
│    │    └─ speedofsoound.m
│    ├─ estimate_grossweight
│    └─ time_adder.m
├─ EoATMS_BS1_S2_TMX2ASTOR_ReduceWpts.m
│    └─ dpsimplify.m
│         └─ simplifyrec
├─ EoATMS_BS1_S2_TMX2ASTOR_export_RouteDB.m
├─ EoATMS_BS1_S2_TMX2ASTOR_export_RouteDB_ReduceWpts.m
├─ SCN_Totals.m
│    └─ SCN_Counts.m
├─ export_SCN_from_RouteDB.m
├─ fixBadRadius.m
│    └─ plotRteData
├─ fixBadVertConstraints.m
```

```
├─ import_AirportDAT.m
├─ import_SCN_file.m
└─ send2noncompat.m
```

- This Function is Called By:
  - *none*
- This Function is preceded by:
  - `S1_Time_Compression.m`, or
  - `S1_Callsign_Replace.m`
- This Function is followed by:
  - **Stage 2 Data Collection [ATOS Test Runs (ASTOR Only)]**
  - `S2_SCNcheckout.m`

Appendix B.7 S2_SCNcheckout.m

Purpose:

- Identify and attempt to fix errors presented in log files from Stage 2 Data Collection [ATOS Test Runs (ASTOR Only)]

Description:

- Primary check of the scenario file that uses an ATOL Stage 2 test run of all ASTOR aircraft with AOP equipped for 10 minutes within the 3- or 4.5-hour scenario. Input is the LogFile_Summary_Developer.log for the run and any aircraft that are have problems with TRIM or bad radius. If possible, aircraft routes are corrected through various means and if these options fails, the aircraft is sent back to non-compatible status as a TMX aircraft.

Input [I] / Output [O] Data:

- [I] Route Database containing air traffic scenario for ATOS
- [I] Log files from Stage 2 Data Collection [ATOS Test Runs (ASTOR Only)]
- [O] Updated Route Database containing air traffic scenario for ATOS
- [O] Air traffic scenario for ATOS containing ASTOR and TMX aircraft types

Cross Reference Information:

- This Function Calls:

```
├─ EoATMS_BS1_S2_SCNcheckout_UpdateSCN_file.m
│    └─ SCN_Totals.m
│         └─ SCN_Counts.m
├─ EoATMS_BS1_S2_SCNcheckout_filepathtoATOSlogs.m
├─ export_SCN_from_RouteDB.m
├─ findBadASTORs.m
│    ├─ createOutputData
│    ├─ fixPostHocBadRadius
│    ├─ identProblemAC
│    ├─ import_AirportDAT.m
│    ├─ plotBadRadErrors
│    ├─ plotTrajPredFail
│    └─ readLogFileScanner
└─ send2noncompat.m
```

- This Function is Called By:
  - *none*

- This Function is preceded by:
  - **Stage 2 Data Collection [ATOS Test Runs (ASTOR Only)]**
  - `S2_TMX2ASTOR.m`
- This Function is followed by:
  - **Stage 2 Data Collection [ATOL ATOS Runs (ASTOR Only)]**
  - `S2_SCNconfirm.m`

Appendix B.8 S2_SCNconfirm.m

Purpose:

- Eliminate any remaining errors presented in log files from Stage 2 Data Collection [ATOL ATOS Runs (ASTOR Only)]

Description:

- Secondary check of the scenario file that uses an ATOL Stage 2 run of all ASTOR aircraft with AOP equipped for 10 minutes within the 3- or 4.5-hour scenario. Input is the log files for the run and any aircraft that are still problems with TRIM or bad radius and sends back to non-compatible status as a TMX aircraft. A full scenario is also created with no TERMINATE commands to be used as a baseline run for Stage 3 data collection.

Input [I] / Output [O] Data:

- [I] Route Database containing air traffic scenario for ATOS
- [I] Log files from Stage 2 Data Collection [ATOL ATOS Runs (ASTOR Only)]
- [O] Updated Route Database containing air traffic scenario for ATOS
- [O] Air traffic scenario for ATOS containing ASTOR and TMX aircraft types

Cross Reference Information:

- This Function Calls:

```
├─ EoATMS_BS1_S2_SCNcheckout_filepathtoATOSlogs.m
├─ EoATMS_BS1_S2_SCNconfirm_S3rename.m
│    └─ export_SCN_from_RouteDB.m
├─ EoATMS_BS1_S2_SCNconfirm_UpdateSCN_file.m
│    └─ SCN_Totals.m
│         └─ SCN_Counts.m
├─ export_SCN_from_RouteDB.m
├─ findBadASTORs.m
└─ send2noncompt.m
```

- This Function is Called By:
  - *none*
- This Function is preceded by:
  - `SCNcheckout.m`
  - **Stage 2 Data Collection [ATOL ATOS Runs (ASTOR Only)]**
- This Function is followed by:
  - `S2_FreeRoute_Conv.m`

Appendix B.9 S2_FreeRoute_Conv.m

Purpose:

- Creates CPDLC messages for ASTORs from AOP logs from Stage 2 Data Collection [ATOL ATOS Runs (ASTOR Only)]

Description:

- Script creates CPDLC messages from AOP logs created from ATOS simulation for the time of interest. Messages are used to identify "Free Route" aircraft, where call signs are updated. Additionally, ADS-B is turned on for all ASTOR aircraft.

Input [I] / Output [O] Data:

- [I] Route Database containing air traffic scenario for ATOS
- [I] AOP log files from Stage 2 Data Collection [ATOL ATOS Runs (ASTOR Only)]
- [O] Updated Route Database containing air traffic scenario for ATOS
- [O] Air traffic scenario for ATOS containing ASTOR and TMX aircraft types
- [O] Air traffic scenario for ATOS containing ASTOR and TMX aircraft types for Stage 3 baseline data collection run.

Cross Reference Information:

- This Function Calls:

```
├─ EoATMS_BS1_S2_FreeRoute_Conv_CPDLC.m
│    ├─ processATOSData
│    └─ readAOPLogs
├─ EoATMS_BS1_S2_FreeRoute_Conv_UpdateSCN.m
├─ EoATMS_BS1_S2_FreeRoute_Conv_filepathtoAOPlogs.m
├─ export_SCN_from_RouteDB.m
└─ SCN_Totals.m
     └─ SCN_Counts.m
```

- This Function is Called By:
  - *none*
- This Function is preceded by:
  - **Stage 2 Data Collection [ATOL ATOS Runs (ASTOR Only)]**
- This Function is followed by:
  - `S3_Integrated.m`

Appendix B.10 S3_Integrated.m

Purpose:

- Performs 60/40 split on available "Free Route" aircraft for a scenario

Description:

- Performs 60/40 split on available "Free Route" aircraft for a scenario. Assignment of 100% of available TCX with associated free routes from the Route Database and a percentage of BCRs with free routes are randomly assigned while the remainder revert to BCX. AOP is only enabled for TCR aircraft. Pilot Model is NORMAL, but pilot model rules developed by in February 2020, will not be enabled. Excess CPDLC messages are removed from the bottom of the SCN file.

Input [I] / Output [O] Data:

- [I] Route Database containing air traffic scenario for ATOS
- [O] Updated Route Database containing air traffic scenario for ATOS
- Stage 3 also requires replicates (or copies of the final scenario file) for the purpose of data analysis and assessment. These modified duplicates of the scenario are also created.

Cross Reference Information:

- This Function Calls:

```
├─ EoATMS_BS1_S3_Integrated_Replicates.m
│    └─ export_SCN_from_RouteDB.m
├─ EoATMS_BS1_S3_Integrated_UpdateSCN.m
│    └─ SCN_Totals.m
│         └─ SCN_Counts.m
└─ export_SCN_from_RouteDB.m
```

- This Function is Called By:
    - *none*
- This Function is preceded by:
    - `S2_FreeRoute_Conv.m`
- This Function is followed by:
    - **Stage 3 Data Collection [ATOL ATOS Runs (TMX & ASTOR)]**

Appendix B.11 Common Functions

The following listing is a series of common functions that were uniquely developed for the scenario development process and shared among the primary scripts.

Appendix B.11.1 export_SCN_from_RouteDB.m

Purpose:

- Export a scenario to a SCN file for a particular column from the Route Database

Description:

- Export a scenario to a SCN file for a particular column from the Route Database.

Input [I] / Output [O] Data:

- [I] Route Database containing air traffic scenario for ATOS
- [I] Route Database column of interest for export to file
- [O] Text file in the ATOS scenario format

Cross Reference Information:

- This Function Calls:
    - *none*
- This Function is Called By:
    - *Multiple functions within script directory*
- This Function is preceded by:
    - *Not Applicable*
- This Function is followed by:
    - *Not Applicable*

Appendix B.11.2 import_AirportDAT.m

Purpose:

- Load an Airport Navigation Database for use as reference

Description:

- Loads the Column Delimited ASCII text file `AIRPORT.DAT`, converts latitude and longitude text strings to numeric values and return a cell array that can be search on by airport identified code (e.g. KLFI).

Input [I] / Output [O] Data:

- [I] Externally prepared Airport Navigation Database file from ATOS
- [O] Airport Listing for simulation consumption

Cross Reference Information:

- This Function Calls:
    - *none*
- This Function is Called By:
    - *Multiple functions within script directory*
- This Function is preceded by:

    - *Not Applicable*
- This Function is followed by:
    - *Not Applicable*

Appendix B.11.3 SCN_Counts.m

Purpose:

- Estimate counts for predefined aircraft categories and matching air carriers for a scenario that will be output from the Route Database

Description:

- Counts the number of aircraft within the scenario that matches the top 6 major US air carriers and the 6 possible ATOS ASTOR aircraft models used to simulate aircraft within the airspace.

Input [I] / Output [O] Data:

- [I] Route Database containing air traffic scenario for ATOS
- [O] Updated Route Database containing aircraft counts for the air traffic scenario

Cross Reference Information:

- This Function Calls:
  └─ `strCell` {Built-in MATLAB Toolbox Function}
- This Function is Called By:
    - `SCN_Totals.m`
    - `SCN_Counts.m`
- This Function is preceded by:
    - *Not Applicable*
- This Function is followed by:
    - *Not Applicable*

Appendix B.11.4 SCN_Totals.m

Purpose:

- Estimate counts for predefined aircraft categories for a scenario that will be output from the Route Database

Description:

- Estimate counts for predefined aircraft categories for a particular column from the Route Database.

Input [I] / Output [O] Data:

- [I] Route Database containing air traffic scenario for ATOS
- [I] Route Database column of interest for export to file
- [O] Updated Route Database containing aircraft counts for the air traffic scenario

Cross Reference Information:

- This Function Calls:
  └─ `SCN_Counts.m`

- This Function is Called By:
  - *Multiple functions within script directory*
- This Function is preceded by:
  - *Not Applicable*
- This Function is followed by:
  - *Not Applicable*

Appendix B.11.5 send2noncompt.m

Purpose:

- Modifies an aircraft's call sign and its associated route from an "ASTOR compatible" type marked with a 'C' back to an 'N'

Description:

- Modifies the call sign of an aircraft included in the input listing from an "ASTOR compatible" type marked with a 'C' back to an 'N'. The new call sign route is updated to the non-compatible label.

Input [I] / Output [O] Data:

- [I] Route Database containing air traffic scenario for ATOS
- [I] Route Database column of interest for export to file
- [I] Listing of aircraft call signs to be modified
- [O] Updated Route Database containing air traffic scenario for ATOS

Cross Reference Information:

- This Function Calls:
  - *none*
- This Function is Called By:
  - *Multiple functions within script directory*
- This Function is preceded by:
  - *Not Applicable*
- This Function is followed by:
  - *Not Applicable*

Appendix B.12 Primary Script Looping Functions

The following listing is a series of looping functions that are used to call the primary scripts that were developed for the scenario development process. Their primary purpose is to streamline the scenario development process within the various stages.

Appendix B.12.1 EoATMS_BS1_Main.m

Purpose/Description:

- Script allows the complete run of multiple timeframes of interest back to back for the script function of interest.

Input [I] / Output [O] Data:

- [I] Start Date and Start Time for time period of interest
- [O] Air traffic scenarios for ATOS containing ASTOR and TMX aircraft types
- [O] Updated Route Database containing air traffic scenario for ATOS

Cross Reference Information:

- This Function Calls:
```
├─ S0_Baseline.m
├─ S1_Callsign_Replace.m
├─ S1_Time_Compression.m
└─ S2_TMX2ASTOR.m
```
- This Function is Called By:
    - *none*
- This Function is preceded by:
    - *Not Applicable*
- This Function is followed by:
    - *Not Applicable*

Appendix B.12.2 EoATMS_S2_SCNcheckout_Loop.m

Purpose/Description:

- Script allows the complete run of multiple timeframes of interest back to back for the script function of interest.

Input [I] / Output [O] Data:

- [I] Start Date and Start Time for time period of interest
- [O] Air traffic scenarios for ATOS containing ASTOR and TMX aircraft types
- [O] Updated Route Database containing air traffic scenario for ATOS

Cross Reference Information:

- This Function Calls:
```
└─ S2_SCNcheckout.m
```
- This Function is Called By:
    - *none*
- This Function is preceded by:
    - *Not Applicable*

- This Function is followed by:
    - *Not Applicable*

Appendix B.12.3 EoATMS_S2_SCNconfirm_Loop.m

Purpose/Description:

- Script allows the complete run of multiple timeframes of interest back to back for the script function of interest.

Input [I] / Output [O] Data:

- [I] Start Date and Start Time for time period of interest
- [O] Air traffic scenarios for ATOS containing ASTOR and TMX aircraft types
- [O] Updated Route Database containing air traffic scenario for ATOS

Cross Reference Information

- This Function Calls:
  └─ `S2_SCNconfirm.m`
- This Function is Called By:
    - *none*
- This Function is preceded by:
    - *Not Applicable*
- This Function is followed by:
    - *Not Applicable*

Appendix B.12.4 EoATMS_BS1_FreeRoute_Loop.m

Purpose/Description:

- Script allows the complete run of multiple timeframes of interest back to back for the script function of interest.

Input [I] / Output [O] Data:

- [I] Start Date and Start Time for time period of interest
- [O] Air traffic scenarios for ATOS containing ASTOR and TMX aircraft types
- [O] Updated Route Database containing air traffic scenario for ATOS

Cross Reference Information:

- This Function Calls:
  └─ `S2_FreeRoute_Conv.m`
- This Function is Called By:
    - *none*
- This Function is preceded by:
    - *Not Applicable*
- This Function is followed by:
    - *Not Applicable*

Appendix B.12.5 EoATMS_S3_Integrated_Loop.m

Purpose/Description:

- Script allows the complete run of multiple timeframes of interest back to back for the script function of interest.

Input [I] / Output [O] Data:

- [I] Start Date and Start Time for time period of interest
- [O] Air traffic scenarios for ATOS containing ASTOR and TMX aircraft types
- [O] Updated Route Database containing air traffic scenario for ATOS

Cross Reference Information:

- This Function Calls:
  └─ `S3_Integrated.m`
- This Function is Called By:
  - *none*
- This Function is preceded by:
  - *Not Applicable*
- This Function is followed by:
  - *Not Applicable*

Appendix C. Input / Output File Naming Convention

The following information presents specific details on the input and output file naming used within the various NASA researcher developed scripts.

All Scenario filenames throughout researcher scripts in Stages 0 through 2 are structured with the following filename format:

> <*Date*>{YYYYMMDD}_<*start hour*>{hhmm}Z_<*end hour*>{hhmm}Z_<*Script Identifier*>{%}_<*Compression Percentage*>{C##}<*file extension*>{.scn}

All ATOS wind filenames are structured with the following filename format:

> <*Batch Study Short-Name*>{BS1}_<*file content*>{ATOS_Wnd}_<*Date*>{YYYMMDD}_<*start hour*>{hh}Z_<*end hour*>{hh}Z_<*Compression Percentage*>{C##}<*file extension*>{.wnd}

All ATOS Special Use Airspace Polygon filenames are structured with the following filename format:

> <*Batch Study Short-Name*>{BS1}_<*file content*>{ATOS_SUA}_<*Date*>{YYYMMDD}_<*start hour*>{hhmm}Z_<*end hour*>{hhmm}Z_<*file extension*>{.txt}

All ATOS Weather Polygon filenames are structured with the following filename format:

> <*Batch Study Short-Name*>{BS1}_<*file content*>{ATOS_WxP}_<*Date*>{YYYMMDD}_<*start hour*>{hhmm}Z_<*end hour*>{hhmm}Z_<*file extension*>{.txt}

All Route Database and Route Database Header filenames referenced within researcher scripts are structured with the following filename format:

> <*Date*>{YYYMMDD}_<*start hour*>{hhmm}Z_<*end hour*>{hhmm}Z_<*MATLAB Database Name*>{RouteDB}<*file extension*>{.mat}
>
> <*Date*>{YYYMMDD}_<*start hour*>{hhmm}Z_<*end hour*>{hhmm}Z_<*MATLAB Database Name*>{RouteDBhdr}<*file extension*>{.mat}

Sub-part information for filenames:

- YYYY = four digit year
- MM = two digit month
- DD = two digit day
- hh = two digit hour
- mm = two digit minute
- C## = Compression Percentage
- Leading zeros are required
- Time is referenced to 24 hour UTC time
- ATOS wind files (*.wnd) UTC times are rounded up to the nearest whole hour

Stage 3 Scenario filenames will be further simplified to the following format:

> <*subproject*>{EoATMS}_<*Batch Study No.*>{#}_<*Compressed/Uncompressed*>{%}<*Scenario Reference No. (of 10)*>*{##}_*<*Iteration No.*>{#}_<*Replicate No.*>{#}<*file extension*>{.scn}

Subpart information for filenames:

- C = Compressed Time Scenario for aircraft routes
- U = Uncompressed Time Scenario for aircraft routes
- # = Single digit counter
- Scenario Reference
  - 20180523_1100Z_1530Z_C66 → 01
  - 20180523_1300Z_1730Z_C66 → 02
  - 20180523_1500Z_1930Z_C66 → 03
  - 20180523_1700Z_2130Z_C66 → 04
  - 20180523_1900Z_2330Z_C66 → 05
  - 20180524_1100Z_1530Z_C66 → 06
  - 20180524_1300Z_1730Z_C66 → 07
  - 20180524_1500Z_1930Z_C66 → 08
  - 20180524_1700Z_2130Z_C66 → 09
  - 20180524_1900Z_2330Z_C66 → 10
- Iteration and Replicate number information can be found in Reference [1].

When Stage 3 Scenario files are run within the ATOL, individual execution of a single scenario file will have the Sim Launch time appended to the end of the Stage 3 filename. This filename format is presented below.

<EoATMS SCN filename>_<Date>{MMDD}*_<Time>*{hhmmss}

Subpart information for filenames:

- MM = two digit month
- DD = two digit day
- hh = two digit hour
- mm = two digit minute
- ss = two digit second

If a rerun occurs for whatever reason (incomplete data run, system patches that cause machine clocks to become out of sync, etc.), the sim launch date/time stamp will reflect this.

Appendix D. SWIM Data Conversion to Baseline TMX Scenario

Software developed by the NASA Langley ATOS Development Team was written to collect SWIM data and convert it to an initial TMX simulation scenario. This software is the first step in the scenario development process. The software makes use of two programs that collect and organize the SWIM data before processing it into a TMX-formatted scenario file.

The following content presents details on the software used to create the initial TMX simulation scenarios. Each subsection describes the individual program's purpose, a brief description of what the program does, input data required by the program, and the resulting output.

Appendix D.1 Data Collection and Organization

Purpose:

- Organize raw SWIM data into a searchable database format

Description:

- Converts SWIM data collected from one of two sources (the NASA Langley SWIM archive or the NASA Ames Sherlock-data warehouse) for a given time period into a SQLite database.

Input [I] / Output [O] Data:

- [I] Start Date and Start Time for time period of interest
- [I] End Date and End Time for time period of interest
- [I] Aircraft identification, flight state data, and flight plan records from SWIM
- [O] Searchable SQLite Database of flight plan and track data

Appendix D.2 Data Processing

Purpose:

- Create initial TMX scenarios based on SWIM information within the SQLite database

Description:

- SWIM information with the SQLite database is screened and checked for flights that meet the following criteria: minimum flight time within airspace of interest, altitude limits, validity checks on the flight data (removal of bad points, correction of speeds, etc.), subsequent updates to an aircraft's flight plans, and validation of airport data.
- This process also identifies the traffic of interest for the specific experiment.

Input [I] / Output [O] Data:

- [I] Scenario Definition file that defines the criteria for each scenario to be created, where each entry contains the start time and end time for the data to be included in the scenario and the scenario filename
- [I] TMX formatted polygon file that defines the experiment area, or region of airspace from which flights are to be included in the scenario
- [I] Airport definition file that provides latitude, longitude, type, and airport code among other parameters
- [O] TMX formatted scenario file containing TMX simulation configuration parameters, as well as initial conditions and routing for aircraft within the time and date specified.

Appendix E. Modifications to Enable ASTORs

Using SWIM data as a starting source for typical traffic within the NAS presents an opportunity to create simulation scenarios that mimic the real-world flight paths of aircraft within the region of interest for the research. However, SWIM data can be considered surveillance information of the aircraft from the ground where aircraft state information (e.g. airspeed, heading, weight, intent, etc.) is not included. Where TMX has the ability to act like a playback utility of SWIM data, an ASTOR aircraft model needs more information to 'fly.' For example:

- There are a small number of performance models for ASTOR Airframe. Therefore, aircraft types present in the SWIM data must be mapped to a suitable ASTOR performance model.
    - Since a mapping of aircraft type to performance model occurs, care must be taken to ensure that other parameters dependent on the performance model (e.g., service ceiling) are considered.
- ASTOR aircraft must be initialized within the simulation with various state variables that are 'balanced' so that an unsteady condition does not begin at the onset of the aircraft's flight. Some of these parameters are not specified in SWIM data, so estimations must occur. For example:
    - An ASTOR requires a Gross Weight parameter to initialize. However, SWIM does not provide aircraft weight. Therefore, the ASTOR needs an estimated weight that is within the aircraft's capability and that allows enough fuel to reach the destination airport, even if does not fly the full-length to the airport in the simulation.
    - An ASTOR aircraft at initialization must have a calibrated airspeed in units of knots or a Mach number specified. SWIM does not provide an airspeed value; it provides a groundspeed value. Therefore, the ASTOR needs an estimated airspeed value based on the groundspeed specified in the SWIM data.
    - An ASTOR can be initialized in a climb or descent, however, the rate of climb must be within specific bounds to prevent aircraft trim issues at simulation initialization. Furthermore, the rate of climb in SWIM data is typically specified in ft/min. An ASTOR aircraft at initialization requires the vertical speed value to be in feet/second, necessitating a conversion of units.
- SWIM surveillance data provides an excellent representation of how an aircraft actually navigated during the course of its flight. However, the number of waypoints in the original as-flown data is generally too much for an ASTOR to fly because of an internal buffer limit in the simulation. Therefore, the SWIM surveillance data must be converted into a simplified route.
    - Care must be taken to ensure that the route is not over-simplified, which may cause excessive turns that are not flyable.
    - Care must be taken to ensure that the vertical definition of the route meets the specifications of the trajectory generator in ASTOR RPFMS (e.g., altitude constraints must be unique and monotonically descending).

Therefore, the SWIM data in its native form and subsequent processed form for a TMX simulation does not meet the initialization criteria or route management/matching requirements to enable an ASTOR to follow a similar flight path.

Part of the scenario development methodology created by the NASA research team takes aircraft specified information in the SWIM data and applies various modifications and estimates to make it compatible with the ASTOR airframe models. The following sections in this Appendix capture several important steps in modifying or estimating the state of a particular aircraft at its initialization in the simulation for the ASTOR aircraft performance models.

Appendix E.1 Aircraft Type Mapping from Source Data to Performance Models

The SWIM data used as the initial simulation source captures all registered aircraft for public access. This includes many aircraft types not specifically supported by ASTOR within the NASA Langley ATOS. To use as much of the traffic data as possible within the captured timeframe of interest for simulation, an aircraft-mapping schema was created to match the available ASTOR aircraft performance models.

The FAA Order [54] describing the aircraft type designators used within the SWIM data was selected to match the SWIM aircraft to available ASTOR aircraft performance models. FAA Order JO 7360.1E provides a listing of the aircraft type identifier, aircraft manufacturer and model, FAA Classification, number of engines and type of engine, and FAA Weight Classifications. The International Civil Aviation Organization (ICAO) Wake Turbulence Category and FAA Re-Categorization (ReCAT) 1.5 Wake Category were also considered in the mapping to ASTOR models.

Appendix Table E-1 presents a summary of the mapping of matching plane types within the simulation scenarios to the ASTOR aircraft performance model.

Appendix Table E-1: Matching Planes Types in Simulation to ASTOR Performance Models

ATOS Model	Matching Plane Types in Simulation	FAA Aircraft Class	No. Engines/ Type	FAA Weight Class	ICAO Wake Turbulence Category	ReCAT 1.5 Wake Category
NASA_HU25	ASTR, BCS1, BE40, C25A, C25B, C25C, C25M, C500, C501, C510, C525, C550, C551, C560, C56X, C650, C680, C68A, C700, C750, CL30, CL35, CL60, CRJ1, CRJ2, CRJ7, CRJ9, DC91, DC93, E135, E145, E170, E190, E35L, E45X, E50P, E545, E550, E55P, E75L, E75S, EA50, F2TH, FA10, FA20, G150, G280, GALX, GA5C, GL5T, GLEX, GLF2, GLF3, GLF4, GLF5, GLF6, H25A, H25B, H25C, HA4T, HDJT, J328, LJ31, LJ35, LJ40, LJ45, LJ55, LJ60, LJ70, LJ75, MU30, PC24, PRM1, SBR1,WW24	Fixed-wing	2 / Jet	Small+ Small Large	Light Medium	D E F
NB137_2E22	B712, B732, B734	Fixed-wing	2 / Jet	Large	Medium	D
NB172_2E27	A319, A320, A321, B38M, B736, B737, B738, B739, MD81, MD82, MD83, MD88, MD90	Fixed-wing	2 / Jet	Large	Medium	D
NB250_2E40	B752, B753	Fixed-wing	2 / Jet	Large	Medium	D
WB315_2E48	A306, A310, B762, B763, B764	Fixed-wing	2 / Jet	Heavy	Heavy	C
WB535_2E77	A332, A333, A339, A343, A346, A359, A388, B744, B748, B772, B77L, B77W, B788, B789, B78X, IL96	Fixed-wing	2/4 Jet	Heavy	Heavy	A/B

Part of this mapping process is the assignment of an aircraft to the background category as described in Section 3.3.1. Information provided within the engine number and type data column provided by Reference [54] that meets the following criteria are directly assigned to the background aircraft category.

- Aircraft has either 1 or 3 engines
- Aircraft has either a propeller or turboprop engine
- Aircraft identifier is a 'B703'
    - From the SWIM data conversion outlined in Appendix D, aircraft with no/unknown aircraft type identifier are represented by 'B703'.
- No information in Reference [54] is present on the matching aircraft identifier from the scenario

The output of the mapping process used within the NASA researcher scripts is a comma delimited text file consisting of the possible aircraft identifiers in the TMX SWIM scenario file, a switch designating if the aircraft must be a background traffic aircraft based on its characteristics, and if there is a possible match then ASTOR aircraft performance model type. An automated process of mapping the aircraft noted within the SWIM data was created by NASA researchers and implemented within the scripts.

Appendix E.2 Gross Weight Estimation for ASTORs

Aircraft weight is not present in the original SWIM data used as a source for aircraft positions in the simulation. As a simulation, TMX does not require aircraft weight to be initialized within a scenario, but ASTOR aircraft cannot be initialized without a gross weight value in pounds. To avoid simulation trim errors, the initial weight value must also be within the performance range of the aircraft performance model being simulated and must provide enough additional weight above the operating empty weight and zero fuel weight that enough fuel can be assumed to be present in the aircraft to reach its route specified destination.

The following is pseudo code for the weight estimation for ASTORs at initialization. Reference information used in the weight estimation is presented in Table 1 (Reference ASTOR Aircraft Performance Information) in the main body of this report and used in the following formulation.

$$W_G = W_{OEW} + W_{Payload_{MAX}} W_{Payload_{PER}} + W_{Fuel} \tag{1}$$

where

W_G = Aircraft Gross Weight (lbs)

W_{OEW} = Aircraft's Operating Empty Weight (lbs)

$W_{Payload_{MAX}}$ = Aircraft's Maximum Payload Weight (lbs)

$W_{Payload_{PER}}$ = percentage of assumed payload for aircraft loading [0.80]

$W_{Fuel} = Fuel_{Flow} D2G + Fuel_{Flow} Fuel_{Flow\_Conv} Fuel_{Resv}$

and where:

W_{Fuel} = Fuel Load (lbs)

$Fuel_{Flow}$ = Estimated average fuel burn rate (lbs/nmi)

$D2G$ = the distance to go, using the Haversine great circle formula, from the initialization point to the destination airport (nmi)

$Fuel_{Flow\_Conv}$ = conversion factor for estimated average fuel burn rate (nmi/min)

$Fuel_{Resv}$ = Assigned fuel reserve (min) [60 min]

Functional Check:

If the estimated gross weight is greater than the maximum take-off weight, set the estimated gross weight to the maximum take-off weight.

Appendix E.3 True Airspeed Estimation for ASTORs

Aircraft groundspeed is present in the original SWIM data used as a source for aircraft positions in the simulation. As a simulation, TMX can work directly with the groundspeed values at initialization, but ASTOR aircraft must be initialized with either calibrated airspeed in knots (kts) or Mach number. A process to convert a groundspeed to calibrated airspeed used by the various aircraft types that are compatible with ASTOR aircraft performance models was required.

The following is pseudo code for the true airspeed estimation for ASTORs at initialization from groundspeed provided in SWIM data.

Estimation Approach

1. Find the Wind Speed (ft/s) at the initialization time and position for the aircraft.
   a. Load the ATOS wind file (*.wnd) that will be used within the simulation.
   b. Query the 4-D files for the north-south wind component, east-west component, and temperature values at the create time, latitude and longitude position, and altitude.
   c. Estimate the total wind speed and direction.
2. Convert wind speed to knots. Convert temperature from Rankine to Kelvin.
3. Estimate the air density adjusted by temperature from the ATOS wind data file. Returned value is in kg/m^3.
4. Estimate pressure adjusted by temperature from the ATOS wind data file. Returned value is in N/m^2.
5. Estimate True Airspeed. Returned values is in knots.

Governing Equation

$$V_T = \sqrt{V_{GS}^2 + WS^2 - 2V_{GS}WS\cos(\psi_t - WD)} \quad (2)$$

where:

V_T = True Airspeed
V_{GS} = Groundspeed
WS = Wind Speed
WD = Wind Direction, True
ψ_t = Heading, True

Subsequent estimations

- Estimate Computed Airspeed using True Airspeed, density, and pressure. Return value in knots.
- Estimate Mach number using True Airspeed and speed of sound. Return value has no units.

Appendix E.4 Airspeed Estimation for ASTORs

To avoid simulation trim errors, the initial airspeed value needs be within the performance limits of the aircraft model being simulated and must match the phase of flight (climb, cruise, descent) at initialization. Reference information used in the airspeed estimation can be found within the ASTOR aircraft performance model-data within ATOS.

The following is pseudo code for the airspeed estimation for ASTORs at initialization using information presented in Appendix E.3. Computed Airspeed is abbreviated as CAS within this pseudo code.

Aircraft in a Climb (Vertical Speed is positive up)

```
if Mach > Mach Max Climb or CAS > CAS Max Climb
   if altitude <= crossover altitude in climb
       Set to Max Climb CAS
   else altitude > crossover altitude
       Set to Mach Max Climb
   end
elseif CAS < CAS Min Climb
   Set to CAS Min Climb
else Speed is within bounds for ASTOR model
   No updated information
end
```

Aircraft in Cruise (Vertical Speed is zero)

```
if Mach > Cruise Mach + 0.02
   Set to Cruise Mach + 0.02
else Speed is within bounds for ASTOR model
   No updated information
end
```

Aircraft in a Descent (Vertical Speed is negative)

```
if Mach > Cruise Mach or CAS > CAS Max Descend
   if altitude <= crossover altitude in descent
      Set to CAS Max Descend
   else altitude > crossover altitude
      Set to Mach Cruise in a descent
   end
elseif CAS < CAS Min Descend
   Set to CAS Min Climb
else Speed is within bounds for ASTOR model
   No updated information
end
```

Airspeed Algorithm Variable Definition

```
CAS Max Climb       = Max Climb CAS minus 10 kts
CAS Min Climb       = Min Climb CAS plus 10 kts
Mach Max Climb      = Max Climb Mach minus 0.05 Mach
Cruise Mach         = Cruise Mach
CAS Max Descend     = Max Descend CAS minus 10 kts
CAS Min Descend     = Min Descend CAS plus 10 kts
Cruise Mach Descend = Cruise Mach minus 0.05 Mach
```

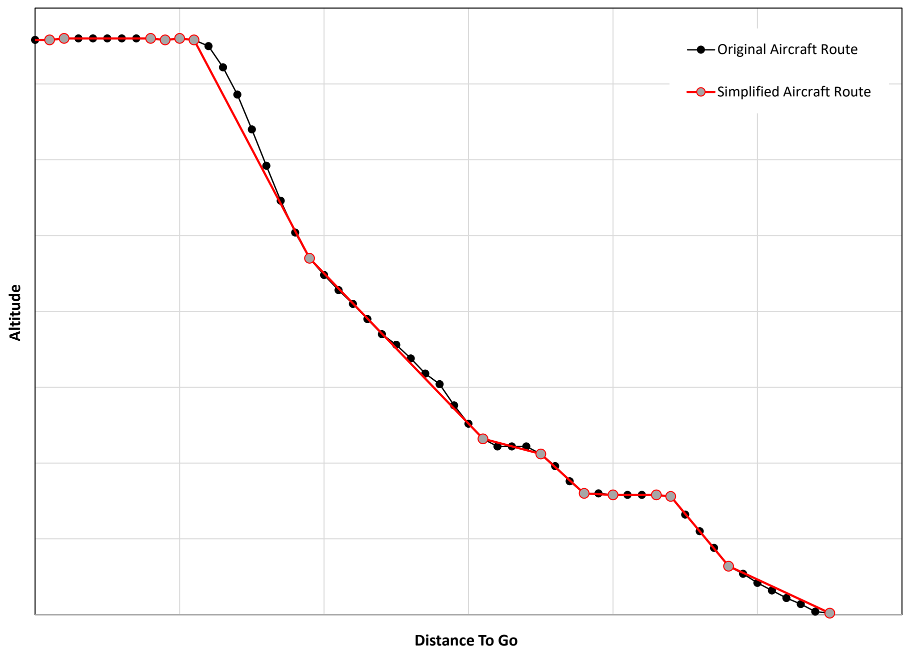
Appendix E.5 Basic Route Simplification

SWIM data captures the flight path or route of an aircraft as individual waypoints over time at varying intervals, where an aircraft typically flies from an origin to a destination airport through a series of named waypoints that can be separated by many nautical miles. Although an ASTOR aircraft performance model can follow the captured waypoints within SWIM data, the number of data points within a typical SWIM data record for a flight can exceed the buffer for the preexisting datalink message used to transmit a route to the RPFMS within ATOS for exceptionally long flights (e.g. transcontinental flight). Since the starting point of the scenarios is the aircraft's recorded ground track within SWIM data, these data need to be reduced to manageable routes that are compatible with the existing simulation framework.

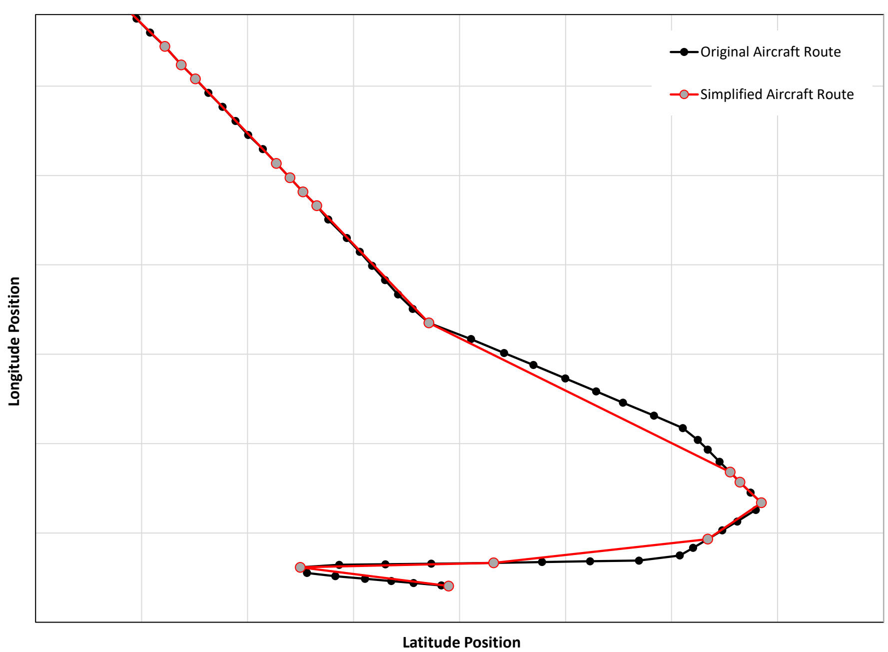
The basic route simplification process chosen for this activity is a recursive application of the Ramer-Douglas-Peucker line simplification method [55, 56] to reduce the number of waypoints (3-D vertices) along a route (polyline) according to a specified tolerance (maximum Euclidean distance allowed between the new line and a vertex point, 0.05). In simple terms, given a curve composed of line segment, a simpler curve can be identified composed of fewer segments while maintaining the original intention of the curve. This process has successfully allowed the incorporation of ground tracks from SWIM into the simulation scenario that reduces the number of data points while maintaining the original intention of the aircraft's route without the normally used named waypoints for air navigation. The research team used the `dpsimplify.m` function (v1.4.0.0, Schwanghart, 2020) for MATLAB that applies the Ramer-Douglas-Peucker line simplification method to the route data from SWIM.

In general, aircraft flight routes are normally simple line segments connecting named waypoints along their path (both horizontal and vertical). For the development of the TBO scenarios, waypoints for the en route segments of a flight above 18,000 feet have been eliminated from the routes. This is justified under the pretext that a new route (served as a route modification through a CPDLC message) is supplied by AOP during Stage 2 of the scenario generation process for all compatible ASTOR aircraft in the simulation. As an aircraft is on climb out and in the final descent portion of their flights, the vectoring of the aircraft within the national airspace generates more key path points that the Ramer-Douglas-Peucker line simplification cannot approach with the research specified tolerance. Part of the simplification process by the research team is to eliminate waypoints of latitude/longitude pairs below 10,000 feet, reducing the chance of excessive vectoring that affects the datalink message to the RPFMS. It will also be noted that a change in value of the tolerance to capture the climb out and final descent portion of a flight will quickly exhaust the capabilities of the RPFMS datalink message. The accepted workaround, discussed in the next subsection, is to correct the 'over simplification' from the Ramer-Douglas-Peucker line simplification method by addressing the resulting tight turns in the aircraft's simplified route.

A basic implementation of the Ramer-Douglas-Peucker line simplification method for aircraft's route is presented for the vertical portion of an aircraft's route in Appendix Figure E-1 and for the lateral portion of an aircraft's route in Appendix Figure E-2.



Appendix Figure E-1: Basic Route Simplification on the Vertical Portion of an Aircraft's Route



Appendix Figure E-2: Basic Route Simplification on the Lateral Portion of an Aircraft's Route

Appendix E.6 Correction of Bad Radii for Flight Routes

While the Ramer-Douglas-Peucker algorithm simplified the number of points in the trajectory to a reasonable number for the RPFMS datalink buffer, on occasion it over simplified the route, which caused issues when the RPFMS attempted to generate a trajectory for the aircraft to fly. In several cases, the Ramer-Douglas-Peucker algorithm created routes that had large turn angles, which prevented the RPFMS trajectory generator from computing a satisfactory turn between segments of the lateral trajectory. The RPFMS defines the lateral trajectory in terms of great-circle segments (Track-To-Fix legs) and turn segments which begin and end at geographical points that are either fixed (e.g., Radius-to-Fix legs) or floating (e.g., turns between Track-To-Fix legs).

Basic turns are computed using the required course change (i.e., the difference between the track into the turn versus the track out of the turn) and the aircraft's predicted groundspeed during the turn segment.

The turn radius (in units of length) is given by the following equation:

$$Turn\ Radius = {V_{GS}}^2/(g \cdot \tan\varphi) \tag{3}$$

where:

V_{GS} = the maximum predicted groundspeed during the turn

g = the acceleration due to gravity

φ = the nominal bank angle used to compute a turn (typically no more than 25 degrees for a commercial airliner).

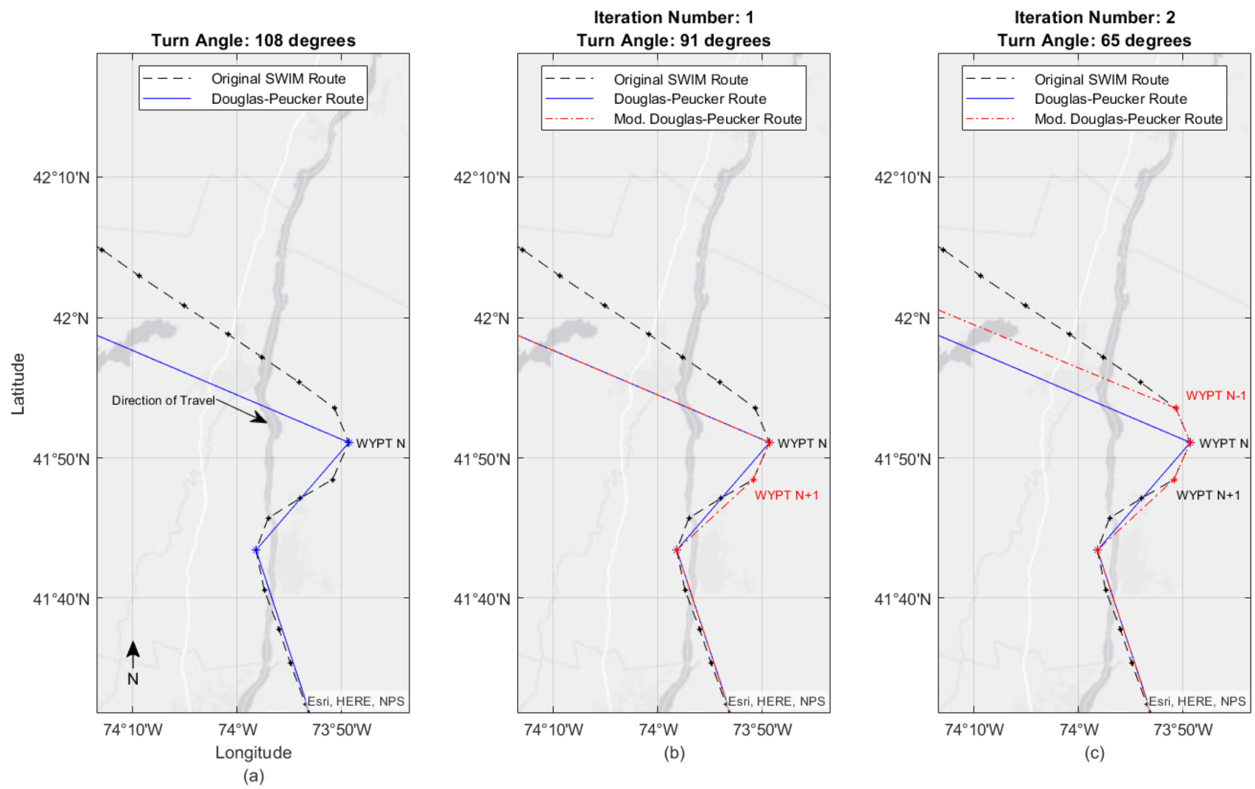
The turn arc length (in units of length) is given by the following equation:

$$Turn\ Arc\ Length = Turn\ Angle \cdot Turn\ Radius \tag{4}$$

Turn Angle is the required track angle change between the two lateral segments of the trajectory. Based on the turn radius and the turn arc length, start-of-turn, middle-of-turn, and end-of-turn points are computed for every turn. Bad radii occur when an end-of-turn point for one turn overlaps the start-of-turn point for the next turn (i.e., there is not enough distance along the path to perform both turns based on each turn's respective turn radius and turn arc length). Typically, bad radii occur when either the turn angle is very large (causing short along-path distances between start-, middle-, and end-of-turn points) or very small (causing long along-path distances between start-, middle-, and end-of-turn points). The bad radii condition is exacerbated if there are multiple turns in a short along-path distance.

In order to identify aircraft that may have bad radii in their routes, a script was written to evaluate all routes for all ASTOR aircraft in the scenario to determine if the routes contained any turns greater than 90 degrees. These often manifested in three locations on the route – during vectoring from the runway to the initial departure fix, during vectoring for the arrival route to the final approach course, or between the last waypoint in the route and the destination airport. The last case occurred as an artifact of the decision to remove low altitude waypoints (i.e., those waypoints that had altitudes below 10,000 feet associated with them). The evaluation used a three-step process. First, based on the latitude/longitude coordinates that define the lateral path, the rhumb line track between the waypoints is determined. Second, based on the tracks between each waypoint, compute the turn angle required at each waypoint. Finally, determine if any of the turn angles in the route are greater than a nominal turn angle limit, which for this exercise was set at 90 degrees, and note which waypoint (hereafter referred to as `WYPT N`) had a turn that violated the limit.

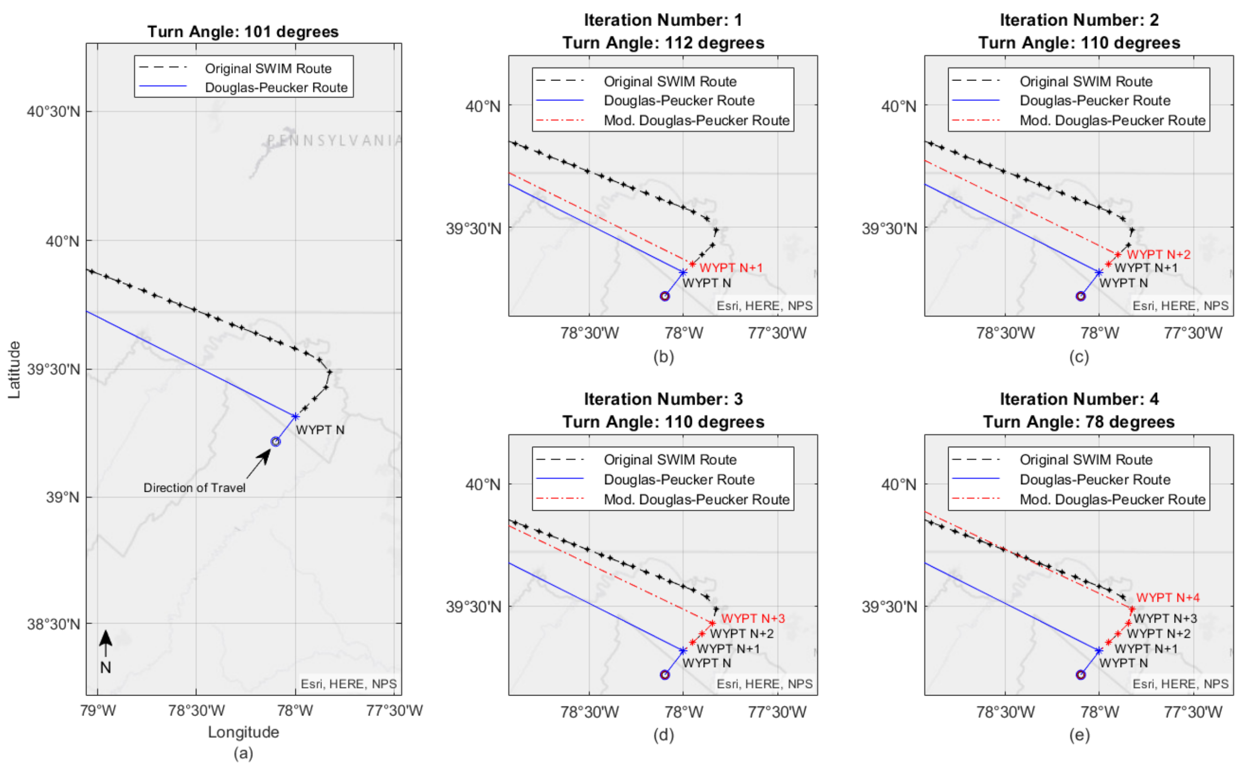
If a route contained a turn that exceeded the turn angle limit, an attempt was made to reduce the turn angle at that waypoint. One of the benefits of the Ramer-Douglas-Peucker algorithm is that during its simplification, it maintains the original vertices of the line that it's simplifying (i.e., the algorithm removes unnecessary points on the line and does not modify the points that are kept - no new points are added). In this implementation of the Ramer-Douglas-Peucker algorithm, since waypoints that exist in the simplified route also exist in the unmodified route, a routine was written that iteratively added waypoints from the unmodified route to the modified route in an attempt to reduce the turn angle. Appendix Figure E-3a demonstrates an example case where the turn angle between lateral segments connected at `WYPT N` was greater than the nominal turn angle limit of 90 degrees, caused by oversimplification using the Ramer-Douglas-Peucker algorithm.



Appendix Figure E-3: Example of Iterative Routine that Fixes Turns Greater than 90 Degrees by Adding Waypoints that Precede and Succeed `WYPT N`

The first iteration (and all subsequent odd-numbered iterations) of the routine finds the waypoint that had a turn which violated the limit in the unmodified route data (`WYPT N`), and then adds the waypoint immediately succeeding that point in the unmodified route data (i.e., `WYPT N+1` shown in Appendix Figure E-3b) to the simplified route. The aforementioned evaluation routine determines if the addition of the waypoint from the unmodified route reduces the magnitude of the excessive turn angle to an acceptable value. If the turn angle is reduced to an acceptable value, the new route (including the added waypoint) is passed into the scenario file as the route for that aircraft. If the turn angle is not reduced enough, as can be seen in Appendix Figure E-3b, another iteration of the routine occurs. The second iteration (and all subsequent even-numbered iterations) of the routine finds `WYPT N` in the unmodified data, and then adds the waypoint immediately preceding that point in the unmodified route data (i.e., `WYPT N-1` shown in Appendix Figure E-3c) to the simplified route. The aforementioned evaluation routine again determines if the addition of another waypoint from the unmodified route reduces the magnitude of the excessive turn angle to an acceptable value, as shown in Appendix Figure E-3c. If so, the new route (including the added waypoints) is passed into the scenario file as the route for that aircraft, and if not, another iteration of the routine occurs. This routine uses a maximum of 10 iterations (i.e., 10 added waypoints, five waypoints succeeding `WYPT N` and five waypoints preceding `WYPT N`) to reduce the magnitude of the turn angle at `WYPT N`. If all attempts are exhausted without a successful conclusion, the aircraft is converted to a TMX background aircraft.

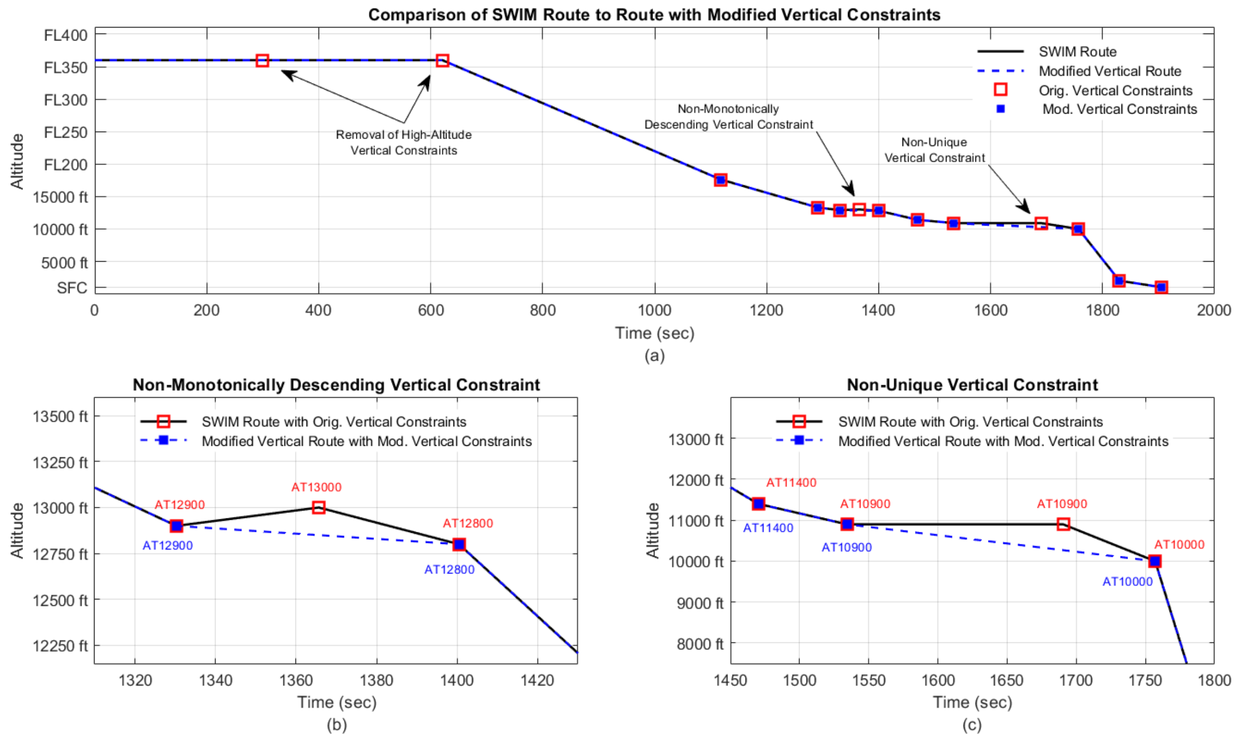
If there are no waypoints either preceding or succeeding `WYPT N`, the iterations add points where they exist, as shown below in Appendix Figure E-4. This route features a large turn immediately after the initialization location, as seen in Appendix Figure E-4a. Since there are no waypoints prior to the initialization point, the routine only uses waypoints that succeed `WYPT N`. In this example, four iterations of the routine, shown in Appendix Figure E-4b through e, are used to add four waypoints to the route, which reduces the turn angle from 101 degrees to 78 degrees.



Appendix Figure E-4: Example of Iterative Routine that Fixes Turns Greater than 90 Degrees by Adding Waypoints that Succeed `WYPT N`

Appendix E.7 Correction of Bad Vertical Constraints for Flight Routes

After fixing routes that could potentially cause bad radii, the next step is to ensure that the vertical trajectory was in a suitable form for the RPFMS. The RPFMS cannot handle high altitude constraints, and requires altitude constraints on the route to be unique and monotonically descending. A routine was scripted to perform three types of modifications to the vertical component of the trajectory: identify and remove any high-altitude vertical constraints (typically at cruise altitude), identify and remove any vertical constraints that did not monotonically descend in altitude, and identify and remove the n^{th} instance of any vertical constraint that is not unique. Appendix Figure E-5 presents an example of a vertical trajectory that required all three modifications to ensure that it was a flyable vertical trajectory.



Appendix Figure E-5: Removal of Vertical Constraints for ASTOR RPFMS Compatibility

Appendix Figure E-5a shows the vertical trajectory as recorded by the SWIM data, the original vertical constraints based on the SWIM data and the resulting vertical trajectory after modifying the trajectory to ensure it was in a form suitable for the RPFMS. First, high-altitude constraints were removed, as shown in the upper-left of Appendix Figure E-5a. The presence of these types of constraints caused the RPFMS to command erroneously the descent mode, which caused problems for the aircraft. The next two modifications are highlighted in Appendix Figure E-5b and Appendix Figure E-5c.

Next, the routine checked to ensure that all constraints monotonically descended in altitude. Appendix Figure E-5b illustrates an example of a vertical constraint that did not monotonically descend in altitude (i.e., a vertical constraint at a point downstream had a higher altitude than a vertical constraint at a point closer to the aircraft). As shown in Appendix Figure E-5b, the second waypoint shown had an altitude that was 100 feet higher than the previous constraint. These types of constraints occur as an artifact of using recorded track and altitude data from SWIM to build the original routes. The routine identifies these constraints by storing all vertical constraints along the route in a vector and determining if the difference between all successive waypoints is a negative value. If any vertical constraints are discovered that have a positive difference, the offending constraints are removed from the route.

Finally, Appendix Figure E-5c demonstrates an example of a non-unique vertical constraint present on the route. In this example, there are two vertical constraints at 10,900 feet. Like the previous case, these types of constraints occur as an artifact of using recorded track and altitude data from SWIM to build the original routes. The routine identifies non-unique values by comparing the number of elements in the vertical constraint vector to the number of unique elements in the vertical constraint vector. If any non-unique vertical constraints are discovered, the routine keeps the first instance of the vertical constraint in the route and removes all other instances of a vertical constraint at that altitude (as shown in Appendix Figure E-5c).

Once all modifications to the vertical trajectory are complete, the new route with removed constraints is passed into the scenario file as the route for that aircraft.

Appendix E.8 Identification of Bad ASTORs during Stage 2 Scenario Generation

Once initial Stage 2 scenarios are created, test data are gathered in an intermediate data collection run. The test data are then analyzed (`S2_SCNcheckout.m`) to determine if the aforementioned fixes for trim conditions, bad radii, and bad vertical constraints had the intended effects. A script called "`findBadASTORs.m`" is used to perform this identification. The script parses the `LogFileScanner_Summary_Developer` file looking for the key terms "`Trim failed to converge!`", "`TRAJ PREDICTION FAILURE`", and "`BAD RADIUS`", which would denote that an aircraft experienced issues during the simulation. The aircraft call signs associated with these error messages were then logged, checked for uniqueness (i.e., if an aircraft experienced multiple issues, it was only counted once), and converted to TMX aircraft for the final Stage 2 scenario. The script permits optional plotting routines to assist the researcher with visualizing the issue; the plotting functionality is controlled by flags in the script. If plotting flags are turned on, the script requires the "`AIRPORT.DAT`" file from the ATOS software build, which contains position data for the airports in the scenario.

Once other scripts modify the Stage 2 scenarios based on the outputs of this script, data are gathered in another intermedia data collection run (a formal Stage 2 data collection activity). This script is then ran again (`S2_SCNconfirm.m`) to identify any remaining issues

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14. ABSTRACT

NASA is supporting research to transition from a legacy, ATM system to Trajectory-Based Operations (TBO) environment targeting the 2035-2045 timeframe by creating simulation scenarios for current and future studies. These simulation scenarios offer a wide dissemination and use of system-level constraints and aircraft state/intent data, routine use of Data Comm to request complex trajectory modifications and to receive clearances, and aircraft that are flying on 4-D trajectories with flexibility when desired, but structure where required. This report describes the end-to-end development of scenarios for the NASA LaRC simulation environment to represent a 2040 TBO airspace for air transport operations research.

15. SUBJECT TERMS

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