

Using Recorded Airspace Traffic Data to Create Simulation Scenarios for Trajectory-Based Operations

Bill K. Buck¹ and Matthew C. Underwood²

NASA Langley Research Center, Hampton, VA 23681, USA

The National Aeronautics and Space Administration is supporting research to transition from the current air traffic management paradigm to Trajectory-Based Operations targeting the 2035-2045 timeframe. Trajectory-Based Operations in the National Airspace System focuses on modernizing current operations and technology to increase efficiency, predictability, resilience, and flexibility while migrating toward greater operational autonomy across the airspace. To understand the impact of new technologies and procedures that enable Trajectory-Based Operations, simulation studies must be conducted using realistic scenarios. This paper describes techniques that can be employed when using recorded airspace traffic data to create scenarios representative of a 2040 Trajectory-Based Operations airspace. The paper provides a use case example and suggests how this methodology may be applied to other simulations studying concepts, technologies, and procedures in a future airspace system.

I. Nomenclature

g	= acceleration due to gravity, in feet per second squared
$dist_{2go}$	= distance to go in nautical miles
$Fuel_{Flow}$	= estimated average fuel burn rate in pounds per nautical mile
$Fuel_{Flow_{Conv}}$	= conversion factor for estimated average fuel burn rate in nautical miles per minute
$Fuel_{Resv}$	= assigned fuel reserve in time
V_{GS}	= velocity, groundspeed in knots
V_T	= velocity, true airspeed in knots
W_G	= aircraft gross weight in pounds
W_{FUEL}	= aircraft's fuel load in pounds
W_{OEW}	= aircraft's operating empty weight in pounds
$W_{Payload_{Max}}$	= aircraft's maximum payload weight in pounds
$W_{Payload_{Per}}$	= percentage of assumed payload for aircraft loading
WD	= wind direction in degrees from true North
WS	= wind speed in knots
ϕ	= bank angle in degrees
ψ_t	= heading in degrees from true North

II. 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 that demonstrate a representative TBO environment in that timeframe.

This paper describes modifications to recorded operational data required to build realistic simulation scenarios for a 2040 TBO environment. A detailed methodology was developed and applied by researchers at NASA Langley

¹ Aerospace Engineer, Crew Systems and Aviation Operations Branch, M/S 152, AIAA Senior Member.

² Aerospace Engineer, Crew Systems and Aviation Operations Branch, M/S 152, AIAA Member.

Research Center [1, 2]. This paper focuses on converting real-world operational traffic data into simulation scenarios and posits how this methodology may be more broadly applied to other simulations studying a future airspace system.

III. Background

NASA is exploring a future service-based airspace system for the 2035-2045 timeframe in domestic United States airspace that enables increasingly diverse operations in dense, controlled airspace [3]. New entrants such as overland supersonic flights, commercial space launch and re-entry vehicles, high-altitude long endurance aircraft, Unmanned Aircraft Systems, and Urban Air Mobility vehicles 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.

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.

The following subsections describe a high-level concept of Trajectory-Based Operations in a Future NAS and present an overview of recent simulations at NASA Langley Research Center of a representative 2040 TBO environment. The final subsection discusses generalized issues when working with airspace traffic data that is recorded within surveillance data for the NAS.

A. Trajectory-Based Operations in a Future NAS

The service-based TBO environment for the 2035-2045 timeframe is expected to exhibit a number of unique characteristics not inherent to the current airspace environment. 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 forums held at NASA Langley Research Center. Key TBO characteristics and attributes with a high likelihood of being a part of airspace environments in the 2035-2045 timeframe were selected for exploration and inclusion within these simulation scenarios.

Information such as aircraft state and intent data, and airspace system-level constraints, will likely be widely disseminated throughout the system, and may be used for decision making by various stakeholders. Digital Data Communication, or “Data Comm” [4, 5], between airspace users and the air navigation service provider will likely be routinely used to request complex trajectory modifications and to receive clearances during all phases of flight. Aircraft will likely 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 [6, 7, 8, 9].

The 2035-2045 TBO environment will also permit 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) [10, 11, 12, 13, 14]. 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 [15] will increase the use of time-based flow management [16], collaborative decision-making [17], and the amount of information shared and used by actors in the system [18, 19]. These technologies, which serve as the foundation of this future TBO environment, are anticipated to increase the capacity and predictability of the NAS, as well as system and user efficiency.

B. Overview of a Simulation of a Representative Future Trajectory-Based Operations Environment

Recent research activities conducted by ATM researchers at NASA Langley Research Center have designed and implemented a scenario creation process for the simulation of 2040 Trajectory-Based Operations environment in support of current and future studies [1]. These simulation scenarios offer a wide dissemination and use of system-level constraints and aircraft state/intent data, routinely use data communications to request complex trajectory modifications and to receive clearances, and feature aircraft that fly on 4-D trajectories with flexibility when desired, but structure where required. Ref. [1] 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. Part of these activities was a corresponding simulation data collection and analysis effort to study

the representative 2040 TBO environment as part of a simulation use case. Ref. [2] includes descriptions of the study design and analysis approach, discussion of the simulation results, and application of these scenarios to potential future research activities.

The TBO simulation scenarios created used Cleveland Air Route Traffic Control Center (ARTCC), referred to as ZOB, Class A airspace as the airspace of interest. The ZOB airspace structure includes several high-density parallel routes and multi-axis merging geometries that enable a large volume of en route traffic. 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. 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.

The simulation scenarios used recorded traffic data from the FAA System-Wide Information Management (SWIM) system, four-dimensional wind and temperature data, four-dimensional convective weather data, and Special Use Airspace data from days/times of interest. To provide increased user flexibility expected in the 2040 TBO environment, approximately 40% of flights in each scenario were equipped with a prototype technology that implements optimized routing. 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 simulated aircraft flying complex 4-D trajectories in 3-hour time periods. Approximately 70% of the aircraft in each scenario are medium-high fidelity simulated aircraft that use a type-specific kinetic math model, known as the Aircraft Simulation for Traffic Operations Research (ASTOR) aircraft. The remaining 30% are low-fidelity simulated aircraft that use a kinematic “trajectory-following” model, known as Traffic Manager (TMX) aircraft. Analyses confirmed that variability between scenarios was minimal, which allows future research activities to utilize these scenarios without concern for effects due to the chosen scenario. The final version of the TBO environment scenarios contain thousands of aircraft in the simulation.

Figure 1 presents an overview of the flights within a 2040 TBO scenario overlaid on a satellite image map. 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 aircraft) or blue triangles with a trailing path shown in red (TMX aircraft). Larger Class B airports are noted by the airport symbol, and state outlines are in gray.

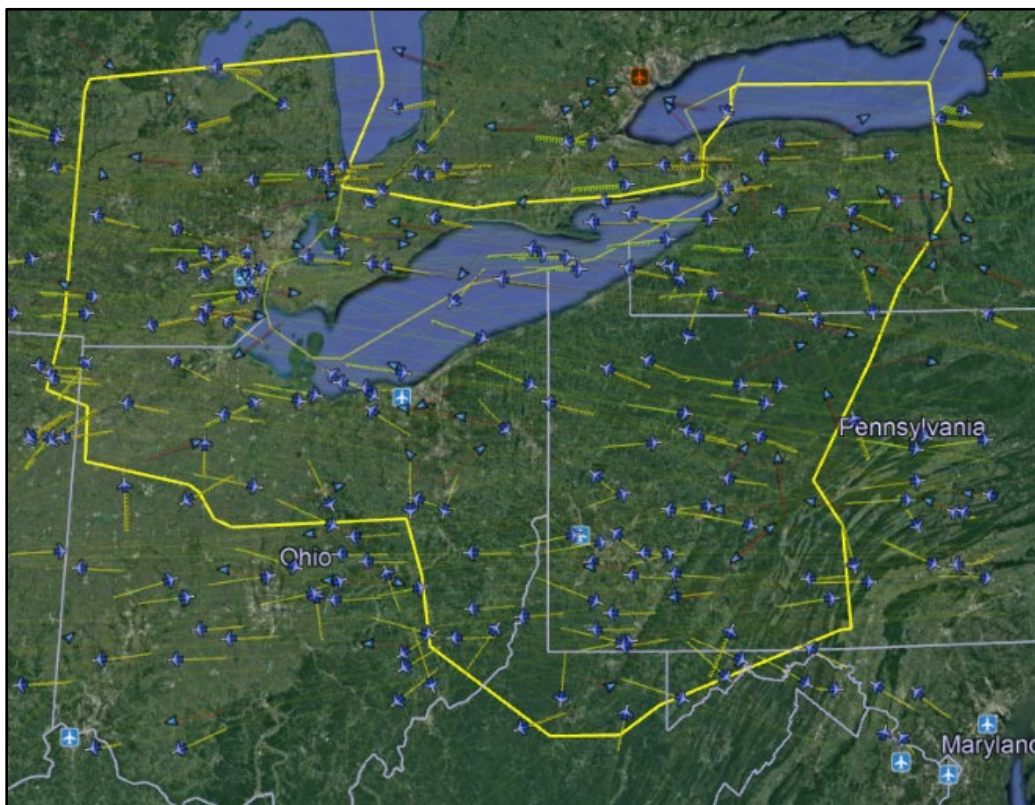


Fig. 1 Overview of Flights within a TBO Scenario

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. 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. Alternatively, 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.

C. Issues with Using SWIM Data as a Starting Point for Simulation Scenarios

SWIM is an FAA information-sharing platform designated to facilitate an increased situational awareness and greater sharing of ATM system information among participants in the NAS [18, 19]. SWIM is composed of multiple data sources with varying and unique purposes, accessible to end users according to their needs.

The NASA research team used recorded aircraft position and state data from SWIM as a starting point for the development of traffic scenarios for the research simulation activity. This air traffic data provides the best source to simulate aircraft along realistic flight paths throughout a day instead of a contrived route. However, 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 the NASA Langley ATM simulation capability scenario file format. Furthermore, 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.

If an aircraft has sufficient route data and a unique identifier, the following are some of the issues identified by the research team while working with the SWIM data when building the simulation scenarios.

- The SWIM data used as the initial simulation source captures all registered aircraft for public access. However, many medium-to-high fidelity kinetic aircraft simulation platforms have a limited number of type-specific performance models that they can employ. Therefore, aircraft types present in the SWIM data may have to be mapped to a suitable performance model.
- 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. However, incorrect or missing airport data found within the SWIM records can cause errors when estimating the distance between the aircraft's initialization point and the destination airport.
- 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 state data that defines their as-flown routes in SWIM data are updated on a non-regular basis (up to once per second), and there may be many waypoints defined for a long flight. The variable periodicity and large number of waypoints may present issues for an aircraft simulation that uses a kinetic trajectory generator. Therefore, the number of waypoints defining a route must be reduced. Once the reduction of waypoints occurs, error-checking must also occur to ensure that the route conforms to the specifications of the kinetic trajectory generator in the aircraft simulation (e.g., no large turns).

The following sections discuss mitigation strategies to deal with these issues when using SWIM data as the starting point for creating ATM simulation scenarios.

IV. Aircraft Type Identification and Initialization

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. Whereas lower-fidelity aircraft simulations may implement a kinematic "trajectory following" model that can act like a playback utility of SWIM data, medium-to-high fidelity aircraft simulations that implement type-specific performance models may use a kinetic math model that requires more information for initialization.

For example, some simulation platforms (such as the NASA Langley ATM simulation capability) may only have a small number of type-specific performance models. Therefore, aircraft types present in the SWIM data must be

mapped to a suitable 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.

Additionally, aircraft simulations that use kinetic math models must be initialized 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, these models may require a gross weight parameter to initialize. However, SWIM does not provide aircraft weight. Therefore, a weight needs to be estimated that is within the type-specific performance envelope and that allows enough fuel to reach the destination airport, even if only a portion of the flight is completed within the simulation scenario. Additionally, a calibrated airspeed in units of knots or a Mach number may be required at initialization. SWIM does not provide an airspeed value; it provides a groundspeed value. Therefore, the airspeed must be estimated based on the groundspeed specified in the SWIM data and the wind data recorded on that day at that time. Finally, many kinetic aircraft simulation models 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. The rate of climb in SWIM data is typically specified in feet per minute, but a conversion to other units may be necessary.

Therefore, the SWIM data in its native form does not meet the initialization criteria to allow a kinetic aircraft simulation to fly like the real-world flight. A significant portion 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 subsections capture several important steps in modifying or estimating the state of an aircraft at its initialization in the simulation for the ASTOR aircraft performance models.

A. 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 that may not be specifically supported by the NASA Langley ATM simulation capability. For simulation environments with a limited set of aircraft performance models, an aircraft-mapping schema should be created to match the available aircraft performance models in the simulation with the real-world aircraft. This allows the simulation to retain as much of the traffic data as possible within the captured timeframe of interest.

FAA Order JO 7360.1E [20] describing the aircraft type designators used within the SWIM data is a suitable source to match the SWIM aircraft to available aircraft performance models in simulation. The FAA Order 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, also defined in the FAA Order, may also be considered useful in the mapping to aircraft performance models in simulation. Table 1 presents the various categories that may be considered when attempting to select aircraft types for which a type-specific math model does not exist in the simulation platform.

Table 1: Categories to be Considered When Matching Aircraft Types in Simulation

Category Description	Potential Category Values
FAA Aircraft Class	Fixed-Wing, Gyrocopter, Helicopter, Remotely Piloted Aircraft, or Tiltrotor
Engine Number and Type	Electric (E), Piston (P), Turboprop/Turboshaft (T), Jet (J), or Rocket (R) Number of engines and engine types as included as part of the aircraft description
FAA Weight Class	Super (J), Heavy (H), Large (L), Small (S), or “+” Separated based on maximum certificated take-off weight
ICAO Wake Turbulence Category	Category Heavy (H), Medium (M), or Light (L) Based on maximum certificated take-off weight
ReCAT 1.5 Wake Category	Category A through Category F Based on wingspan and maximum take-off weight

For example, Table 2 presents a summary of the mapping of matching aircraft types within the simulation scenarios to the ASTOR performance model types used in the simulation described in Section III. The assignment of an aircraft from SWIM data to an ASTOR performance model type is important to the estimation of an aircraft’s gross weight and airspeed at initialization, as well as the assumptions within the kinetic trajectory generator. Electric, piston, and turboprop aircraft were not included in the simulation scenarios because no appropriate ASTOR performance model exists for those types.

Table 2: ASTOR Performance Models Matched to Categories of Aircraft Types from Source SWIM Data

Aircraft Type	FAA Aircraft Class	No. Engines/ Type	FAA Weight Class	ICAO Wake Turbulence Category	ReCAT 1.5 Wake Category
Business/Regional Jet	Fixed-wing	2 / Jet	Small+ Small/ Large	Light Medium	D / E / F
Narrow-body Short Range	Fixed-wing	2 / Jet	Large	Medium	D
Narrow-body Medium Range	Fixed-wing	2 / Jet	Large	Medium	D
Narrow-body Long Range	Fixed-wing	2 / Jet	Large	Medium	D
Wide-body Medium Range	Fixed-wing	2 / Jet	Heavy	Heavy	C
Wide-body Long Range	Fixed-wing	2/4 Jet	Heavy	Heavy	A/B

Table 3 presents the typical specifications for the aircraft types represented by the ASTOR performance models in a simulation. These values support the estimation processes at aircraft initialization for kinetic math models and functional checks of the aircraft's performance capabilities.

Table 3: Typical Specifications for Aircraft Types Represented by ASTOR Performance Models

Aircraft Type	Service Ceiling (ft)	Cruise Speed (Mach Number)	Maximum Take-off Weight (lbs)	Operating Empty Weight (lbs)	Max Payload Weight (lbs)
Business/ Regional Jet	42,000	0.64	32,000	17,937	6,213
Narrow-body Short Range	37,000	0.76	137,000	72,540	33,960
Narrow-body Medium Range	41,000	0.78	172,500	91,000	45,000
Narrow-body Long Range	41,000	0.78	250,000	136,940	47,060
Wide-body Medium Range	41,000	0.78	315,000	176,650	73,350
Wide-body Long Range	43,100	0.79	535,000	297,250	122,750

B. Initialization Gross Weight Estimation

Aircraft weight is not present in the sourced SWIM data. However, aircraft simulators that use a kinetic trajectory generator typically require a gross weight parameter in pounds at initialization. Therefore, an estimated weight must be provided in the simulation scenario. To avoid simulation trim errors, the initial weight value must be within the performance range of the aircraft performance model being simulated. Furthermore, the weight estimate must account for enough fuel for the aircraft to reach its route specified destination. Reference information used in the weight estimation is presented in Table 3 in the previous subsection and is used in the following calculations.

The gross weight estimate, presented in Eq. (1), is computed by adding three factors: the operating empty weight, an estimate for the payload weight, and an estimate for the fuel weight. The operating empty weight is referenced from the type-specific aircraft performance model. An estimate for the payload weight is computed by multiplying the maximum payload weight obtained from the type-specific aircraft performance model by a percentage (e.g., 80%). Finally, the fuel weight is estimated.

$$W_G = W_{OEW} + (W_{Payload_{MAX}} * W_{Payload_{PER}}) + W_{Fuel} \quad (1)$$

The fuel weight estimate, presented in Eq. (2), considers two parameters: the amount of fuel required for the aircraft to reach its destination airport, and the amount of fuel legally required in the reserves. The fuel required to reach the destination airport is computed by multiplying a fuel flow parameter in pounds per nautical mile by the great circle distance (calculated using the Haversine formula) between the aircraft's initialization location and the location of the destination airport. The fuel flow parameter is obtained from the type-specific aircraft performance model. The fuel reserve estimation is computed by multiplying the fuel flow parameter by a conversion factor (nautical miles per minute) and a fuel reserve time (e.g., 60 minutes).

$$W_{Fuel} = (Fuel_{Flow} * dist_{2go}) + (Fuel_{Flow} * Fuel_{Flow_{Conv}} * Fuel_{Resv}) \quad (2)$$

Once the calculation of the weight estimate is complete, a functional check occurs to ensure that the estimated gross weight is less than the maximum take-off weight. If the estimated gross weight is greater than the maximum take-off weight, the estimated gross weight is set to the maximum take-off weight.

C. Initialization Airspeed Estimation

Aircraft groundspeed is present in the original SWIM data and can be used directly in simulation platforms that accept groundspeed at initialization (e.g., TMX). However, some higher-fidelity aircraft simulations (e.g., NASA Langley's ASTOR aircraft) must be initialized with either calibrated airspeed or Mach number. The following is an approach to estimate true airspeed for an aircraft at initialization from the groundspeed provided in SWIM data [1].

First, the total wind speed and direction at the initialization time and position must be found for the selected aircraft. Date and time gridded wind and temperature reference data like NOAA's RAP may be used to identify the north-south wind component, east-west component, and temperature values at the initialization time, latitude and longitude position, and altitude. Using the groundspeed and wind velocity, true airspeed may be estimated by Eq. (3).

$$V_T = \sqrt{V_{GS}^2 + WS^2 - 2V_{GS} * WS * \cos(\psi_t - WD)} \quad (3)$$

Mach number may be estimated from true airspeed and the speed of sound for the altitude of the aircraft. An estimate of Computed Airspeed requires the air density and pressure, both adjusted by temperature, from the same initialization point in space and time for the aircraft. Equations for both are expressed in Ref. [21].

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. Aircraft specific reference information identified by the user is used in the airspeed estimation for different phases of flight. Figure 2 presents a pseudo code for airspeed estimation adjusted for a phase of flight at the aircraft's initialization. Computed Airspeed is abbreviated as CAS within this pseudo code.

<u>Aircraft in a Climb (Vertical Speed is positive up)</u> 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 aircraft model No updated information end	<u>Aircraft in a Descent (Vertical Speed is negative)</u> 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 aircraft model No updated information end
<u>Aircraft in Cruise (Vertical Speed is zero)</u> if Mach > Cruise Mach + 0.02 Set to Cruise Mach + 0.02 else Speed is within bounds for aircraft model No updated information end	<u>Airspeed Algorithm Variable Definition</u> 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

Fig. 2 Pseudo Code for Airspeed Estimation at Aircraft Initialization

D. Aircraft Exclusion Considerations

Additional insight and setup are required for some flights within the SWIM data because of missing or incomplete information required for initialization. An individual aircraft should be considered for exclusion from a simulation using SWIM surveillance track data if any of the following criteria are met:

- The aircraft's origin and destination airport are the same, empty, or missing.
- The aircraft's origin airport is empty or missing. This 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 destination airport.
- 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. This may occur due to the aircraft cancelling an Instrument Flight Rules flight plan and continuing to the destination airport under Visual Flight Rules.

- When modeling cruise flight conditions, if the real-world aircraft's cruise altitude is determined to be less than or equal to 10,000 feet, or greater than maximum cruise ceiling of the simulated aircraft. This avoids the potential for bad trim conditions when the simulated aircraft initializes.

V. Flight Route Simplification and Correction

SWIM surveillance data provides an excellent representation of how an aircraft navigated during its flight. The route of flight is identified as a series of three-dimensional (3-D) waypoints (latitude, longitude, and altitude) parameterized by time. SWIM track data are not recorded on a consistent periodic basis (e.g., a waypoint every 12 seconds); the time between subsequent waypoints may be variable. Furthermore, there may be many waypoints for a long flight. The variable periodicity and large number of waypoints may present issues for an aircraft simulation that uses a kinetic trajectory generator. Therefore, the SWIM surveillance data must be converted into a simplified route that is ingestible by a kinetic trajectory generator.

When simplifying the SWIM surveillance data, care must be taken to ensure that the route is not over-simplified, which may cause excessive turns that are not flyable. Furthermore, care must be taken to ensure that the vertical definition of the route is properly formatted for the kinetic trajectory generator inherent the aircraft simulation (e.g., altitude constraints must be unique and monotonically descending). The following subsections describe the simplification algorithm used in the simulation study described in Section III and presents methods to ensure that the lateral and vertical route data are flyable for the simulated aircraft.

A. Basic Simplification of Flight Routes

SWIM radar track 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. Some aircraft simulations can follow the captured waypoints within SWIM data (e.g., a trajectory-following kinematic model). However, the number of radar track points within a typical SWIM data record for long flights (e.g. transcontinental flight) can exceed the capabilities for defining a route for a kinetic simulation model. To allow kinetic models to use routes defined by SWIM radar track data, these data need to be reduced to manageable routes that are compatible with the existing simulation framework.

The route simplification algorithm chosen for this methodology is a recursive application of the Ramer-Douglas-Peucker line simplification method [22, 23]. The Ramer-Douglas-Peucker algorithm reduces 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). The premise of the algorithm is this: given a curve composed of line segments, a simpler curve can be identified composed of fewer segments while maintaining the original intention of the curve. In practice, the Ramer-Douglas-Peucker algorithm application in this methodology reduces the number of radar track points while maintaining the original intention of the aircraft's 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 Fig. 3 and for the lateral portion of an aircraft's route in Fig. 4.

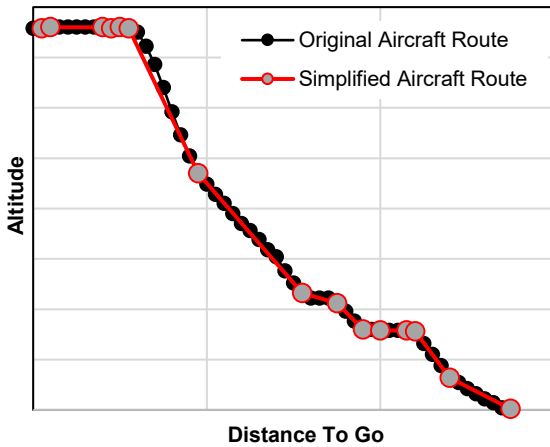


Fig. 3 Simplification of the Vertical Portion of an Aircraft's Route

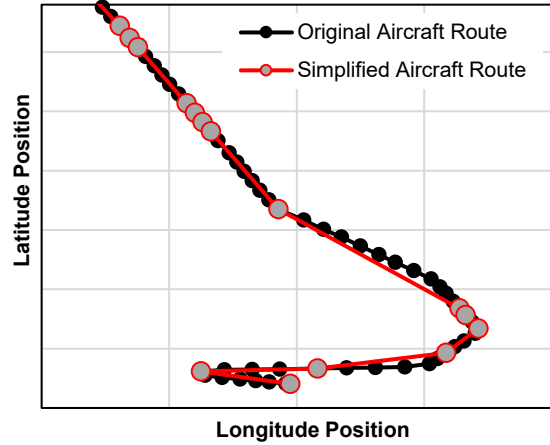


Fig. 4 Simplification of the Lateral Portion of an Aircraft's Route

B. Correction of Bad Radii for Flight Routes

Generally, the Ramer-Douglas-Peucker algorithm simplifies the number of points in the SWIM radar track route to a reasonable number for a kinetic aircraft simulation. However, there are instances when the algorithm may over-simplify the route. This typically manifests early and late in the flight. As an aircraft is on climb out and in the final descent portion of their flights, radar vectoring and intermediate level-off instructions from air traffic controllers generate key path points that the Ramer-Douglas-Peucker line simplification may over-simplify using the specified tolerance. This results in routes that have large turn angles, which may prevent a kinetic trajectory generator for a simulated aircraft from computing a satisfactory turn between segments of the lateral trajectory.

Many kinetic trajectory generators define 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 in Eq. (4). The nominal bank angle used is assumed to be no more than 25 degrees for a commercial airliner.

$$\text{Turn Radius} = V_{GS}^2 / (g * \tan(\phi)) \quad (4)$$

The turn arc length (in units of length) is given by Eq. (5).

$$\text{Turn Arc Length} = \text{Turn Angle} * \text{Turn Radius} \quad (5)$$

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 in the trajectory. Bad radii in a kinetic trajectory 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 evaluates all simplified trajectories in the scenario to determine if the lateral trajectory contains any turns greater than 90 degrees. The evaluation uses a three-step process. First, based on the radar track points that define the lateral path, the rhumb line track between each waypoint is determined. Second, based on the rhumb line tracks between each waypoint, the turn angle at each waypoint is computed. Finally, any turn angles in the route greater than a nominal turn angle limit (90 degrees) are found, and waypoints with a turn that violates the limit (hereafter referred to as WYPT N) are noted.

If a route contains a turn that exceeded the turn angle limit, an attempt is 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 is used to iteratively added waypoints from the unmodified route to the modified route in an attempt to reduce the turn angle. Figure 5a 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.

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 Fig. 5b) to the simplified route. The routine determines if the addition of the waypoint from the unmodified route reduces the magnitude of the excessive turn angle to an acceptable value (i.e., less than 90 degrees). 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 Fig. 5b, 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 Fig. 5c) to the simplified route. The 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 Fig. 5c. 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 discarded from the simulation.

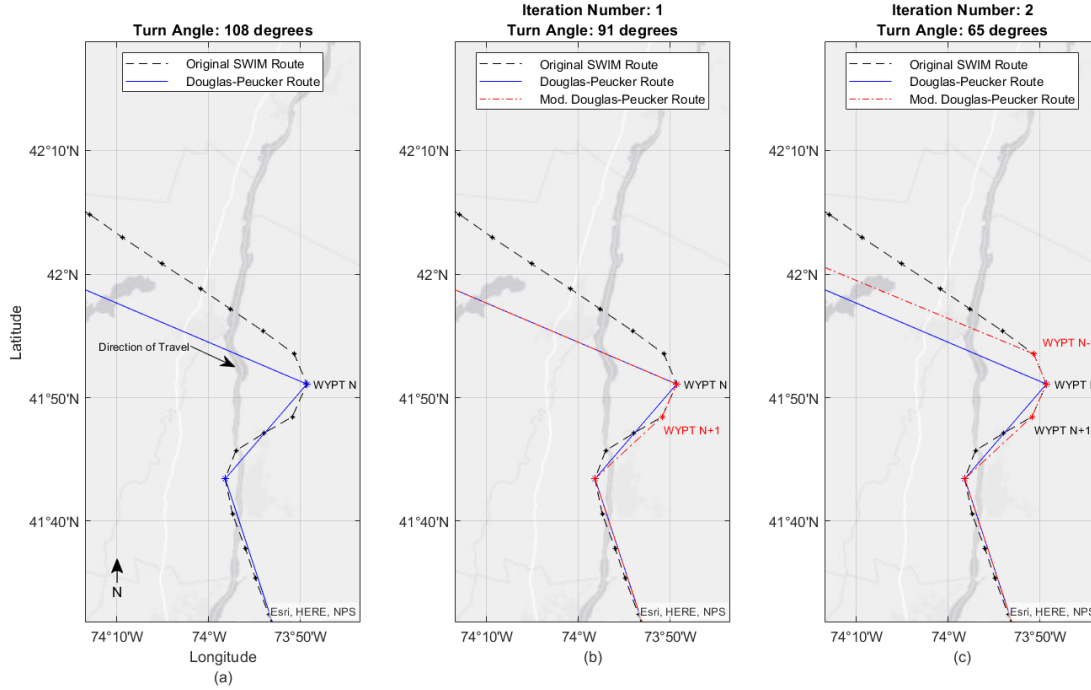


Fig. 5 Example of Iterative Routine that Fixes Turns Greater than 90 Degrees by Adding Waypoints that Precede and Succeed WYPT N

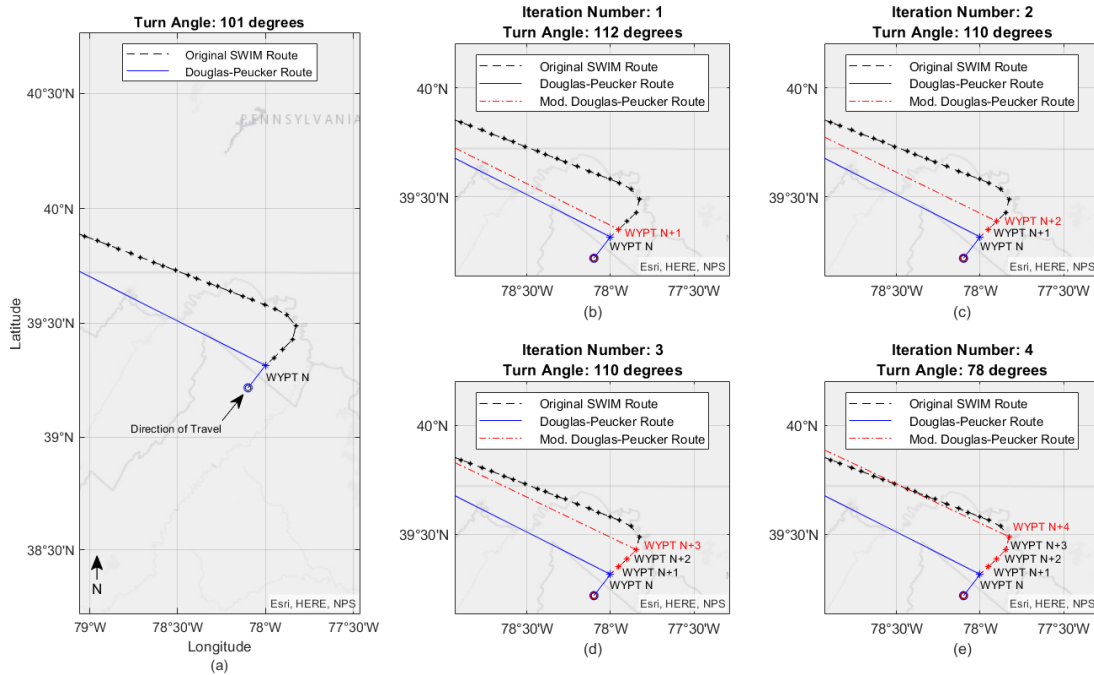


Fig. 6 Example of Iterative Routine that Fixes Turns Greater than 90 Degrees by Adding Waypoints that Succeed WYPT N

If there are no waypoints either preceding or succeeding WYPT N, the iterations add points where they exist, as shown in Fig. 6. This route features a large turn immediately after the initialization location, as seen in Fig. 6a. 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 Fig. 6b through e, are used to add four waypoints to the route, which reduces the turn angle from 101 degrees to 78 degrees. If all attempts are exhausted without a successful conclusion, the aircraft is discarded from the simulation.

C. 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 is in a suitable form for the kinetic trajectory generator. Many high-fidelity kinetic trajectory generators that emulate those found in commercial transport flight management systems cannot accommodate high altitude constraints. Furthermore, they require altitude constraints in the descent phase of flight to be unique and monotonically descending. A routine is used to evaluate each aircraft's vertical trajectory. If necessary, the routine performs 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. Figure 7 presents an example of a vertical trajectory that required all three modifications to ensure that it was a flyable vertical trajectory.

Figure 7a shows the vertical trajectory as recorded by the SWIM data, the original vertical constraints based on the SWIM track data and the resulting vertical trajectory after modifying the trajectory to ensure it was in a form suitable for a kinetic trajectory generator. First, high-altitude constraints are removed, as shown in the upper left of Fig. 7a. These types of constraints may erroneously command the descent mode for the simulated aircraft, which results in incorrect flight behavior.

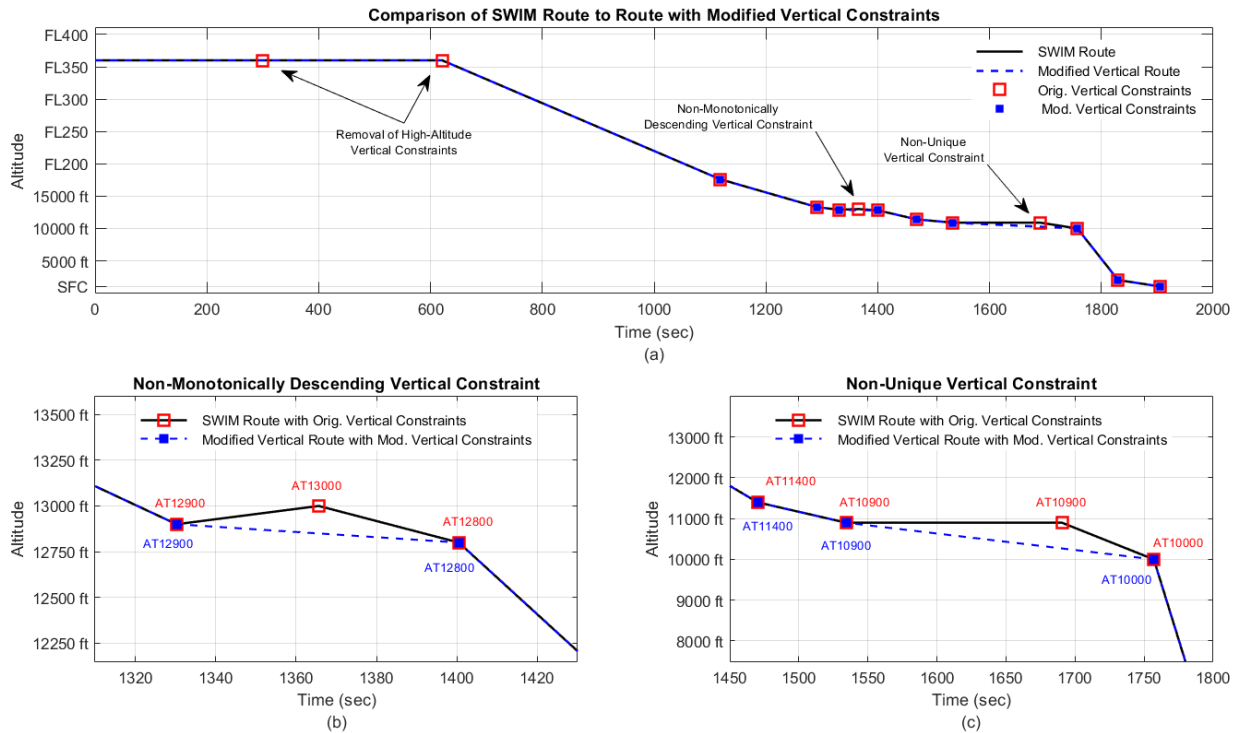


Fig. 7 Removal of Vertical Constraints for Kinetic Trajectory Generation Compatibility

Next, the routine checks to ensure that all constraints monotonically descend in altitude. Figure 7b 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 Fig. 7b, the second waypoint shown has 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, Fig. 7c 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 Fig. 7c). 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.

VI. Use Case Example for Scenario Development for NASA Langley Simulation Environment

This following presents a single use case example that applies the methodology outlined in Sections IV and V that augments or modifies the source SWIM data. This power of this process is that it can be expanded for any number of vehicle types, aircraft routes, and vertical profiles. The aircraft selected for this use case example from the NASA Langley 2040 TBO Simulation was chosen because it requires significant augmentation and modification from the as-flown information from SWIM. However, most aircraft only require minimal changes from the as-flown SWIM data.

The aircraft selected for this particular single use case is a MD-90 aircraft with a filed flight plan from Syracuse Hancock International Airport (KSYR) in New York to Hartsfield - Jackson Atlanta International Airport (KATL) in Georgia with a cruising altitude of 30,000 ft on the afternoon of May 24, 2018. From the NASA Langley 2040 TBO Simulation developed in Ref. [1, 2], the aircraft call sign assigned to this flight is BCX0405.

One of the first steps in using the SWIM data to create complex and realistic based scenarios is to use the information presented in Section IV.A to assign an aircraft performance model to the real-world aircraft that is to be simulated. From Ref [20], the MD-90 aircraft type is identified as a fixed-wing, two engine jet, with an FAA Weight Classification of Large, an ICAO Wake Turbulence Category of Medium, and a ReCAT 1.5 Wake Category of D. Matching this with the information presented in Table 2, any aircraft identified as a MD-90 is assigned the generic ASTOR performance model of a Narrow-body Medium Range Aircraft in the NASA Langley's ASTOR aircraft simulation.

The Gross Weight at simulation initialization is not present within the SWIM data, so it is estimated from the equations presented in Section IV.B and information within Table 3. The weight of the Fuel is estimated to be 13,205 pounds for a Distance To Go value of 602 nautical miles to the destination airport of KATL and Fuel Reserve time of 60 minutes using Eq. (2). With an Operating Empty Weight assumption of 91,000 pounds, a maximum Payload Weight of 45,000 pounds, and the previous estimation of weight of onboard fuel, the computed Gross Weight of simulated aircraft BCX0405 is found to be 142,205 pounds using Eq. (1).

The required initialization Computed Airspeed of the simulated aircraft can be estimated using Eq. (3) presented in Section IV.C. The Groundspeed (477.87 knots), Altitude (26,300 feet), and True Heading (195.22 degrees) are available from the SWIM data. Gridded wind and temperature data from a matched date and time provide estimated values of Wind Speed (33.16 knots), Wind Direction (142.95 degrees), and Temperature (241.32 Kelvin). Subsequent values of Atmospheric Pressure (832.79 pound-force/square-foot), Atmospheric Density (3.596 pound/cubic-foot), and the Speed of Sound (605.33 knots) at the altitude can be calculated using equations presented in Ref. [21]. From Eq. (3), the True Airspeed is estimated to be 458.33 knots with an equivalent value of Computed Airspeed to be 327.08 knots and a Mach value of 0.7572. This particular aircraft is on climb out from its origin airport to a cruising altitude of 30,000 feet, so it has a positive, non-zero Vertical Speed at simulation initialization. Using the information presented in Fig. 2, the Computed Airspeed is adjusted to the maximum Mach in a climb minus 0.05 Mach for the ASTOR performance model, a value of 323.76 knots. This is because the aircraft is in a climb, both estimated Mach and Computed Airspeed are greater than their maximum climb equivalents, and the initialization altitude is greater than the Crossover Altitude value between Mach and Computed Airspeed.

Application of the Ramer-Douglas-Peucker algorithm simplifies the original quantity of waypoints of the route for BCX0405 from 161 to just 8, allowing for a more manageable route to be used in the NASA Langley ASTOR aircraft simulation and the final portion of this route is presented in Fig. 8. However, the removal of all waypoints below 10,000 feet has caused a turn in excess of the nominal turn angle limit of 90 degrees between the final waypoint and the destination airport. This particular example case happens when an aircraft flies a downwind approach to final at the airport. This reduction in waypoints, if presented to a commercial transport flight management system, will create an error within the solution of a kinetic trajectory generator and must be corrected before a simulation can begin.

Through the iterative process of the correction of bad radii described in Section V.B, 9 waypoints were added back from the original SWIM route to the Ramer-Douglas-Peucker route, thereby reducing the turn angle to below 90 degrees.

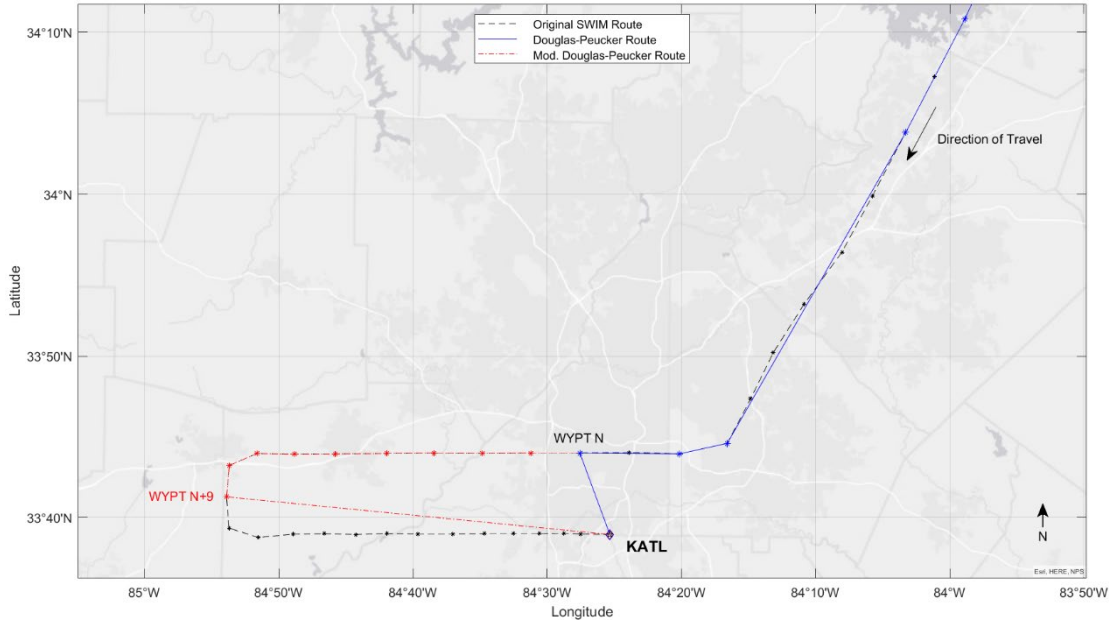


Fig. 8 Lateral Trajectory Modification to Fix Turn of Greater than 90 Degrees for BCX0405

After fixing routes that could potentially cause bad radii, the next step is to ensure that the vertical trajectory is in a suitable form for the kinetic trajectory generator as described in Section V.C. As previously mentioned, altitude constraints in the descent phase of flight are required to be unique and monotonically descending. Presented within Fig. 9 are the necessary modifications for BCX0405 to have a flyable vertical trajectory that is acceptable to modern commercial transport flight management systems.

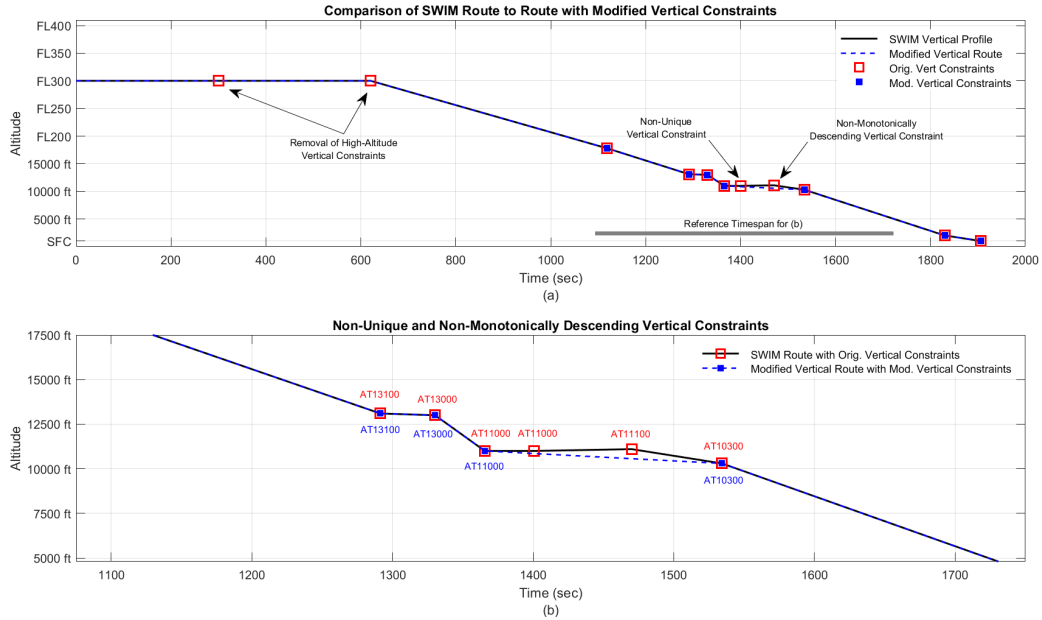


Fig. 9 Removal of Vertical Constraints for Kinetic Trajectory Generation Compatibility of BCX0405

The vertical trajectory as recorded by the SWIM data, the original vertical constraints based on the SWIM track data, and the resulting vertical trajectory after modifying the trajectory to ensure it was in a form suitable for a kinetic

trajectory generator are presented in Fig. 9a. This highlights the removal of high-altitude vertical constraints and the location of non-unique and non-monotonically descending vertical constraints. Part of the correction process applied to BCX0405 is presented within Fig. 9b indicating the original SWIM data with the removal of the excess non-unique vertical constraint at 11,000 feet, followed by the removal of a single non-monotonically descending point at 11,100 feet. As presented in the methodology example Fig. 7c, the constraint is an artifact of using the recorded track and altitude data within SWIM.

VII. Extensibility of the Methodology

The methodology described in this paper is extensible to other research activities that seek to study a future airspace system through simulation. Several entities in government, industry, and academia are currently conducting research in this domain. This research provides a wealth of information and expedite the maturation process towards in-situ testing (e.g., flight test) or an operational evaluation with an industry partner. Several different simulation platforms exist within these entities to conduct such activities, but each simulation platform makes use of operational scenarios to gather data. The methodology described in this report can be used to create operational scenarios for numerous types of research analyses, such as:

- **Algorithm Performance.** Individual aircraft within an operational scenario 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.
- **Benefits Analyses.** Single aircraft, or fleets of aircraft (by aircraft type or by air carrier) within an operational scenario may be equipped with one or more airspace services to conduct medium-high fidelity benefits analyses. These analyses may be conducted to provide interested parties with information regarding the operational improvements that the airspace service may provide.
- **Procedure Development.** By equipping select aircraft in an operational scenario with one or more airspace services in a human-in-the-loop (HITL) simulation, procedures may be evaluated using operationally realistic scenarios. These operational scenarios allow flight crews and/or air traffic controllers to evaluate how the technology is used during realistic operations.
- **Human Factors Analyses.** By equipping select aircraft in an operational scenario with one or more airspace services in a HITL simulation, human factors data collection activities may be conducted. Data gathered from these simulations may include both quantitative metrics (e.g., eye tracking data) and qualitative metrics (e.g., subjective workload, situation awareness, and human-centric design gaps) to determine how humans interact with the airspace services.
- **Integrated Simulation Studies.** By connecting the simulation capabilities used throughout this process with external simulations, realistic integrated air-ground simulation activities with realistic operational scenarios may be conducted. This type of activity presents a unique opportunity to not only evaluate a given technology's performance or the procedures used to operate it, but to do so in a more realistic ATM operational environment, by including simulations or emulations of ground-based ATM technologies.

VIII. Conclusions

Research conducted at NASA has supported the transition from the current air traffic management system to a TBO environment targeting the 2035-2040 timeframe with the development of simulation scenarios representative of the 2040 TBO environment. The paper describes challenges of working with SWIM data and techniques that can be employed to manipulate and/or augment the SWIM data. The techniques presented in this paper can be expanded for any number of vehicle types, aircraft routes, and vertical profiles.

Since SWIM data are not a perfect recording of aircraft positional state data, considerable care must be taken to preserve the intent of the data while incorporating them into an ATM simulation capability. Processes for mapping different types of aircraft present in SWIM data to simulation performance models are described. A method for estimating initial conditions using data from SWIM is presented. A novel approach for converting recorded aircraft track data into a trajectory definition suitable for a kinetic trajectory generator is discussed, and an exemplary use case was shown that justifies this methodology of converting SWIM data into an operational scenario.

Because of the methods documented in this report, ATM researchers can now simulate high-density and realistic flight operations. This methodology may be more broadly applied to other simulations attempting to study concepts, technologies, and procedures in a future airspace system. Data from these research activities may provide a wealth of information and expedite the maturation process towards in-situ testing or an operational evaluation with industry.

IX. References

- [1] B. K. Buck, T. L. Barney, M. C. Underwood and R. C. Chartrand, "Design and Implementation of a Scenario Development Process for a 2040 Trajectory-Based Operations Simulation," NASA/TM-2020-5006526, Hampton, VA, 2020.
- [2] T. L. Barney, K. M. Ballard, B. K. Buck, M. C. Underwood and R. C. Chartrand, "Simulation of a Representative Future Trajectory-Based Operations Environment," NASA/TM-2020-5006885, Hampton, VA, 2020.
- [3] W. N. Chan, B. E. Barmore, J. L. Kibler, P. U. Lee, C. J. O'Connor, K. Palopo, D. P. Thipphavong and S. J. Zelinski, "Overview of NASA's Air Traffic Management-eXploration (ATM-X) Project," in *AIAA Aviation Technology, Integration, and Operations Conference*, Atlanta, GA, 2018.
- [4] Federal Aviation Administration, "Data Communications," 25 06 2019. [Online]. Available: https://www.faa.gov/nextgen/how_nextgen_works/new_technology/data_comm/. [Accessed 08 10 2019].
- [5] Federal Aviation Administration, "Advisory Circular 90-117," Washington, D.C., 2017.
- [6] NextGen Joint Planning and Development Office, "JPDO Trajectory-Based Operations (TBO) Study Team Report," JPDO, Washington, D.C., 2011.
- [7] E. Hoffman, D. Ivanescu, C. Shaw and K. Zeghal, "Analysis of Constant Time Delay Airborne Spacing Between Aircraft of Mixed Types in Varying Wind Conditions," in *5th USA/Europe Air Traffic Management R&D Seminar*, Budapest, Hungary, 2003.
- [8] J. K. Klooster, A. Del Amo and P. Manzi, "Controlled Time-of-Arrival Flight Trials: Results and Analysis," in *8th USA/Europe Air Traffic Management Research and Development Seminar*, Napa, CA, 2009.
- [9] D. H. Williams and S. M. Green, "Airborne Four-Dimensional Flight Management in a Time-Based Air Traffic Control Environment," NASA/TM-4249, Hampton, VA, 1991.
- [10] W. B. Cotton, R. Hilb, S. Kocz and D. J. Wing, "A Vision and Roadmap for Increasing User Autonomy in Flight Operations in the National Airspace," in *16th AIAA Aviation Technology, Integration, and Operations Conference*, Washington, D.C., 2016.
- [11] D. J. Wing, "The TASAR Project: Launching Aviation on an Optimized Route Toward Aircraft Autonomy," NASA/TP-2019-220432, Hampton, VA, 2019.
- [12] M. C. Underwood, W. B. Cotton, C. E. Hubbs, M. J. Vincent, S. KC and D. J. Wing, "Intelligent User-Preferred Reroutes Using Digital Data Communication," NASA/TM-2020-5002126, Hampton, VA, 2020.
- [13] M. C. Underwood, W. B. Cotton, C. E. Hubbs, M. J. Vincent, S. KC and D. A. Karr, "Incorporation of Time of Arrival Constraints in a Trajectory Optimization Technology," NASA/TM-2020-5005117, Hampton, VA, 2020.
- [14] W. B. Cotton, M. C. Underwood and C. E. Hubbs, "Strategic Airborne Trajectory Management," NASA/TM-2020-5007619, Hampton, VA, 2020.
- [15] Federal Aviation Administration, "FAA's NextGen Implementation Plan," US Department of Transportation, Washington, D.C., 2016.
- [16] Federal Aviation Administration, "Time-Based Flow Management System Specification Document," U.S. Department Of Transportation, Washington, D.C., 2016.
- [17] Federal Aviation Administration, "CDM Net," [Online]. Available: https://cdm.fly.faa.gov/?page_id=55. [Accessed 20 August 2020].
- [18] Federal Aviation Administration, "SWIM Questions & Answers: What is SWIM?," Federal Aviation Administration, 8 February 2018. [Online]. Available: https://www.faa.gov/air_traffic/technology/swim/questions_answers/. [Accessed June 2020].
- [19] Federal Aviation Administration, "System Wide Information Management (SWIM)," 01 10 2019. [Online]. Available: https://www.faa.gov/air_traffic/technology/swim/. [Accessed 11 10 2019].
- [20] Federal Aviation Administration, "Aircraft Type Designators, Effective Date 09/17/2019," FAA Order JO 7360.1E, Washington, D.C., 2019.
- [21] W. Gracey, "Measurement of Aircraft Speed and Altitude," NASA/RP-1046, Hampton, VA, 1980.
- [22] Wikimedia Foundation, "Ramer-Douglas-Peucker Algorithm," Wikipedia, 28 April 2020. [Online]. Available: https://en.wikipedia.org/wiki/Ramer-Douglas-Peucker_algorithm. [Accessed 1 July 2020].
- [23] D. H. Douglas and T. K. Peucker, "Algorithms for the Reduction of the Number of Points Required to Represent a Digitized Line or its Caricature," *Cartographica: The International Journal for Geographic Information and Geovisualization*, vol. 10, pp. 112-122, 1973.