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Modeling of Complex and Diverse Aircraft Trajectories with the Trajectory Synthesizer Generalized Profile Interface

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A flexible method to describe and generate aircraft trajectories called GenProf was developed for the Center TRACON Automation System (CTAS) software research platform. Generally CTAS is used to prototype new air traffic management decision support tools and concepts. Beyond this purpose, the GenProf methodology has enabled a variety of research and validation tasks to be performed. This paper briefly describes the methodology and details these applications.

Introduction

The ability to generate accurate and aircraft trajectories is essential to Air Traffic Management (ATM). Trajectory-Based Operations (TBO) was identified as a key capability in achieving the goals of the Next Generation Air Transportation System (NextGen) in the United States[1]. Similarly in Europe, the Single European Sky Air Traffic Management Research (SESAR) embraces the concept of a 4-D trajectory as the core of the future ATM system[2]. ATM requires trajectories for tasks such as conflict detection (detecting a potential collision with another aircraft), conflict resolution (redirecting the aircraft to avoid the collision), scheduling, and re-routing (due to weather, traffic, airport conditions, etc.). Decision Support Tools (DSTs) performing these tasks can only be as accurate as the trajectory predictions that they use.

Progress of ATM in recent years present new challenges for a trajectory generation tool, or a trajectory generator. Firstly, advances in avionics, navigation, and guidance technologies allow aircraft to fly more precise routes and vertical profiles. New types of trajectory constraints required and pilot procedures developed for flying such trajectories can be complex and diverse. Secondly, trajectory communication/sharing between the ground, flight deck, and other components in the system, requires flexible yet interoperable trajectory input. In many situations, ATM research benefits from a common interface of the trajectory generator that allows detailed specification of the flight's intent. Thirdly, the Unmanned Aircraft Systems (UAS) are expected to be integrated with the National Airspace (NAS) in the United States in the near future. The great diversity in the flight envelopes and mission profiles of these UAS can be difficult to accommodate by previous trajectory generators that were designed mainly for modeling commercial aircraft's flights. As the mission profiles become more complex, the advisory and prediction trajectories generated for TBO such as scheduling and conflict avoidance will likely also become more complex. (These future trajectories will need the ability to characterize the aircraft's flight with more flexibility and fidelity than before.)

Recent advances to the Center TRACON Automation System (CTAS)[3] Trajectory Synthesizer (TS) software[4] have allowed flexible and detailed modelling of many of these complex and diverse trajectories. The CTAS TS was designed originally to provide trajectory predictions for the Traffic Management Advisor (TMA). Initially the TS (known as TS Classic) could only handle six distinct types of en-route climb and descent vertical profiles. This limitation prevented the CTAS TS from handling additional trajectory constraints and diverse pilot procedures and limited its usability for various ATM research areas. The Generalized Trajectory Profile (GenProf) framework[5] was developed to directly address this short-coming with the capability to describe trajectory constraints and pilot procedures in variable order. The GenProf framework allows finer levels of granularity in the trajectory request specification and potentially achieves more fidelity than previous capabilities allowed. A more detailed description of the GenProf framework will follow later in this paper.

The GenProf interface has been successfully applied to the modeling of predicted descent trajectories and generating advisories for arrival flight guidance[6,7], small jets' descent pilot procedure[8], maneuver execution delay[9], and fuel burn analysis[10].

The goal of this paper is to demonstrate the application of the new capabilities enabled by TS and the the GenProf framework to various ATM research problems. This paper will first discuss the background of the TS and GenProf framework. The paper will then demonstrate its application with the following examples.

- Fundamental modeling of trajectory constraints and pilot procedures
- Estimation of fuel burn from arrival flights with controller interruptions
- Validation of performance model for UAS

These examples are just a sample of the research applications of the GenProf framework. Other research applications are conceivable as well.

Background

Aircraft trajectory generation is based on information from aircraft performance data, site specific airspace information (e.g., waypoints), weather information, and initial aircraft state conditions and constraints (e.g. altitude and speed restrictions). Each of these segments can have changes in aircraft states such as speed, altitude, and direction. Furthermore, there are a number of ways to transition from these aircraft states to another desired state. An altitude change, for instance, may be performed in a number of ways. Does the pilot hold the airspeed constant throughout the descent? Does the pilot descend using minimum power settings (idle thrust)? Or does the pilot hold a constant descent rate? Also, aircraft trajectory generation is influenced by many different factors including what and how trajectory elements are modelled, data availability, as well as hardware. In terms of the aircraft performance envelopes that the trajectories are based on, the aircraft used in the current National Airspace System can vary greatly, from the passenger jets used by airlines to the propeller driven planes used by the private pilots.

The Trajectory Synthesizer (TS) can generate aircraft trajectories given inputs consisting of the aircraft type, weight, initial state information, list of waypoints, constraints (such as speed or altitude), and weather information. The TS models the horizontal path and vertical profile of an aircraft in a somewhat decoupled way. It will first calculate the trajectory horizontal path, modeled by a sequence of straight lines and arcs, using a list of waypoints. The client can define how each waypoint is to be captured by the turn type. These turn types can range from turning at the waypoint, turning inside the waypoint, or ending the turn at the waypoint. Rough estimates of the airspeed at each turn, as well as default bank angles are used to compute the turn radius around each waypoint. Alternatively, the turn radii can be specified for each waypoint by the client.

Once the horizontal path is determined, the TS will then compute the vertical profile using either a kinetic or kinematic set of equations (as per request) to calculate the aircraft trajectory states within the given constraints. The kinetic equations are suitable for modeling pilot procedures that involve specific throttle settings and aircraft configurations. Fuel burn can usually be computed from the kinetic equations, too. The kinematic equations are suitable when the desired speed profile is known but the specific pilot procedure and the aircraft configuration are unknown.

GenProf interface

The GenProf Interface is the abbreviated name for the Generalized Profile Interface module. This module was designed to provide a flexible language to describe vertical trajectory profiles and was intended to replace and expand the older static set of predetermined trajectory profile shapes that were part of the TS.

The GenProf description language uses a building block approach to provide flexibility. A given trajectory can be described by stringing together different trajectory segments. Each segment contains a target constraint (altitude, speed, time, or path distance) along with the pilot control setting (ex. fixed speed, engine control, speed brake, vertical rate, flight path angle) to achieve the constraint.

The pilot control settings are modeled holding two parameters fixed and used typically in the following flight regimes:

- Fixed speed (CAS or mach) and fixed engine control - climb, cruise, and descent
- Fixed speed and fixed Flight Path Angle (FPA) - descent of small jets
- Fixed speed and fixed vertical rate - descent of some smaller jets
- Fixed FPA and fixed engine control - deceleration in descent

In GenProf terminology, a given aircraft state with a specified speed, altitude, path distance, and time is called an “Anchor”. The target capture state is called a “Stop”.
And the pilot control settings used to achieve the “Stop” is called a “Profile”. Typically, an “Anchor” is used to define the initial state of the aircraft trajectory which, for a trajectory prediction, would be the initial track state of the aircraft. Below is an example of a GenProf trajectory description. Note how multiple Profiles and Stops can be chained together to describe a trajectory.

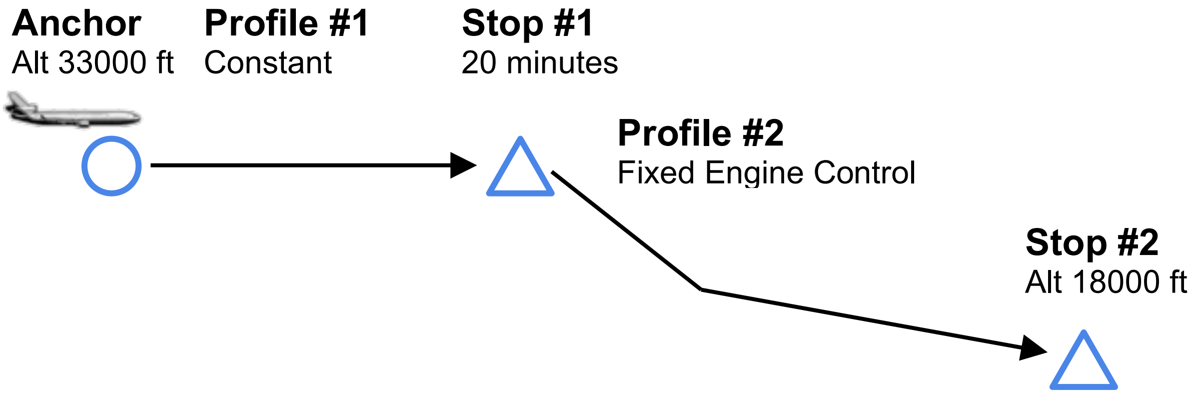

Figure 1. GenProf Notional Example

To solve the described trajectory, the TS will integrate each segment starting from an Anchor to the target constraint (Stop). When the target constraint is met, the remaining aircraft state values (speed, altitude, path distance, and/or time) are determined for the trajectory point. The resultant point becomes the next Anchor from which the integration will start from to obtain the next target constraint. The process repeats until all the segments are solved for. The TS can be specified to solve the segments using either kinetic or kinematic sets of equations.

An “Anchor” can also be used to define a desired end state for a trajectory. The TS processing in this case would involve both a forward integration starting from the initial Anchor state and a reverse integration starting from the end Anchor state. Anchors can be used to define points in the middle of a trajectory.

The GenProf Interface can model trajectories of Flight Management Systems (FMS)’s allowing GenProf to be readily utilized for research in the area of aircraft intent synchronization. The language used by the GenProf interface has similarities to the Aircraft Intent Description Language (AIDL)[11] but is simpler and not as rich in detail.

Applications Utilizing TS

From a software architectural perspective, the TS and GenProf modules are libraries used by various processes. The primary application is CTAS where a TS instance is used in two CTAS processes. A number of different support tools for software testing and additional research also use the TS. One of these tools, the CmSimTrackComparer will be described in the following section. The following diagram shows the relationship between the tools and software modules.

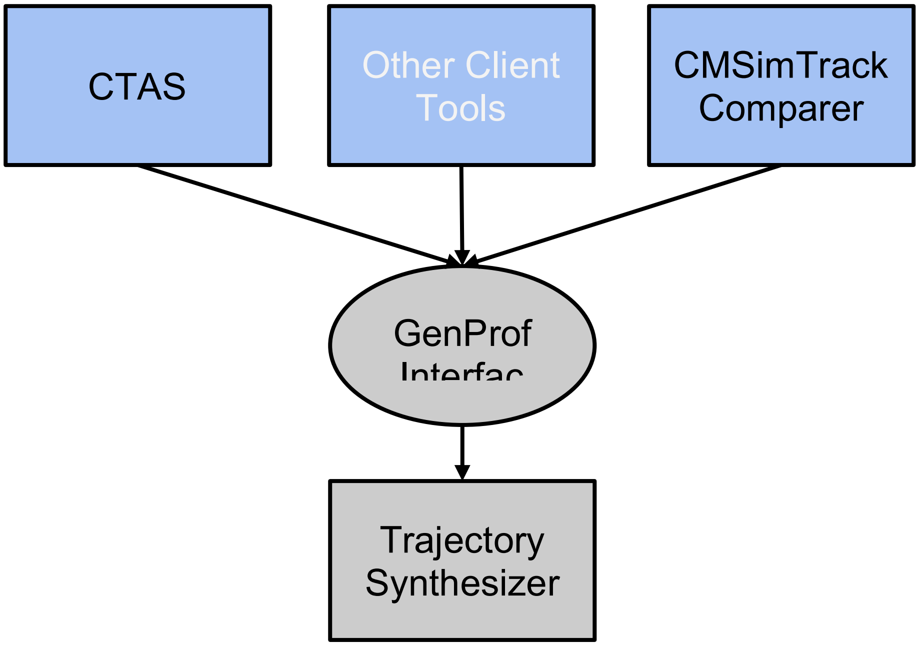

Figure 2: Relationship Diagram of TS Modules and Application Tools

CmSimTrackComparer tool

The CmSimTrackComparer tool receives part of its name after the (internally used) file format that is used as input to the tool, the CMSim file. The CMSim file contains radar track data of the aircraft flights. The CmSimTrackComparer tool was originally developed for the specific task of comparing CTAS trajectory predictions against track data for idle-thrust descents with controlled cruise and descent speeds that were recorded for Denver arrivals in 2009, studied in[12, 13]. The tool was later extended for comparisons between any CTAS trajectory predictions and corresponding track data and is used to provide a set of quality metrics.

CmSimTrackComparer operation includes the following steps:

1. Reads radar track data from a CMSim file
2. From Step 1, automatically generates requests to CTAS TS using the GenProf interface
3. Invokes TS for each request
4. Compares generated predictions against tracks and calculates a number of statistical metrics
5. Stores detailed results in an SQLite database
6. Outputs metrics as an HTML Summary file

Research Applications

The GenProf interface enables the modeling of a variety of constraints used in Air Traffic Control (ATC) procedures. The next sections describe application of the TS and the GenProf Interface to various modeling tasks. They are presented in order starting with the least complex, progressing to more complex usage of the GenProf Interface.

Modeling of Air Traffic Control Constraints and Procedures

Altitude Constraint in the Center Airspace

Many of the Standard Terminal Arrival Routes (STAR) contain altitude and speed restrictions on some of the waypoints along the route. TS Original models an arrival flight by an en-route trajectory and a terminal-area trajectory that are connected at a waypoint at boundary to the terminal area. TS models the en-route trajectory is modeled in a kinetic way. However, TS Original can only model very simple vertical profiles such as cruise-descent or descent-cruise-descent.

Figure 2 shows the radar track of an Boeing 767 flight arriving to the JFK airport following an arrival route called the KINGSTON STAR. This arrival route has an altitude constraint of Flight Level (FL) 200 at the waypoint LOLLY. After LOLLY, there are altitude and speed constraints of FL190 and 250 knots CAS, respectively, at LENDY. Prior to its top-of-descent, the aircraft received a altitude clearance of FL280 from ATC. When used in real-time simulations, CTAS constructs the predicted arrival trajectory for this flight from its current track position to the boundary of the terminal area, which is the waypoint LENDY in this case.

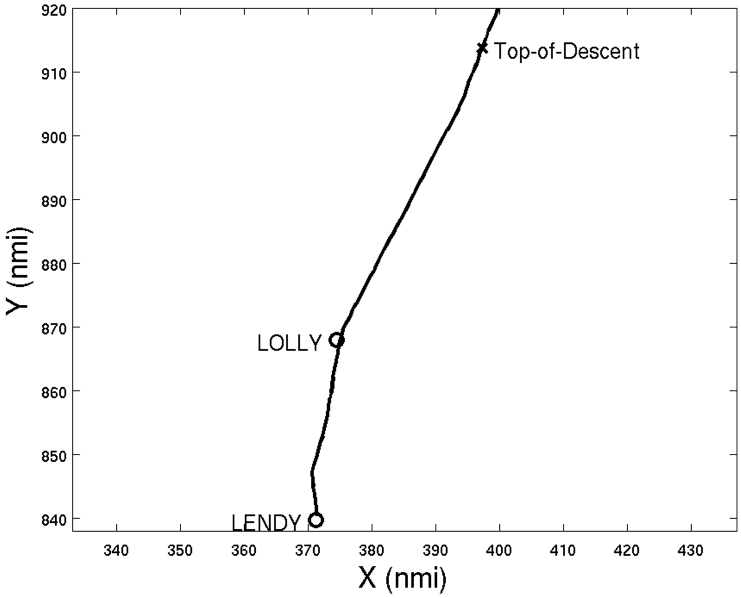

Figure 2. Radar track of an arrival flight to JFK that followed the KINGSTON STAR that has an altitude restriction at LOLLY.

Figure 3 compares the predicted trajectories for this flight, starting from a point right before its top-of-descent to LENDY. Idle thrust was assumed for the predicted descent. Wind forecasts from the Rapid Update Cycle by National Oceanic and Atmospheric Administration (NOAA) were used for computation of the predicted trajectories. Although TS Original can handle the temporary altitude of FL280, it cannot handle additional altitude restrictions at LOLLY. TS GenProf, on the other hand, allows the specification of multiple altitude constraints and therefore was able to create a trajectory that satisfied the altitude constraint at LOLLY. This improvements reduced the altitude error at LOLLY by 8,000 ft. Note that the aircraft did not stay at FL280 because it received another clearance during its descent to change its target altitude to FL200.

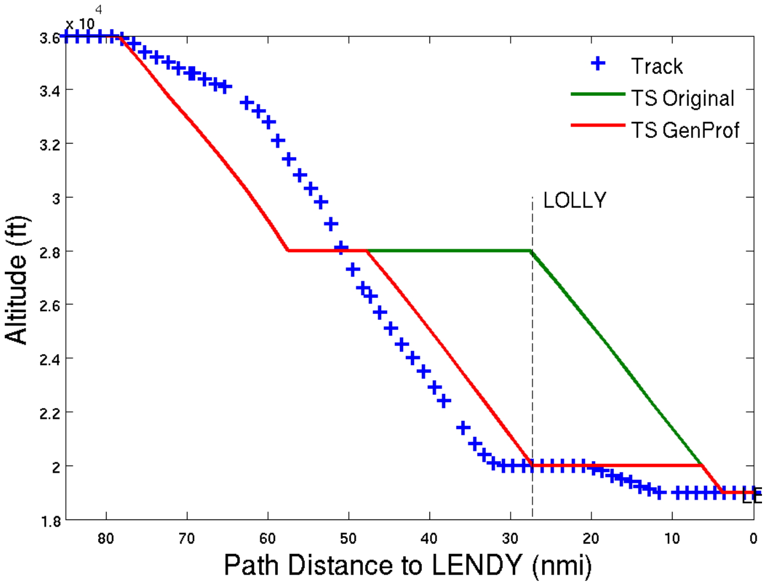

Figure 3. The TS GenProf handling an altitude restriction at LOLLY.

Altitude and Speed Constraints

An "Anchor" can also be used to define a state in the middle of the trajectory. This capability may be used to model a procedural restriction having multiple dimensions (ex. speed, altitude, path distance). Another possible purpose could be for a retrospective analysis (ex. fuel burn estimation) where Anchors in the middle of the trajectory would represent known aircraft states and used to improve accuracy. In the diagram below is an example descent case highlighting the use of a middle Anchor at a Path Distance of -26 nmi, Altitude of 25K feet, and 275 knots CAS. This series of "strip charts" (from top to bottom), show Altitude, Mach, CAS, and a zoom-in of CAS with the Middle Anchor circled in red.

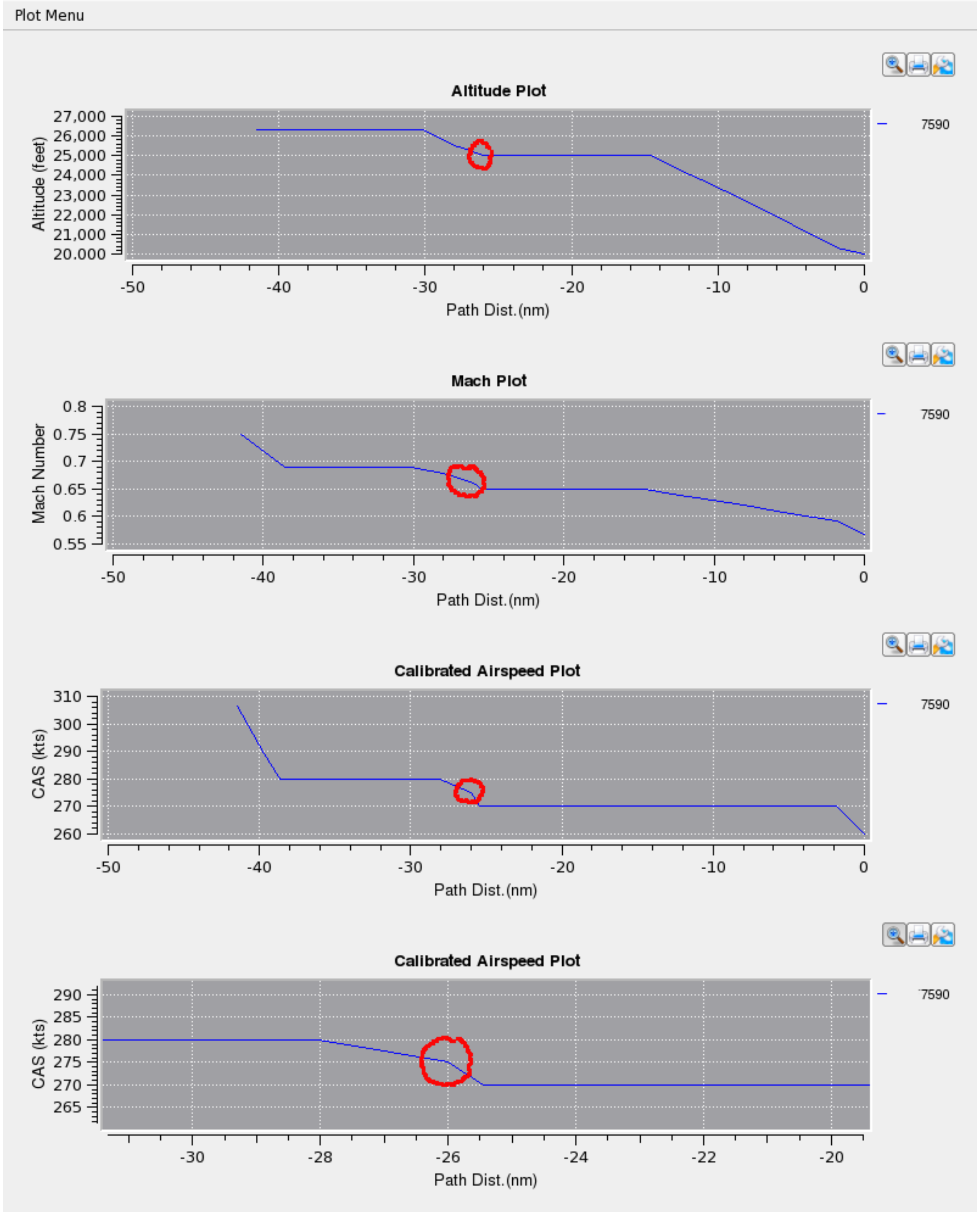

Figure 4: The example case shows one Middle Anchor but additional ones can also be specified.

Fixed-FPA Descent with Deceleration

This section demonstrates how TS GenProf was applied to the modeling of pilot procedures in a flight trial conducted at Denver in 2010. The objective of the flight trial was to evaluate the execution of the Three Dimensional Path Arrival Management clearances by regional jets in the transition airspace[14]. Descent planning for these regional jets typically utilizes the FMS Geometric Flight Path Angle capabilities. For each arrival flight, prescribed speed clearances were issued, and pilots used a predefined speed-FPA table to determine the FPA to fly by. On-board data and radar track data collected for the vertical descent profile were compared against predicted trajectories to quantify sources of error[15].

For each participating arrival flight, controllers issued a speed clearance, asking the aircraft to maintain its cruise Mach number and transition to an issued descent CAS during descent. The clearance also instructed the aircraft to descend to a waypoint with altitude and speed constraints. In one flight, the aircraft was asked to descend at 300 knots in CAS and cross the waypoint, RAMMS, with a flight level (FL) of 190 and a speed of 250 knots CAS. The FPA for the descent was 2.5° for the descent speed of 300 knots CAS. The vertical profile of this flight was modeled by TS GenProf as consisting of the following four distinct segments:

1. A constant Mach level segment
2. A constant Mach, constant FPA descent segment
3. A constant CAS, constant FPA descent segment
4. An idle thrust, constant FPA descent segment for deceleration

The trajectory must satisfy the altitude and speed constraints at the waypoint RAMMS. Figure 5 shows comparison of the predicted trajectory to the actual trajectory recorded by the on-board Quick Access Recorder (QAR). The X-axis for all three plots represents the path distance of the aircraft from the waypoint RAMMS. The top plot in the figure indicates excellent agreement between the predicted and actual trajectories in the location of top-of-descent and the descent profile above FL250. For the descent below FL250, the actual trajectory descended with a slightly steeper FPA and captured 19,000 ft at about two nmi before RAMMS. The middle plot shows comparison of CAS values. The four vertical segments of the predicted speed profile described above capture the essence of the actual speed profile. The kinetic trajectory generated by TS included fuel burn, which is shown in the bottom plot and is compared to the actual fuel burn recorded by QAR. The results show that the predicted trajectory overestimates the overall fuel burn by about 20% to 30%.

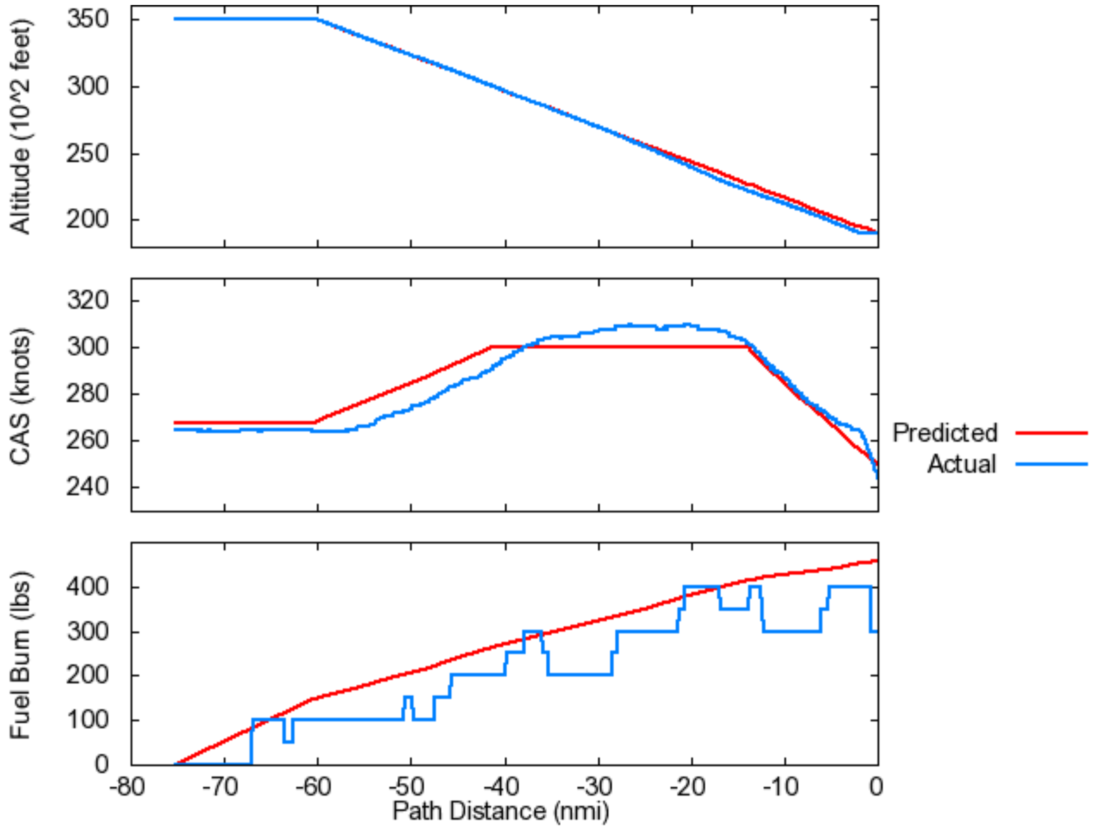

Figure 5. Comparison of predicted and actual trajectories for a flight in the 3D PAM flight test in 2010.

Analysis of Simulated Track Data

This section demonstrates the use of TS GenProf to identify speed profiles and estimate fuel burn of simulated track data. The same methodology can be applied to analyze radar track data as well.

A Human-In-The-Loop (HITL) simulation was conducted in January of 2013 in the Airspace Operations Laboratory (AOL) at NASA's Ames Research Center (ARC). The goal of the simulation was to evaluate the impact of the trajectory predictor's accuracy on controllers' acceptance of the decision support tools. This study focused on time-based metering operations for arrival flights, and controllers were required to deliver arrival traffic in accordance with scheduled times over the meter-fix[16]. The Multi-Aircraft Control System (MACS)[17] was used for both controllers' automation system and the simulated aircraft. One of the goals of the data analysis for this simulation was to correlate the fuel efficiency of flights with wind uncertainties. Since two sets of controllers were staffed to run the same simulation, fuel efficiency of controllers' guidance strategies were also investigated and compared. It was desirable to identify speed changes in the actual trajectory as a result of controllers' speed clearances. Since each arrival flight received multiple maneuvers involving both speed changes and altitude changes, the actual trajectory could have complex speed and altitude profiles.

A methodology was developed to simultaneously estimate fuel burn and identify distinct speed changes from the simulated track data. The idea of this methodology was to synthesize a trajectory by fitting the vertical profile of the actual trajectory with a series of vertical segments with specific pilot procedures. The fitting was refined until the difference between the synthesized trajectory and the actual trajectory is within specific tolerances. A similar approach to the estimation of fuel burn was proposed before[10].

This methodology was implemented on a modified version of the CmSimTrackComparer. CmSimTrackComparer identified turns and straight segments of the actual trajectory for modeling of the horizontal path. To model the complex vertical profile, the methodology identified a series of change points along the actual trajectory by examining both altitude and speeds. These change points were used to define procedurally distinct segments of the actual trajectory. Each segment was modeled by one of the following procedures:

- Constant speed level segment
- Level segment with constant engine control parameter, which can be maximum cruise for acceleration or idle thrust for deceleration
- Constant Mach, constant FPA, non-level segment
- Constant CAS, constant FPA, non-level segment
- Constant FPA, non-level segment with constant engine control parameter, which can be maximum cruise for acceleration or idle for deceleration

These segments, combined with the horizontal path, defined a synthesized trajectory from which fuel burn can be calculated.

Figure 6 shows for one arrival flight the results of the estimated fuel burn as well as the speed profile derived from the simulated track data. This flight was a CRJ7 type, which transitioned from cruise phase at 207 nmi away from the meter fix to descend and cross the meter fix at an altitude of 12,000 ft and a CAS of 250 knots. The path distance in the X-axis refers to the distance from the meter fix. The top two plots show a very good agreement for altitude and ground speed between the synthesized and actual trajectories. In order to meet the time at the meter fix, controllers' multiple clearances guided the flight to reduce its CAS speed from 300 knots to 260 knots, back up in stages to 280 knots, and finally down to 250 knots when crossing the meter fix. Visual inspection of the synthesized trajectory's Mach and CAS plots (3rd and 4th ones) in Figure 6 shows at least 10 distinct segments. Combining the altitude changes with speed changes, and due to the small tolerances set in the methodology for speed changes, more than thirty segments were identified for this flight. The progressive fuel burn was estimated by the synthesized trajectory and shown on the 5th plot of Figure 6.

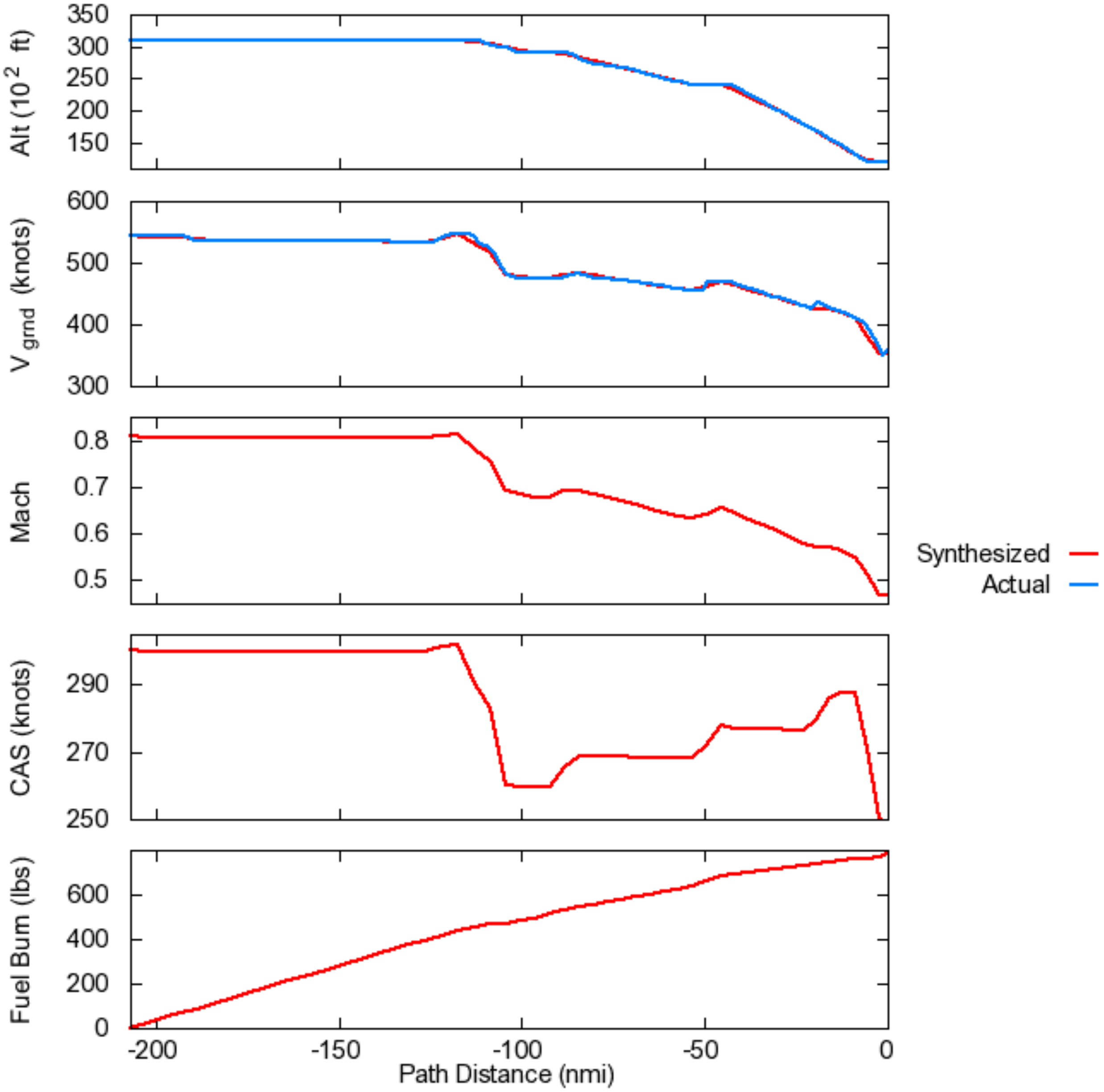

Figure 6. Comparison of the synthesized and actual trajectories, the speed profiles, and the fuel burn of a flight.

Validation of UAS Performance Model

The U.S. Congress mandated the “safe integration” of UAS in the NAS beginning in September 2015. To support this goal, the Radio Technical Commission for Aeronautics (RTCA) is developing the technological requirements and minimum operational performance standards (MOPS) for a UAS Sense-and-Avoid (SAA) System. The ongoing research at NASA ARC plays a critical role in development and validation of the MOPS by conducting closed-loop and HITL simulations for various UAS missions and scenarios. These simulations required developing aircraft performance models (APMs) for UAS. ARC and ARC research partners created the

APMs for several UAS types presented in the form of the Base of Aircraft DAta (BADA) Operation Performance Files (OPF)[18]. These files provide the most important geometrical, aerodynamic, and physical aircraft parameters that can be used to calculate aircraft trajectories for nominal speeds and operational procedures. However, these “nominal” APMs may be difficult to use because of large variety of UAS missions and operational procedures. This situation becomes even more extreme in context of SAA system simulations. To avoid a collision with another aircraft, a UAS would likely not use its nominal, but rather the fastest possible rate of turn, climb, or descent. Hence, validation of APMs for both nominal and off-nominal conditions is more important for UAS than it would be for commercial aircraft. However this is also more challenging. Validation of the BADA APMs for commercial aircraft was previously done in[13] by comparisons between predicted trajectories and actual track data for thousands flights recorded in CMSim files. However, the availability of track data for UAS is more limited. This section demonstrates how TS GenProf can be used to validate the APM for a typical high altitude - long endurance UAS by comparison with track data for a single test flight. The flight had a very complex horizontal path with multiple turns, including a series of loops, and a vertical profile with many climbs and descents in rapid succession at different altitude levels. The CmSimTrackComparer tool was used to derive horizontal and vertical intent from track data. The tool automatically extracts a path, approximated by a sequence of turn-inside waypoints, from horizontal trajectory. As shown in Figure 7, the extracted (predicted) path is very close to actual (track) trajectory.

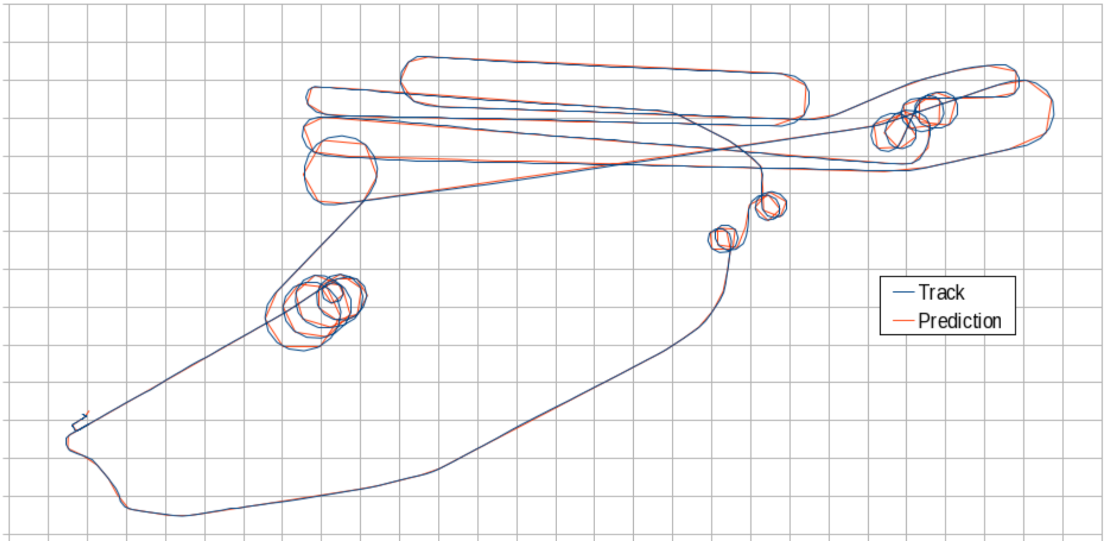

Figure 7. Horizontal trajectory

A detailed altitude and speed profile along this path was generated from track data by running CmSimTrackComparer with -genAltFlex and -trackSpeed options. This allowed TS to generate predictions that closely followed the actual track. Hence, the effect of intent errors on results of comparisons between TS predictions and track data was minimized, because the errors in these comparisons could be caused only by the differences between predicted and observed rates of turn, climb, and descent.

The vertical profile was constructed as follows:

- A series of procedurally distinct segments were extracted by examining track altitudes as described in Analysis of Simulated Track Data section.
- For each climb or descent segment, a GenProf segment with altitude capture was added. Otherwise a GenProf segment with path-distance capture was added. Therefore, path distances for the ending points of all major cruise segments were aligned with actual track.
- If a descent immediately followed after a climb or the climb immediately followed after descent, a short cruise segment with 30 second delta time capture was inserted to model a transition between climb and descent in CTAS TS.
- Maximum thrust was used for all climb segments, and idle thrust was assumed for all descent segments.
- Profile CAS and Mach were determined from track ground speeds at start and end points of each segment using the weather forecast data for approximate time when the test flight was performed.

Figure 8 shows a predicted altitude compared with track as a function of time.

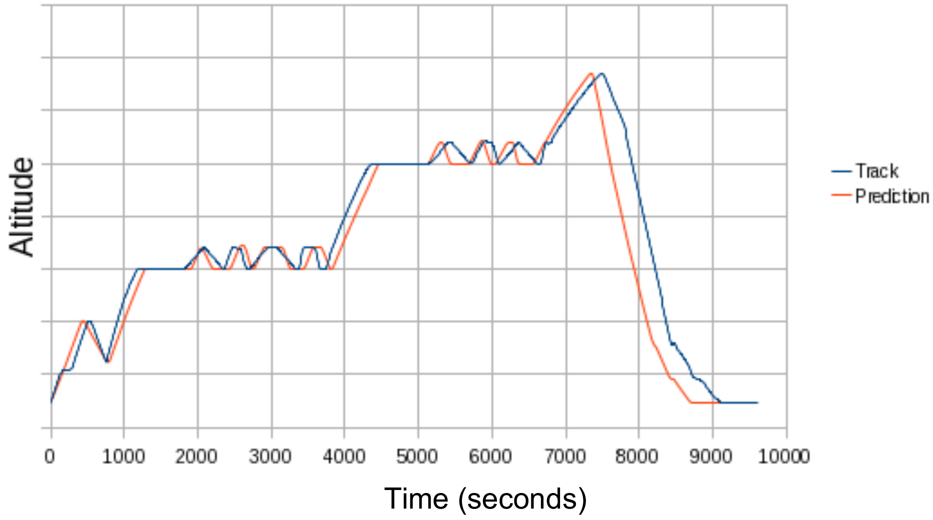

Figure 8. Altitude as a function of time

It can be seen that predicted rates of climb and descent are fairly close to track data for most typical climbs and descents. However, it can be noticed that in the portion of flight around 3500 seconds the actual aircraft used a faster climb and descent, and in this case TS substantially underpredicted the rates of climb and descent. Several other times the actual aircraft used a slower climb and descent resulting in large altitude prediction errors. It can be noted that a relatively small error in predicted rates of climb and descent for final climb and long descent segments translated to altitude prediction error larger than the altitude itself.

A predicted ground speed profile is similar overall to track as shown in Figure 9. This is to be expected since CmSimTrackComparer with -trackSpeed option uses profile speeds extracted from track data. The biggest discrepancy can be observed in the final descent segment due to a time shift caused by the overestimated rate of climb before the last descent (see Figure 8). Also, it can be noticed that TS predicts sharper peaks in ground speed. This is probably due to the fact that TS tends to overestimate acceleration and deceleration.

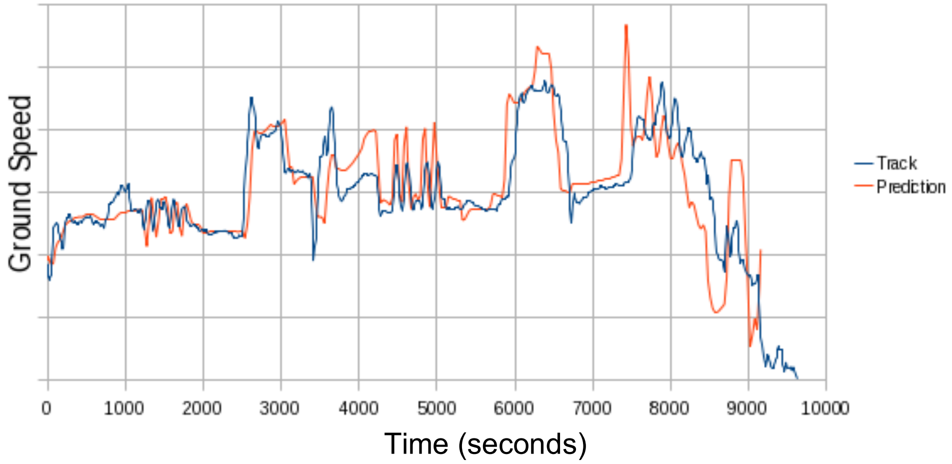

Figure 9. Ground speed as a function of time

Conclusion

The TS GenProf has provided a flexible approach to generate trajectories characterized with various ATC constraints and pilot procedures. It allows horizontal and vertical profiles to be modelled with varying degrees of detail. This has enabled various types of research and analysis to be performed. TS GenProf can handle the analysis highlighted in this paper; modeling of constraints/procedures, fuel burn analysis, UAS performance model validation, and other types of analysis as well.

The future ATM environment will consist of new advisories, procedures, aircraft types, and missions. With its flexibility, TS GenProf should be able to adapt to the ever-changing research requirements of ATM.

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