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Abstract

The Center-Terminal Radar Approach Control (TRACON) Automation System (CTAS), developed at NASA Ames Research Center for assisting controllers in the management and control of air traffic in the extended terminal area, supports the modeling of more than four hundred aircraft types. However, 90% of them are supported indirectly by mapping them to one of a relatively few aircraft types for which CTAS has detailed drag and engine thrust models. On the other hand, the Base of Aircraft Data (BADA), developed and maintained by Eurocontrol, supports more than 300 aircraft types, about one third of which are directly supported, i.e. they have validated performance data. All these data were made available for CTAS by integrating BADA version 3.8 into CTAS Trajectory Synthesizer (TS). Several validation tools were developed and used to validate the integrated code and to evaluate the accuracy of trajectory predictions generated using CTAS "native" and BADA Aircraft Performance Models (APM) comparing them with radar track data. Results of these comparisons indicate that the two models have different strengths and weaknesses. The BADA APM can improve the accuracy of CTAS predictions at least for some aircraft types, especially small aircraft, and for some flight phases, especially climb.

LIST OF ACRONYMS

A306	Airbus A300B4-600
APM	Aircraft Performance Model
ARTCC	Air Route Traffic Control Center
ATR72	Alenia ATR-72
B190	Beechcraft 1900
B733	Boeing 737-300
B737	Boeing 737-700
B738	Boeing 737-800
B752	Boeing 757-200
BADA	Base of Aircraft DAta
BADA TS	CTAS TS using any elements of BADA APM
BE20	Beechcraft Super King Air 200
BE36	Beechcraft Bonanza Model 36
BE40	Beechjet 400/T-1 Jayhawk
BE9L	Beechcraft King Air 90
C182	Cessna 182 Skylane
C560	Cessna Citation V
C56X	Cessna Citation Excel/560XL
C750	Cessna Citation X
CAS	Calibrated Air Speed
CRJ2	Canadair Regional Jet CRJ-200
CRJ7	Canadair Regional Jet CRJ-700
CRJ9	Canadair Regional Jet CRJ-900
CTAS	Center-TRACON Automation System
CTAS/BADA TS	CTAS TS with support for BADA APM
CTAS TS	CTAS Trajectory Synthesizer with CTAS APM

E120	Embraer EMB 120 Brasilia
E135	Embraer ERJ-135
E145	Embraer ERJ-145
E170	Embraer E-170
ETA	Estimated Time of Arrival
H25B	Raytheon BAe-125-700/800
HCS	Host Computer System
IBST	Interval-Based Sampling Technique
LJ35	Learjet 35
MD82	McDonnell Douglas MD-82
MD83	McDonnell Douglas MD-83
PC12	Pilatus PC-12 Spectre
PTD	Performance Table Data
ROCD	Rate of Climb or Descent
RUC	Rapid Update Cycle
SA	Separation Assurance
SR22	Cirrus SR-22
TAS	True Air Speed
TOC	Top of Climb
TOD	Top of Descent
TRACON	Terminal Radar Approach Control
TS	Trajectory Synthesizer
ZDV	Denver Air Route Traffic Control Center (ARTCC)
ZFW	Fort Worth ARTCC
ZLA	Los Angeles ARTCC

1 Introduction

The Center-Terminal Radar Approach Control (TRACON) Automation System (CTAS) is a set of tools developed to help air traffic controllers manage complex air traffic flows to reduce delays and increase safety [1]. These tools, known also as CTAS client applications, rely on the Trajectory Synthesizer (TS) [3, 4] as the core computational engine for generating accurate predictions of 4D-trajectories using the detailed aircraft performance characteristics, weather data, and data from the Host Computer System (HCS). TS outputs predicted aircraft position, altitude, and performance parameters, such as drag, thrust, weight, Rate of Climb or Descent (ROCD), and fuel consumption, as a function of time.

CTAS currently supports more than four hundred aircraft types, but about 90% of them are supported indirectly by mapping to aircraft types with known drag and engine thrust models. Obtaining the detailed performance data for more aircraft types from manufacturers and validating them may be problematic and time-consuming. Besides that, previous research validating the accuracy of CTAS TS (see [5] and [6]) was limited to certain centers and aircraft types, and the overall accuracy of CTAS predictions remained largely unknown.

On the other hand, the Base of Aircraft DATA (BADA) supports more than 300 aircraft types, including about a hundred aircraft types with extensively validated performance data. BADA is an

Aircraft Performance Model (APM) developed and maintained by Eurocontrol and available free of charge. This model is documented in the BADA User Manual [7]. The complementary "Base of Aircraft DATA (BADA) Aircraft Performance Modelling Report" [8] provides further definition of BADA parameters.

Note that BADA documentation [7] does not always make a clear distinction between the physical and operational components. For instance, BADA thrust model blends together the physical parameters, such as maximum engine thrust, and operational considerations like the flight configuration or using reduced climb power. Note also that BADA does not include any official software implementation, but it provides the data that can be used to verify correctness of any software that implements the BADA APM.

The main potential advantage of using BADA is that it directly supports more aircraft types in comparison with CTAS and may provide more accurate aircraft parameters for some aircraft types currently supported by CTAS. Besides that, some elements of the BADA operational model, such as default speeds and the use of reduced climb power, may be based on more realistic assumptions. Another important benefit of using BADA is that it is maintained by Eurocontrol and it is expected to be regularly updated and improved over time.

To take full advantage of these benefits, BADA APM was integrated in CTAS TS to augment the "native" CTAS APM for aircraft types not supported by CTAS or having the better models in BADA. A set of validation tools was developed and used to judge the accuracy of BADA APM and CTAS APM by comparing trajectory predictions built using both performance models to radar track and other reference data.

Software design for BADA-CTAS Integration is presented in Section 2 of this TM. Section 3 describes the tools developed to validate the correctness of software implementation and the accuracy of BADA APM in comparison with CTAS APM. Section 4 briefly describes the results of software validation. Section 5 describes the results of evaluation of CTAS TS with "native" CTAS and integrated BADA model for various aircraft types and operational parameters. The TM is concluded with Section 6, summarizing the main findings. The Appendix includes examples of BADA Operation Performance Files (OPF) and Performance Table Data (PTD) files.

2 BADA-CTAS Integration

CTAS TS with support for BADA will be referenced in this TM as "CTAS/BADA TS". The term "CTAS TS" will refer to CTAS/BADA TS using only "native" CTAS APM, which is functionally equivalent to the "original" CTAS TS without support for BADA APM.

CTAS TS is a faster-than-real-time trajectory predictor that can be called for every radar track hit, or every 12 seconds, for each of thousands flights managed by CTAS tools. So, the main design requirement was to minimize performance penalty introduced by adding support for both CTAS and BADA models. Also, it was desirable to minimize CTAS TS code changes, to separate clearly the BADA-specific code from the rest of CTAS TS, and to make new code consistent with existing CTAS TS infrastructure.

These requirements motivated the design of container class APMDef, encapsulating CTAS and

BADA APMs in abstract model definition interfaces, such as ADragDef, AThrustDef, etc., as shown in Figure 1. Here “[CTAS TS]” denotes any classes of “original” CTAS TS reused in CTAS/BADA TS code. In particular, VSFixed is the base CTAS TS class for all vertical solution classes, and DragModel and ThrustModel are the existing CTAS TS classes modeling drag and engine thrust. Each model definition interface member variable in APMDef class, such as mDragDef and mThrustDef, is instantiated only once to CTAS or BADA implementation in constructors of corresponding Model Definition subclasses for each aircraft type based on BADA configuration files. Hence, extending CTAS TS for BADA APM does not introduce any performance penalty in run time.

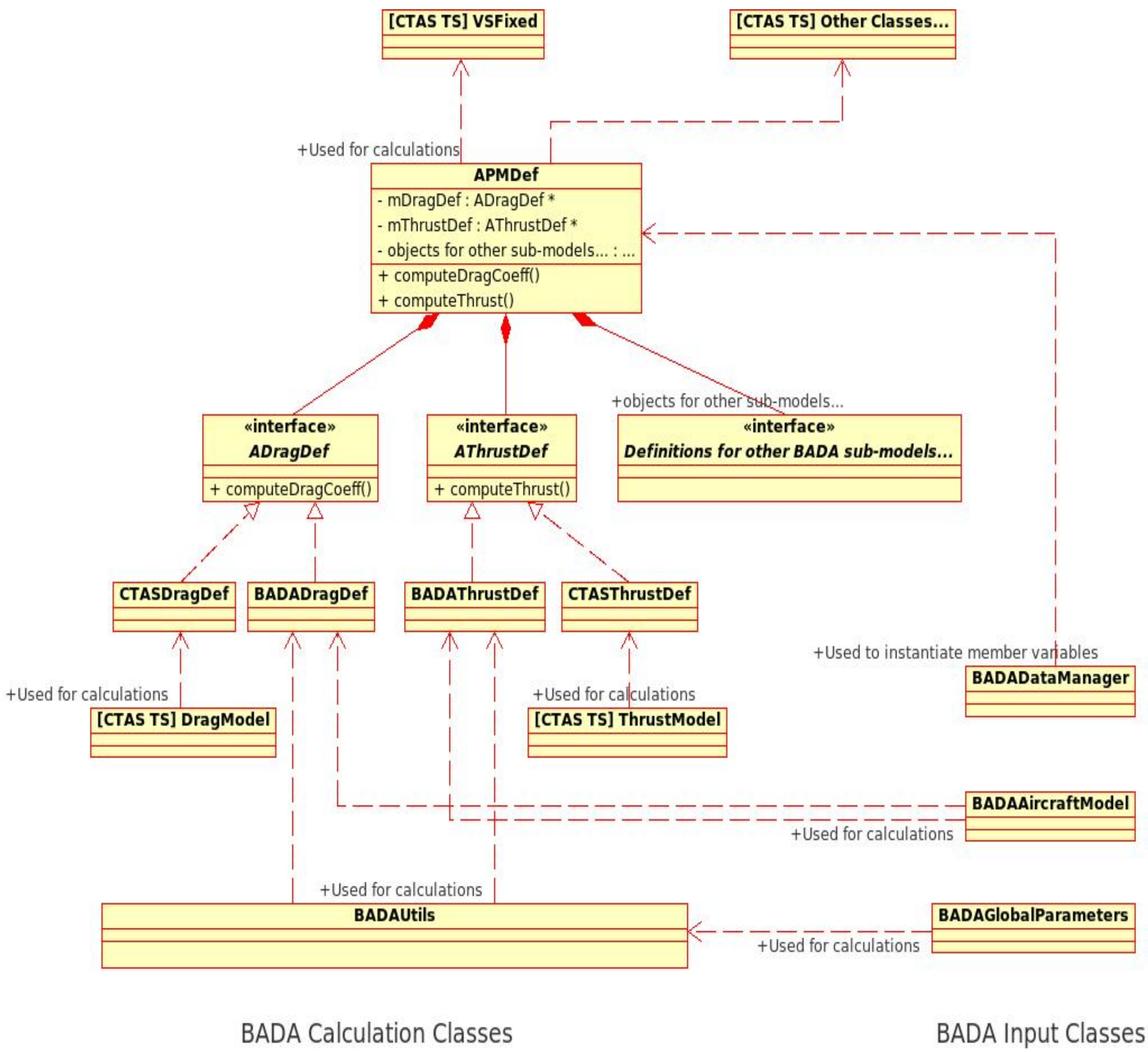

Figure 1. CTAS/BADA TS Class Diagram

Our implementation of CTAS/BADA TS fully supports BADA APM with additional features and extensions listed below:

- Easy switch between CTAS "native" and BADA APM by changes in user-defined configuration files;
- BADA can be used for specific aircraft types or for all aircraft types;
- Each element of BADA APM (drag model, thrust model, speed profile, etc.) can be turned on/off and tested separately;
- Some parameters of BADA APM, such as aircraft weight, can be specified as aircraft-specific user-defined values;
- The weight of aircraft can be specified as a constant or variable. In the latter case, the weight is calculated as a function of time based on fuel consumption as described in [9];
- BADA thrust model was extended to allow the variable power settings to control the engine thrust in response on client speed requests, such as speed advisories for trial planning. Specifically, the maximum climb power is used for acceleration, and the BADA idle-thrust is used for deceleration in any flight phase;
- Fuel consumption is always based on instantaneous thrust value, even if it deviates from nominal BADA thrust due to client requests;
- Speed profile can be defined as CTAS, BADA "exact" with nominal BADA speeds defined in [7], and BADA "hybrid" with BADA speeds that can be updated by speed requests from CTAS client applications;
- Some BADA options defined as "global" in [7], such as reduced climb power or expedited descent, can be defined as aircraft-specific in CTAS/BADA TS.

This rich functionality is controlled by two BADA-CTAS Configuration Files, loaded by CTAS at startup time:

- data_sources, which specifies the available data sources (currently CTAS and BADA 3.8, but other versions of BADA can be added later);
- aircraft_data_sources, which defines the additional options for each element (sub-model) of APM.

If BADA APM is requested, the following BADA Input Files will be used (see [7] for details):

- SYNONYM.NEW: the ICAO codes and prefixes for files with aircraft-specific data;
- BADA.GPF - Global Parameters Files, containing the values for BADA global parameters;
- OPF files - Operation Performance Files (one file for each aircraft type, see Appendix A);
- APF files - Airline Procedures Files (one file for each aircraft type).

Typical operation of CTAS/BADA TS includes three steps:

1. Read BADA-CTAS configuration files;
2. Read CTAS common aircraft data files and BADA data files, and use the data from configuration files to instantiate CTAS or BADA implementations for each APM element;
3. Generate trajectories using CTAS and/or BADA APM as defined in configuration files.

The trajectories generated by CTAS/BADA TS may be saved in archive files for further analysis and comparisons with radar track and other benchmark data using validation tools described in next section.

3 Validation Tools and Methods

The goals of validation are two-fold. First of all, it should be confirmed that implementation of BADA APM in CTAS/BADA TS is correct by comparison with benchmark data, provided by Eurocontrol in the form of "Performance Table Data" (PTD) files (see [7] and Appendix B). Next, it should be examined how the usage of BADA APM will help improve CTAS. This second goal can be accomplished by running CTAS/BADA TS with CTAS APM and BADA APM side by side and comparing their predictions to each other and to radar track data.

For a first goal, the PTD validation tool was developed to validate the implementation of BADA APM by reporting how closely the results produced by the current version of CTAS/BADA TS match the reference data from PTD files. For these comparisons linear interpolation on the TS output is used to get data at flight levels, specified in BADA PTD files.

For a second goal, namely, validation of CTAS APM and BADA APM, a number of other tools was created. Two of them are briefly considered in this section:

1. TrackComparer tool
2. CmSimTrackComparer tool

TrackComparer tool uses methodology similar to what was described in [6]. It combines three different analysis techniques:

- **Systematic analysis** - Comparison of every predicted position with actual track data, and of predictions against each other, provided that data can be compared for a specified minimum time or path distance. This analysis generates systematic error statistics for all aircraft types, but it does not reflect the evolution of error along track.
- **Interval-based sampling technique (IBST)** - Samples track data and predictions at regular intervals along the track, as described in [10].
- **Separation assurance trajectory accuracy algorithm (SA analysis)** - Computes metrics at a specific lookahead time starting at (user-defined) climb and descending altitudes. SA analysis is a truncated variant of IBST that computes metrics for only one (first) prediction for each track. This makes it less computationally expensive than IBST, at the cost of a reduced size of data set.

The tool requires the following inputs:

- Cm_sim file, generated by CTAS using HCS data. It contains flight plans, flight plan amendments, and radar tracks.
- Trajectory archive files for trajectories generated by CTAS/BADA TS. These files are used for comparison with track data.

CmSimTrackComparer tool was originally developed for comparing CTAS/BADA TS predictions against track data for idle-thrust descents with controlled cruise and descent speeds that were recorded for Denver arrivals in 2009, studied in [11]. The tool can also be useful for other CTAS data analysis/validation tasks.

It combines the following functions:

- automatically generate requests to TS from radar track data;
- invoke TS for each request;
- compare generated predictions against tracks.

In contrast to TrackComparer, CmSimTrackComparer has only one required input, a cm_sim file, that makes possible to run it without running CTAS. Optional input text files can be used to limit analysis to particular flights and to specify estimated values for descent speeds and aircraft weights.

On the other hand, CmSimTrackComparer compares track data to predictions generated using only one APM, either CTAS or BADA, while TrackComparer can simultaneously compare CTAS predictions to track data, BADA predictions to track data, and BADA predictions to CTAS predictions.

Both TrackComparer and CmSimTrackComparer tools use the metrics defined in [10]:

along-track error (time-correlated):

$$\Delta AT_t = \frac{\vec{U} \cdot \vec{V}}{\|\vec{V}\|} \tag{1}$$

along-track error (path-correlated):

$$\Delta AT_p = t_p - t_t \tag{2}$$

cross-track error (time-correlated):

$$\Delta CT = \frac{\|\vec{U} \times \vec{V}\|}{\|\vec{V}\|} \tag{3}$$

altitude error:

$$\Delta h = h_t - h_p \tag{4}$$

where t is a time, h is an altitude, and the subcripts p and t designate the path-based and time-based correlations. The vectors $\vec{U}$ and $\vec{V}$ are based on the position of aircraft denoted as AC and a trajectory segment between the points TJ_1 and TJ_2 as shown on Figure 2.

All metrics, except for the along-track error for the path distance correlation, have the characteristic that *the predicted trajectory is subtracted from the reference (or track).* For BADA predictions compared against CTAS, the reference is always the CTAS prediction.

Besides these metrics, TrackComparer calculates the metrics for "events," such as the Top of Climb (TOC), the Top of Descent (TOD), and the Estimated Time of Arrival (ETA). In this study the Top of Climb is defined as the end of the longest procedural climb in the flight or prediction, and the Top of Descent is defined as the start of the longest procedural descent in the flight or prediction. A procedural climb is defined as a non-decreasing sequence of altitudes with at least one strictly increasing sequence of altitudes, and procedural descent as a non-increasing sequence of altitudes with at least one strictly decreasing sequence of altitudes.

For arriving flights, CTAS makes a clear distinction between Center predictions originating in the ARTCC and ending at the meterfix, and TRACON predictions within the TRACON. Consequently, the metrics for ETA are defined differently for these two classes of predictions. For a Center

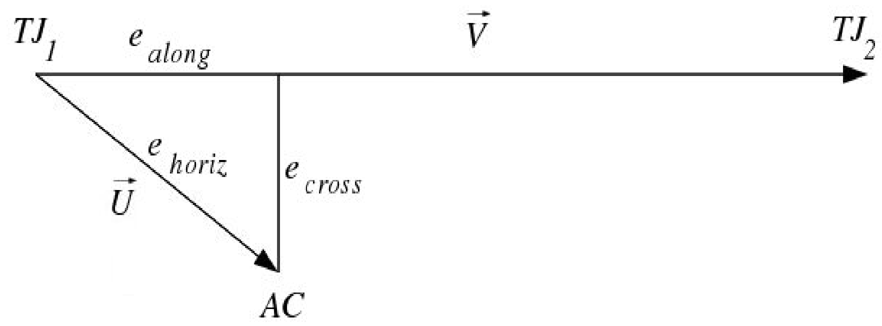

Figure 2. Horizontal Trajectory Prediction Metrics

prediction, the ETA is the time when the track or prediction reaches the Center-TRACON boundary (the meterfix), while for a TRACON prediction the ETA is based on the end of trajectory.

For each comparison (e.g. for each prediction-reference pair) the maximum, minimum, mean, and absolute mean errors are calculated and stored in SQL-lite database. Then the maximum, mean, minimum, and standard deviation are calculated over each of these metrics separately for CTAS vs. Track, BADA vs. Track, and BADA vs. CTAS comparisons. For example, the "mean of absolute mean errors" is the mean of absolute mean errors for all predictions. Other metrics used in this TM are defined similarly.

4 CTAS/BADA TS Software Validation

Implementation of BADA APM in CTAS/BADA TS was validated using the PTD validation tool with benchmark PTD files as of the 5th of May 2011. This validation was performed only for BADA "exact" speeds and constant weight, since the PTD files were generated for these conditions

The following two metrics were considered: a trajectory success rate, and a comparison success rate. The trajectory success rate is defined as a percentage of trajectories successfully generated by CTAS/BADA TS to all trajectory requests. CTAS/BADA TS may fail to generate trajectories for certain requests because of unrealistic constraints or aircraft performance data or due to limitations imposed by implementation of TS computational algorithms.

Over all considered aircraft types, e.g. all types for which the BADA provided the PTD files, the PTD validation gives **99.8%** trajectory success rate.

The comparison success rate is defined as a percentage of successful comparisons to all comparisons. Comparison is considered successful if the mean absolute errors for all trajectory parameters are less than the specified tolerances listed in Table 1:

Table 1. PTD Comparison Tolerances

Parameter	Tolerance
True Air Speed (TAS)	5 knots
Calibrated Air Speed (CAS)	5 knots
Mach	0.1
Thrust	1000 Newtons
Drag	1000 Newtons
ROCD	100 feet per minute

With these tolerances a comparison success rate with the PTD reference was **78.3%**. The majority of failed comparisons were due to thrust or ROCD. These failures occurred because "the PTF/PTD files do not take into account the flight envelope limitations", as the BADA support group acknowledged responding on request by the authors of this TM. Therefore, the tables in BADA PTD files include the data up to the maximum altitudes with a negative rate of climb indicating that aircraft cannot climb up to that altitudes. CTAS TS copes with this situation by increasing thrust to achieve a minimum energy rate required for climb, while ROCD is calculated from the Newton's equation of motion and can never be negative in climb. Therefore, the BADA implementation in CTAS/BADA TS disagrees with BADA PTD reference for conditions that are not physically possible.

Increasing the thrust tolerance to 2000 Newtons and the ROCD tolerance to 200 feet per minute resulted in an increased comparison success rate of **90.5%**. All remaining failures were due to failed comparisons in drag. All data in BADA PTD files are expressed on the coarse grid as functions of the flight level (FL) (see Appendix B). Hence, comparisons of CTAS/BADA TS results against the PTD data require interpolation between this coarse grid and the the grid used by CTAS/BADA TS. The lift coefficient, and hence the drag, appear to be especially sensitive to these interpolation errors. Other parameters, such as altitude and CAS, were not affected by these errors.

5 Evaluation of CTAS/BADA TS

BADA documentation [7] already allows certain variability in some elements of BADA APM. For example, a user can choose to use full or reduced climb power, standard descent or expedited descent with spoilers, and so on. Implementation of BADA APM in CTAS/BADA TS further extends this variability. Hence, any discussion of CTAS/BADA TS evaluation results requires specification of "the variant" of BADA APM used.

First, the definitions of CTAS and BADA speed profiles should be considered. CTAS TS uses aircraft-specific default speeds, but they can be updated from client speed requests and the initial speed from track. On another hand, BADA User Manual, [7], defines aircraft-specific speeds for all flight phases, which will be called the "BADA exact" speed profile. In addition to this, CTAS/BADA TS supports the "BADA hybrid" speed profile, defined as BADA exact speeds, replaced when necessary with speeds requested by CTAS clients. A variant of "BADA hybrid" speed profile, which will be referred in this TM as "BADA hybrid hold," holds initial speeds as CTAS TS does. Therefore, the "BADA hybrid hold" speed profile is similar to CTAS speed profile, except the definition of default speeds: the BADA "exact" speeds from [7] are used as default speeds for BADA, while for CTAS the default speeds are explicitly specified for each aircraft type.

Next, the "default" initial aircraft weight should be defined, which is based on BADA reference weight, corrected to account for a starting point of aircraft. CTAS TS does not have access to flight history before the first prediction point, so the method of initial weight correction based on estimated fuel burn, suggested in [12] and [13], could not be used. Therefore, a more practical, although less accurate, correction technique was necessary. This technique used heuristics, taking into account a starting point of aircraft. Effectively, these heuristics ensured that the initial weight gradually approached the BADA maximum weight at the beginning of climb, and the "landing weight", defined as BADA empty weight increased by 20%, at the end of descent. The code also ensured that the actual aircraft weight could not fall below the "landing weight".

BADA Base case can be defined as follows:

1. BADA thrust model;
2. BADA drag model;
3. BADA weight model that implies the weight starting from "default" initial weight and changing as a function of consumed fuel;
4. Reduced climb power, which will give more realistic climb profile than the maximum thrust does (see [7], p.24);
5. BADA "exact" speed profile (requests are ignored);
6. BADA model limits (trajectories assumed invalid if BADA limits are violated).

Therefore, the BADA Base case can be seen as the most "authentic" implementation of [7]. All other BADA test cases are built upon the BADA Base case as shown in Table 2. Examining these cases allows to study the effects of extensions of BADA APM and, to some degree, the effects of uncertanties in speeds, weight, thrust, and drag.

Note that only the BADA Base case can be considered as a "nominal" case, for which the BADA APM was validated by the Eurocontrol. All other cases are "off-nominal" models that require additional validation by comparisons of predicted trajectories against track data as described in this section.

All comparisons were made using BADA version 3.8 and RUC weather files with 40km grid for corresponding days and locations.

Table 2. BADA APM variants

CTAS speeds	Base case, but CTAS speed profile
Hybrid Hold	Base case, but BADA hybrid hold speed profile
Increased Weight	Base case, but weight ratio = 110% (10% above "default" weight)
Reduced Weight	Base case, but weight ratio = 90% (10% below "default" weight)
Maximum Climb Thrust	Base case, but without reduced climb power
Expedited Descent	Base case, but with expedited descent
Reduced Climb and Descent	Maximum climb thrust, but with expedited descent

5.1 Fort Worth Center (ZFW), 3 days

The TrackComparer tool, briefly described in previous section, was used to compare radar track data with predictions obtained using CTAS/BADA TS for different BADA variants for 3 days of traffic from Feb 23 to Feb 25 of 2011 in Fort Worth Center (ZFW).

Tables 3 and 4 summarize the performance of CTAS and various BADA variants for time-based correlations. Each row in these tables includes the averaged (over all predictions) absolute values of maximal errors, mean errors, absolute values of mean errors, maximal errors, minimal errors, and standard deviations of metrics defined in Section 3.

As can be seen from Tables 3 and 4, all BADA variants perform as well or slightly better than CTAS in terms of altitude and along-track errors. However, the differences between BADA and CTAS and between different BADA variants in mean of absolute mean errors do not exceed a few percent of error magnitudes, except for BADA Hybrid Hold variant that shows the most noticeable advantage over CTAS in terms of mean of absolute mean along-track errors.

The differences between CTAS and BADA become more pronounced when plotted for specific aircraft types and flight phases. Note that the aircraft-type-specific data on all histograms are shown in the order of decreasing aircraft-type frequency from the left to the right, so the data for most frequent aircraft types always appear on the left side.

All plots below for along-track and altitude errors are given for time-based correlations. The plots for cross-track errors are not included, since these errors were found to be practically the same for BADA and CTAS. This should be expected since the cross-track errors are mostly related to intent and flight plan amendments, and so they are not sensitive to a particular APM.

Table 3. Mean altitude errors (ft) for CTAS/BADA TS

Test case	Comparison	Abs Max	Mean	Abs Mean	Max	Min	Std Dev
Base Case	CTAS vs. Track	25592	-267	938	25592	-21308	1932
	BADA vs. Track	25834	-176	899	25834	-21308	1874
CTAS Speeds	CTAS vs. Track	22831	-281	867	22831	-19415	1835
	BADA vs. Track	24782	-223	846	24782	-19415	1808
Hybrid Hold	CTAS vs. Track	24506	-280	898	24506	-19763	1882
	BADA vs. Track	25109	-213	866	25109	-19763	1837
Increased Weight	CTAS vs. Track	25592	-267	927	25592	-19415	1917
	BADA vs. Track	25834	-173	883	25834	-21170	1851
Reduced Weight	CTAS vs. Track	27250	-97	1095	27250	-19763	2245
	BADA vs. Track	27250	-96	1083	27250	-19763	2228
Maximum Climb Thrust	CTAS vs. Track	25592	-263	923	25592	-21308	1916
	BADA vs. Track	25834	-196	891	25834	-21308	1867
Expedited Descent	CTAS vs. Track	25592	-267	937	25592	-21308	1932
	BADA vs. Track	25834	-238	903	25834	-21308	1874
Reduced Climb and Descent	CTAS vs. Track	25479	-267	927	25479	-19943	1922
	BADA vs. Track	25834	-264	898	25834	-21170	1867

Table 4. Mean along-track errors (nmi) for CTAS/BADA TS

Test case	Comparison	Abs Max	Mean	Abs Mean	Max	Min	Std Dev
Base Case	CTAS vs. Track	129.87	0.2	2.7	45.47	-129.87	4.73
	BADA vs. Track	129.86	0.1	2.61	45.47	-129.86	4.52
CTAS Speeds	CTAS vs. Track	129.71	0.61	2.43	45.48	-129.71	4
	BADA vs. Track	129.73	0.77	2.35	45.48	-129.73	3.81
Hybrid Hold	CTAS vs. Track	129.71	0.38	2.55	45.48	-129.71	4.22
	BADA vs. Track	129.73	0.49	2.2	45.48	-129.73	3.59
Increased Weight	CTAS vs. Track	129.87	0.17	2.7	45.47	-129.87	4.68
	BADA vs. Track	131.32	-0.03	2.78	45.47	-131.32	4.63
Reduced Weight	CTAS vs. Track	129.87	-0.07	3.09	45.47	-129.87	5.62
	BADA vs. Track	129.86	-0.19	3.05	45.47	-129.86	5.52
Maximum Climb Thrust	CTAS vs. Track	129.87	0.19	2.73	45.47	-129.87	4.85
	BADA vs. Track	129.86	0.05	2.65	45.47	-129.86	4.65
Expedited Descent	CTAS vs. Track	129.87	0.18	2.7	45.48	-129.87	4.7
	BADA vs. Track	129.86	0.04	2.66	45.48	-129.86	4.52
Reduced Climb and Descent	CTAS vs. Track	129.87	0.2	2.7	45.48	-129.87	4.68
	BADA vs. Track	131.32	-0.03	2.8	45.48	-131.32	4.64

Figure 3 shows the most frequently observed aircraft types for Fort Worth Center in comparisons between CTAS and BADA Base case.

Figures 4 and 5 show that overall mean altitude error distributions for all flight phases together are similar for CTAS and BADA.

However, Figure 6 indicates that BADA APM may reduce the bias in altitude predictions when compared with CTAS APM because of lower mean of mean altitude errors for 20 of 40 aircraft types and for 6 of 10 most frequent aircraft types. Furthermore, as can be seen from Figure 7, BADA may significantly improve the altitude prediction accuracy of CTAS TS for certain aircraft types, such as CRJ7, CRJ9, BE9L, and E145.

Figure 8 shows that using BADA Base case may also help reduce the bias in the along-track error for several aircraft types, including A320, B737, B738, B752, CRJ7, CRJ9, and E145. This may indicate that BADA "exact" speeds can be more realistic than the default CTAS speeds.

The event errors are plotted on Figures 9 through 14. These results show an improvement in the TOC time accuracy and generally similar results for TOD time accuracy. The results for ETA indicate that BADA APM may perform slightly better in predicting arrival times for many aircraft types, but for certain aircraft types (E135, BE40, BE36, C182) the BADA ETA errors are much higher when compared with CTAS.

Figures 15 through 17 show the IBST analysis results for climb prediction errors expressed as a function of look-ahead time, which is defined as the time interval between the sample time and the future time at which the prediction is made. The plots indicate that BADA may help improve the altitude prediction accuracy in climbs. This can be seen from the fact that the mean altitude error remains essentially flat along the track, and the mean absolute and standard deviation of altitude error are lower than in CTAS for the whole range of look-ahead times. At the same time, in descents BADA underperforms in the interval-based sampling results for mean, mean absolute and standard deviation of altitude error, shown on Figures 18 through 20.

Note that the graphs do not start from zero errors because of the logic of the IBST that does not use the track position as the initial position for comparisons between track and predicted points. Instead, the IBST selects a first (most recent) eligible prediction for each track that might be generated some time before a sample point (see [10]). This time difference can be especially large if some predictions after the "first eligible prediction" fail.

It is instructive to look at results for the TRACON area only, e.g. excluding en-route predictions. In the TRACON CTAS TS generates predictions only for arriving flights. Modeling of TRACON trajectories is challenging since the arriving aircraft changes its altitude and speed in wide limits, makes frequent turns, uses variable thrust, and deploys flaps, spoilers, and the landing gear affecting the drag. CTAS TS copes with these challenges using the kinematic modeling specifically taylored for arrivals [2]. In contrast, BADA APM is kinetic for all flight phases, including the terminal approach and landing.

Figure 21 shows most frequent aircraft types with more than 10 flights for subset of flights including TRACON arrivals only. As can be seen from comparison to Figure 3, restricting the data set to the TRACON arrivals results in different most frequent aircraft types, with increased gap between MD82 and other aircraft and significantly reduced fraction of B737. These changes are not unexpected since CTAS is Center-specific, and the flights through particular ARTCC to other Centers can be performed by different airlines using different aircraft.

Figures 22 and 23 show that BADA may reduce the altitude bias for several most frequent aircraft types in the TRACON, although the mean of absolute mean altitude errors remains roughly the same as in CTAS TS. This finding may not hold for all TRACONs in all Centers, but it is still significant since it proves that BADA kinetic model can outperform the kinematic model, used by CTAS TS in TRACON, [2].

All results discussed so far were obtained using the BADA Base case. The BADA Hybrid Hold variant performs similarly, but in the TRACON it reduces the values of mean of mean altitude errors for almost all most frequent aircraft types (except most of Boeing aircraft types), as shown in Figure 24.

The improvement over BADA Base case in TRACON area can be attributed to the fact that in BADA Hybrid Hold case the BADA default speeds can be changed by client requests. This advantage becomes even more apparent from comparisons with Denver 2009 descent data (see section 5.4 below). For this reason, for other centers the BADA Hybrid Hold variant was used rather than the BADA Base case.

The BADA Expedited Descent variant achieves even more reductions in altitude errors in the TRACON. As can be seen from Figure 25 the mean of mean altitude errors is significantly lower then in CTAS TS for most aircraft types including MD82, MD83, B752, E135 and E145. However, for some aircraft types the mean of mean altitude errors is much larger, as in the case of B733 and B737.

The plots for BADA reduced and increased weight variants, shown in Figures 26 through 31 compared with results for BADA Base case with nominal weight in Figures 6 and 7, demonstrate the effect of weight uncertainty on prediction accuracy in climb. Again, these plots show the different ordering of aircraft types, because some flights can fly over the center and so the most frequent aircraft types for departing flights are not necessarily the same as for all flights.

The reduced weight variant (Figures 26 and 29) shows a very good improvement over the BADA Base case in climbs. We can see that in contrast to the BADA Base case, the reduced weight variant performs better than CTAS, rather than worse, for the mean of mean altitude errors for MD82, MD83, E135, B738, and B737 aircraft types. The mean of absolute mean altitude errors have also improved for many aircraft types.

The effect of increased weight in climb is less pronounced as can be seen from Figures 28 and 31 compared with Figures 27 and 30 for BADA Base case with nominal weight. This can be explained by inverse dependency of ROCD, and hence the altitude, on aircraft weight, making the altitude errors less sensitive to weight when the weight increases. Using the BADA reduced climb power further reduces this sensitivity as can be seen from equations (3.8-1) and (3.8-2) in [7].

It can be noted that CTAS default aircraft weights can also be adjusted to reduce errors of CTAS APM, although this is beyond the scope of this study.

One especially interesting BADA variant is the BADA with CTAS speeds since its comparison with CTAS APM allows to study separately the effect of the aircraft performance model for the same speed profile. It is clear from Figures 32 and 33 that the BADA with CTAS speeds reduced the altitude errors for most frequent aircraft types, except CRJ7 and CRJ9.

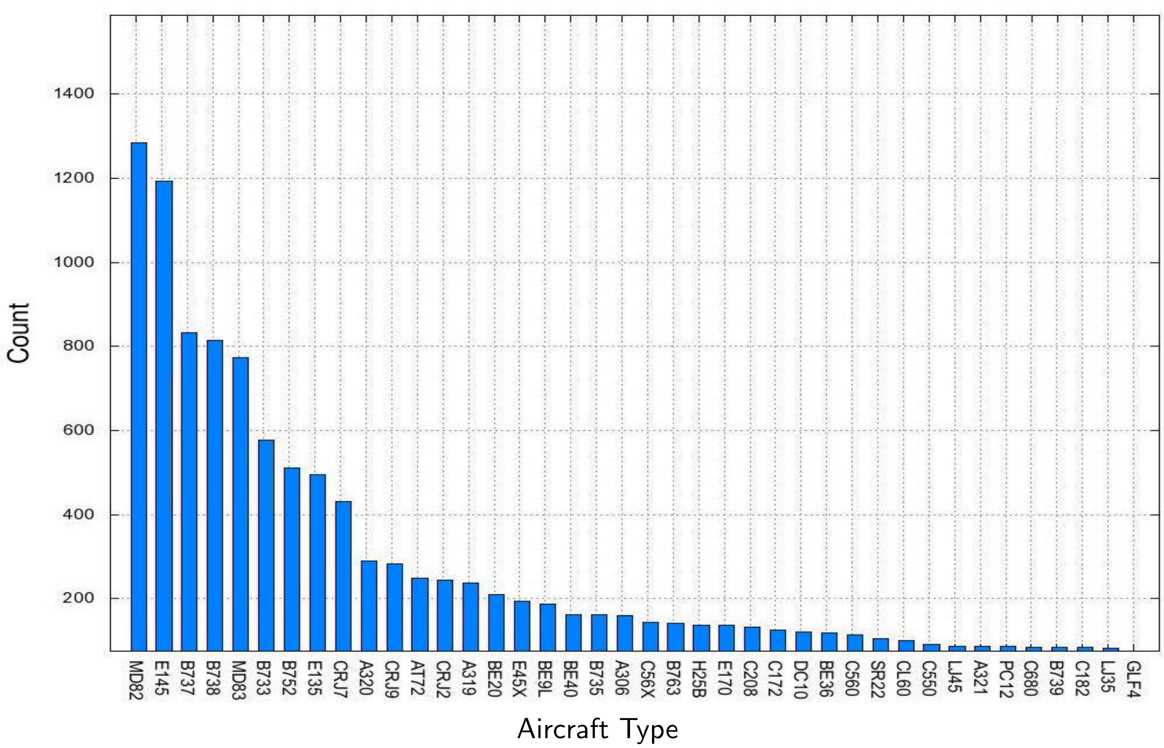

Figure 3. Most frequent aircraft types for Fort Worth center

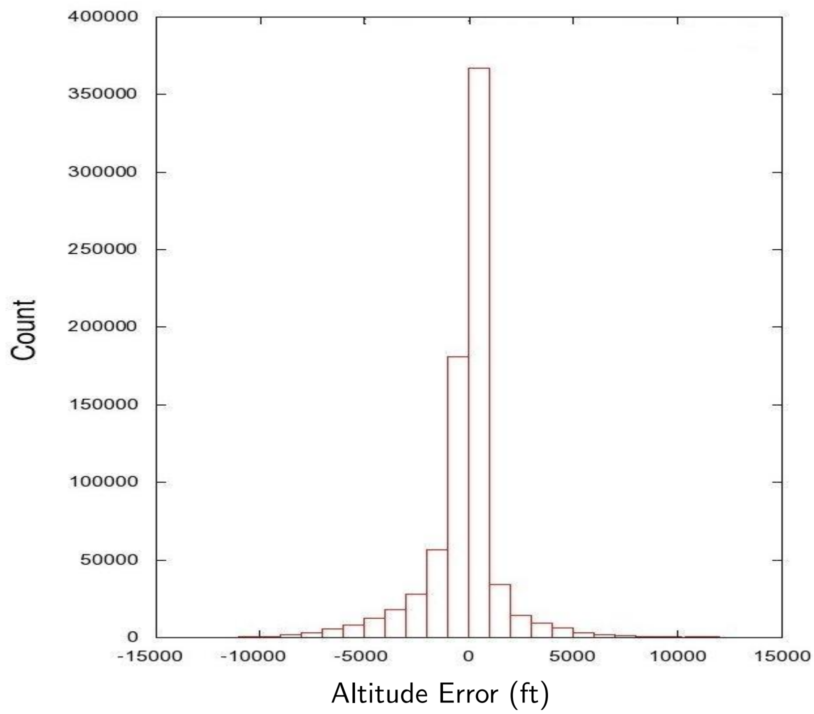

Figure 4. Overall mean altitude error, CTAS distribution

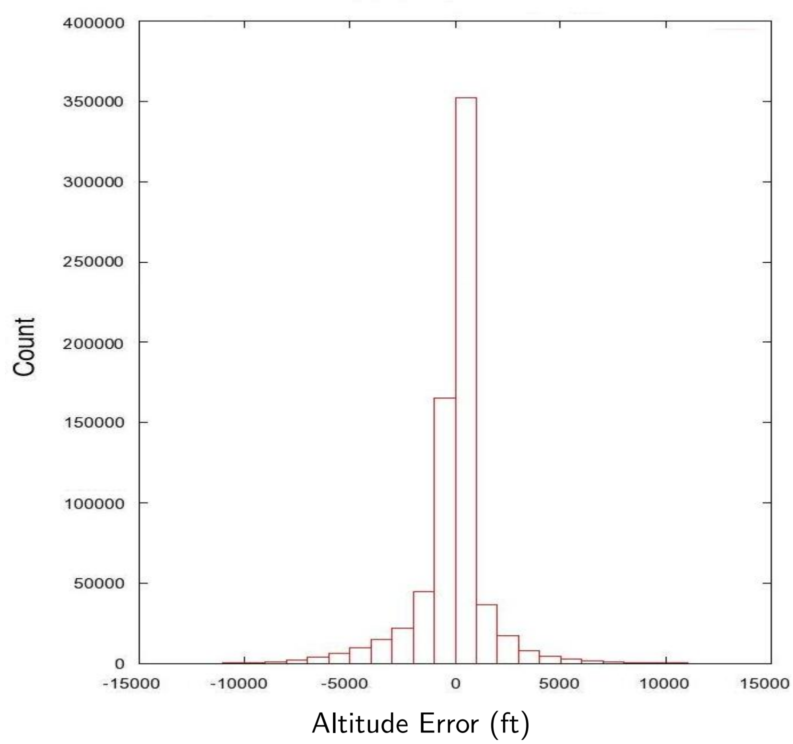

Figure 5. Overall mean altitude error, BADA distribution

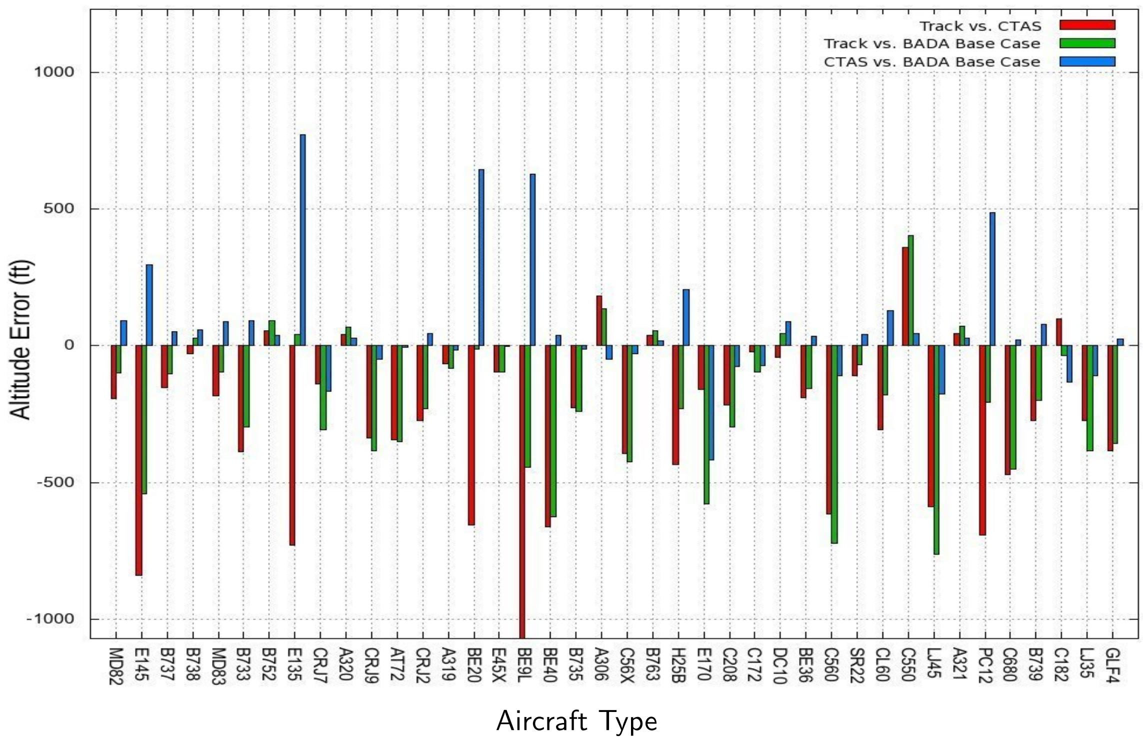

Figure 6. Mean of mean altitude errors

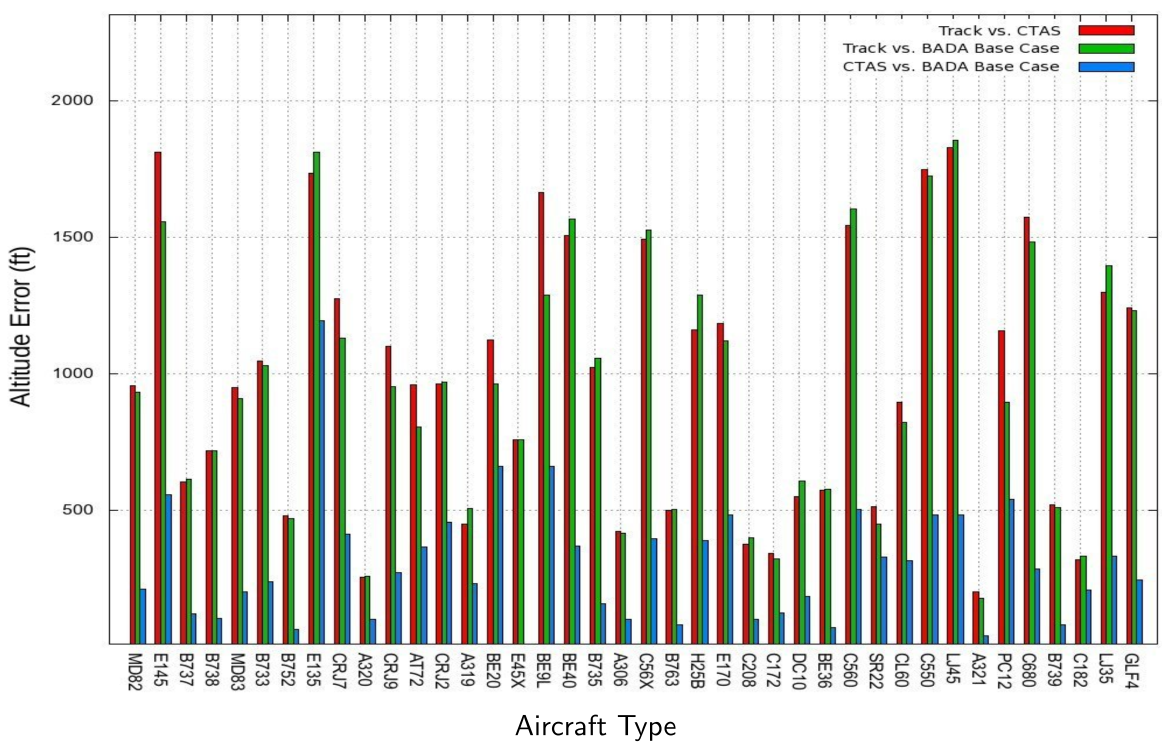

Figure 7. Mean of absolute mean altitude errors

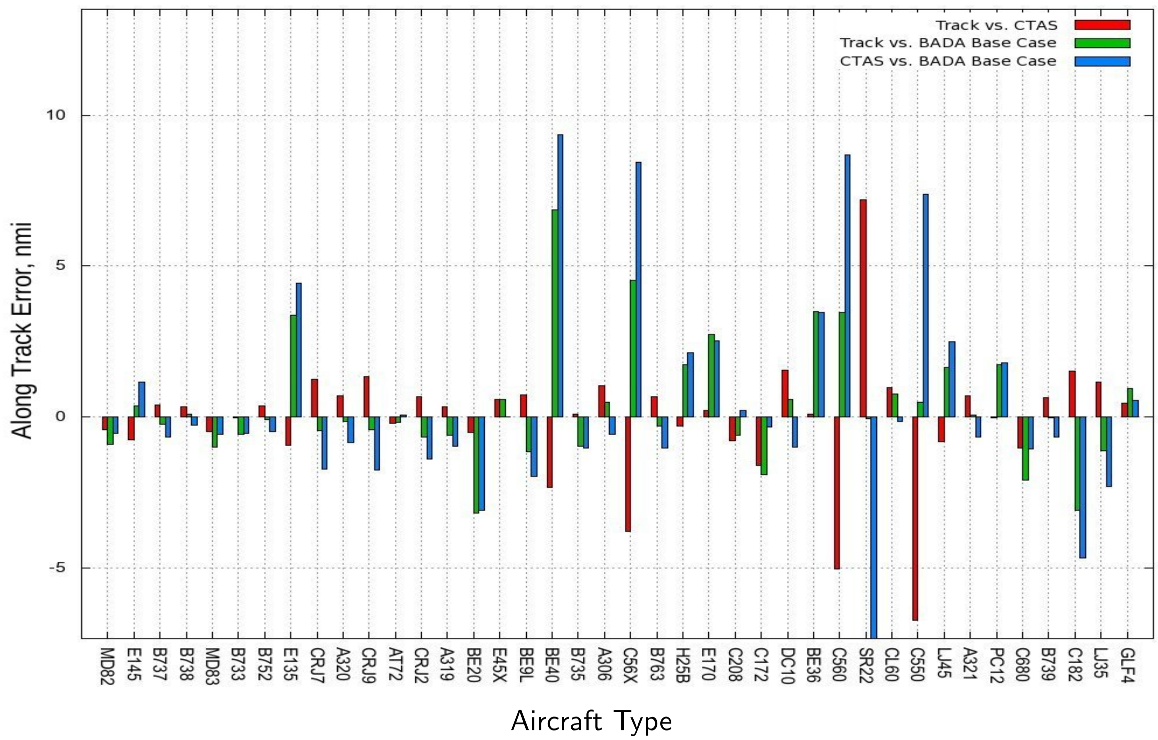

Figure 8. Mean of mean along-track errors

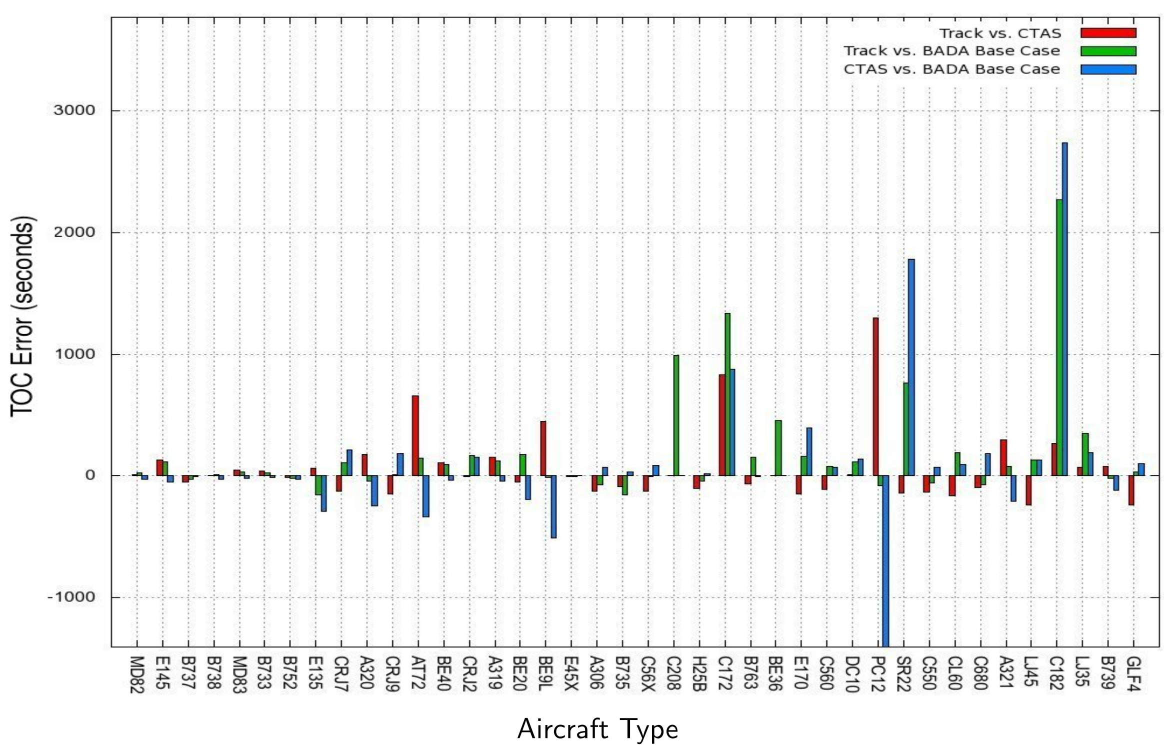

Figure 9. Events, Mean of mean TOC time errors

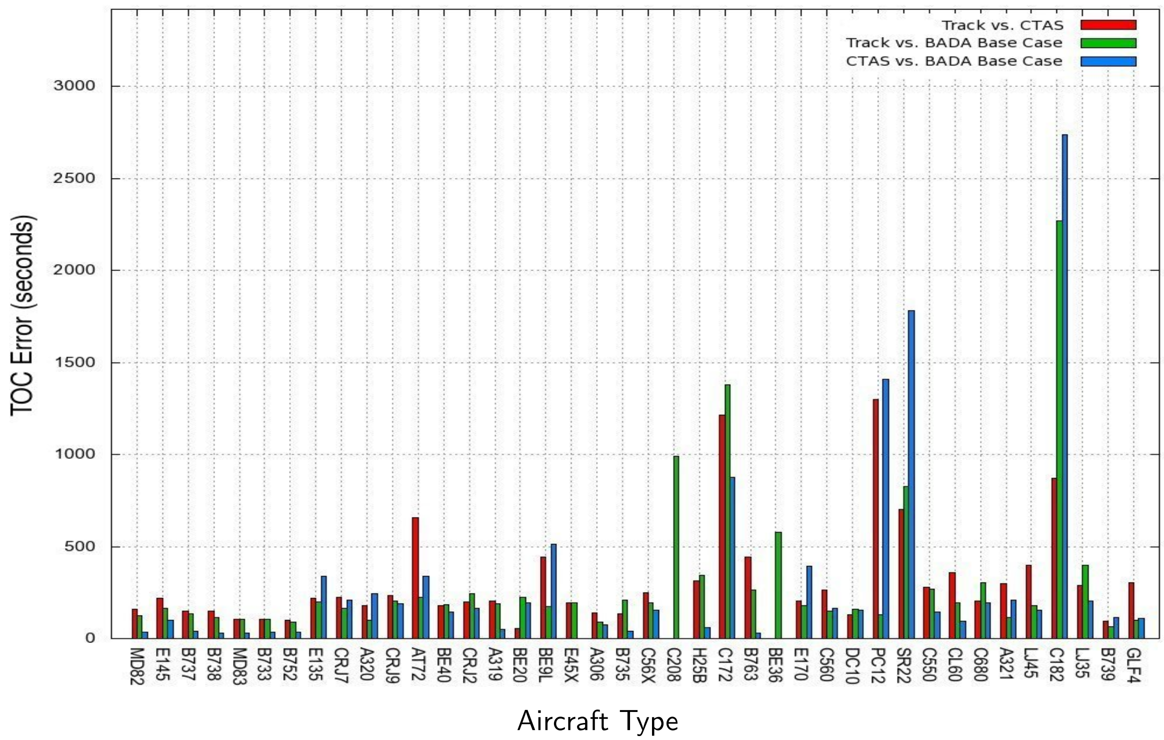

Figure 10. Events, Mean of absolute mean TOC time errors

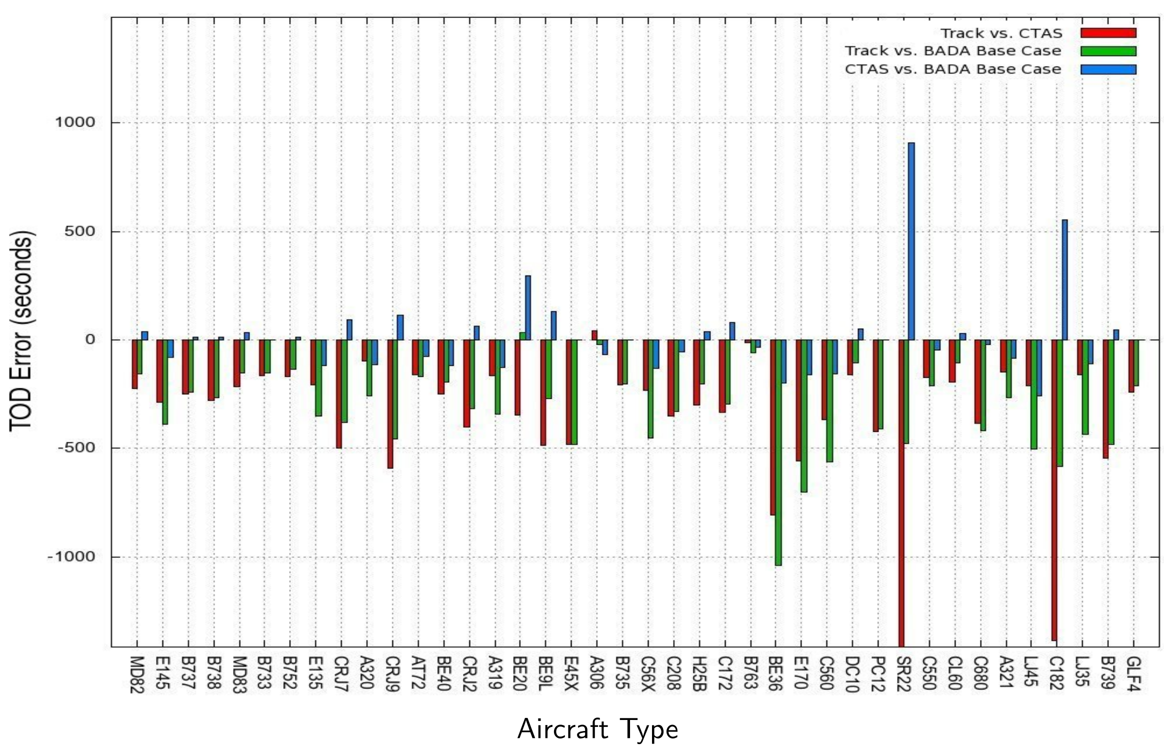

Figure 11. Events, Mean of mean TOD time errors

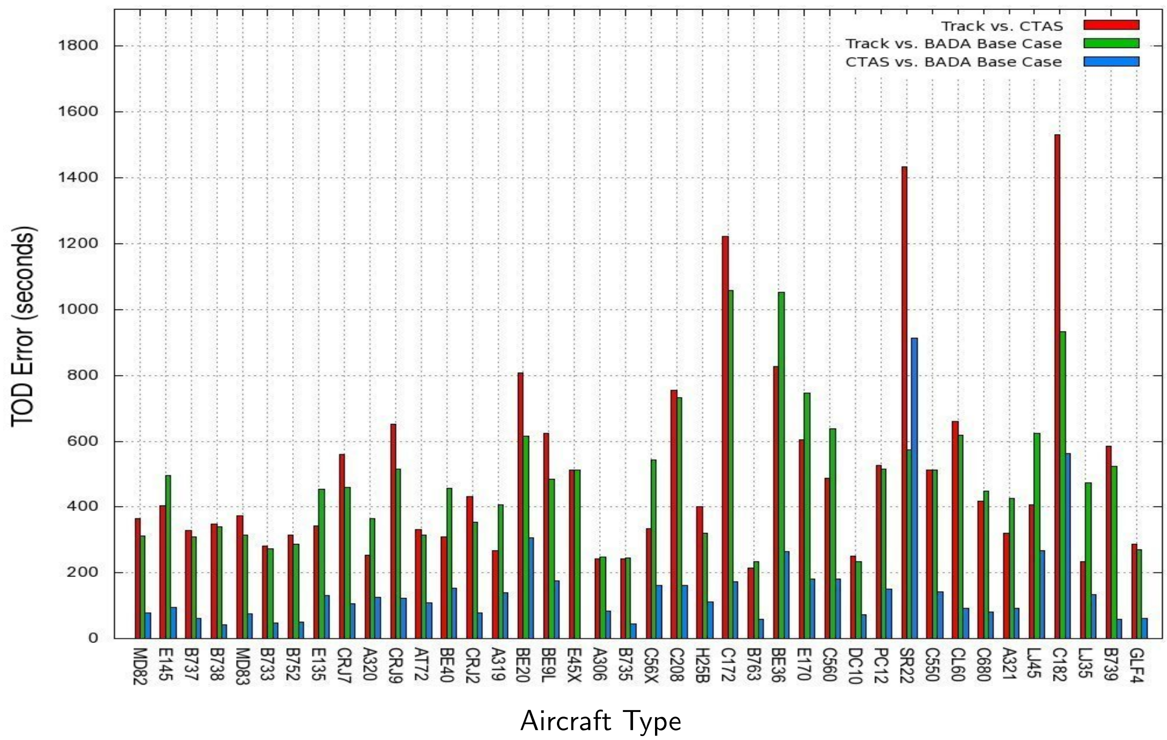

Figure 12. Events, Mean of absolute mean TOD time errors

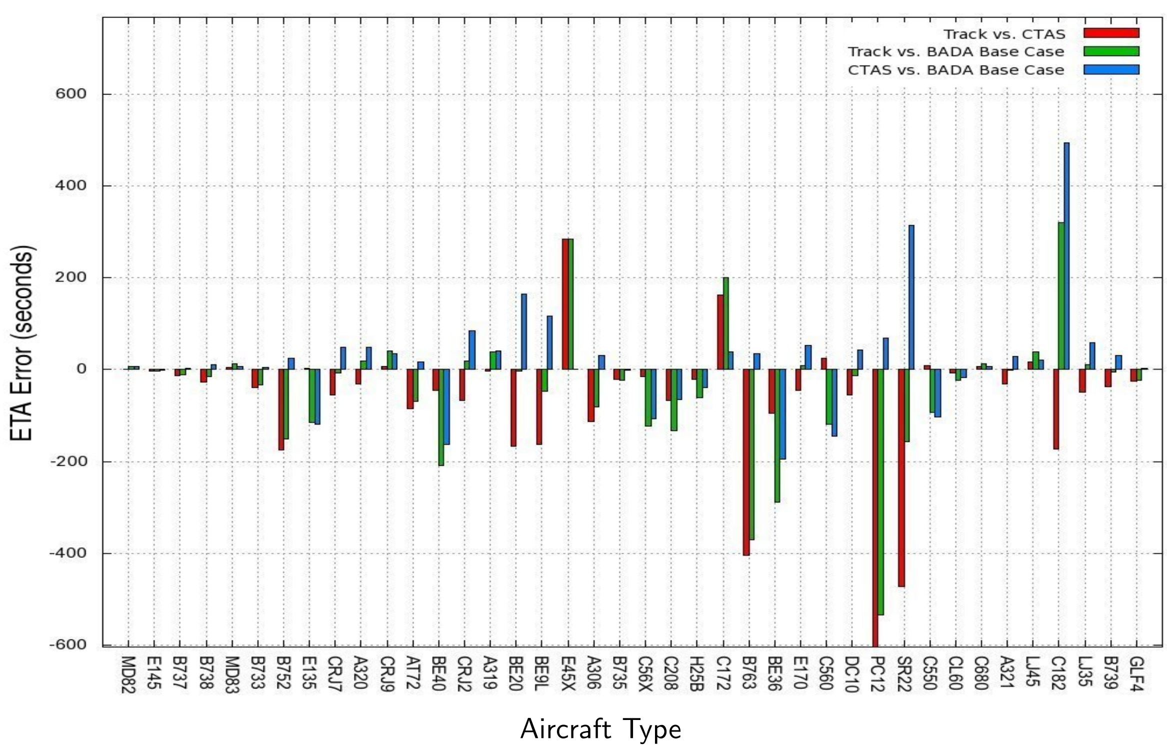

Figure 13. Events, Mean of mean ETA time errors

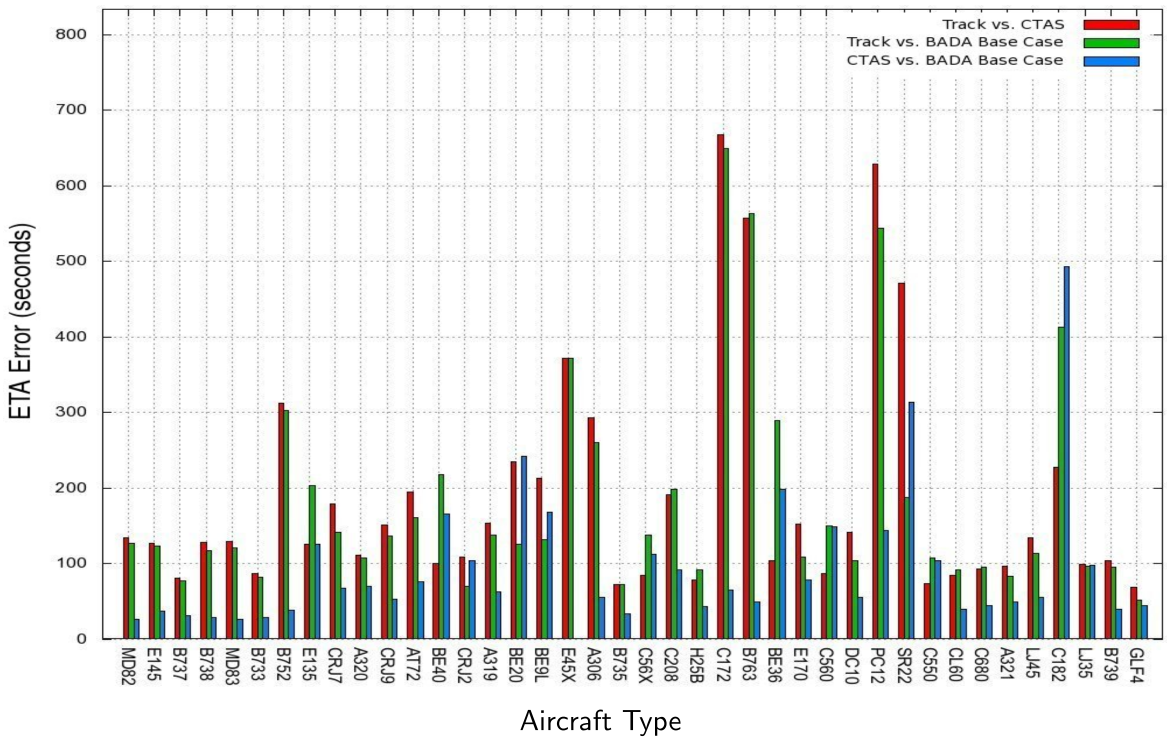

Figure 14. Events, Mean of absolute mean ETA time errors

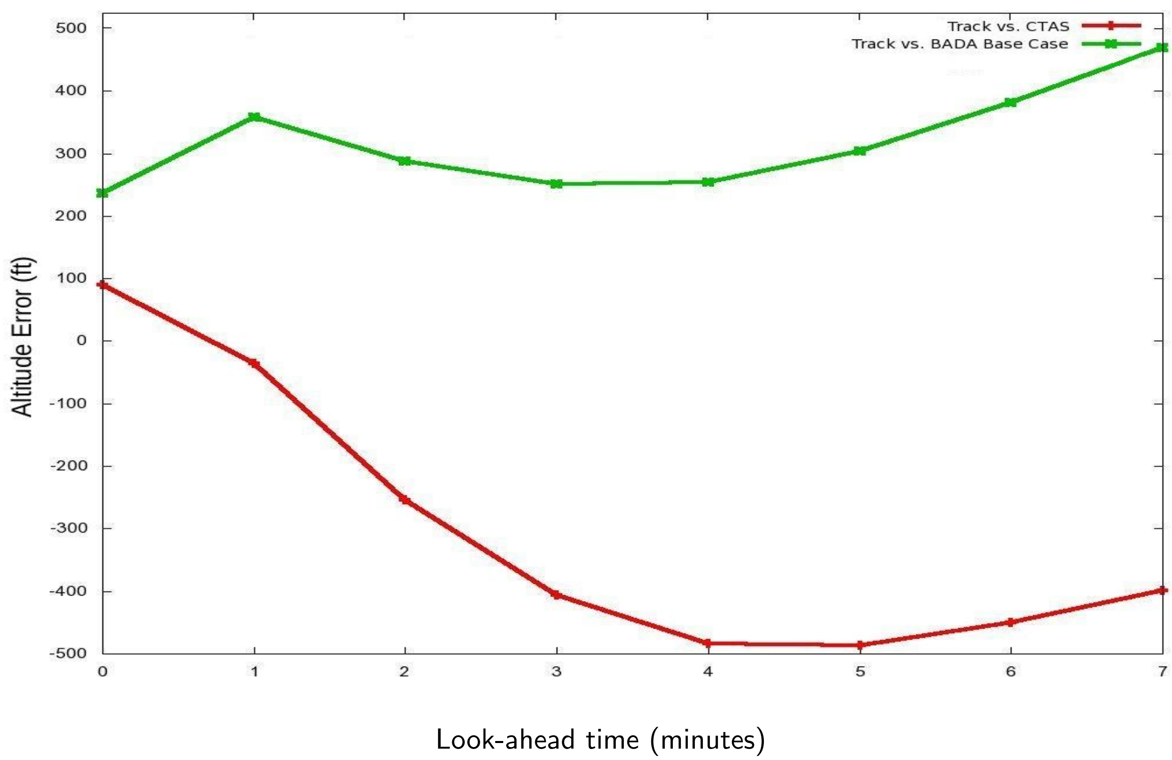

Figure 15. Interval-based sampling, mean altitude error during climb

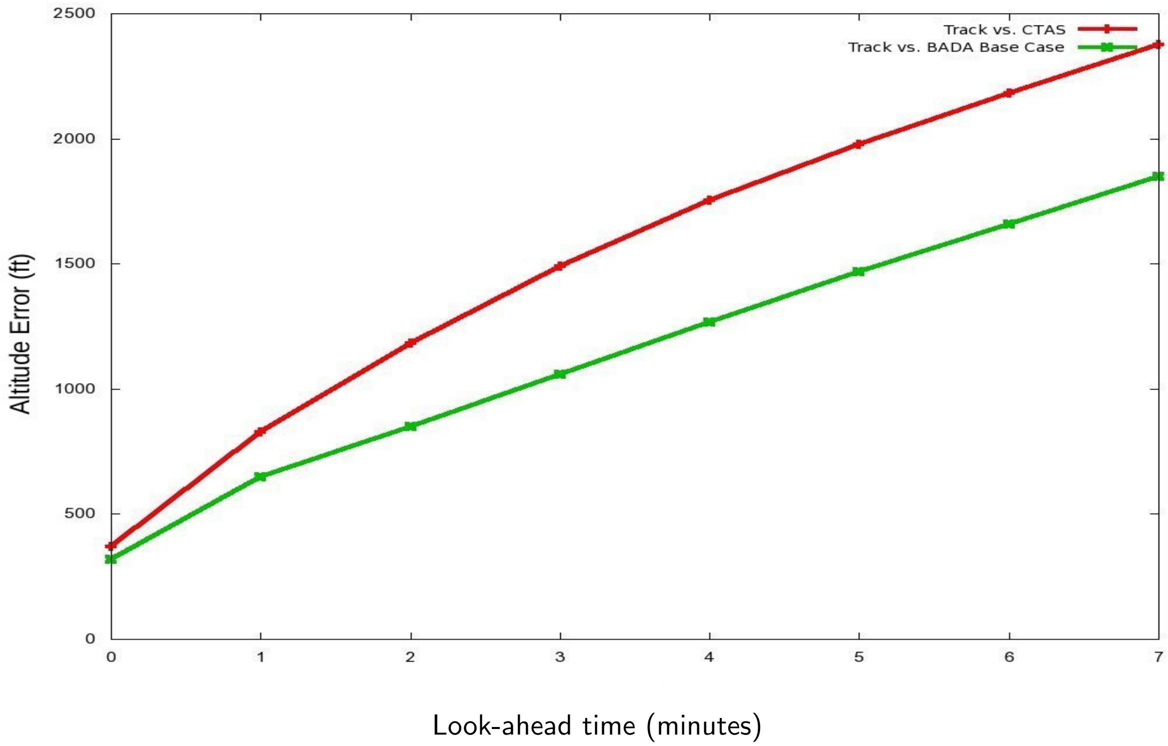

Figure 16. Interval-based sampling, mean absolute altitude error during climb

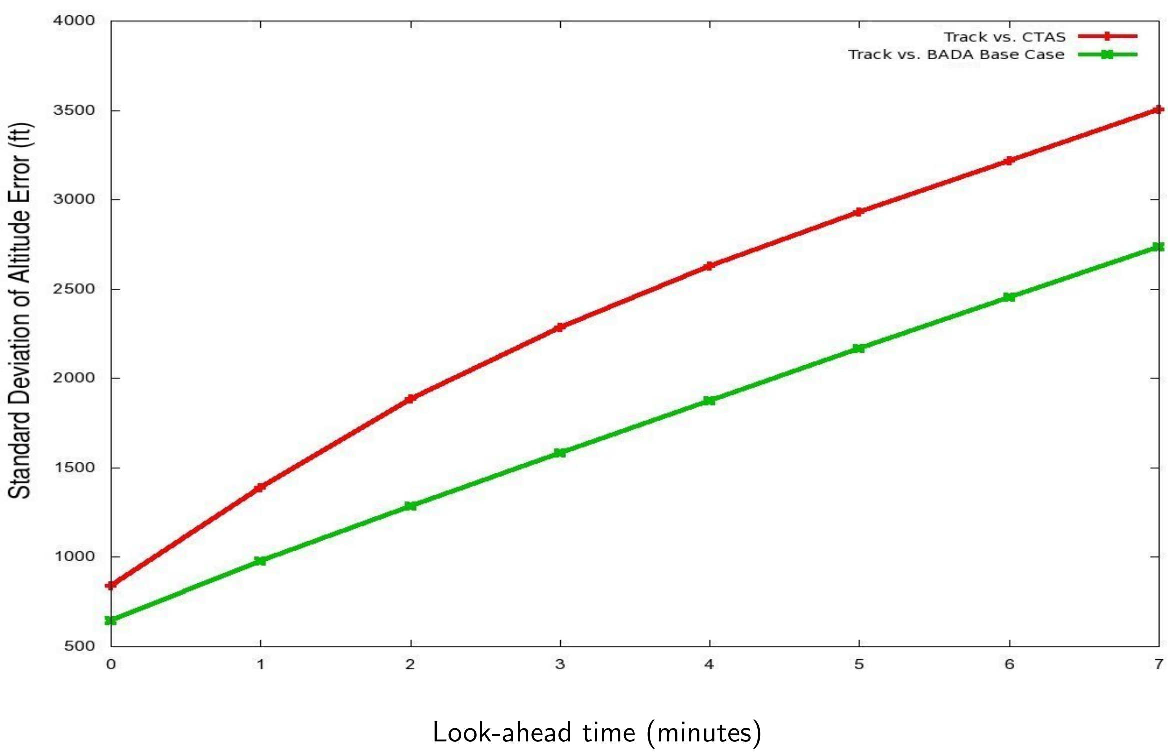

Figure 17. Interval-based sampling, standard deviation of altitude error during climb

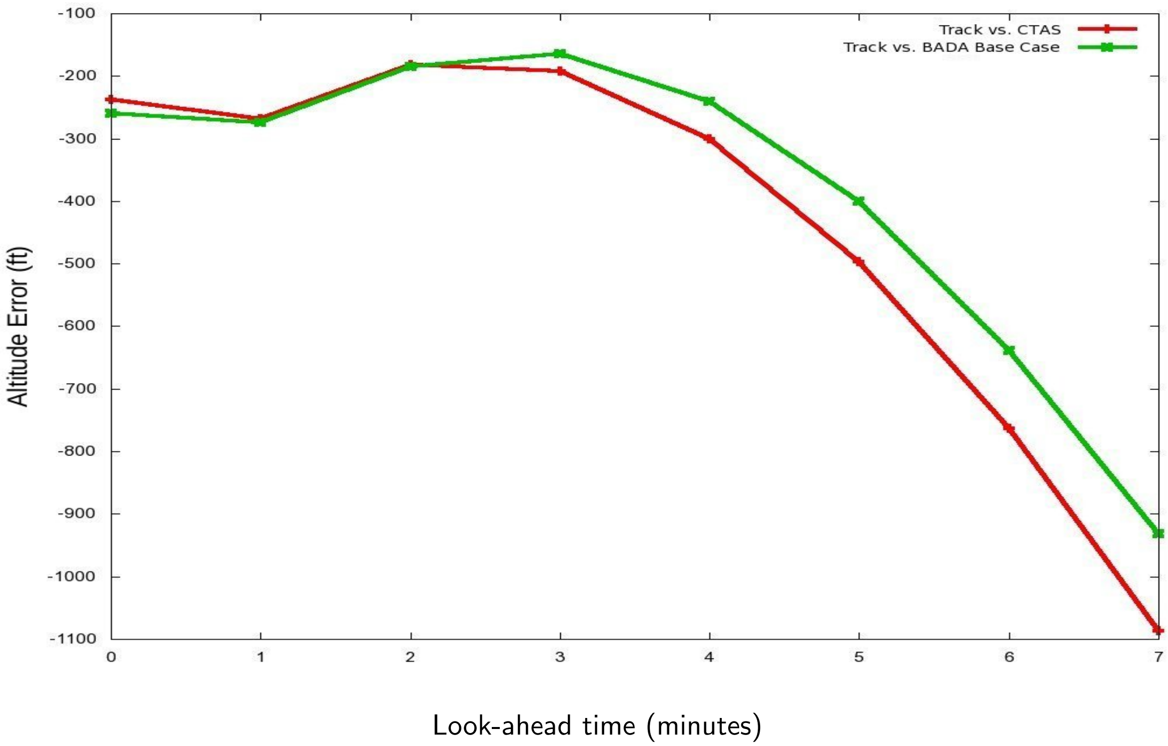

Figure 18. Interval-based sampling, mean altitude error during descent

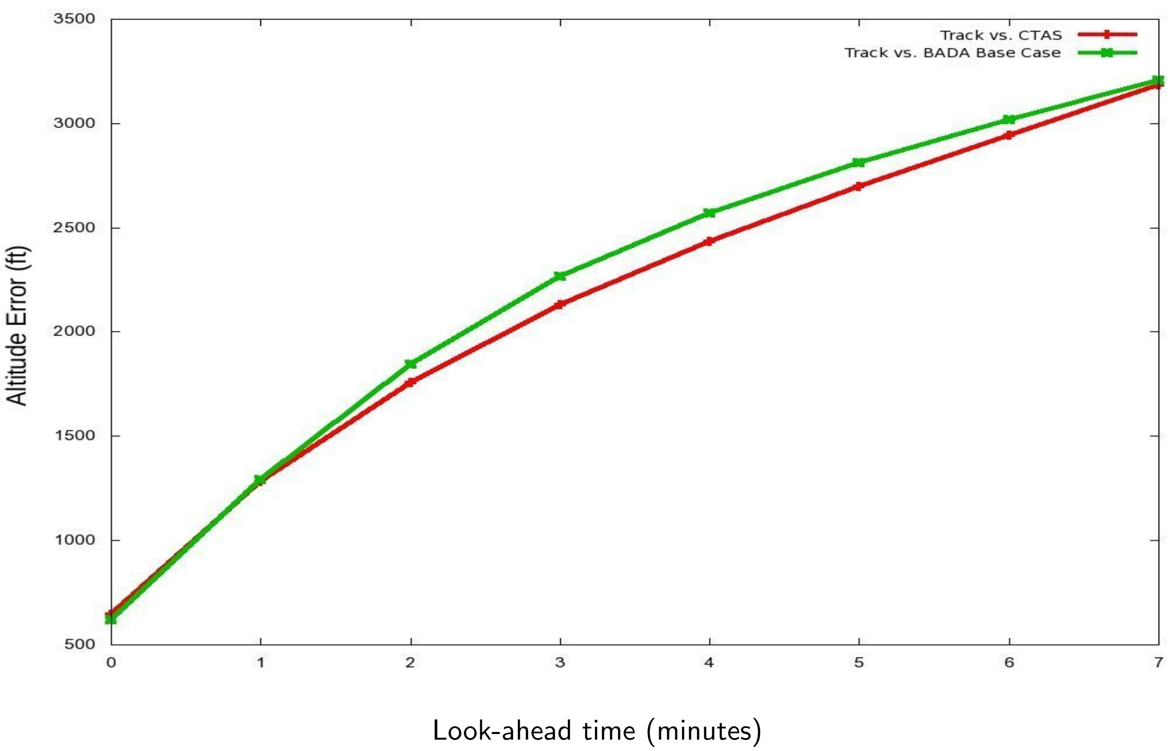

Figure 19. Interval-based sampling, mean absolute altitude error during descent

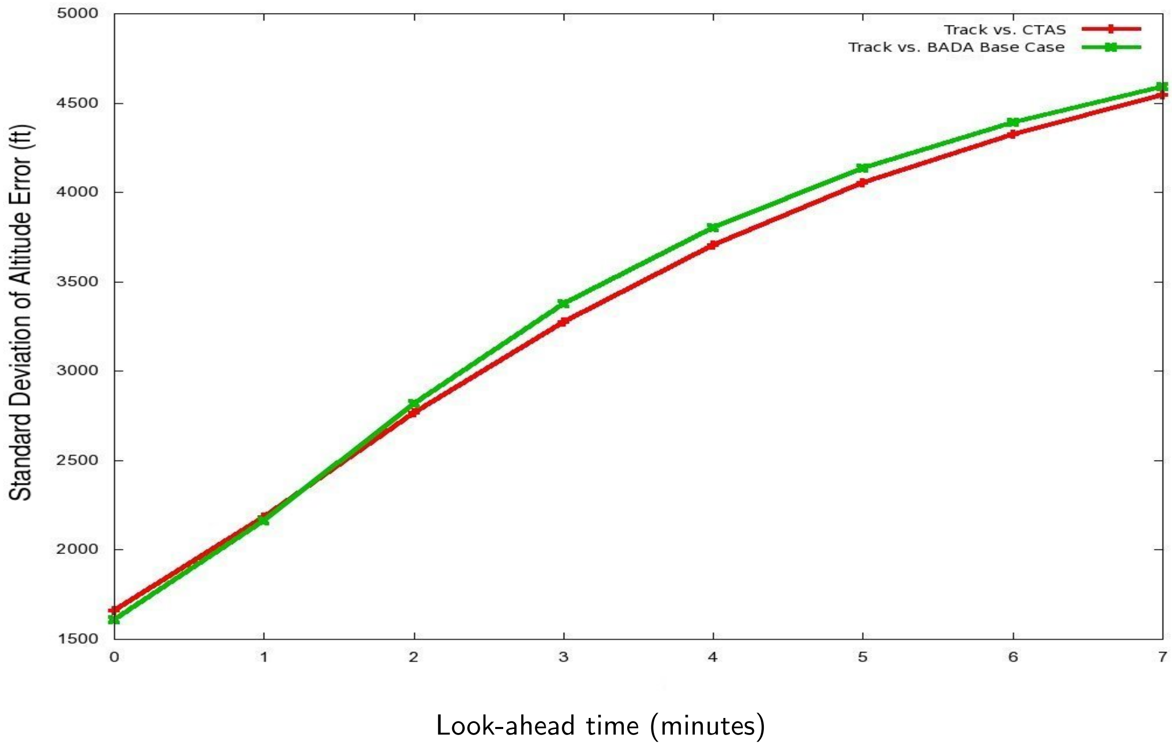

Figure 20. Interval-based sampling, standard deviation of altitude error during descent

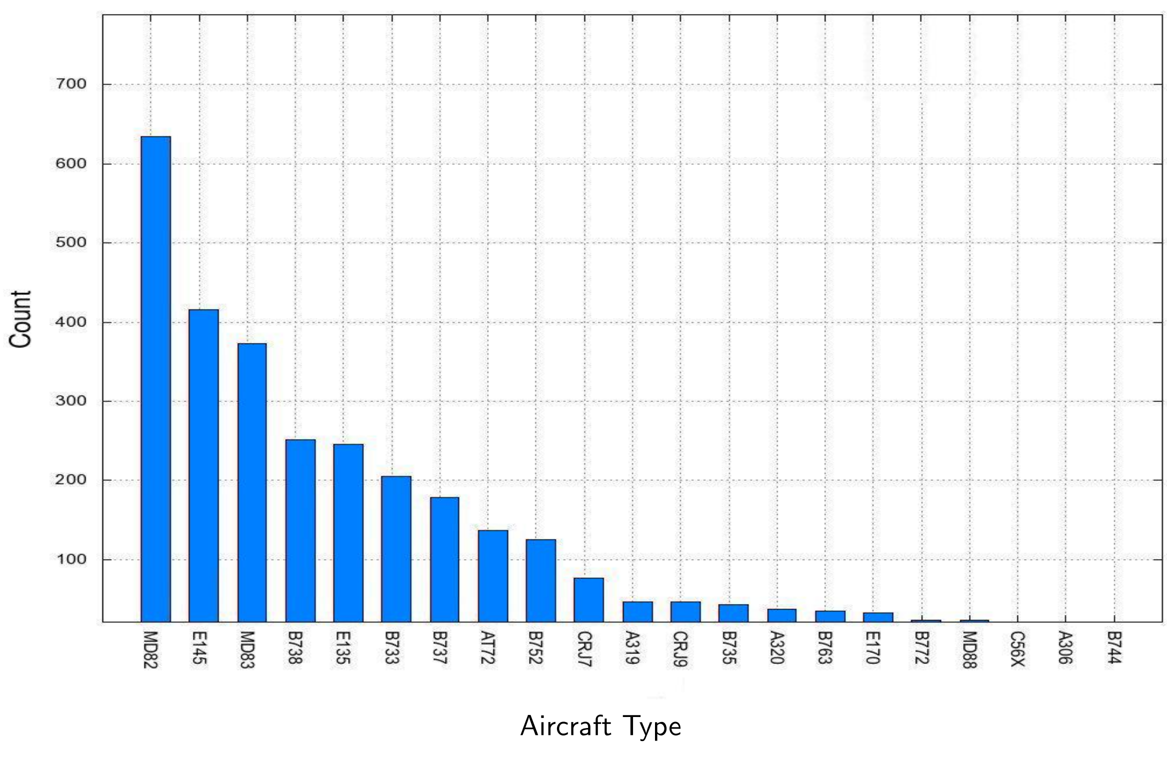

Figure 21. Most frequent aircraft types for samples with more than 10 flights in TRACON

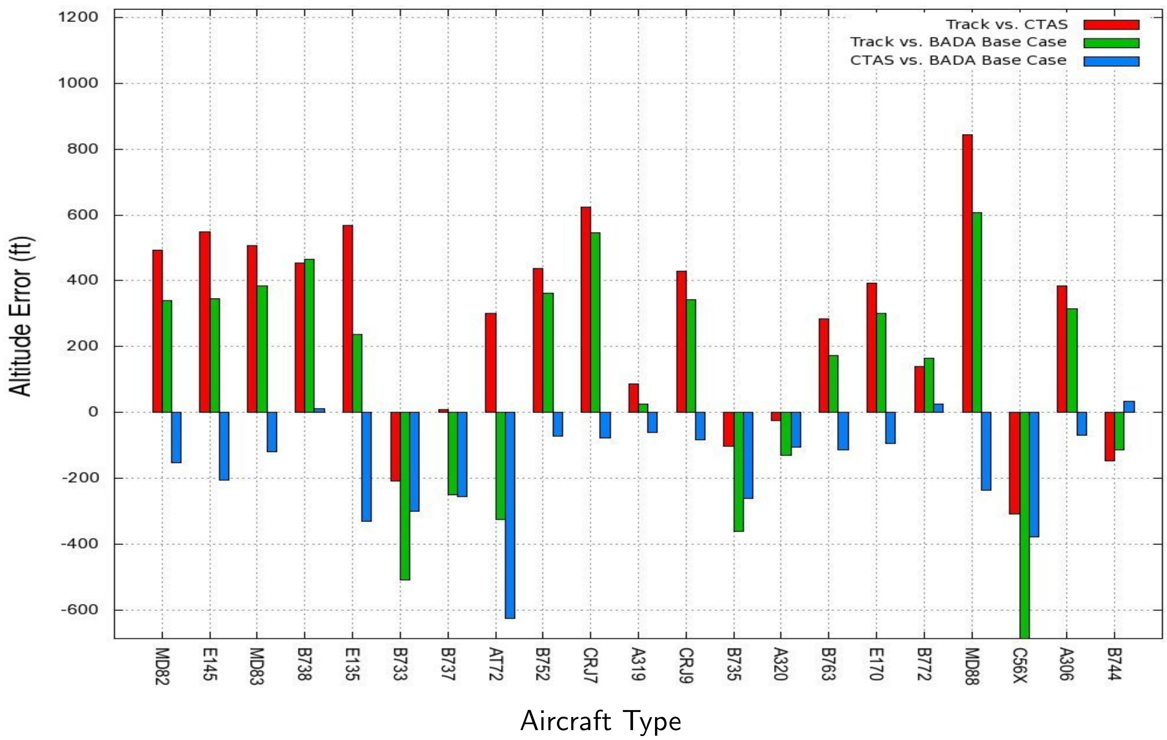

Figure 22. Mean of mean altitude errors, TRACON only

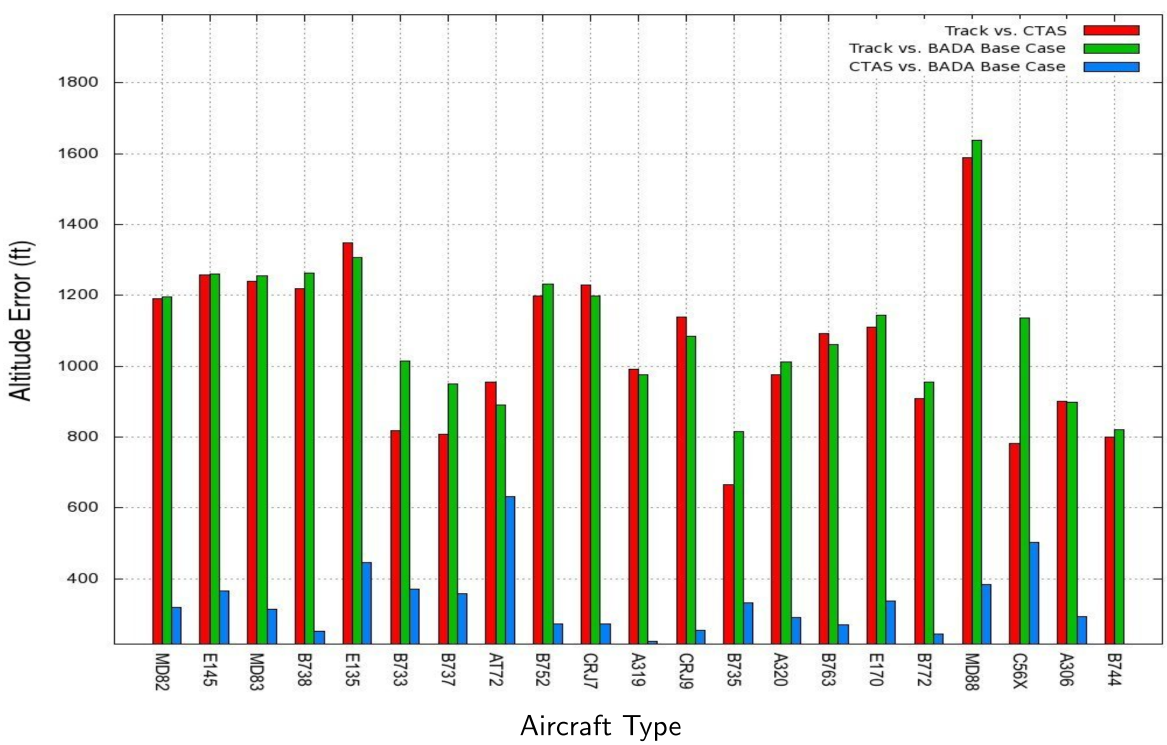

Figure 23. Mean of absolute mean altitude errors, TRACON only

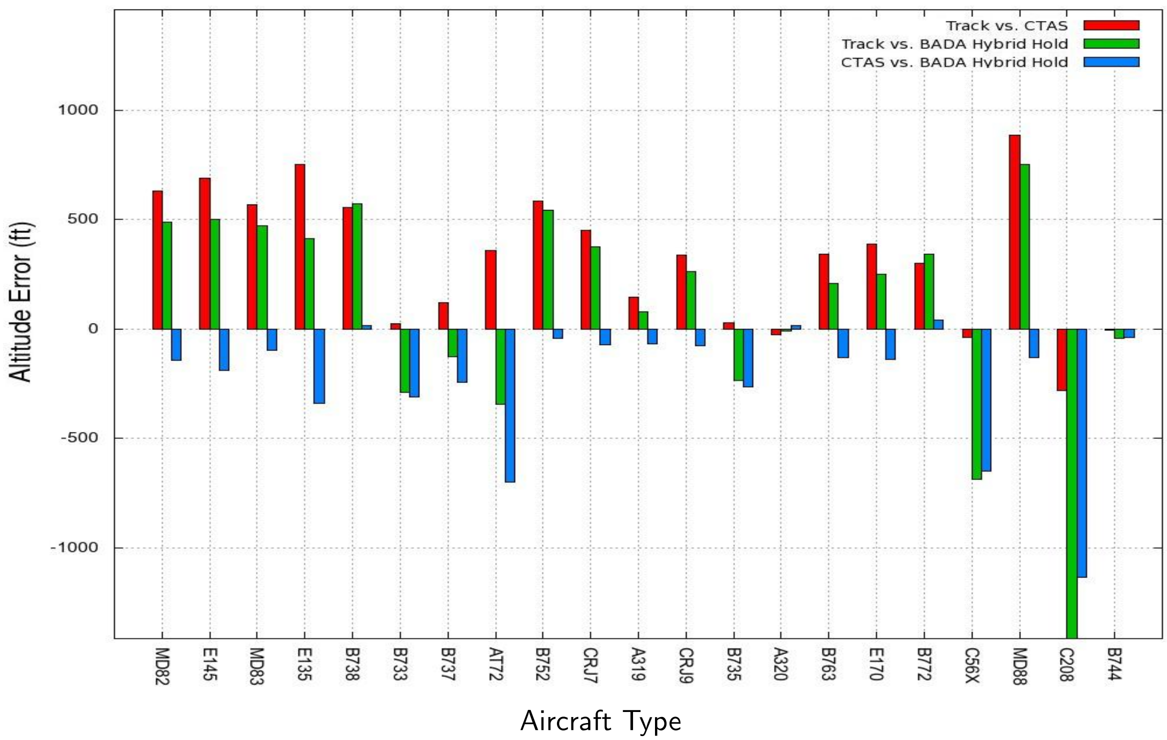

Figure 24. Mean of mean altitude errors for BADA Hybrid Hold, TRACON only

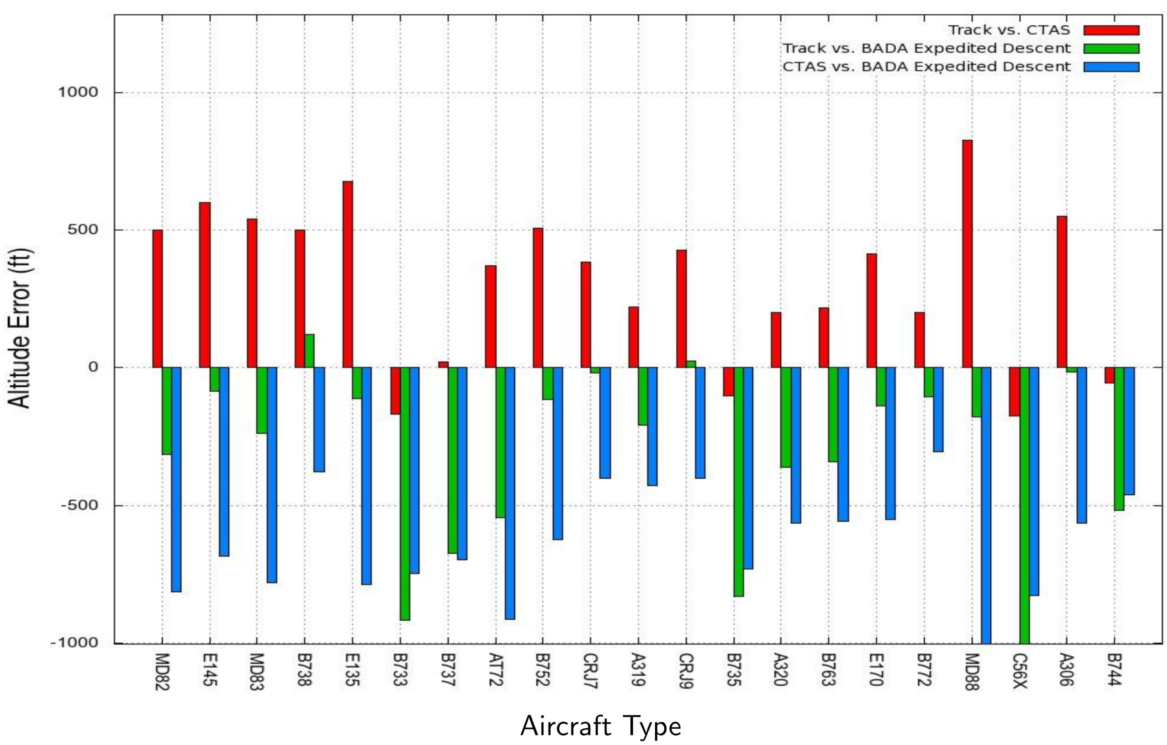

Figure 25. Mean of mean altitude errors for BADA Expedited Descent, TRACON only

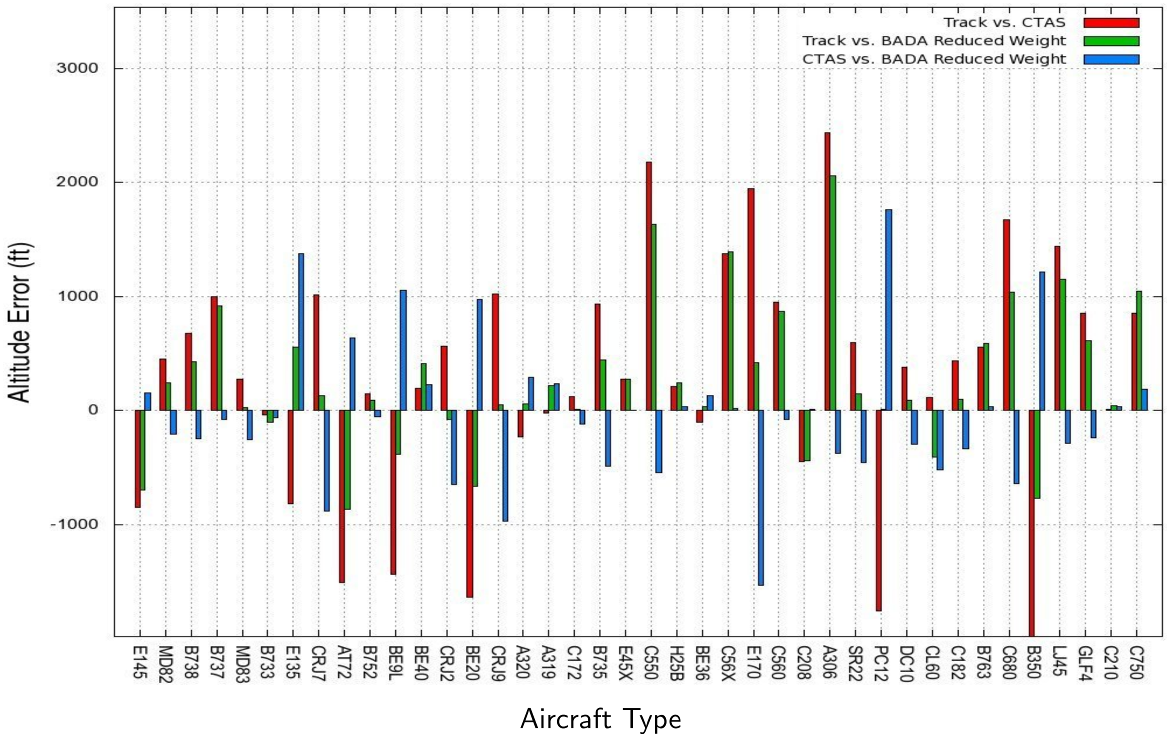

Figure 26. Mean of mean altitude errors in climb, BADA Reduced Weight

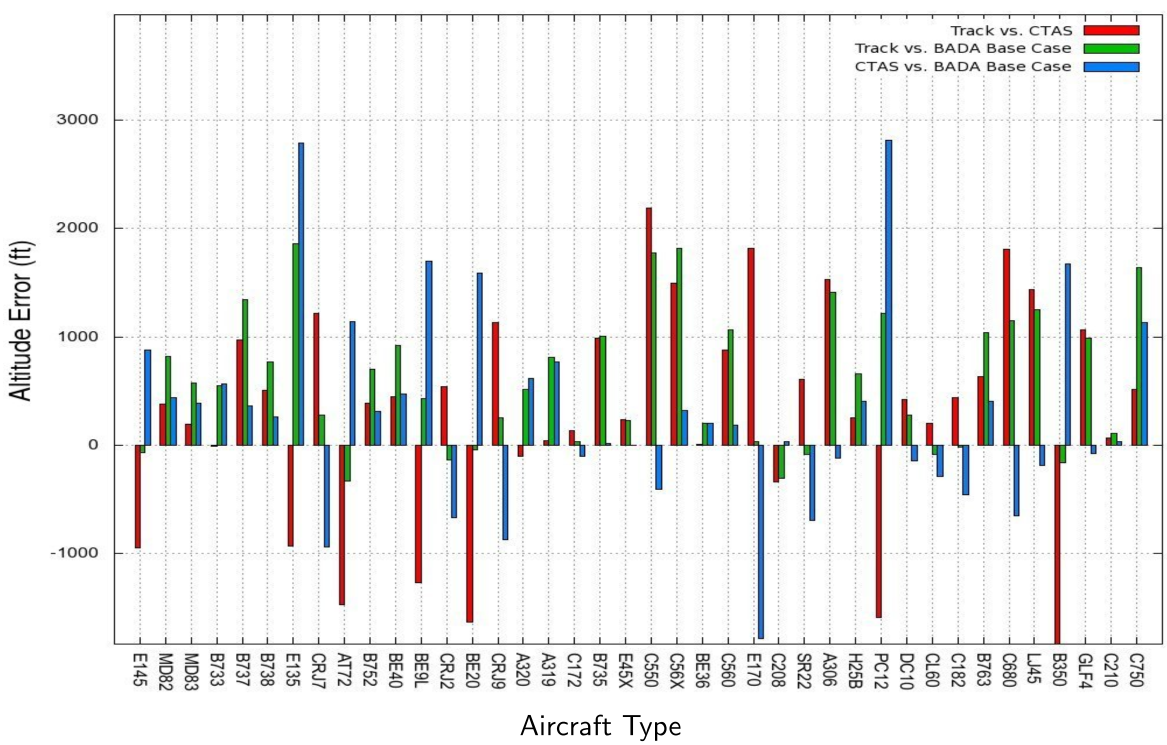

Figure 27. Mean of mean altitude errors in climb, BADA Nominal Weight

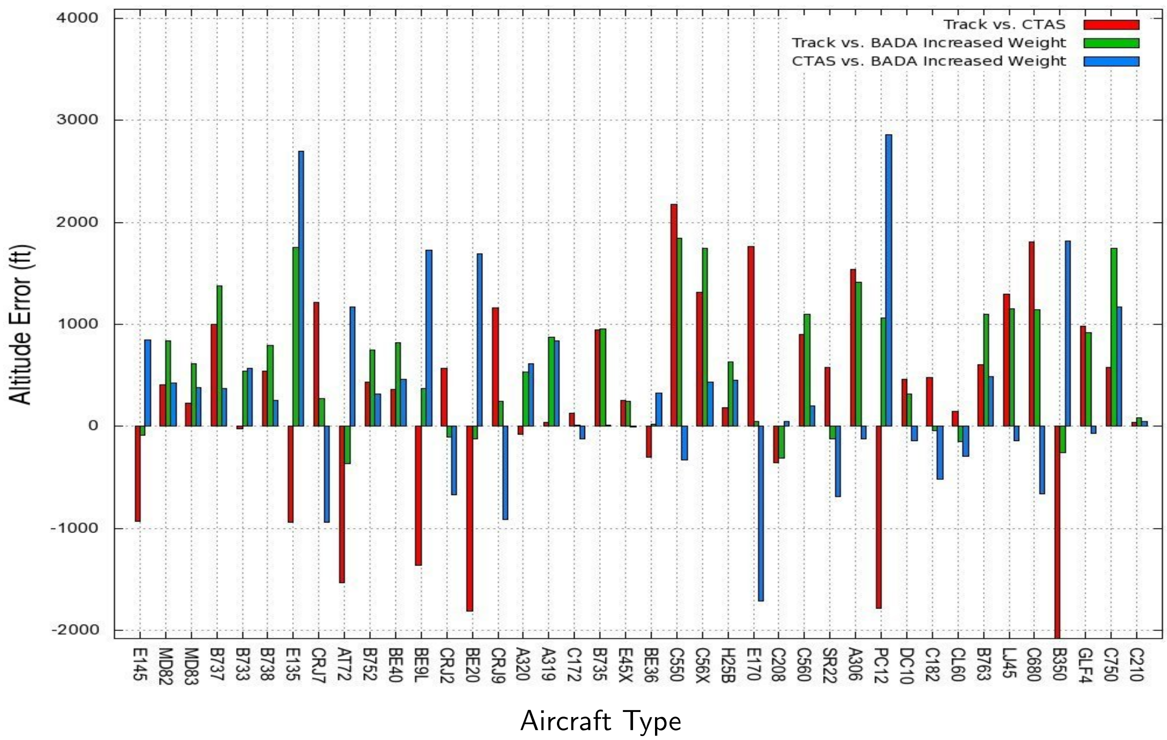

Figure 28. Mean of mean altitude errors in climb, BADA Increased Weight

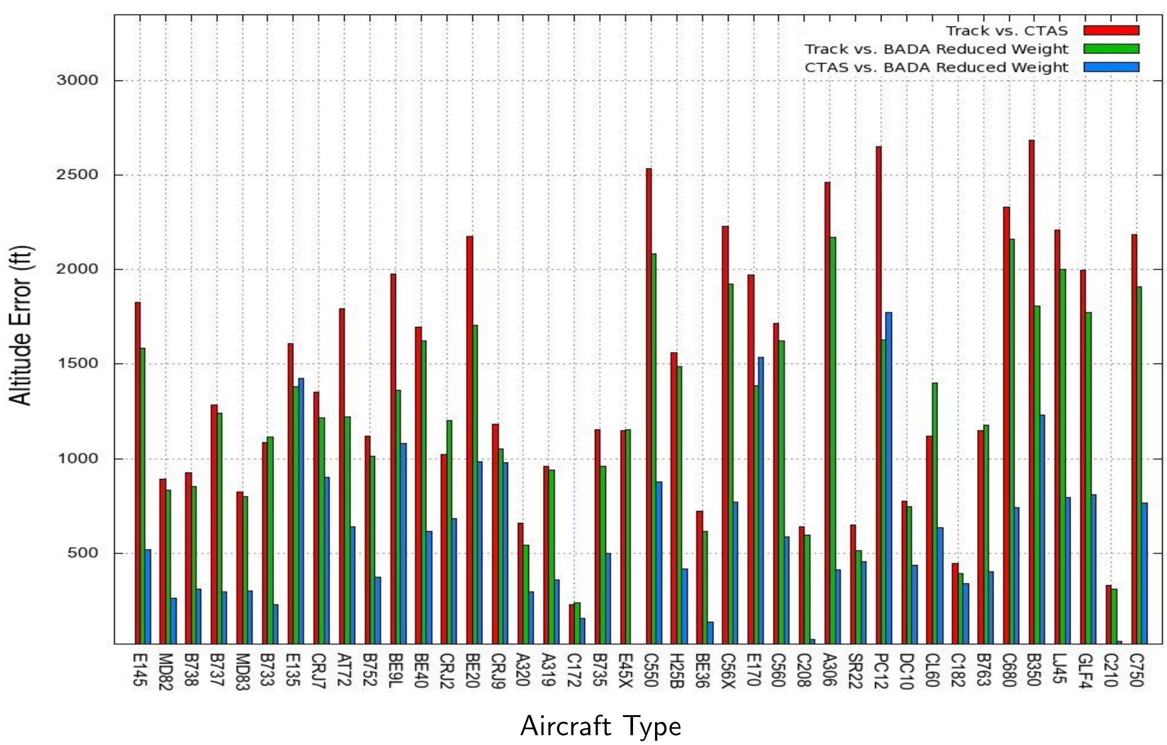

Figure 29. Mean of absolute mean altitude errors in climb, BADA Reduced Weight

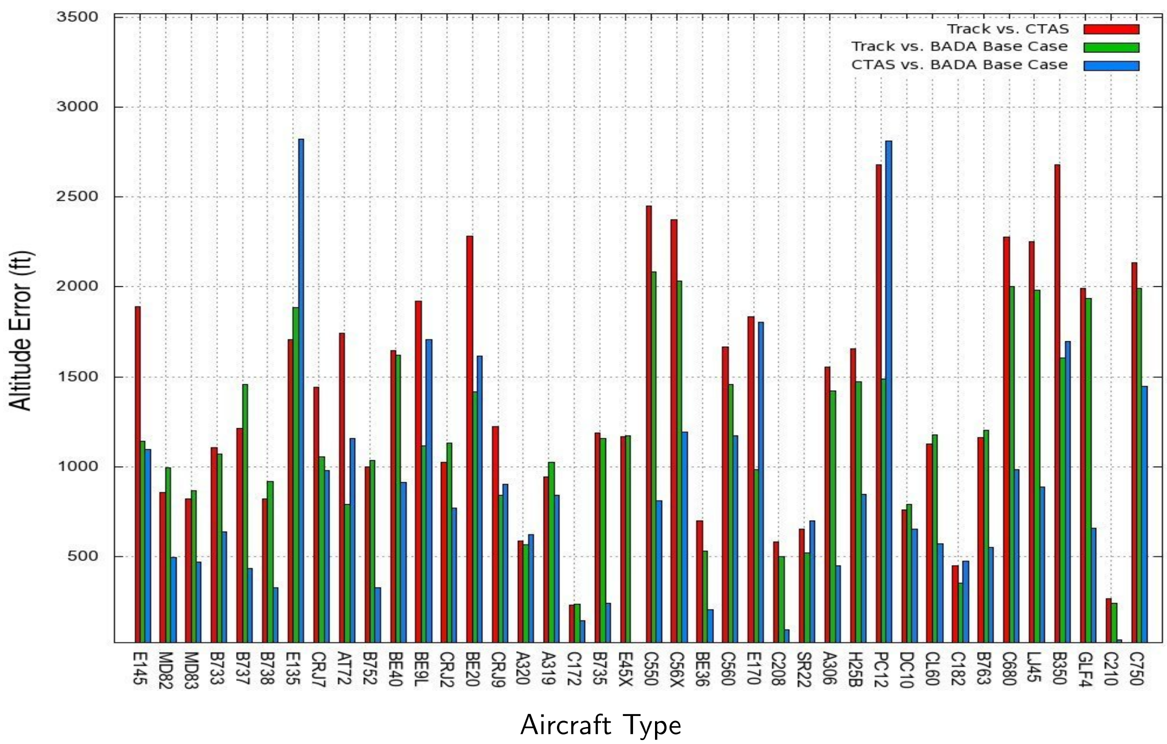

Figure 30. Mean of absolute mean altitude errors in climb, BADA Nominal Weight

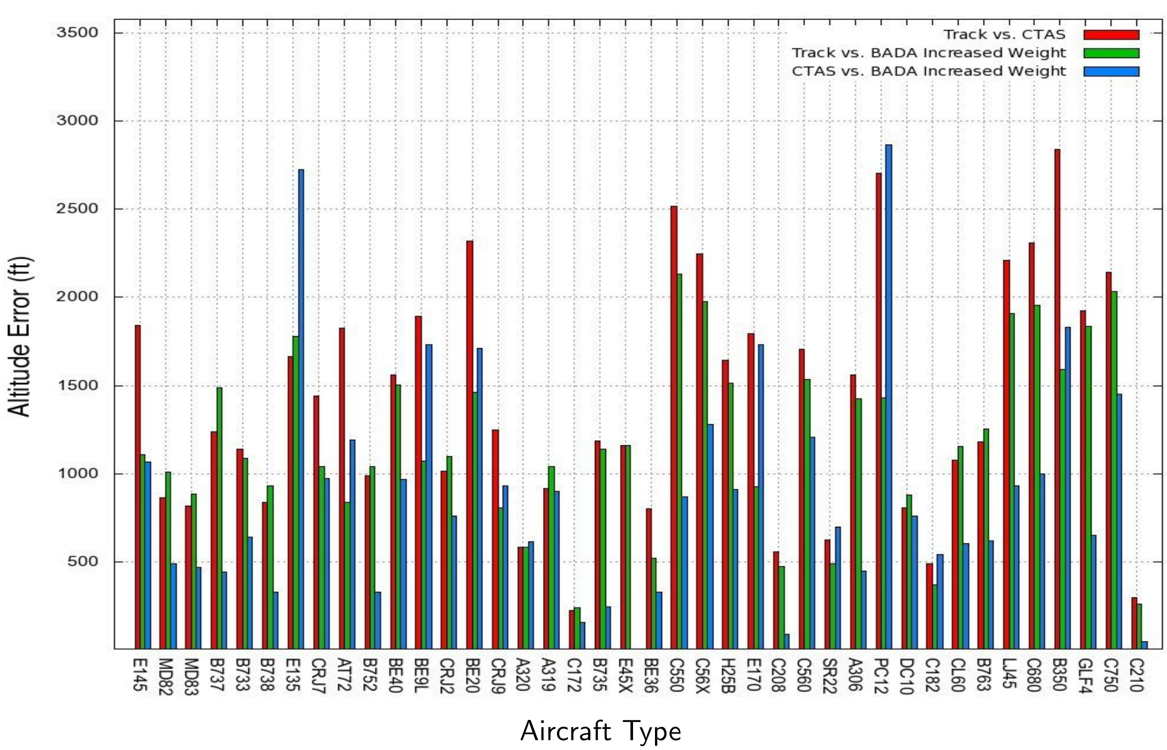

Figure 31. Mean of absolute mean altitude errors in climb, BADA Increased Weight

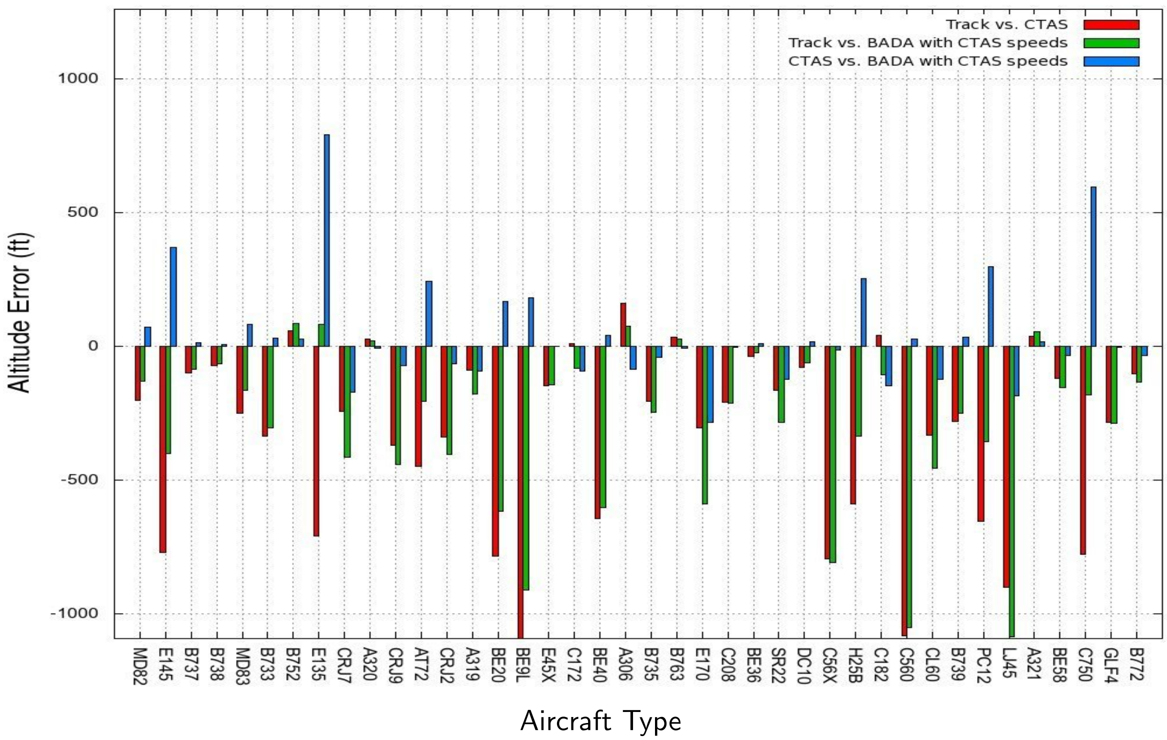

Figure 32. Mean of mean altitude errors for BADA with CTAS speeds

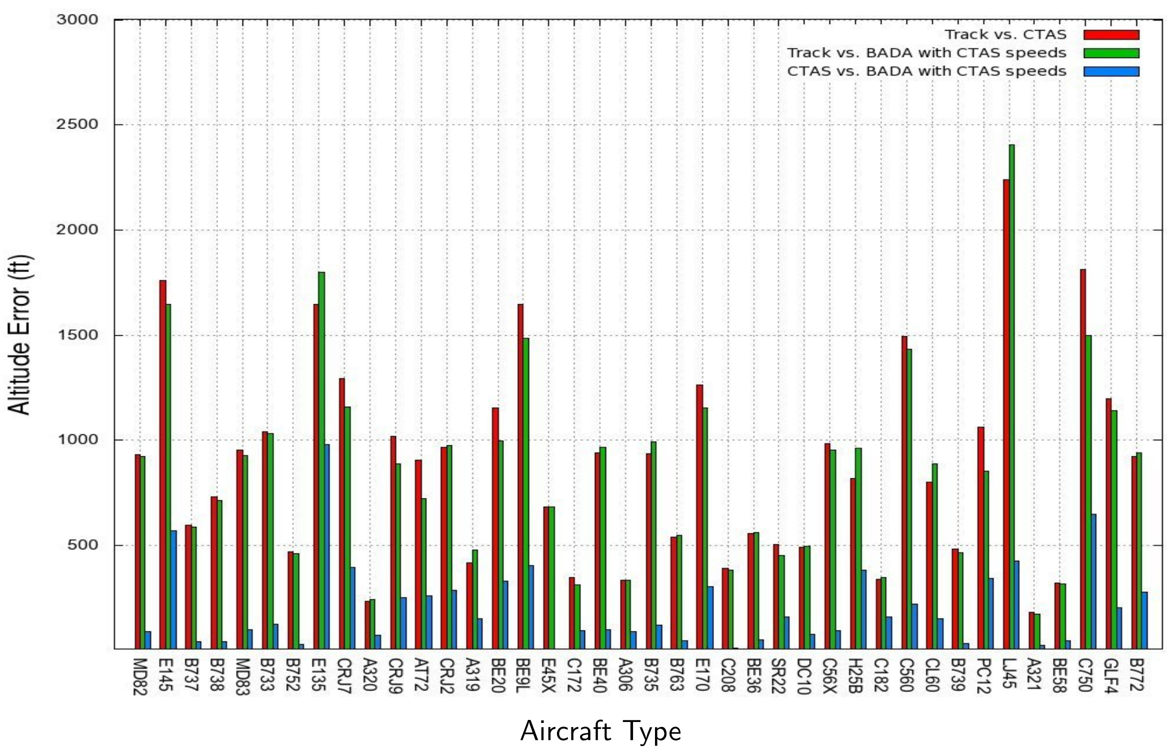

Figure 33. Mean of absolute mean altitude errors for BADA with CTAS speeds

Moreover, for aircraft types with largest altitude errors in CTAS, such as E145, E135, BE20, and BE9L, the BADA with CTAS speeds yields substantially better accuracy. These results demonstrate that the BADA APM is superior for the vast majority of aircraft types, and especially for smaller aircraft types, such as E145 and E135. At the same time, comparison of these plots with Figures 6 and 7 does not show significant advantage of using BADA speeds (e.g. Base case variant) over CTAS speeds in terms of altitude accuracy.

5.2 Los Angeles Center (ZLA), 1 day

Using the same methodology, the radar track data for 1 day of traffic in Los Angeles center (ZLA) were compared with CTAS TS and BADA Hybrid Hold predictions.

Table 5 summarizes results obtained from these comparisons:

Table 5. Mean altitude and along-track errors for BADA Hybrid Hold for Los Angeles center

Error type	Comparison	Abs Max	Mean	Abs Mean	Max	Min	Std Dev
Altitude (ft)	CTAS vs. Track	25960	797	1966	22475	-25960	3507
	BADA vs. Track	25598	863	1963	19756	-25598	3492
Along-track (nm)	CTAS vs. Track	122.47	3.66	7.35	54.26	-122.47	8.9
	BADA vs. Track	125.94	3.83	6.73	51.59	-125.94	8.37

For this center BADA does not have clear advantages over CTAS in terms of altitude and along-track errors. This can be partially explained by the different aircraft type decomposition with most frequent aircraft type B737 rather than MD82, as evident from Figure 34.

The results plotted on Figures 35 and 36 show that for this center BADA clearly outperforms CTAS in terms of altitude errors for A319, CRJ7, and CRJ9.

In TRACON area, BADA altitude errors are much lower in comparison with CTAS only for two aircraft types - A319 and CRJ2, and consistently higher for all other aircraft as becomes apparent from Figures 37 and 38.

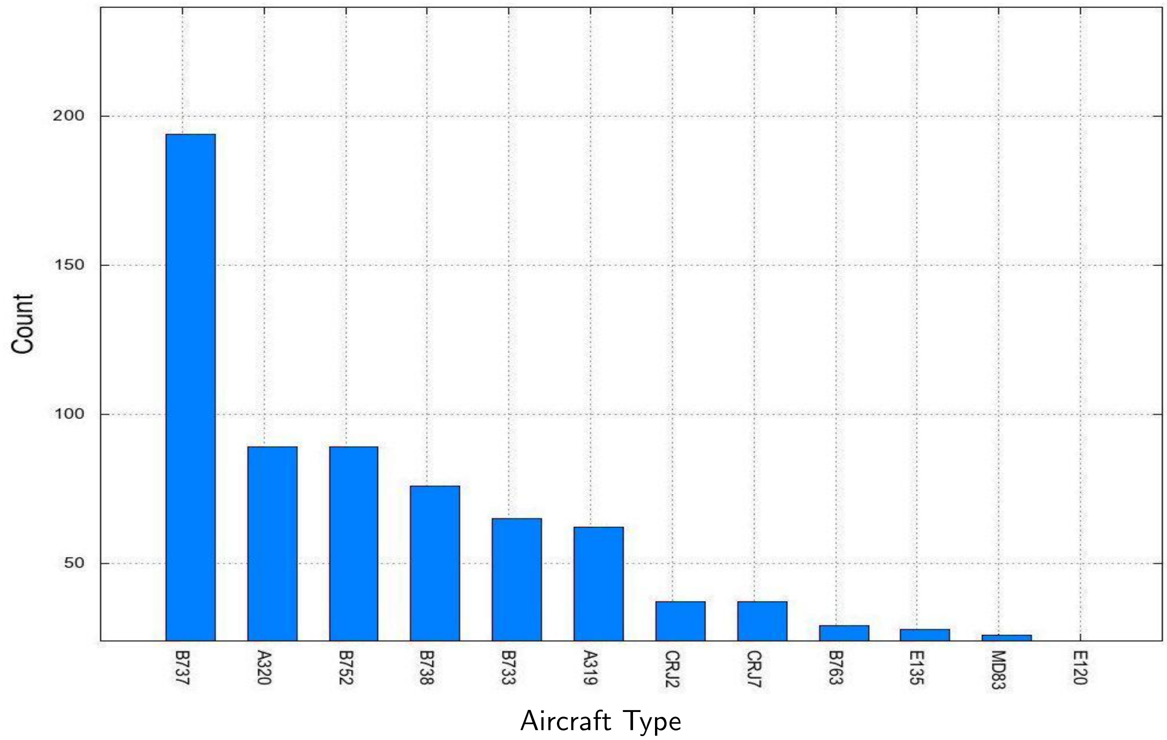

Figure 34. Most frequent aircraft types for samples with more than 10 flights in Los Angeles center

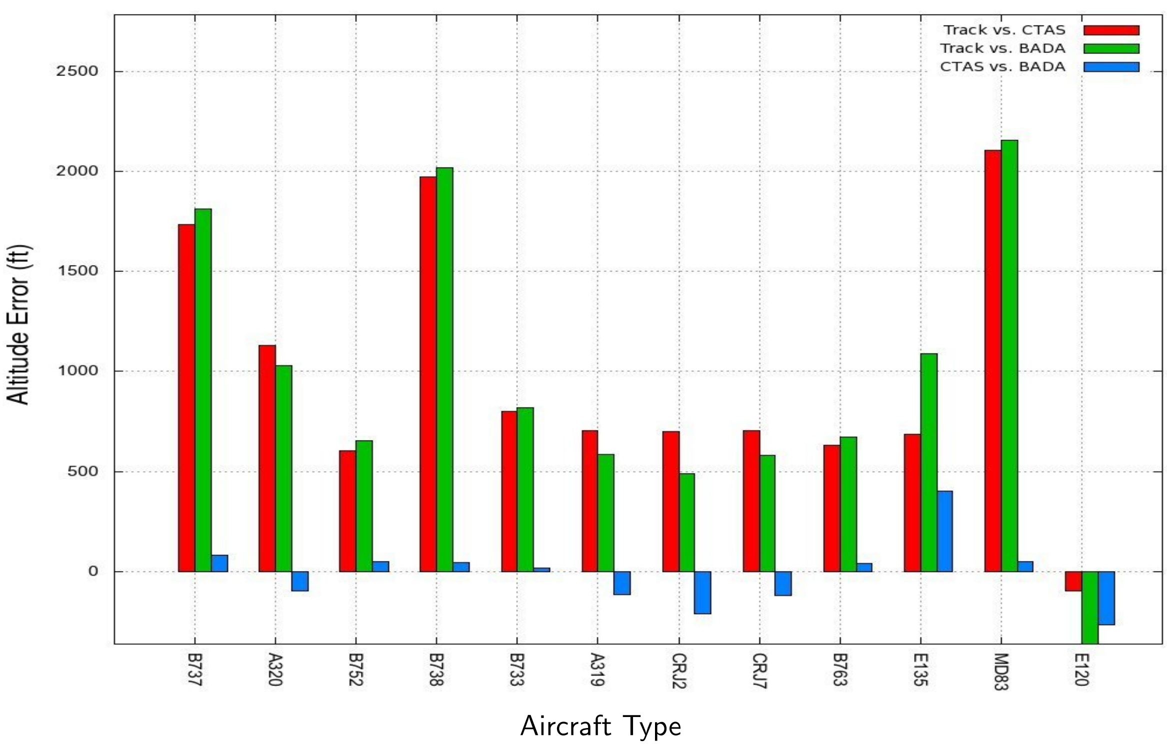

Figure 35. Mean of mean altitude errors in Los Angeles center

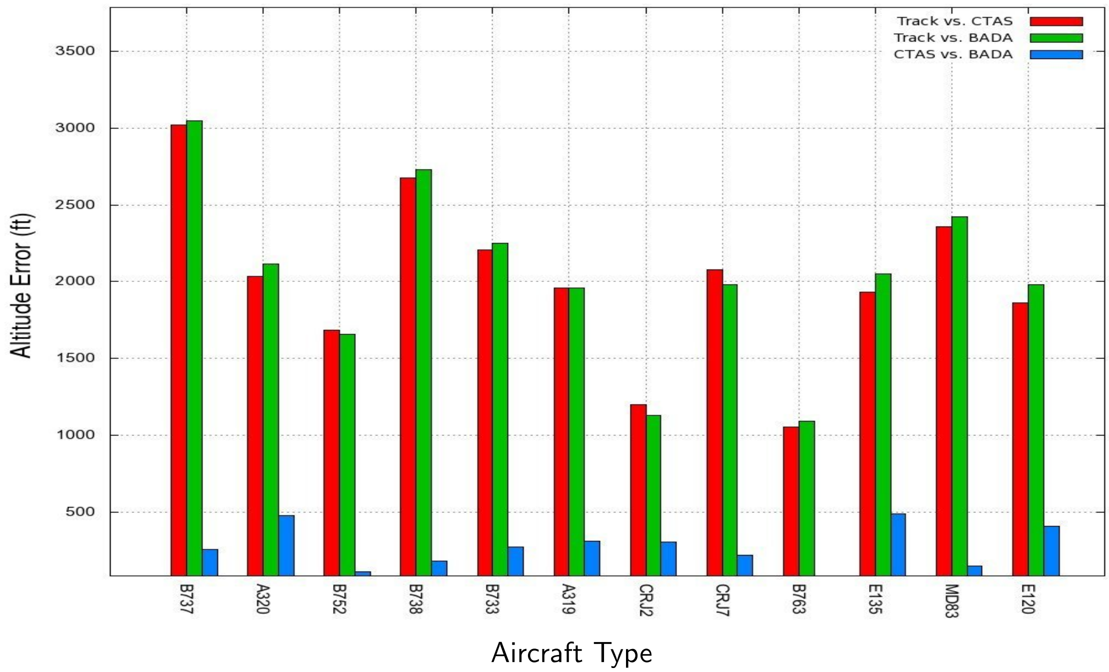

Figure 36. Mean of absolute mean altitude errors in Los Angeles center

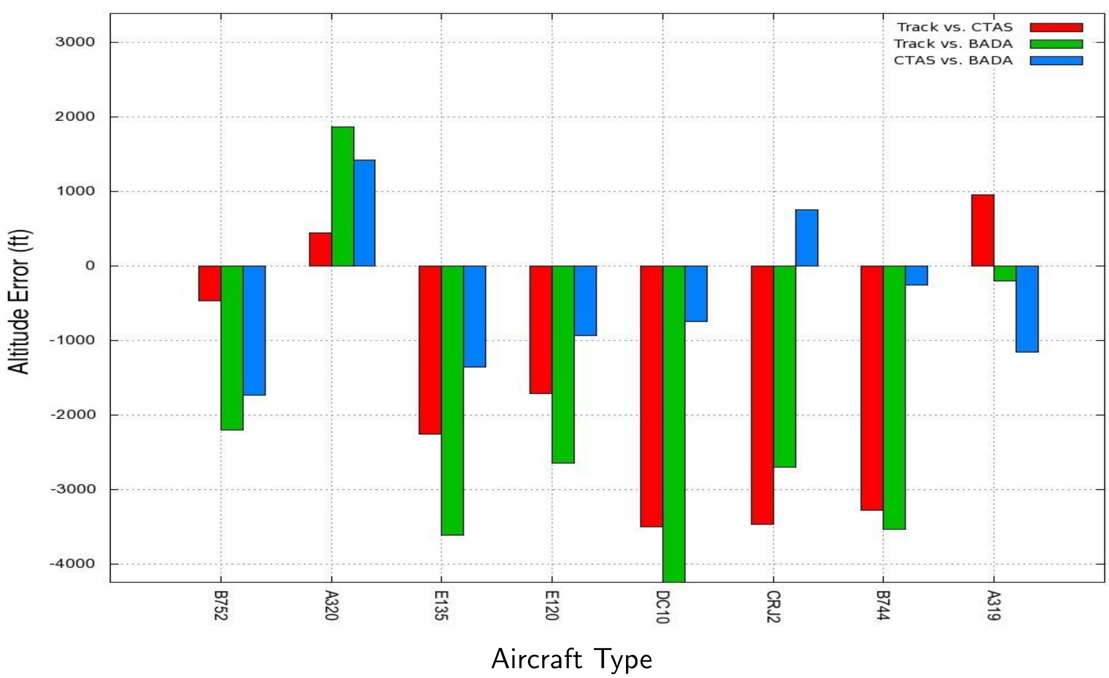

Figure 37. Mean of mean altitude errors in Los Angeles center, TRACON only

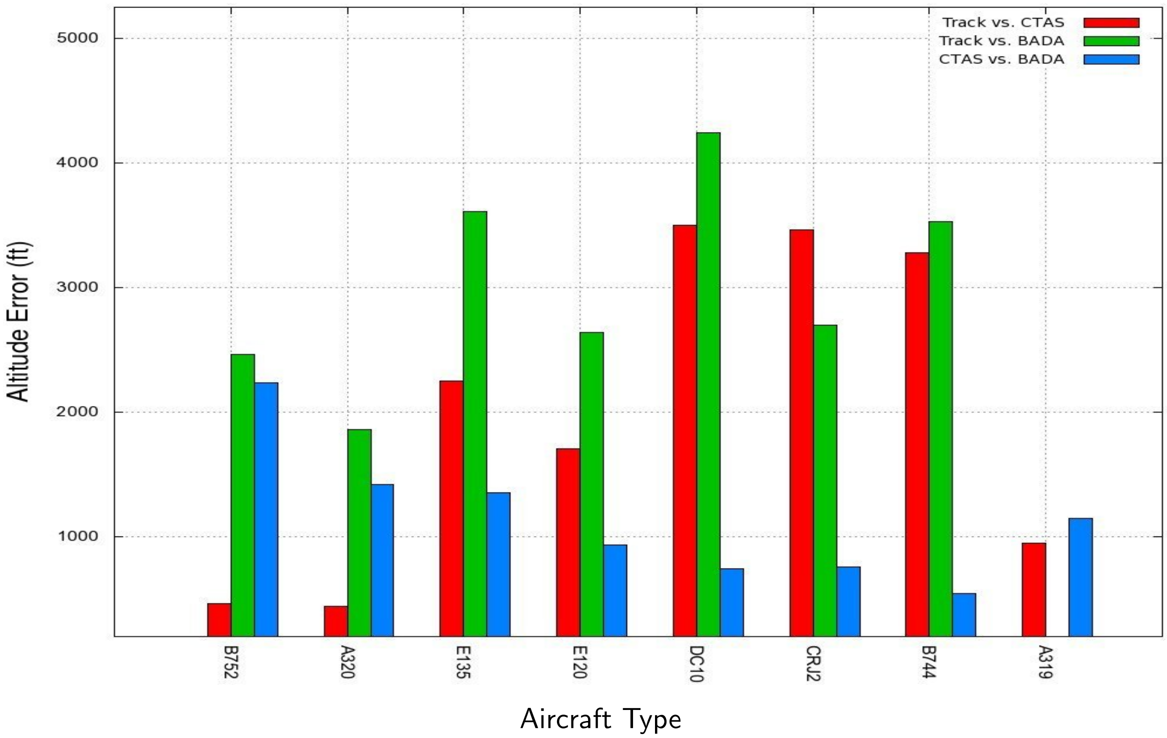

Figure 38. Mean of absolute mean altitude errors in Los Angeles center, TRACON only

5.3 Denver Center (ZDV), 5 days

This sub-section discusses the performance of the BADA Hybrid Hold variant against CTAS APM for January 31st through February 4th 2011 in Denver Center. This time period was characterized by variable weather, including days with rain and snow, low ceilings, and strong winds. Therefore, it was important to verify whether the comparison results for these conditions are consistent with results for two other centers presented above.

Table 6 summarizes the comparison results for Denver center:

Table 6. Mean altitude and along-track errors for BADA Hybrid Hold for Denver center

Error type	Comparison	Abs Max	Mean	Abs Mean	Max	Min	Std Dev
Altitude (ft)	CTAS vs. Track	22156	-52	524	22156	-17490	1383
	BADA vs. Track	23969	-64	534	23969	-17688	1414
Along-track (nm)	CTAS vs. Track	138.23	1.76	3.42	105.46	-138.23	4.84
	BADA vs. Track	138.38	2.02	3.22	105.46	-138.38	4.37

Clearly for this center BADA does not have any advantages over CTAS in terms of altitude errors, and it shows only minor improvements in terms of along-track errors.

Once again, Figure 39 shows a different type decomposition; the most frequently observed aircraft types were the B737, A320, B752, and A319.

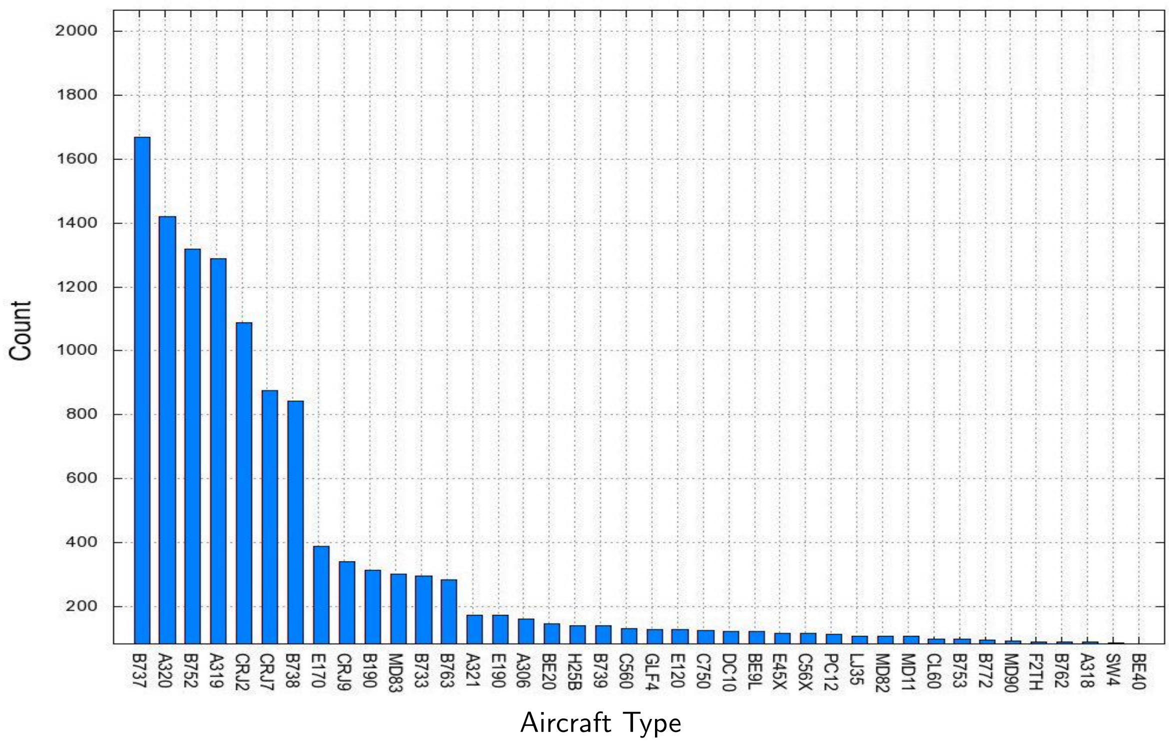

Figure 39. Most frequent aircraft types in Denver center

Figures 40 and 41 show uneven results for altitude errors, with BADA being substantially more accurate for several aircraft types (CRJ7, E170, B190, BE20, C750, MD82, BE9L), and CTAS much more accurate for other aircraft types (CRJ2, C560, C56X, E120, LJ35). However, the overall BADA performance is affected by the fact that BADA is a little less accurate for the four aircraft types most frequently observed in Denver center: B737, A320, B752, and A319.

It is interesting to note that BADA is much more accurate than CTAS in predicting TOC for the vast majority of the most frequently observed aircraft types. This is consistent with results for Los Angeles Center and for several BADA variants for Fort Worth Center as well (compare, for instance, Figure 9 with Figure 42).

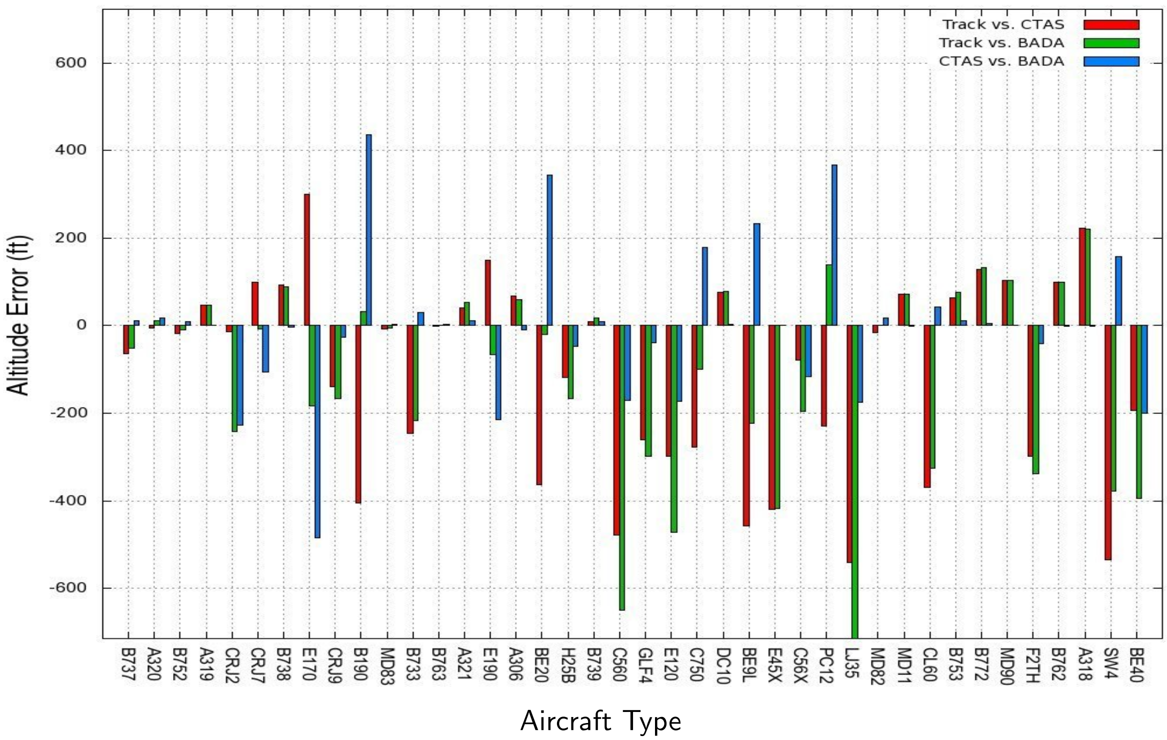

Figure 40. Mean of mean altitude errors in Denver center

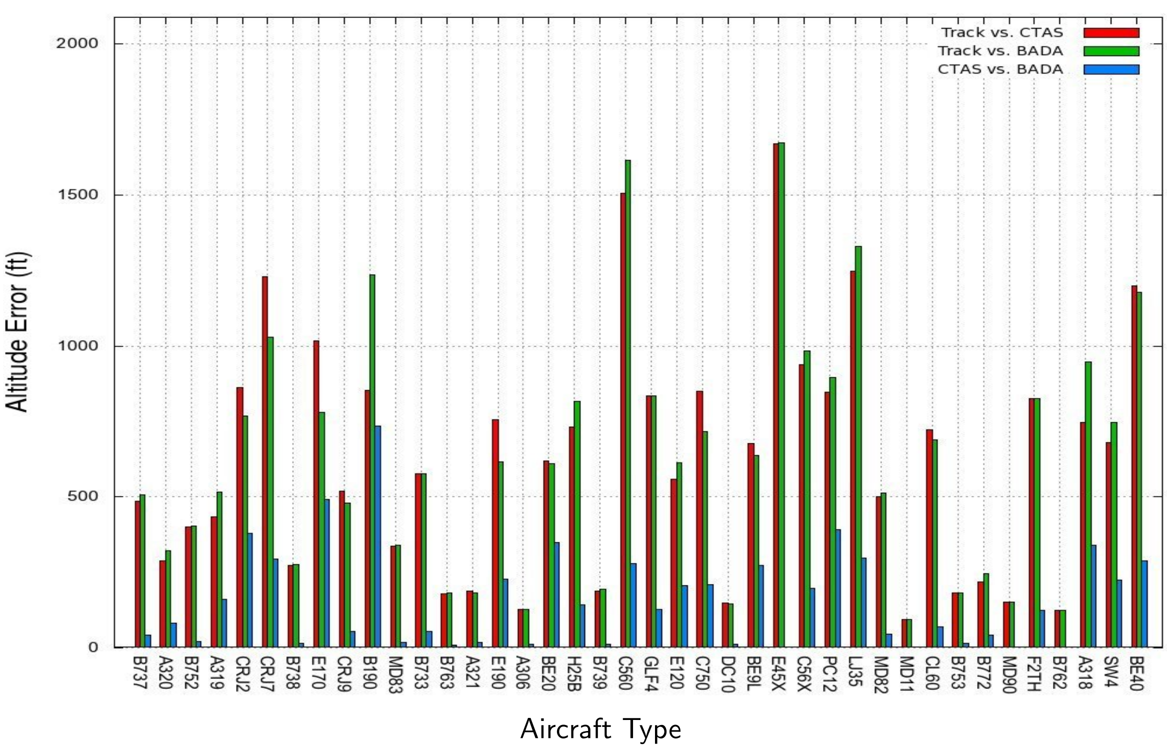

Figure 41. Mean of absolute mean altitude errors in Denver center

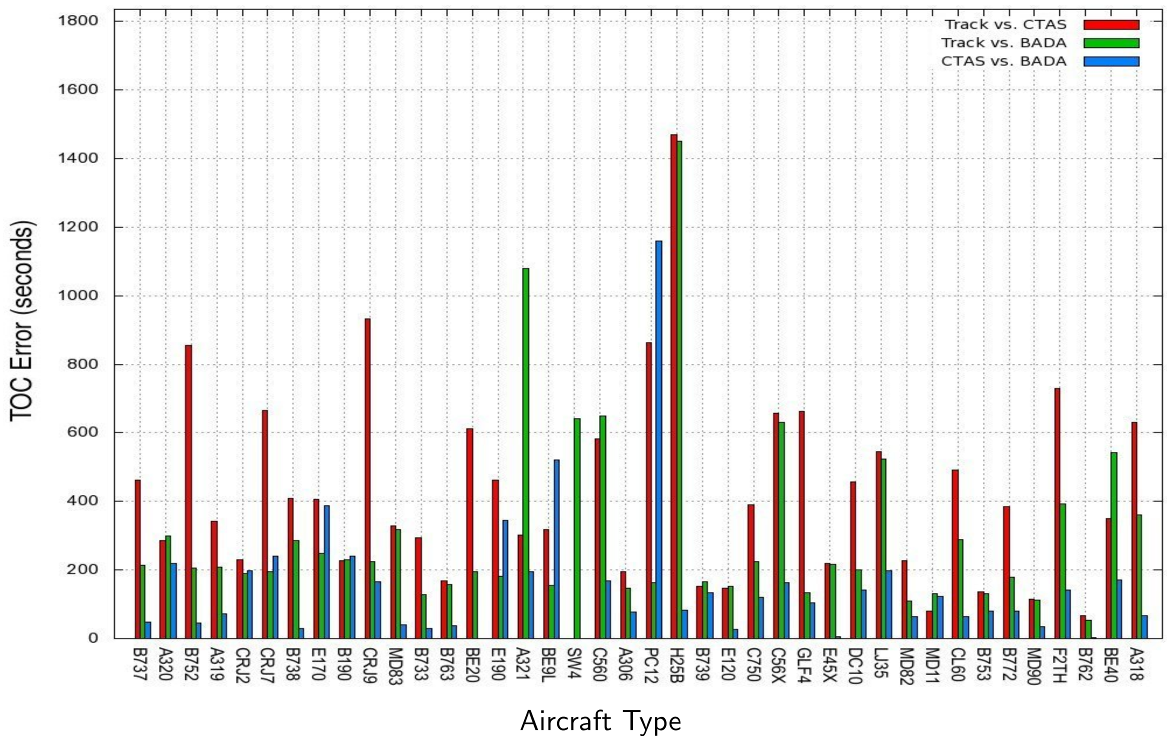

Figure 42. Mean of absolute mean TOC time errors in Denver center

5.4 Off-nominal conditions, Denver 2009

We could have seen already from comparison between Figures 24 and 22 that the BADA Hybrid Hold variant showed a similar or even better performance than the BADA Base case. This finding could be seen as an indirect evidence of relative insensitivity of BADA accuracy to limited deviations from nominal BADA speeds, allowed by BADA Hybrid Hold speed profile.

However, it was desirable to study the effect of off-nominal speeds for better controlled conditions with reduced uncertainty in aircraft weight, speed, and pilot intent. This was done by utilizing the data collected in Denver in 2009, which included descending flights performed according to predefined descent profiles. The data set for Denver-2009 included, in addition to cm_sim files with radar tracks, the weather Rapid Update Cycle (RUC) files, the data for advisory descent speeds and, for some flights, the actual descent weights. This is the same data set that was used in study [11].

We used for this analysis the CmSimTrackComparer tool, which generated the predictions and calculated their errors for all tracks from cm_sim files for the filtered set of flights. Filtering was necessary for two reasons:

- The flights with missing/inconsistent data, e.g. all flights not listed in the input files given to us for Denver-2009 data set, had to be excluded,
- CmSimTrackComparer does not parse the route from the flight plan, so the flights with cross-track error exceeding 10 nm were filtered out in order to analyze only the flights close

to direct-to routes.

After this filtering our analysis included more than 40 thousand predictions for 256 flights.

Tables 7 and 8 summarize the comparison results for path- and time-based correlations:

Table 7. Mean altitude errors (ft), path-based correlations

Test case	Abs Max	Mean	Abs Mean	Max	Min	Std Dev
CTAS TS	11667	-192	505	11667	-5113	760
BADA Hybrid Hold	11528	-433	563	11528	-10608	759
BADA Base Case	10276	-960	1014	10276	-5987	815

Table 8. Mean altitude errors (ft), time-based correlations

Test case	Abs Max	Mean	Abs Mean	Max	Min	Std Dev
CTAS TS	21426	-427	846	21426	-4527	1158
BADA Hybrid Hold	21515	-673	930	21515	-13799	1136
BADA Base Case	20981	-632	1099	20981	-5404	1330

As can be seen from these tables, the altitude errors for time-based correlations are significantly higher than for path-based correlations. This is not surprising because location and altitude of the final prediction point in our analysis were determined from the meterfix position and crossing altitude, while the meterfix crossing time was affected by along-track errors.

However, even for path-based correlations the BADA Base case is substantially less accurate than CTAS or BADA Hybrid Hold. This is explained by the fact that ignoring the commanded descent, descent and control speeds results in inaccurate TOD positions and hence in large altitude errors. This can be illustrated by plots for one flight of Boeing 757-200 aircraft, shown on Figures 43 and 44.

It is interesting to note that the BADA Hybrid Hold model performs almost as well as the CTAS model, with the mean absolute altitude error and standard deviation of altitude error being slightly larger. This can be explained by noting that the advised descent and initial Mach do not differ much from the BADA recommended speeds, hence the altitude profile becomes more accurate. This can be observed from the plots shown on Figures 45 and 46 for the same flight.

Further analysis is required to determine if BADA accuracy will suffer for off-nominal conditions. These limited results indicate that the performance of BADA APM in idle descents may be similar or slightly worse in comparison with CTAS APM for advised speeds that do not differ significantly from the BADA advised speeds.

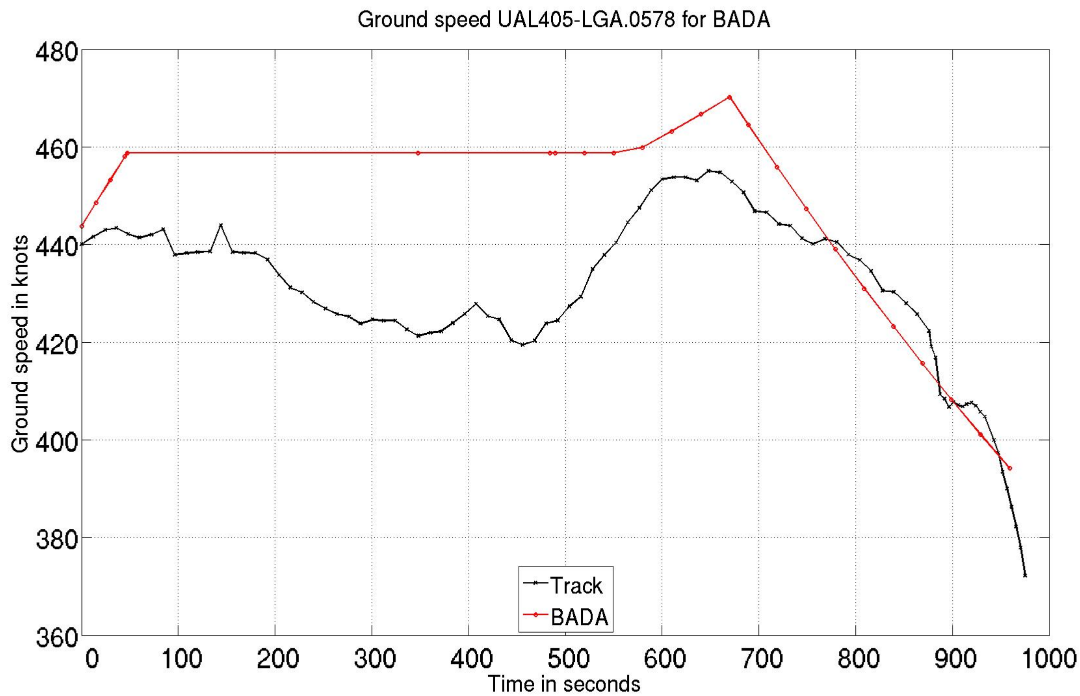

Figure 43. Boeing 757-200 BADA Base Case idle descent: ground speed

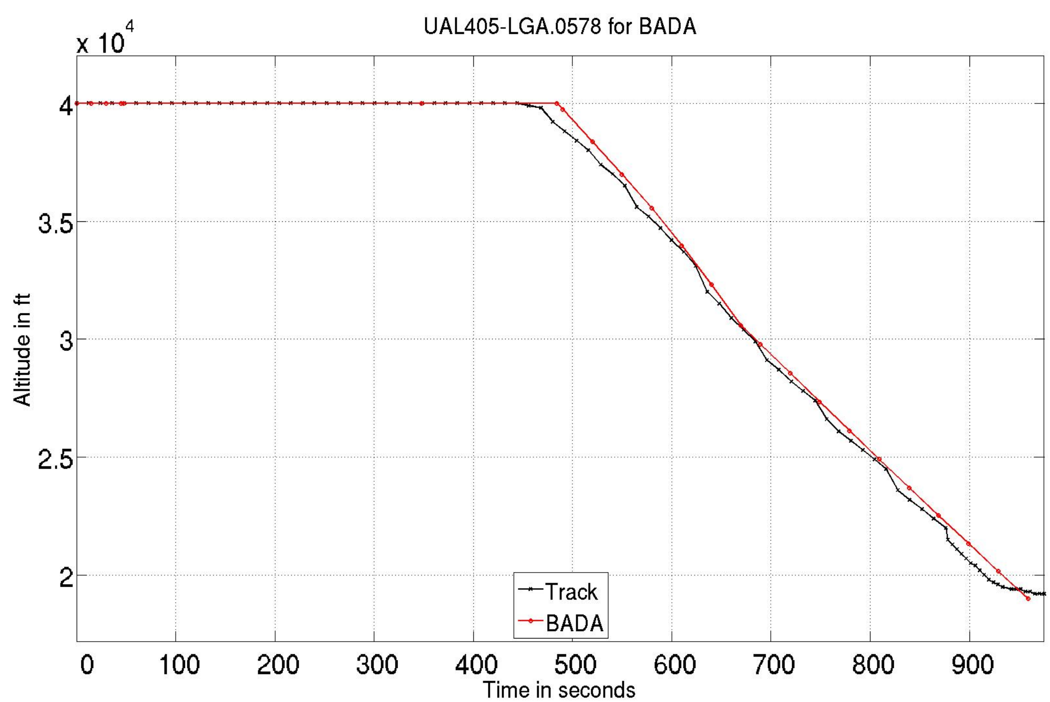

Figure 44. Boeing 757-200 BADA Base Case idle descent: altitude

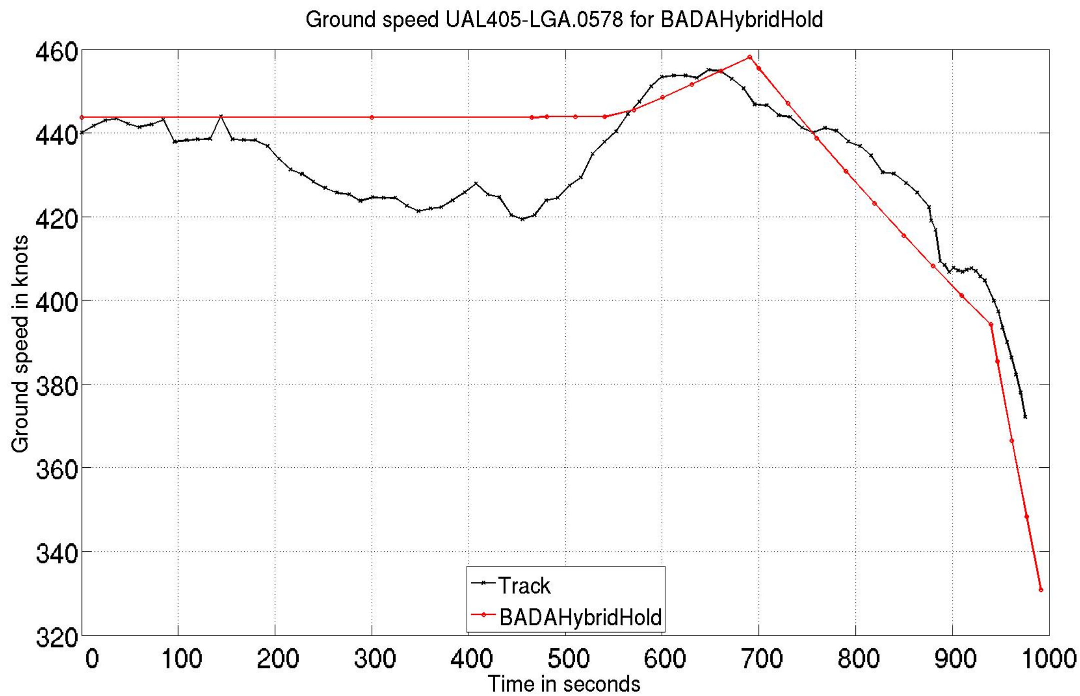

Figure 45. Boeing 757-200 BADA Hybrid Hold idle descent: ground speed

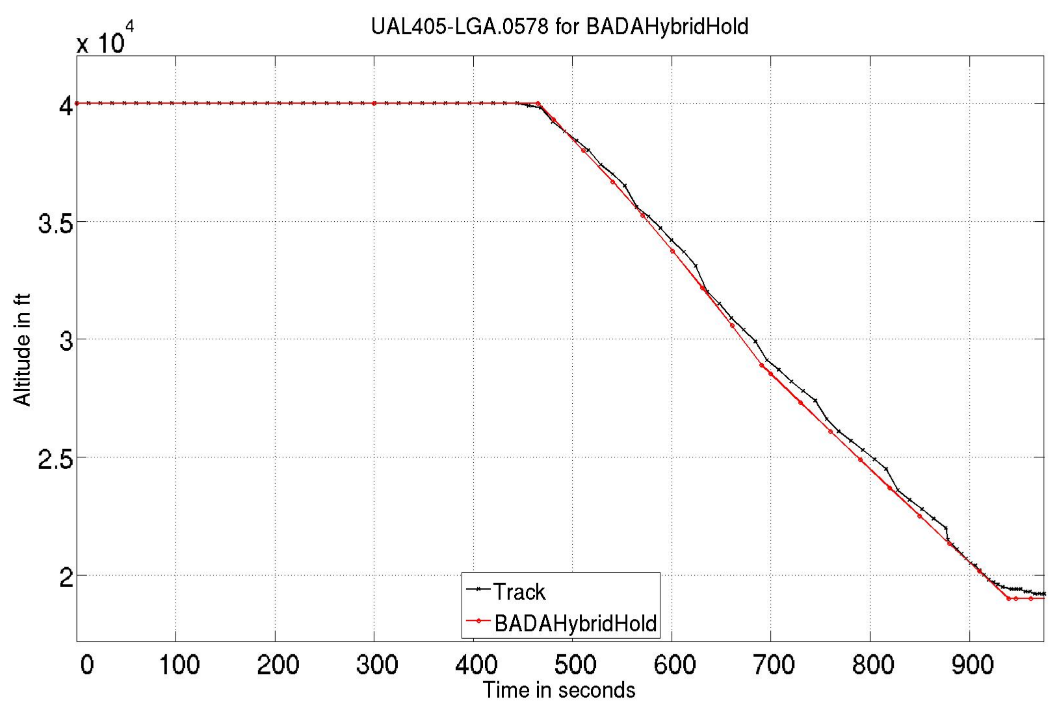

Figure 46. Boeing 757-200 BADA Hybrid Hold idle descent: altitude

6 Conclusion

The BADA performance and operational model was integrated into the CTAS TS, the core computational engine of CTAS software. The integrated CTAS/BADA TS software incorporated all possible variants of the BADA model, along with the native CTAS model. The CTAS/BADA TS software was thoroughly validated by comparison of predictions for the BADA Base case with the BADA PTD file reference and other available benchmark data.

To assess the accuracy of CTAS/BADA TS for different variants of BADA APM, several validation tools for interval-based sampling and systematic analysis were developed and used to perform the analysis for three different centers, Fort Worth, Los Angeles, and Denver, and for several BADA variants over Fort Worth center.

The following observations can be made from these comparisons:

- In general, some BADA variants perform as well or slightly better than CTAS in terms of altitude and along-track errors.
- Cross-track errors are mostly related to intent errors and flight plan amendments, so they remain practically the same for BADA and CTAS.
- Overall the differences between BADA and CTAS in terms of mean of absolute mean errors are relatively small (a few percent of error magnitudes) and statistically insignificant.
- There is no one BADA variant that would improve performance for all flight phases and all aircraft types.
- BADA has more accurate models for many aircraft types, such as AT72, BE20, BE36, BE9L, CRJ7, E145, PC12, and SR22. These are mostly small or regional aircraft.
- CTAS has more accurate models for A319, A320, B190, B733, B737, B738, C182, C56X, and E120. Most notably these aircraft types include large commercial aircraft from Airbus and Boeing.
- Both CTAS and BADA have good models for several aircraft types - A306, B752, C750, CRJ2, CRJ9, E135, E170, H25B, MD82, and MD83, including popular McDonnell Douglas, Embraer, and Canadair aircraft.
- BADA is found to be most beneficial in climb, especially with the BADA Reduced Weight variant.
- Typically BADA is much more accurate than CTAS in predicting Top Of Climb (TOC) for the most prevalent aircraft types.
- When compared with CTAS, BADA has slightly worse performance in descent, especially for Boeing aircraft types that have very good models in CTAS. However, BADA performance for descents can be improved by using the BADA Hybrid Hold variant with speeds responding to client requests, or the BADA Expedited Descent reducing the altitude errors for most aircraft types in the TRACON.
- Most BADA variants fail more frequently than CTAS, mainly due to inconsistency in definition of maximum operating altitude in BADA, where it is defined as aircraft-specific, and in CTAS TS, where the value of $60,000$ ft is used for all aircraft types.

Our performance metrics did not include fuel consumption. It is known that the BADA fuel consumption model works well in cruise, but does not perform in climb and descent as accurately compared with cruise (see [14]).

The analysis of BADA off-nominal performance with controlled cruise and descent speeds confirmed that

- the BADA Base Case was substantially less accurate for descents than CTAS;
- the BADA Hybrid Hold variant performed almost as well as CTAS TS did.

Finally, on the basis of this limited analysis we can conclude that using BADA APM with "hybrid hold" speed profile and expedited descent can improve the accuracy of CTAS for small and regional aircraft types. More substantial improvement in prediction accuracy can be expected using adaptive estimation of aircraft parameters, such as speed and weight, from historical track data for each flight.

Acknowledgments

This work would not have been possible without help and support from many people. We especially want to express our gratitude to Karen Cate for her guidance, to Hassan Eslami for continuous support and encouragement, to Martin Brown for contributions in data analysis and development of validation tools, to Alan Lee and Steven Chan for invaluable help in studying the existing CTAS TS code, to Gano Chatterji and Gilbert Wu for valuable discussions, to Jinn-Hwei Cheng for all her help with check-ins and ClearCase issues, to Pat O'Neal for assistance with data analysis for Denver-2009, and to Laurel Stell for providing data sets for Denver-2009.

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Appendix A

Example of the BADA Operation Performance File

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCC P28A__.OPF CCCCCCCCCCCCCCCCCCCCCCCCCCCC/
CC                                                                    /
CC               AIRCRAFT PERFORMANCE OPERATIONAL FILE                /
CC                                                                    /
CC                                                                    /
CC      File_name: P28A__.OPF                                         /
CC                                                                    /
CC      Creation_date: Apr 30 2002                                    /
CC                                                                    /
CC      Modification_date: Nov 10 2008                               /
CC                                                                    /
CC                                                                    /
CC====== Actype ======================================================/
CD   P28A__         1 engines    Piston                   L          /
CC  Piper PA-28-161 CW    with Lycoming-O-320-D3G engines wake       /
CC                                                                    /
CC====== Mass (t) ====================================================/
CC    reference      minimum      maximum     max payload  mass grad  /
CD     .10550E+01   .61300E+00   .11060E+01   .33000E+00   .00000E+00 /
CC====== Flight envelope =============================================/
CC     VMO(KCAS)       MMO        Max.Alt       Hmax       temp grad  /
CD     .12600E+03   .24000E+00   .12000E+05   .00000E+00   .00000E+00 /
CC====== Aerodynamics ================================================/
CC Wing Area and Buffet coefficients (SIM)                            /
CCndrst Surf(m2)     Clbo(M=0)       k          CM16                  /
CD 5   .15790E+02   .00000E+00   .00000E+00   .00000E+00              /
CC   Configuration characteristics                                    /
CC n Phase  Name    Vstall(KCAS)    CD0          CD2        unused    /
CD 1 CR   Clean     .50000E+02   .15315E-01   .41587E-01   .00000E+00 /
CD 2 IC   Clean     .50000E+02   .00000E+00   .00000E+00   .00000E+00 /
CD 3 TO   Flap25    .48000E+02   .00000E+00   .00000E+00   .00000E+00 /
CD 4 AP   Flap40    .43000E+02   .00000E+00   .00000E+00   .00000E+00 /
CD 5 LD   Flap40    .43000E+02   .00000E+00   .00000E+00   .00000E+00 /
CC   Spoiler                                                          /
CD 1      RET                                                         /
CD 2      EXT                             .00000E+00   .00000E+00     /
CC   Gear                                                             /
CD 1      UP                                                          /
CD 2      DOWN                .00000E+00   .00000E+00   .00000E+00    /
CC   Brakes                                                           /
```

```
CD 1      OFF                                                      /
CD 2      ON                                 .00000E+00   .00000E+00 /
CC====== Engine Thrust ===============================================/
CC         Max climb thrust coefficients (SIM)                       /
CD     .11167E+04   .28192E+05   .88240E+04   .00000E+00   .35552E-02 /
CC     Desc(low)    Desc(high)   Desc level   Desc(app)    Desc(ld)  /
CD     .16007E+00   .00000E+00   .43850E+04   .16007E+00   .38908E-01 /
CC     Desc CAS     Desc Mach     unused       unused       unused   /
CD     .12600E+03   .24000E+00   .00000E+00   .00000E+00   .00000E+00 /
CC====== Fuel Consumption ============================================/
CC   Thrust Specific Fuel Consumption Coefficients                   /
CD     .44515E+00   .00000E+00                                       /
CC   Descent Fuel Flow Coefficients                                  /
CD     .30872E+00   .00000E+00                                       /
CC   Cruise Corr.    unused       unused       unused       unused   /
CD     .87274E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00 /
CC====== Ground ======================================================/
CC        TOL          LDL        span         length       unused   /
CD     .50300E+03   .35400E+03   .10670E+02   .72500E+01   .00000E+00 /
CC====================================================================/
FI                                                                   /
```

Appendix B

Example of the BADA Performance Table Data File

Not all columns in the following table are shown due to a page width limitation.

```
BADA PERFORMANCE FILE RESULTS
=============================
=============================

Low mass CLIMBS
===============
```

FL[-]	T[K]	p[Pa]	rho[kg/m3]	a[m/s]	TAS[kt]	CAS[kt]	M[-]	mass[kg]	Thrust[N]	Drag[N]
0	288	101325	1.225	340	72.12	72.12	0.11	736	1239	367
5	287	99508	1.207	340	79.58	79.00	0.12	736	1208	380
10	286	97717	1.190	339	80.16	79.00	0.12	736	1187	380
15	285	95952	1.172	339	80.75	79.00	0.12	736	1167	380
20	284	94213	1.155	338	81.35	79.00	0.12	736	1146	380
30	282	90812	1.121	337	82.57	79.00	0.13	736	1105	380
40	280	87511	1.088	336	83.81	79.00	0.13	736	1064	380
60	276	81200	1.024	333	86.37	79.00	0.13	736	981	380
80	272	75262	0.963	331	89.05	79.00	0.14	736	899	380
100	268	69682	0.905	328	91.86	79.00	0.14	736	817	380
120	264	64441	0.849	326	94.79	79.00	0.15	736	734	380

```
Medium mass CLIMBS
==================
```

FL[-]	T[K]	p[Pa]	rho[kg/m3]	a[m/s]	TAS[kt]	CAS[kt]	M[-]	mass[kg]	Thrust[N]	Drag[N]
0	288	101325	1.225	340	79.00	79.00	0.12	1055	1228	523
5	287	99508	1.207	340	79.58	79.00	0.12	1055	1208	523
10	286	97717	1.190	339	80.16	79.00	0.12	1055	1187	523
15	285	95952	1.172	339	80.75	79.00	0.12	1055	1167	523
20	284	94213	1.155	338	81.35	79.00	0.12	1055	1146	523
30	282	90812	1.121	337	82.57	79.00	0.13	1055	1105	523
40	280	87511	1.088	336	83.81	79.00	0.13	1055	1064	523
60	276	81200	1.024	333	86.37	79.00	0.13	1055	981	523
80	272	75262	0.963	331	89.05	79.00	0.14	1055	899	523
100	268	69682	0.905	328	91.86	79.00	0.14	1055	817	523
120	264	64441	0.849	326	94.79	79.00	0.15	1055	734	523

High mass CLIMBS
================

FL[-]	T[K]	p[Pa]	rho[kg/m3]	a[m/s]	TAS[kt]	CAS[kt]	M[-]	mass[kg]	Thrust[N]	Drag[N]
0	288	101325	1.225	340	79.00	79.00	0.12	1106	1228	551
5	287	99508	1.207	340	79.58	79.00	0.12	1106	1208	551
10	286	97717	1.190	339	80.16	79.00	0.12	1106	1187	551
15	285	95952	1.172	339	80.75	79.00	0.12	1106	1167	551
20	284	94213	1.155	338	81.35	79.00	0.12	1106	1146	551
30	282	90812	1.121	337	82.57	79.00	0.13	1106	1105	551
40	280	87511	1.088	336	83.81	79.00	0.13	1106	1064	551
60	276	81200	1.024	333	86.37	79.00	0.13	1106	981	551
80	272	75262	0.963	331	89.05	79.00	0.14	1106	899	551
100	268	69682	0.905	328	91.86	79.00	0.14	1106	817	551
120	264	64441	0.849	326	94.79	79.00	0.15	1106	734	551

Medium mass DESCENTS
====================

FL[-]	T[K]	p[Pa]	rho[kg/m3]	a[m/s]	TAS[kt]	CAS[kt]	M[-]	mass[kg]	Thrust[N]	Drag[N]
0	288	101325	1.225	340	60.90	60.90	0.09	1055	49	614
5	287	99508	1.207	340	66.38	65.90	0.10	1055	197	571
10	286	97717	1.190	339	77.02	75.90	0.12	1055	191	528
15	285	95952	1.172	339	128.78	126.00	0.20	1055	180	732
20	284	94213	1.155	338	129.72	126.00	0.20	1055	177	732
30	282	90812	1.121	337	131.65	126.00	0.20	1055	170	731
40	280	87511	1.088	336	133.61	126.00	0.20	1055	164	731
60	276	81200	1.024	333	137.66	126.00	0.21	1055	0	731
80	272	75262	0.963	331	141.90	126.00	0.22	1055	0	730
100	268	69682	0.905	328	146.33	126.00	0.23	1055	0	730
120	264	64441	0.849	326	150.95	126.00	0.24	1055	0	729

TDC stands for (Thrust - Drag) * Cred