NASA/CR-2017-219645

ATD-1 Avionics Phase 2 Flight Test: Post-Flight Data Analysis Report

Julien Scharl
Boeing, Seattle, Washington

July 2017

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/CR-2017-219645

ATD-1 Avionics Phase 2 Flight Test: Post-Flight Data Analysis Report

Julien Scharl
Boeing, Seattle, Washington

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Contract NNL13AA03B, NNL15AB46T

July 2017

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

CAGE Code 81205

NASA ATD-1 Avionics Phase 2

NNL13AA03B-NNL15AB46T

Post-Flight Data Analysis Report

Prepared for: Denise Scearce

NASA Langley Research Center

Hampton VA, 23681-2199

DOCUMENT NUMBER:	RELEASE/REVISION:	RELEASE/REVISION DATE:
D780-10416-1	**A**	**31 May 2017**

CONTENT OWNER:

Boeing (Airspace & Operational Efficiency 9M-PW-ERCS)

All future revisions to this document must be approved by the content owner before release.

Table of Contents

List of Figures ... 3

Introduction ... 6

1. Data Set ... 7
   - Differences from Annex C of Flight Test Plan ... 7

2. Individual Run Graphical Data ... 9
   - Interval Management Performance ... 9
   - IM Speed Performance ... 10
   - IM Speed Limiting Information ... 11
   - Lateral TG ... 13
   - Vertical TG ... 15
   - Speed Profile TG ... 17

3. IM Performance Metrics ... 21
   - IM Performance Data Description ... 21

4. Summary Statistics ... 25
   - All Time-Based Operations ... 25
   - All Distance-Based Operations ... 28
   - Time-Based MAINTAIN Operations ... 30
   - Time-Based CAPTURE Operations ... 33
   - Time-Based CROSS Operations ... 35
   - Time-Based SPACE Operations ... 39
   - Distance-Based Operations by Clearance Type ... 40
   - Along-Track Wind Forecast Error ... 41
   - Fuel Burn ... 44
   - Flight Technical Error ... 44
   - Path Definition Error ... 49

5. Analysis of Variance ... 52

6. Generalized Regression Models ... 93
   - Objective ... 93
   - Methodology ... 94
   - Regression Models ... 95
   - Summary of Regression Analysis ... 109

7. Summary and Conclusions ... 110

Acronyms ... 113

Revision Record ... 115

List of Figures

Figure 1: IM Performance Plot Example, Day 9, B19 10
Figure 2: IM Speed Plot Example, Day 9, B19 11
Figure 3: TBO Speed Limiting Example, B19, Day 9 12
Figure 4: CTD Speed Limiting example, B19, Day 9 13
Figure 5: Lateral Ownship (737) TG Plot Example: Day 9, B19 14
Figure 6: Lateral Traffic (757) TG Plot Example: Day 9, B19 15
Figure 7: Vertical TG (Ownship) Plot Example, Day 9, B19 16
Figure 8: Vertical TG (traffic) example, Day 9, B19 17
Figure 9: TG Speed Profile Example (Ownship), B19, Day 9 18
Figure 10: TG Speed Profile Example (Traffic), B19, Day 9 19
Figure 11: TG Speed Profile Example (Traffic is Non-FIM), B19, Day 9 20
Figure 12: IM Performance - All Time-Based Clearances 26
Figure 13: Initial Spacing Error Distribution (Time-Based Clearances)...........................27
Figure 14: Cumulative Distribution of Mean Absolute PTP Error (Time-Based Clearances) 28
Figure 15: IM Performance - All Distance-Based Clearances 29
Figure 16: IM Performance - Time-Based MAINTAIN 31
Figure 17: IM Performance - En Route Time-Based MAINTAIN 32
Figure 18: IM Performance - Time-Based CAPTURE 34
Figure 19: IM Performance - Time-Based CROSS 36
Figure 20: IM Performance - Time-Based CROSS (ZAVYO) 38
Figure 21: IM Performance - Time-Based CROSS (NALTE) 39
Figure 22: IM Performance - Time-Based SPACE (5 samples).......................................40
Figure 23: IM Performance - Distance-Based MAINTAIN (Three Samples, all A Scenarios) 40
Figure 24: IM Performance - Distance-Based CAPTURE (Two Samples, all A Scenarios) 40
Figure 25: IM Performance - Distance-Based CROSS (Seven Samples, all B Scenarios) 41
Figure 26: IM Performance - Distance-Based SPACE (Five Samples) 41
Figure 27: Along-Track Wind Forecast Error 42
Figure 28: Along Track True Wind (ownship)..43
Figure 29: Average Fuel Burn Rate by Operation 44
Figure 30: FMS Lateral Deviation RMS by Path 46
Figure 31: FIM Lateral Deviation RMS by Path 47
Figure 32: FMS Vertical Deviation RMS by Path..48
Figure 33: FIM Vertical Deviation RMS by Path 49
Figure 34: Lateral PDE RMS by Path 50
Figure 35: Vertical PDE RMS by Path...51

Figure 36: ATWFE By Flight Day 53
Figure 37: ATWFE By Ownship Path 54
Figure 38: Average Fuel Burn Rate by IM Operation Units (time/distance) 55
Figure 39: Average Fuel Burn Rate by Clearance Type 56
Figure 40: Average Fuel Burn Rate by Ownship Aircraft Type 57
Figure 41: Average Fuel Burn Rate by Ownship Path 58
Figure 42: Average Fuel Burn Rate by Operation Type (A/B/C) 59
Figure 43: Average Fuel Burn Rate by Chain Position 60
Figure 44: Lateral FTE RMS (FIM) by Descent Paths 62
Figure 45: FIM Lateral FTE by Aircraft 63
Figure 46: FIM Vertical RMS by Descent Paths 64
Figure 47: FIM Vertical FTE RMS by Aircraft 65
Figure 48: Lateral PDE by Descent Path 66
Figure 49: Time-Based PTP Error By Clearance Type 67
Figure 50: Time-Based PTP Error by Ownship Path 68
Figure 51: Time-Based PTP Error by Traffic Path 69
Figure 52: Time-Based PTP Error By Scenario Type 70
Figure 53: IM Speed Rate by Clearance Type 71
Figure 54: IM Speed Rate by Operation Unit Type (TIME versus DISTANCE) 72
Figure 55: IM Speed Rate by Ownship Path 73
Figure 56: IM Speed Rate by Traffic Path 74
Figure 57: Pilot Implementation Time by Aircraft 75
Figure 58: Time-Based CROSS, PTP Error by Ownship Path 76
Figure 59: Time-Based CROSS, PTP Error By ABP Placement 77
Figure 60: Time-Based CROSS, ABP Delivery by Ownship Path 78
Figure 61: Time-Based CROSS, ABP error By ABP Placement 79
Figure 62: Time-Based CROSS, IM Speed Rate by ABP placement 80
Figure 63: Time-Based CROSS, IM Speed Rate by Ownship Path 81
Figure 64: Time-Based CAPTURE, PTP Error by Aircraft Type 82
Figure 65: Time-Based CAPTURE, PTP Error by Scenario Type 83
Figure 66: Capture Rate by Aircraft Type 84
Figure 67: Capture Rate by Ownship Path 85
Figure 68: Capture Rate by Lead Aircraft Type 85
Figure 69: Capture Rate by Chain Position 86
Figure 70: Time-Based CAPTURE, Maintain RMS by Chain Position 87
Figure 71: Time-Based CAPTURE, maintain RMS by scenario type 88
Figure 72: Time-Based MAINTAIN, PTP Error by Aircraft Type 89
Figure 73: Time-Based MAINTAIN, PTP Error by Chain Position 90
Figure 74: Time-Based MAINTAIN, IM Speed Rate by Path 91
Figure 75: Time-Based MAINTAIN, IM Speed Rate, by Scenario Type 92
Figure 76: plotSlice Output for PTP Error Model (Distance-Based Operations) 99

Figure 77: Regression Model Search Summary 109

Introduction

This report aims to satisfy Air Traffic Management Technology Demonstration – 1 (ATD-1) Statement of Work (SOW) 3.6.19 and serves as the delivery mechanism for the analysis described in Annex C of the Flight Test Plan. The report describes the data collected and derived as well as the analysis methodology and associated results extracted from the data set collected during the ATD-1 Flight Test.

All analyses described in the SOW were performed and are covered in this report except for the analysis of Final Approach Speed and its effect on performance. This analysis was de-prioritized and, at the time of this report, is not considered feasible in the schedule and costs remaining.

1. Data Set

The data set described in this document was obtained during the execution of the flight test program described in the Flight Test Plan document (D4.22). The data set consists of Electronic Flight Bag (EFB) data collected on the two aircraft performing FIM during the flight tests conducted Jan 20-Feb 22 2017 in the Seattle, WA, area. Aircraft state data was collected from all three aircraft in the flight test. The aircraft were a United 737-900, a Honeywell 757, and a Honeywell Dassault F900. Only the 737 and the 757 are equipped with Flight Deck Interval Management (FIM) and flew FIM missions. The F900 acted as a lead in a merging chain of aircraft on all but two flight test days. No significant difference in performance has been observed because different lead aircraft are used.

Nineteen flying days resulted in 198 unique FIM operations. Approximately 11% of the experiments were discarded because of bad or unusable data that resulted from operator error, software errors, and scenario setup difficulties. Of the good data, 80% was retained for performance and other analysis included in this report; the remainder (9%) was flagged for further study to investigate system behavior deemed incorrect or not fully understood. The data set used for this analysis report consists of 144 flown FIM experiments (runs): 11 en route (A conditions) experiments, 8 final approach spacing experiments, and 125 arrival/descent experiments (B conditions). The data set includes 75 conditions for the 757 and 69 conditions for the 737. Of the four clearance types the prototype FIM system can handle, the data set contains 25 MAINTAIN, 36 CAPTURE, 75 CROSS, and 8 SPACE operations. Fifteen of the operations used a distance-based spacing goal and 129 used a time-based spacing goal.

The Flight Test Data was delivered to NASA under Deliverable 4.24 on March 29, 2017. An accompanying document on the delivered physical media describes the form of the data, and Appendix C of the Flight Test Plan describes its content, with differences described in the next section.

Differences from Annex C of Flight Test Plan

Many more data items are found in the delivered Flight Test Data than are documented in Annex C of the Flight Test Plan. Some of the mappings between data items in some logs and the NASA data requests are found in the “NASA ATD1 Data Recording details_v4-4.xlsx” spreadsheet accompanying D4.24. The major difference between what was collected and what was planned to be collected as documented in Annex C of the Flight Test Plan relates to the Honeywell 757 aircraft and the collection of Flight Management System (FMS) data.

The Cross-Track Distance (ARINC Label 116) and Vertical Deviation (ARINC Label 117) parameters from the FMS are not valid in the 757 aircraft state data recordings. These data were previously reported to be available based on published Interface Control Document (ICD) data; however, examination of the data during flight test shows only zeroes were recorded. Unfortunately, spot checking of the data recordings made after equipment installation and periodically during the flight test did not reveal these data were invalid until very late in the flight test campaign. At this time, it is not known if this results from FMS configuration or FMS software version differences between the published ICD and the installed software.

Consequently, the FMS Flight Technical Error (FTE) metrics could not be extracted for the 757 and thus the associated derivation of FIM system Path Definition Error (PDE) could not be performed for that aircraft (see IM Performance Metrics section for a description).

2. Individual Run Graphical Data

For each run, several graphical artifacts are produced to inspect its general health and performance. Many of these artifacts are used during data review to identify which runs to keep based on an initial assessment of performance. The major types of graphical artifacts that can be produced from the Matlab code developed under the program is described later in this report, including a few examples for a number of runs. This code is not itself a deliverable on the program but is shared with NASA as a courtesy.

Interval Management Performance

Interval Management (IM) performance is depicted in the form of a Measured Spacing Interval/Predicted Spacing Interval (MSI/PSI) versus a distance-to-go (DTG) chart with many overlaid pieces of information. The alignment of all data is accomplished through the common Coordinated Universal Time (UTC) time stamp present in all FIM logs and non-FIM data logs. An example of such a plot for condition B19 (CROSS) on Day 9 is shown in Figure 1.

The chart is bounded by IM operation start on the right (green vertical line), and ownship passing PTP on the left (DTG=0 nm). The black horizontal line near the middle is the assigned spacing goal (ASG) used for the operation. The blue line (or set of dots) are the MSI or PSI reports in the units of the operation (time or distance). Each IM speed issued is represented by a magenta circle, with the value and UTC time of the issued speed as accompanying text. Trajectory generation events are shown as squares with different colors for ownship and traffic. Vertical lines of different styles are depicting key times/events, such as ownship and traffic passing Achieve-by Point (ABP) or PTP. This type of chart is typically inspected to get a sense of the evolution of the spacing error and associated issued IM speeds (values and frequencies) and Trajectory Generator (TG) generation events. For operations that involve the use of two different spacing algorithms in the prototype (Constant Time Delay [CTD] and Trajectory-Based Operations [TBO]), both MSI and PSI are shown jointly on the one graph (Figure 1) with PSI reported by the TBO algorithm up to the point ownship passes the ABP. MSI is then reported by the CTD algorithm up to the point ownship passes the PTP.

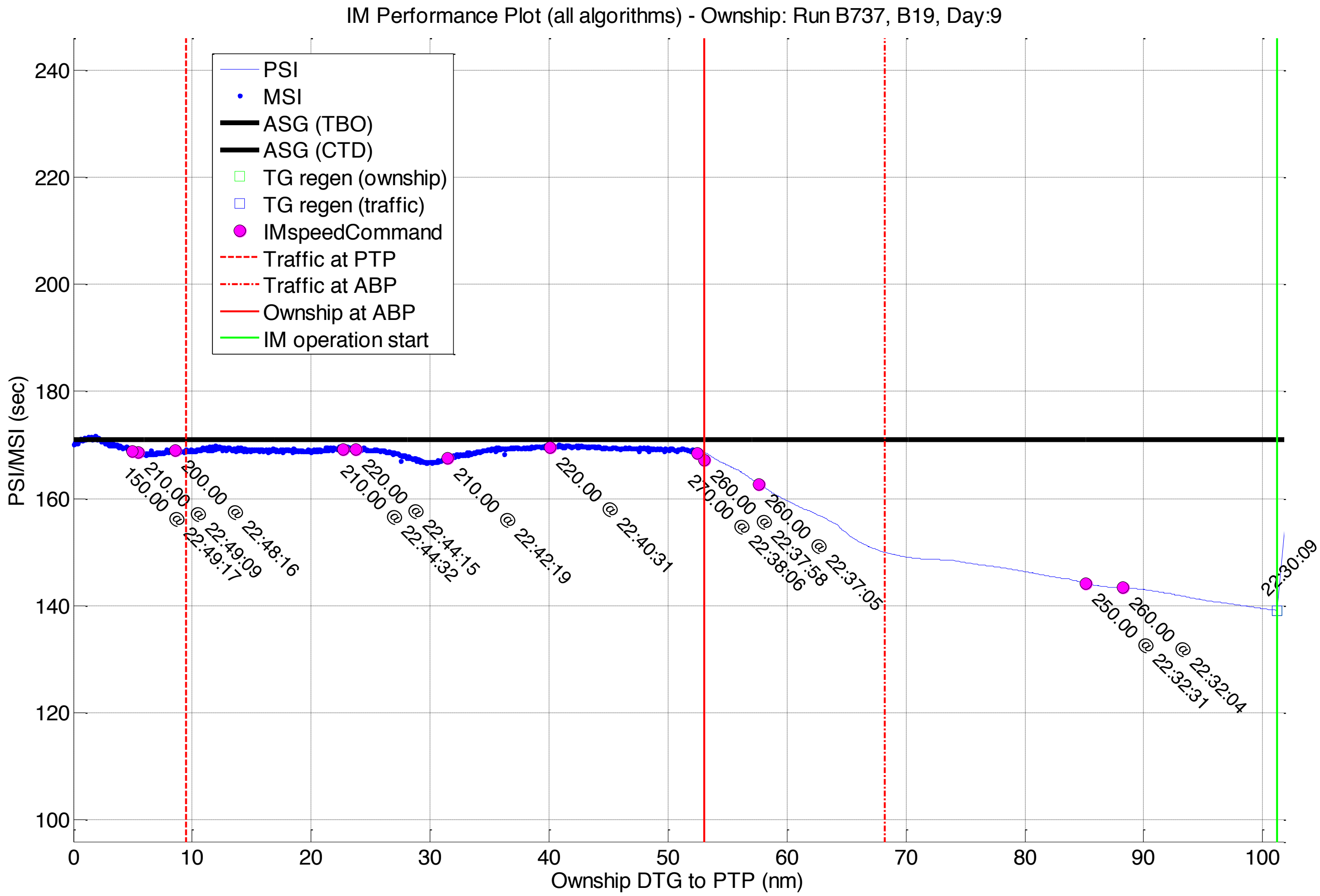


Figure 1: IM Performance Plot Example, Day 9, B19

IM Speed Performance

IM Speed Performance is depicted in the form of calibrated airspeed (CAS) versus DTG with many overlaid pieces of information aligned using common UTC time stamps. The blue line represents the nominal speed profile generated by the Trajectory Generator (TG). The green line represents the actual flown CAS by ownship. The magenta line represents the IM commanded speeds issued, and the red line represents the instantaneous commanded speed. Each trajectory generation event is depicted by a square; vertical lines indicate key times as in the IM Performance chart. An example of such a plot for the B19 condition flown by the 737 on Day 9 is shown in Figure 2.

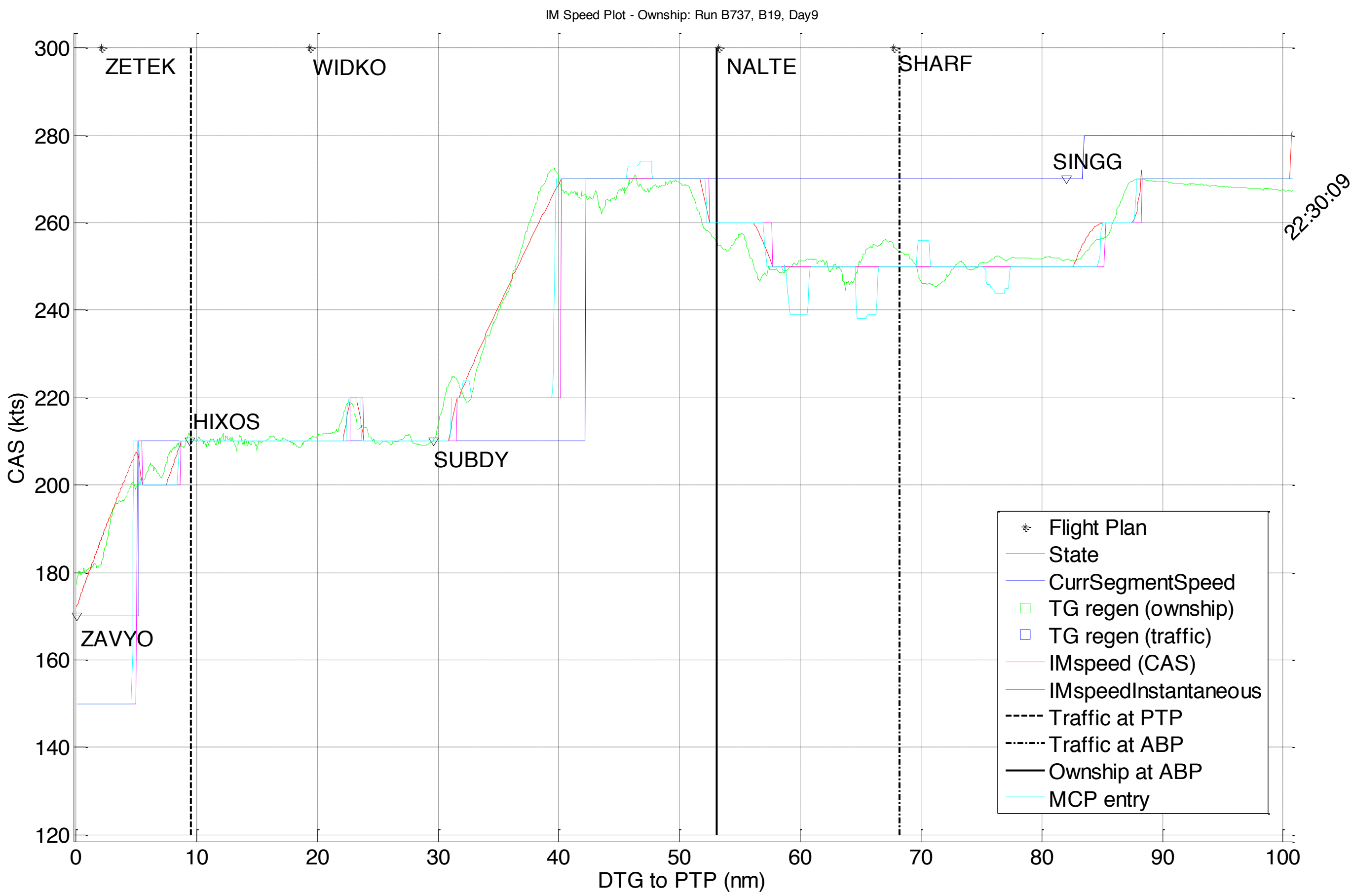


Figure 2: IM Speed Plot Example, Day 9, B19

Figure 2 reveals four instances where pilots dialed Mode Control Panel (MCP) speeds that did not correspond to an issued IM speed prior to NALTE. This is atypical and can be caused by pilots either choosing to not follow the FIM speed at their discretion (safe speeds, turbulence penetration limits, etc.) or follow Mach issued speeds, which for the figure are translated to CAS.

IM Speed Limiting Information

The IM speed limits applied by each algorithm during an IM operation is depicted along DTG. Figure 3 and Figure 4 depict examples of such plots for condition B19 on Day 9. Because this is a CROSS operation, the first example shows the limiting applied during the achieve portion of the operation by the TBO algorithm. Each dashed line represents an applicable limit. The thin green line is the ownship CAS and the magenta line is the IM speed issued by the algorithm. If the IM speed is limited, the line is thickened during the limiting portion and is sitting on top of one of the limiting lines. For example, in the condition depicted, the maintain portion of the operation (CTD algorithm) was limited on the low side in the last 5 miles (Figure 4). If the IM speed line sits on top of a limit and is not thickened (e.g., 40-37 nm DTG in Figure 4) the system is not technically reporting a limit condition and no limiting indication is sent to the pilot through EFB or CGD. It only indicates a limit condition when the algorithm desires a higher or lower speed but cannot issue it because of the limit.

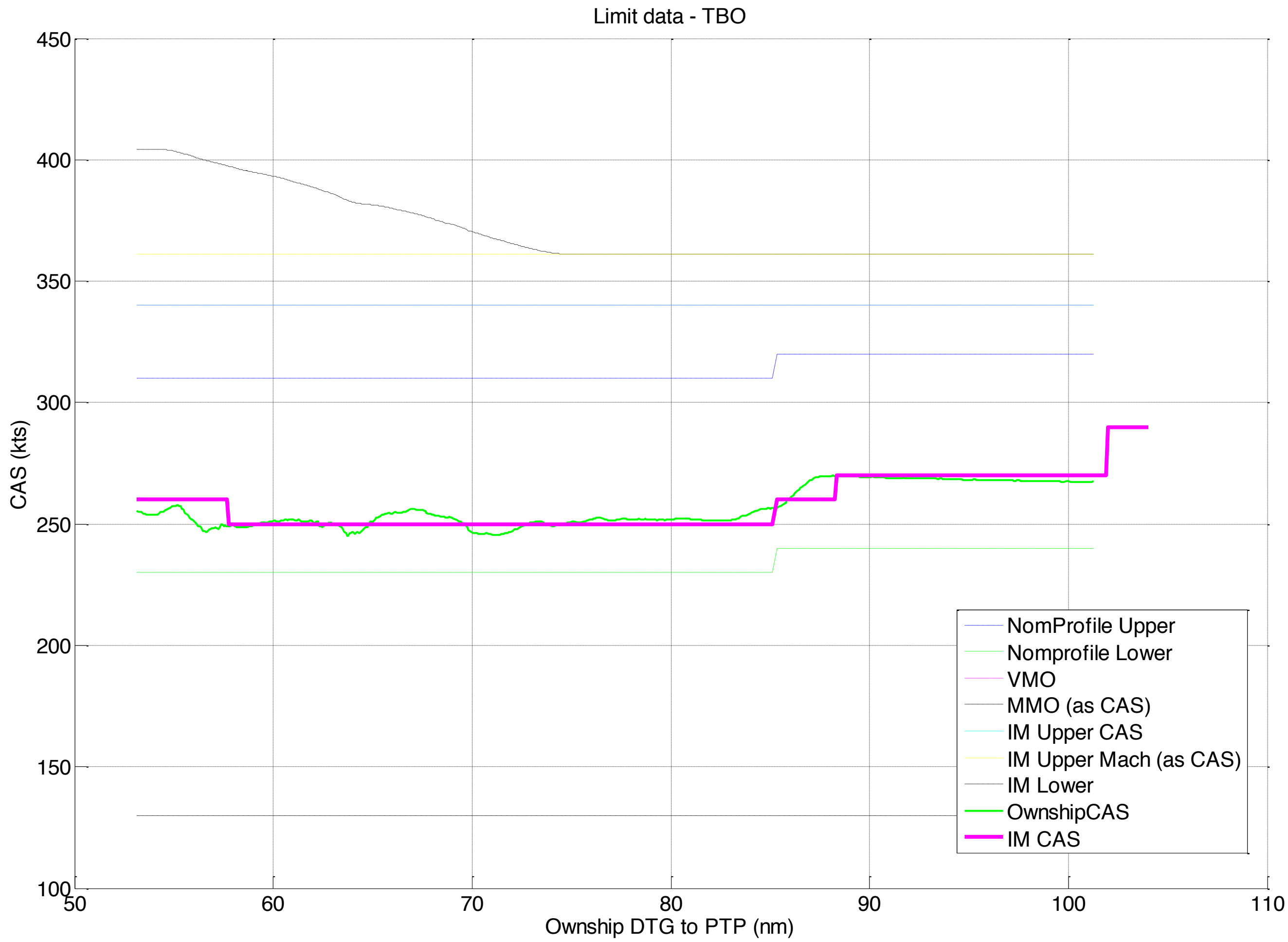


Figure 3: TBO Speed Limiting Example, B19, Day 9

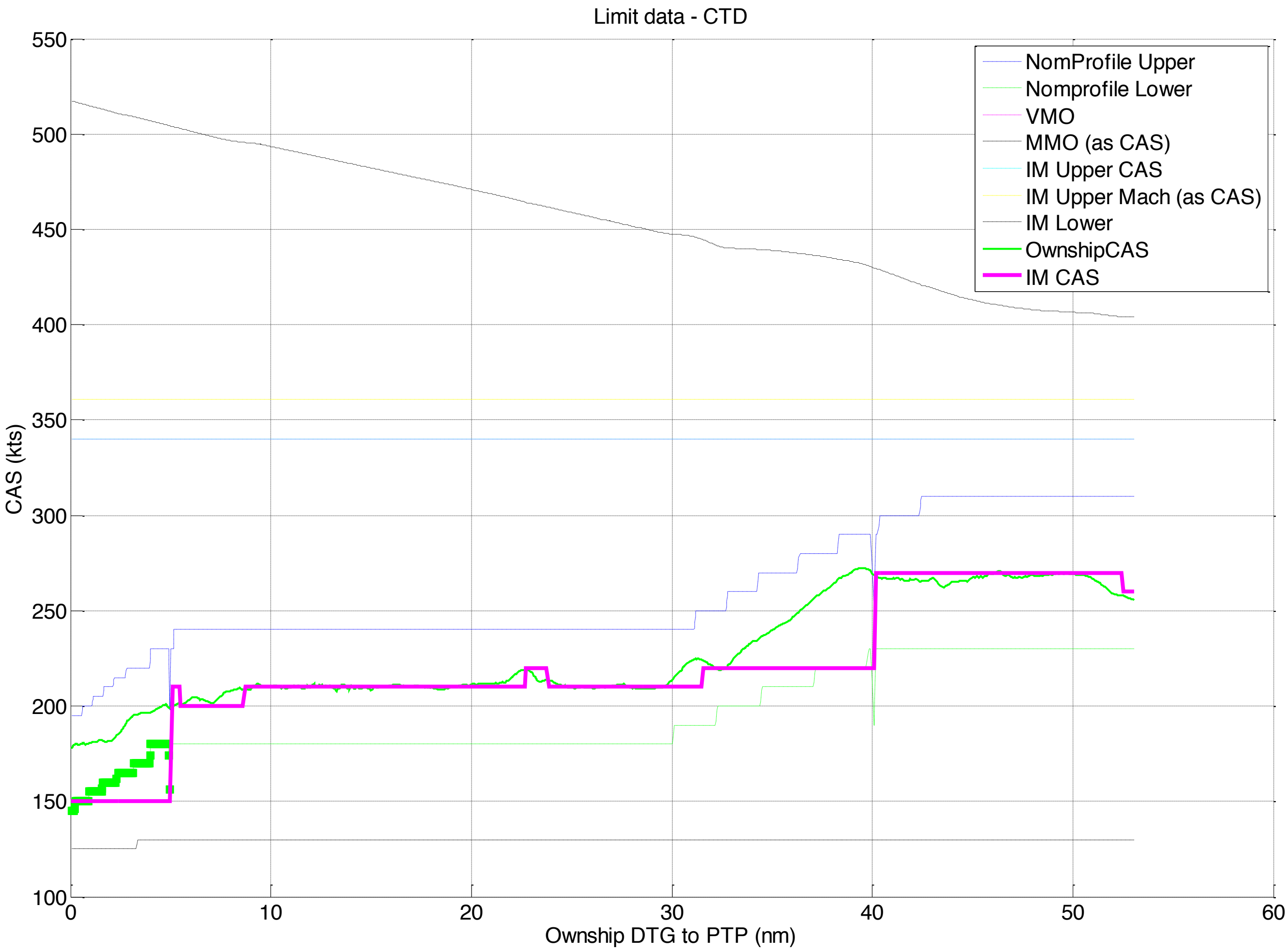


Figure 4: CTD Speed Limiting example, B19, Day 9

Lateral TG

The lateral view of the flown experiment overlays the actual lat/lon state of ownship on top of the generated trajectory. There will be one such plot for every trajectory generation, both for ownship and traffic. By default, the plotting only occurs for generations occurring at IM start and beyond. Key points in the procedure (waypoints, ABP, PTP) are shown in Figure 5, as well as all lateral and vertical Trajectory Change Points (TCP) (magenta circles).

The along-track wind forecast error (ATWFE) is also overlaid on top of the geometry to get a sense of its magnitude and sign (headwind or tailwind forecast error) throughout the IM operation. Figure 5 displays an example of such a plot for Day 9, condition B19, for ownship aircraft being the 737, following the 757. Figure 6 is the companion figure for its lead (757). Figure 5 shows that the 737 was subject to a large (~25 kt) forecast tailwind error in the upper part of the operation, reversing sign in the middle, with near zero forecast error in the low altitude portions. Almost all operations through the RF turn in the SUBDY approach to runway 32R (RW32R) experience a change in sign and magnitude in the forecast error, likely caused by significant changes in altitude and track direction through that segment.

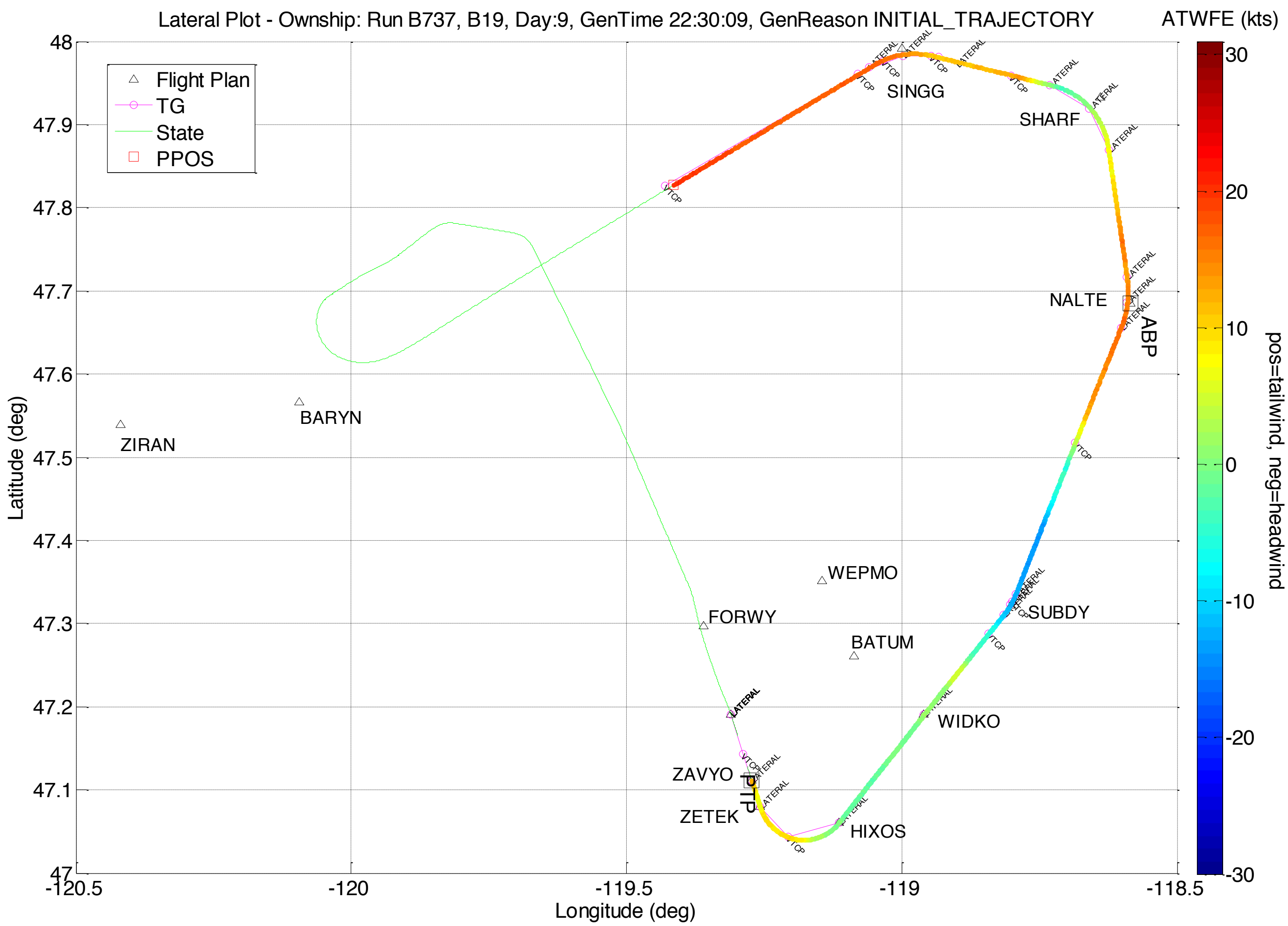


Figure 5: Lateral Ownship (737) TG Plot Example: Day 9, B19

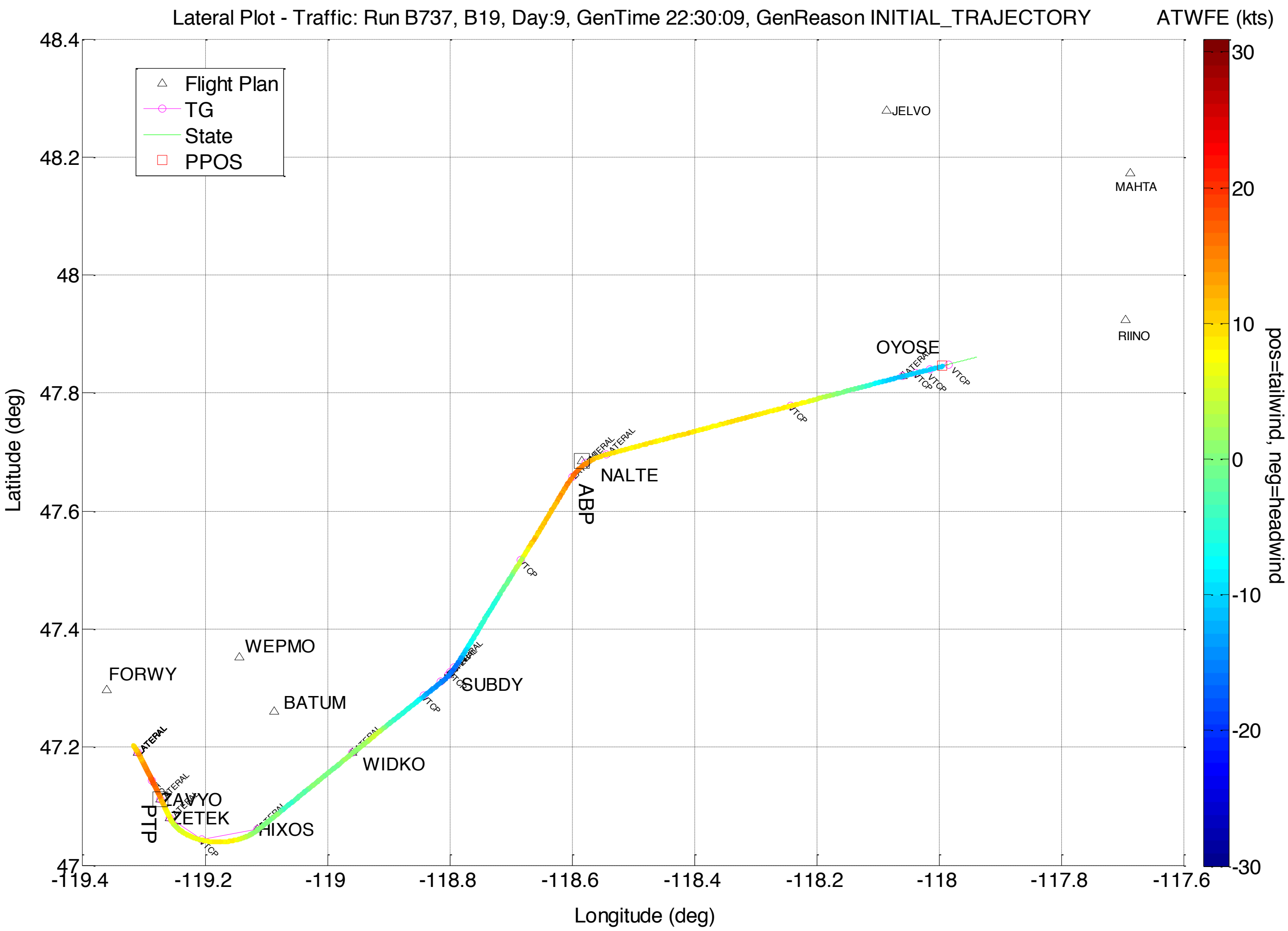


Figure 6: Lateral Traffic (757) TG Plot Example: Day 9, B19

Vertical TG

The vertical view of the flown experiment overlays the actual altitude of ownship and traffic on top of the generated vertical trajectory against DTG. There is one such plot for every trajectory generation, both for ownship and traffic. By default, the plotting only occurs for generations occurring at IM start and beyond. Key points in the procedure (waypoints, ABP, PTP) are shown in Figure 7, as well as all lateral and vertical TCPs (magenta circles). Constrained waypoints are indicated in Figure 7 with a square (AT), upright triangle (AT or ABOVE), upside down triangle (AT or BELOW), or a vertical line segment (WINDOW). Figure 7 exemplifies such a plot for ownship on condition B19 of Day 9 and Figure 8 for the lead aircraft of that pair.

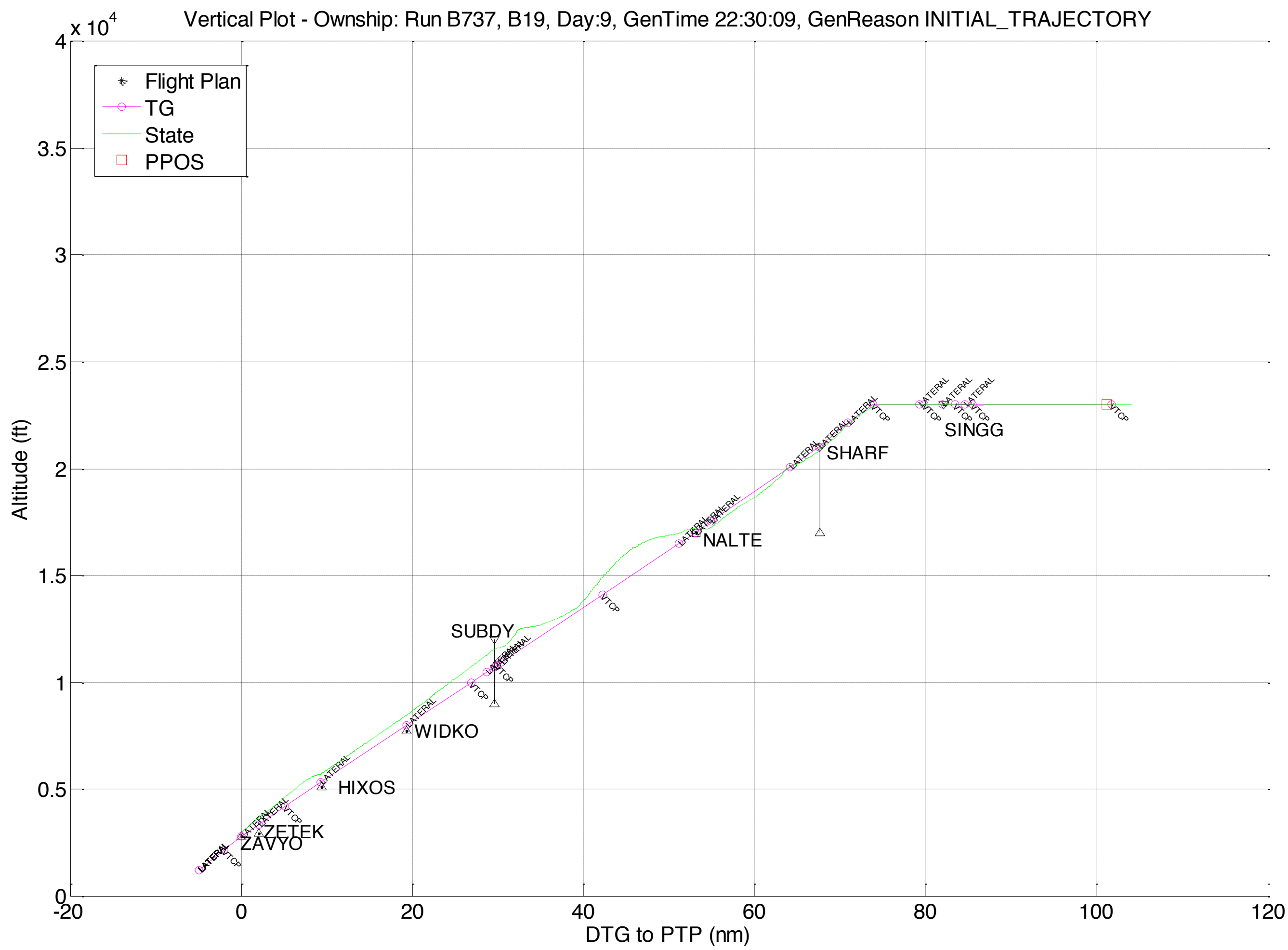


Figure 7: Vertical TG (Ownship) Plot Example, Day 9, B19

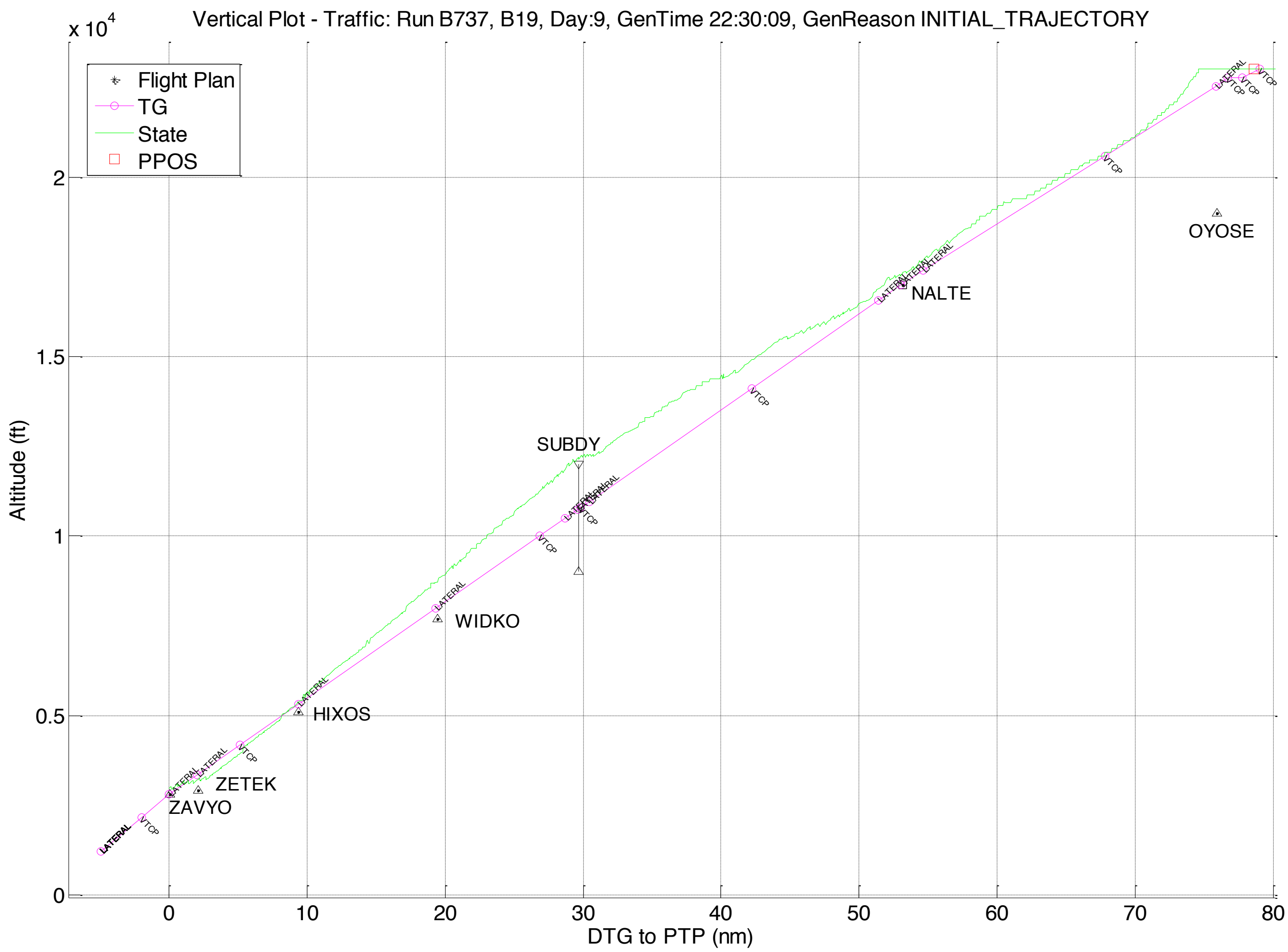


Figure 8: Vertical TG (traffic) example, Day 9, B19

Speed Profile TG

The speed profile view of the flown experiment overlays the actual CAS of ownship and traffic on top of the generated nominal speed profile in the trajectory against DTG. There is one such plot for every trajectory generation, both for ownship and traffic. By default, the plotting only occurs for generations occurring at IM start and beyond. Key points in the procedure (waypoints, ABP, PTP), as well as all lateral and vertical TCPs (magenta circles), are shown in the figure. Constrained waypoints are indicated in the figure with an upright triangle. Unconstrained waypoints are depicted at the 300 kt CAS level with a star as marker. The blue line in the figure is the generated nominal speed profile; the green line on the ownship figure is the CAS found in the ownship state IM log, and the red line on the traffic figure is the CAS found in the time-correlated aircraft state data.

Note that the plot does not include IM speed information--only the nominal speed profile and the flown CAS--which may reflect pilots following issued IM speeds in cases where the plot is for a FIM aircraft (Figure 9). In the case of the plot for the pair lead (traffic)

(Figure 10), the flown CAS (red line) may also reflect IM speeds followed by that aircraft when it was performing FIM (it is in the example).

In cases where the lead aircraft is not performing FIM (lead of pair 1, Figure 11), the figure reflects the delay condition flown by the lead. Such plots were used during flight test to stress the importance of achieving a given lead aircraft delay condition repeatedly in cases where it could be demonstrated that pilots did not fly the intended speed profile. The example shown in Figure 11 is for the first pair for condition B19 on Day 9, where the lead aircraft is the F900 flying relatively close to the nominal CAS profile for a no-delay scenario.

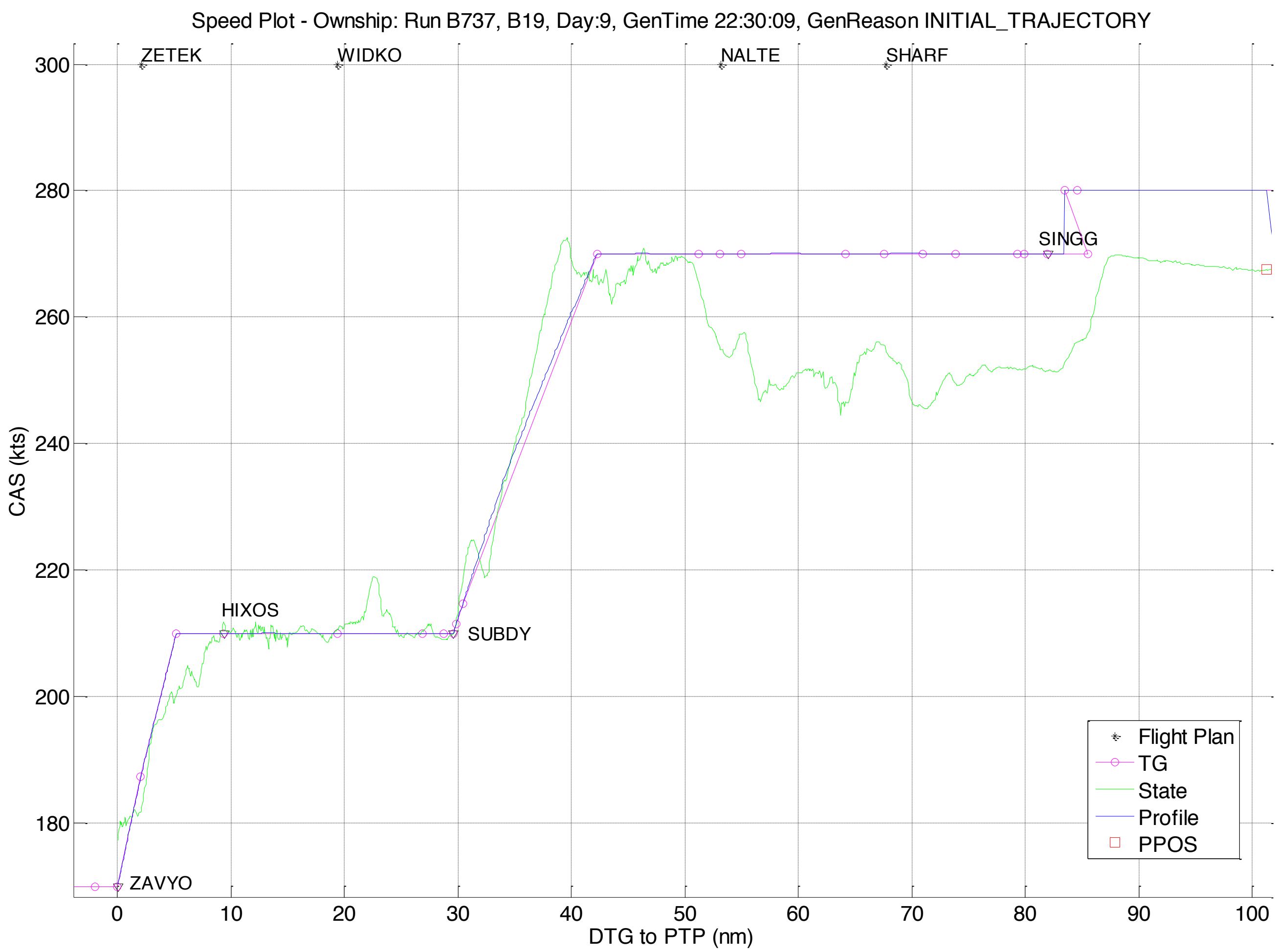


Figure 9: TG Speed Profile Example (Ownship), B19, Day 9

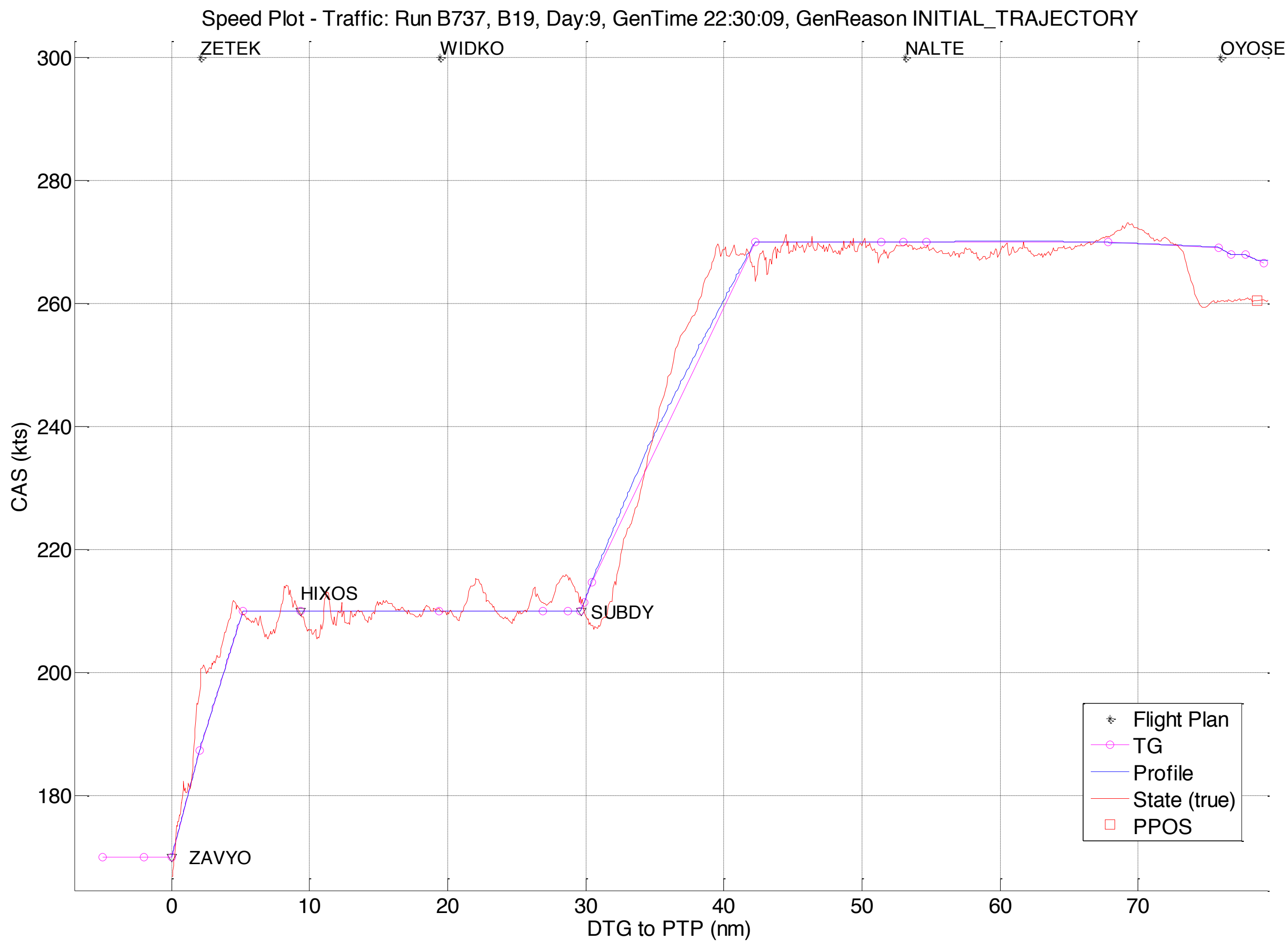


Figure 10: TG Speed Profile Example (Traffic), B19, Day 9

Figure 11: TG Speed Profile Example (Traffic is Non-FIM), B19, Day 9

3. IM Performance Metrics

Each run was analyzed to extract a set of 34 metrics capturing IM and aircraft performance. Each metric is defined here, including its method of computation. Some data related to the description of the run are described as well, although they are technically not metrics used for analysis. The IM Performance data was delivered under Deliverable 4.25a on March 29, 2017. An accompanying document on the delivered physical media describes the form of the data. Description of the data from that document is replicated in the following sections.

IM Performance Data Description

Each run was first inspected to determine the bounds of the IM operation (start and end times). All computations involving determination of the actual time of arrival (ATA) at a particular point are based on computing the closest time of approach to that point (based on position definition in the flight plan EFB log) using a spline fitting process to the set of great circle distance from the time history aircraft position data and the fixed point. The spline is fitted through the actual data for time history position points within a threshold distance, typically 0.5 to 1.0 nm.

The IM performance data is tabulated in an Excel spreadsheet for each of the 144 runs that are part of this analysis. The raw and derived data is in Matlab form and exists in a corresponding MAT file, both as a structure array ("ATD1_metrics_array") and a Table Matlab variable ("ATD1_metrics_table"). The following paragraphs describe each metric and how it is computed. The metric name (in italic) matches the column name in the Excel spreadsheet. The Matlab structure array field name and corresponding Table variable name are also included in the description.

The *start time (tStart)* in most cases is automatically determined from the data based on the time the system went to the PAIRED state, at the ASG for the operation. In cases where data were lost or significant suspend events (more than a few seconds) exist downstream of the automatically determined start time, the start time was manually adjusted by inspecting the time history plot of MSI or PSI.

The *end time (tEnd)* is defined per the FIM Minimum Operational Performance Standards (MOPS) as

1. Time when traffic passes the PTP (distance-based operations).
2. Time when ownship passes the PTP (time-based operations).

Once the start and end times are known, the IM operation duration (*IMduration*) and distance (*IMlength*) are computed. *IMlength* is the along-track distance covered by ownship between tStart and tEnd. *IMduration* is the difference in time between tEnd and tStart.

The *Initial Spacing Error* is computed as the difference between the MSI (or PSI) at *tStart* and the ASG. Its units are in seconds or nautical miles, based on the units of the operation (time or distance). Based on this definition, a positive value indicates the IM operation aims for the aircraft to speed up (decrease spacing); a negative value aims for the aircraft to slow down (increase spacing).

The *initial ABP distance (DTG_ABP)* is computed as the ownship along-track distance remaining to the ABP at *tStart*. This is a computable metric for CROSS operations only.

The *initial ABP predicted time (TTG_ABP_pred)* is the reported ownship time to go (TTG) to the ABP at *tStart*. This is a computable metric for CROSS operations only.

The *achieved spacing error at the PTP (achievedSpacingError_PTP)* is defined as

1. The difference between ownship and traffic ATA at the PTP and the ASG, for time-based clearances.

2. The difference between the along-track distance remaining for ownship when traffic reaches the PTP and the ASG, for distance-based clearances.

The *achieved spacing error at the ABP (achievedSpacingError_ABP)* is defined as

1. The difference between ownship and traffic ATA at the ABP and the ASG for time-based clearances.

2. The difference between the along-track distance remaining for ownship when traffic reaches the PTP and the ASG, for distance-based clearances.

The number of times the system was speed limited (*numLimited*) is a count of the speed limited reports in each of the logs (CTD and TBO). Because the logs are at 1Hz, it is equivalent to the number of seconds (not necessarily consecutively) the system was speed limited. The details of which speed limit condition is applied are found in the Matlab structure array data. The field “limitData” contains a 2 by 1 cell array with each cell element being a Map with the key being the limit condition and value being the number of times the algorithm reported that limited condition in the log. The first cell is for the TBO algorithm and the second cell is for the CTD algorithm.

The number of IM speeds (*numSpeeds*) is a count of unique speeds issued by the IM system, including whatever speed is displayed by the system at *tStart*. This includes both algorithms and both Mach and CAS values. If the speed remains the same across an algorithm transition (TBO to CTD), it is not counted separately. For distance-based operations, speeds issued after the lead passes the PTP are counted separately (see numSpeeds_GS_segment). Speeds are included in the Matlab structure array data in the field “speeds” in order of issue.

The number of IM speeds per minute (*numSpeeds_perMin*) is the ratio of *numSpeeds* to *IMduration*.

The *number of IM speeds in Ground Speed matching mode (numSpeeds_GS_segment)* is defined as the number of IM speeds (CAS or Mach) displayed to the pilot by the system in distance-based operations after the traffic reaches the PTP. During the interval between traffic and ownship passing the PTP in distance-based operations the IM system does not maintain the ASG, it only attempts to have ownship pass the PTP at the same ground speed as its lead aircraft passed the PTP.

The number of speed reversals (*numSpeedReversals*) is a count of the number of times an IM speed issued has changed direction from the previous speed issuance (going down after having gone up and vice versa). This does not include reversals that may occur in the ground speed (GS) segment.

The pilot time metrics (*pilotTime_mean* and *pilotTime_std*) are computed for each run by cross correlating the FIM and non-FIM data through the UTC time, which is present in both logs. For each IM speed issued, in order, a corresponding MCP value is searched for starting at the time of IM speed issue forward to the minimum of 5 minutes or the time of the next IM speed issued. If a value within 1 kt (for CAS) or 0.01Mach (M) is found, the time difference between the IM speed issued and that time is reported as the time (in seconds) the pilot took to implement the IM speed in the MCP. If a value is not found, a NaN value is reported. The mean and standard deviation of these times for each experiment is contained in the corresponding variables. Note that the NaNs do not affect those statistics, and thus the reported pilot times are not affected by times when pilots chose not to implement a displayed IM speed or missed it altogether. The details of each IM speed issued and its associated pilot implementation is found in the Matlab data. The data structure fields *pilotTime_cas* and *pilotTime_mach* contain arrays where the first column is each IM speed and the second column is the elapsed time between display and pilot action in seconds.

The *time of capture (tCapture)* is defined as the elapsed time (in seconds) between IM operation start and the transition between the capture and maintain segment, for CAPTURE operations only. The point of capture is defined as the point in time when the error is first within ±10 s of the ASG. For distance-based operations, the time-based error is used (it is found in the logs).

The *maintain-stage error (spacingErrorMaintainSegment_rms)* is defined as the root mean square (RMS) of the time-based history of the difference between the MSI and the ASG for the maintain portion of the IM operation. This portion is the entirety of a MAINTAIN operation, the portion downstream of the capture portion of a CAPTURE operation (see *tCapture* definition previously) or the portion downstream of the ABP of a CROSS operation. This is in units of the ASG.

The MOPS maintain metric (*MOPS_maintain_metric*) is the MOPS defined metric for the maintain stage of IM operations. It is defined as a percentage of the maintain segment time where the error was outside of 10 seconds from the ASG.

The *along track wind forecast error (ATWFE)* is defined as the along-track component of the difference between the wind forecast and the sensed wind. Sensed wind (speed and direction) is available in the EFB data set at approximately 1 Hz. The forecast wind (speed and direction) is interpolated based on the wind forecast entry and the aircraft altitude, which are available at approximately 1Hz. Thus, the wind forecast error can be computed at 1 Hz and projected along the aircraft ground speed and track at the same frequency. The complete time history of the ATWFE between IM operation start and end times for both ownship and traffic is computed. The aggregate metric per operation is computed as the RMS of that error. The difference in the error between traffic and ownship is also computed and extracted as an RMS value for each run. The raw values for ATWFE for ownship, traffic and their difference are in the Matlab data under structure field names *ATWE*, *ATWE_traffic*, and *ATWE_diff* correspondingly.

The *fuel burn metric (fuelBurn)* is defined as the fuel expensed by ownship between the IM operation start and end times in pounds.

The *average fuel rate* (*avg_fuel_rate*) is computed as the ratio of *fuelBurn* to *IMduration*, reported in lbs/hr. It corresponds to the average fuel burn rate over the IM operation.

The *lateral path FMS deviation (latDev_FMS_RMS)* is reported by the FMS as the difference between the aircraft position of the FMS reference lateral guidance path. The RMS value of this error history is the aggregate metric. Because the 757 did not produce FMS deviation data, this metric is computed only for the 737.

The *vertical path FMS deviation (latDev_FMS_RMS)* is reported by the FMS as the difference between the aircraft altitude of the FMS reference vertical guidance path. The RMS value of this error history is the aggregate metric. Because the 757 did not produce FMS deviation data, this metric is computed only for the 737.

The IM system computes the deviations to its computed trajectory (lateral and vertical) for both ownship and traffic. The RMS values for both lateral and vertical deviations, for both ownship and traffic are correspondingly reported as aggregate metrics as *latDev_FIM_ownship_RMS, vertDev_FIM_ownship_RMS, latDev_FIM_traffic_RMS, vertDev_FIM_ownship_RMS*. Lateral deviations are reported in nm, vertical deviations in feet. The difference between the FMS- and FIM-reported deviations corresponds to the difference between the FMS computed guidance path and the FIM constructed trajectory, a measure of instantaneous FIM System Path Definition Error (PDE) as described in Annex C of the Flight Test Plan. The RMS values for that difference for both lateral and vertical dimensions are reported as *PDE_lat_rms* and *PDE_vert_rms* in nm and feet. Because the 757 did not produce FMS deviation data, PDE metrics are computed only for the 737.

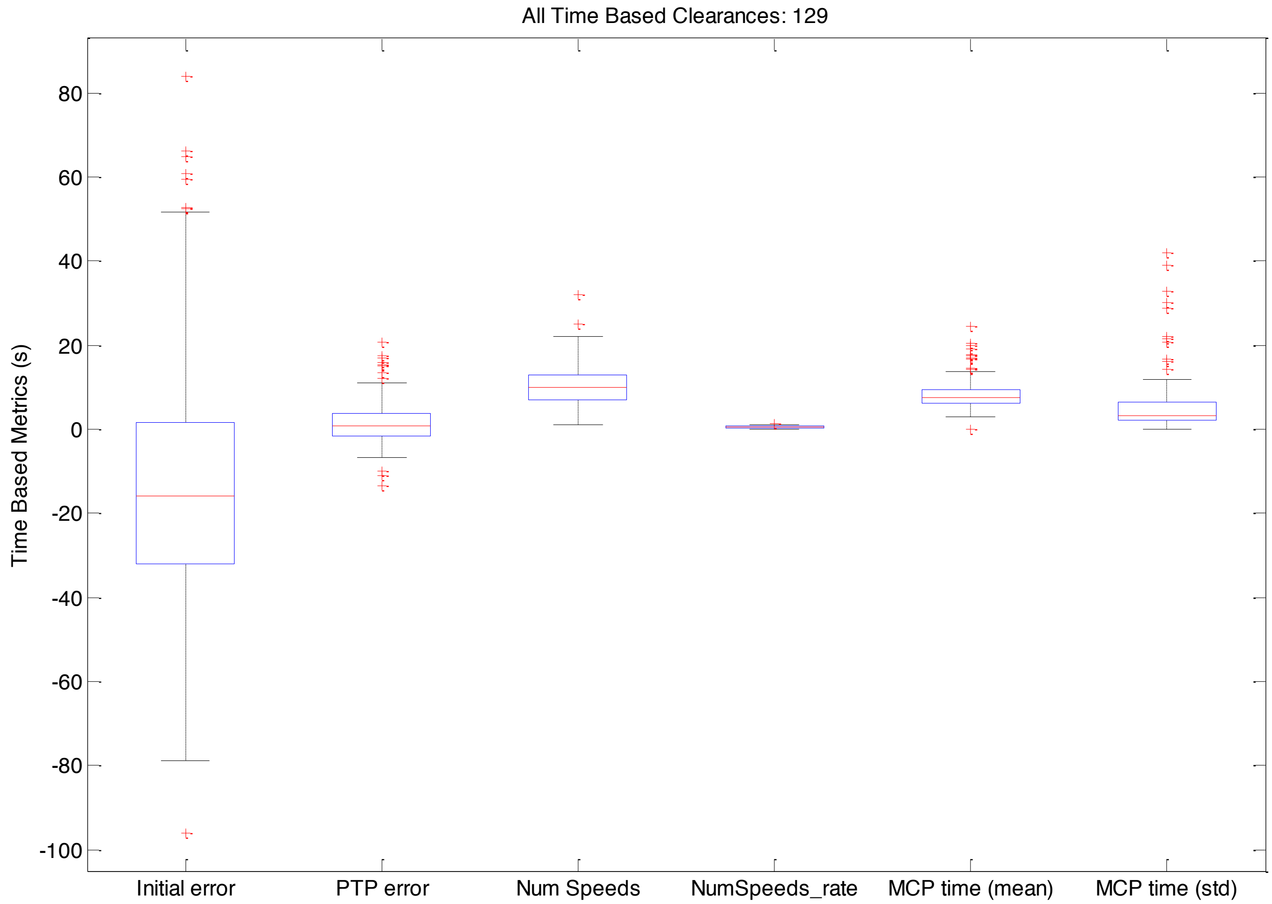
4. Summary Statistics

The summary statistics for each category of IM operation are shown in Figure 12 using box plots. Box plots are standardized statistic graphical representations of slices of the data set depicting the median, lower and upper quartiles outliers for each metric. The values for those descriptive statistics can also be found in the D4.25a Excel spreadsheet under the “Descriptive Stats” tab and associated tables in this section under each figure. Boxplots are only shown for slices of the experiment matrix with sample size of seven or more. Tables also include the 95% confidence interval for each data item from the samples. Performance metrics reported include input conditions (initial spacing error) as well as IM performance in the form of delivery performance (at PTP and ABP), number of IM speeds, IM speed rate, and MCP times. In addition, for CAPTURE operations, the time-to-capture is included. For operations with a maintain segment the maintain segment RMS error is shown.

Note that the intent of the contracted effort was not to prove that the prototype implementation meets the MOPS performance, but rather is a first attempt to measure performance of the first prototype of a FIM system flown in realistic operations. Therefore, mentions are made to some, but not all, MOPS performance criteria in this report. Most of the criteria investigated are PTP and ABP delivery performance (within 10 seconds 95% of the time).

All Time-Based Operations

The time-based operations statistics are shown in Figure 12. This figure clearly shows the power of the IM system, taking the Initial Spacing Error at IM initiation (median=-15.981 s, IQR=33.57 s) and delivering a much smaller spacing error at the PTP (median=0.9506 s, IQR=5.36 s). This is done by correcting aircraft speeds on average 10.6 times (median=10, IQR=6) or 0.57 speed corrections per minute of operation (numSpeeds_rate), with the pilot taking an average of 8.51 (MCP time mean) with dispersion of 5.8 seconds (mean of MCP time std).



	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	numSpeeds	numSpeeds_ perMin	pilotTime_mean (s)	pilotTime_std (s)
Mean	-11.55	83.65	1.79	10.60	0.57	8.51	5.80
95% CI low	-17.32	79.78	0.75	9.69	0.53	7.85	4.54
95% CI high	-5.78	87.53	2.84	11.52	0.61	9.18	7.05
Range	180.00	114.03	34.22	31.00	1.34	24.60	42.00
IQR	33.57	26.02	5.36	6.00	0.30	3.18	4.39

Figure 12: IM Performance - All Time-Based Clearances

Because of the design of the experiment matrix and the difficulty in setting up each condition, the initial spacing error is not normally distributed (Figure 13). Many of the experiments had near zero initial spacing error, as is expected for MAINTAIN operations. However, the resulting spacing error at the PTP is close to a normal distribution between -5 s and +5 s of error, which covers ~70% of the data. In fact, constructing a cumulative distribution function for the absolute PTP error distribution reveals that the probability of the delivered error at the PTP being within 10 s is 89.58% (Figure 14). Absence of true normality warrants specialized techniques when performing Analysis of Variance (ANOVA) on the data presented in the next section.

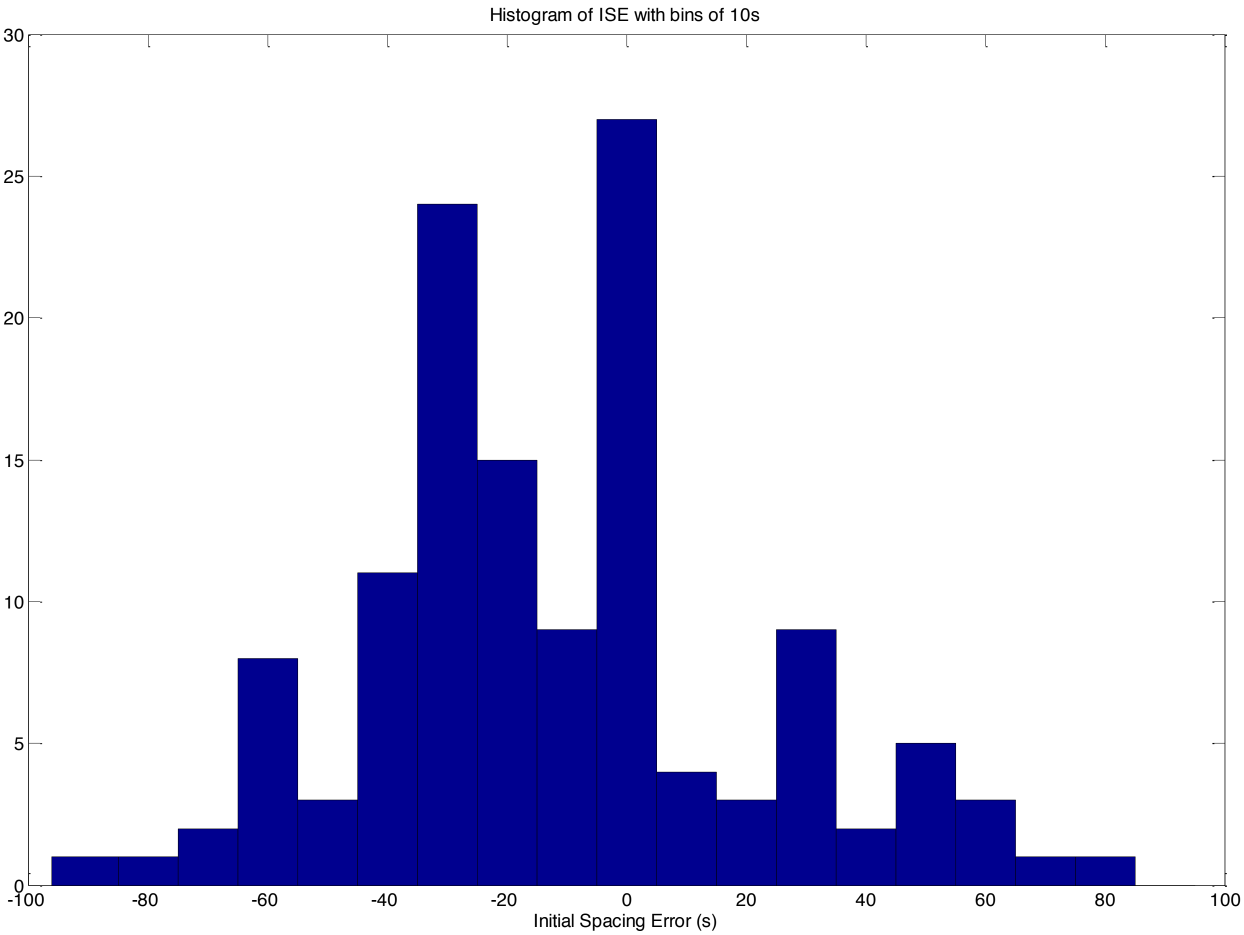


Figure 13: Initial Spacing Error Distribution (Time-Based Clearances)

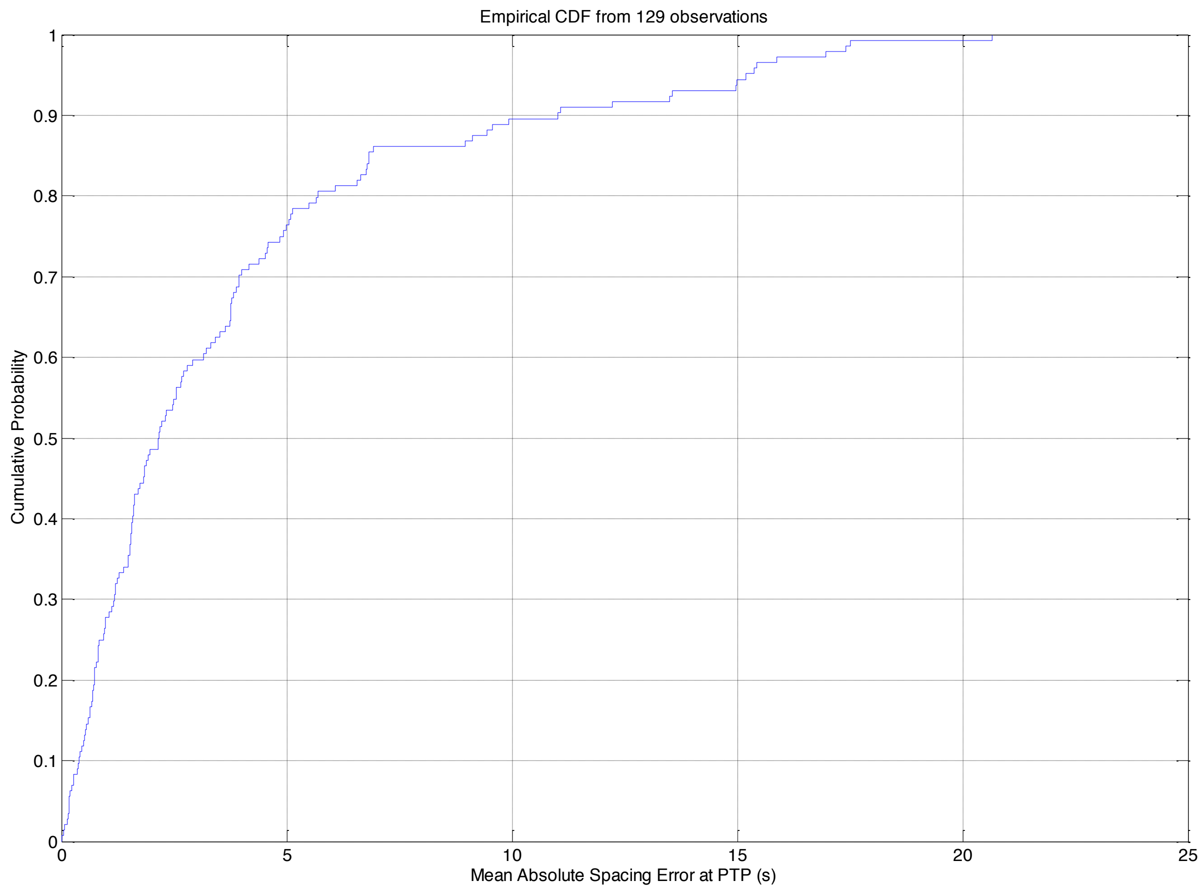
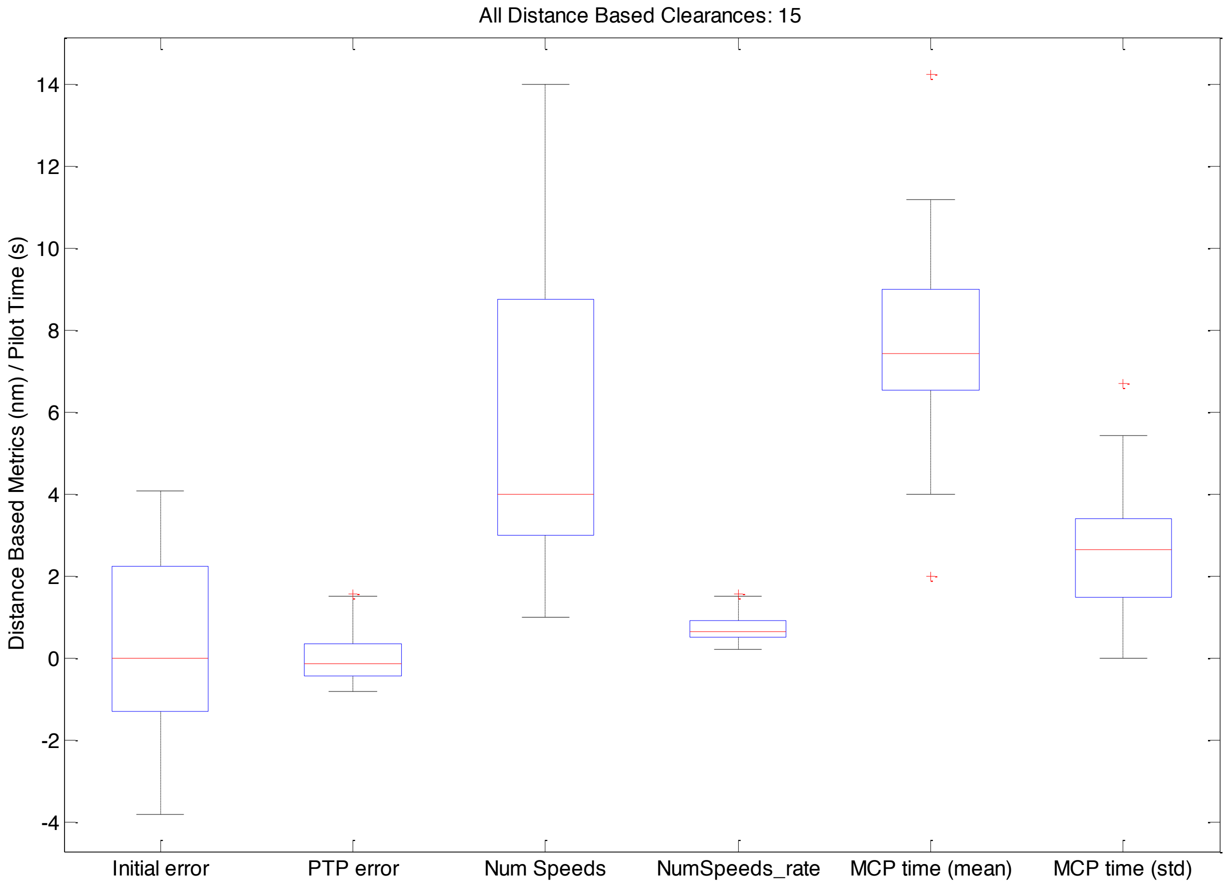


Figure 14: Cumulative Distribution of Mean Absolute PTP Error (Time-Based Clearances)

All Distance-Based Operations

All distance-based operation statistics are shown in Figure 15. The sample size is much smaller (15) but the statistics reveal similar trends. The initial spacing error has a median of 0 nm (IQR=3.55 nm) as many of the distance-based runs were in fact en route MAINTAIN operations. However, the delivered error has less spread (IQR=0.8 nm). The number of speeds issued is on average 5.8 (median=4, IQR=5.75), slightly less than time-based clearances, although they are likely not statistically comparable because of the difference in sample size.



	InitialSpacing Error (nm)	IM Length (nm)	PTP error (nm)	numSpeeds	numSpeeds_perMin	numSpeeds_GS_Segment	pilotTime_mean (s)	pilotTime_std (s)
Mean	0.19	46.13	0.18	5.80	0.77	2.07	7.71	2.68
95% CI low	-1.09	29.47	-0.27	3.67	0.55	1.03	6.06	1.71
95% CI high	1.47	62.79	0.62	7.93	0.99	3.10	9.37	3.66
Range	7.89	84.80	2.39	13.00	1.34	6.00	12.25	6.70
IQR	3.55	56.08	0.80	5.75	0.40	2.75	2.46	1.93

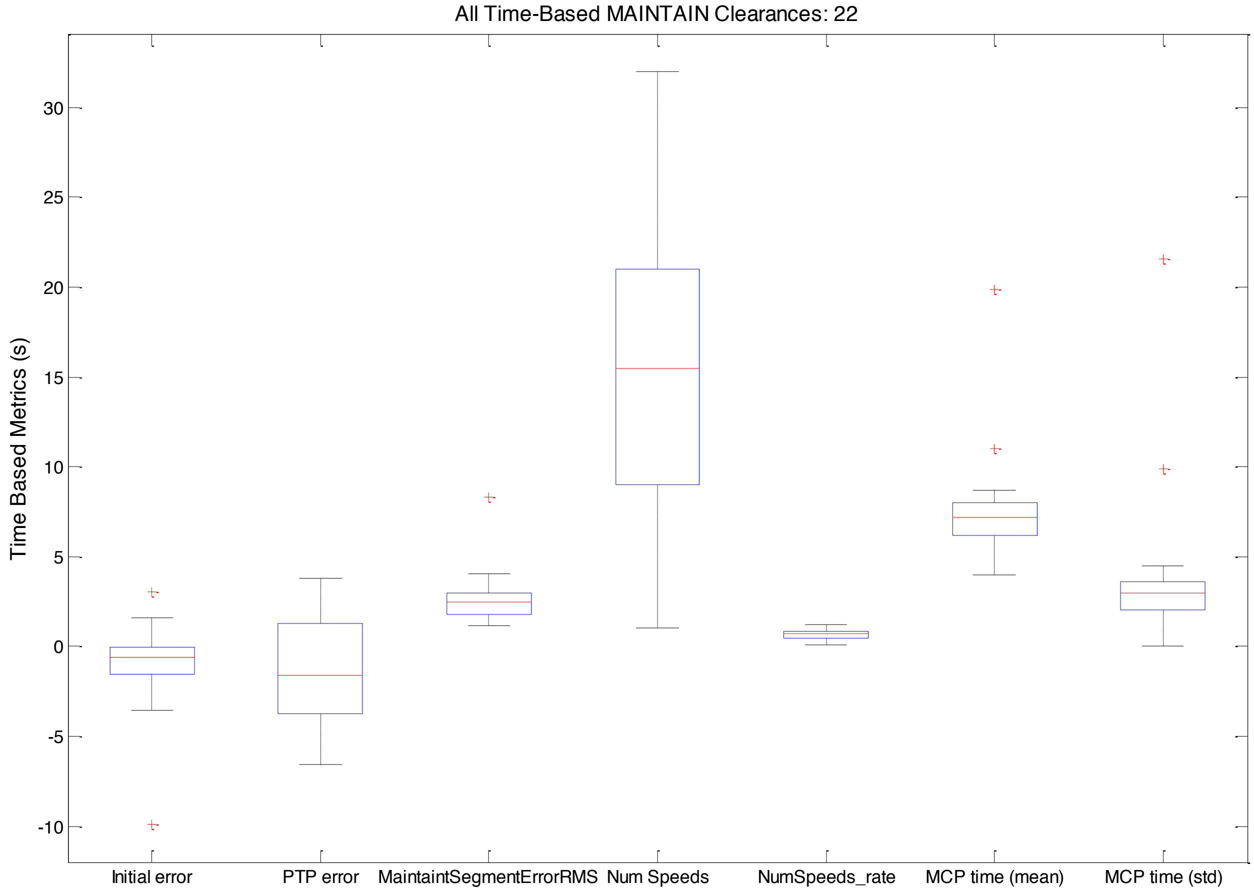
Figure 15: IM Performance - All Distance-Based Clearances

Time-Based MAINTAIN Operations

Looking at each clearance type operated in time (sample is much larger), we start with MAINTAIN operations in Figure 16. Note from Figure 16 that the median of the initial spacing error is not zero. This is caused by two main factors:

1. In MAINTAIN operations, the ASG is set when the system transitions to the AVAILABLE state, but the initial error is computed when the system transitions to the PAIRED state. Pilots typically wait about a minute in the AVAILABLE state to verify system function during which time the system is operated in open-loop fashion. Thus, during the two state transitions, the indicated MSI can drift and thus a non-zero initial error can occur.

2. Several runs start time were adjusted to portions downstream of the system transition to the PAIRED state for a variety of reasons. This results in the same effect as in item 1; however, there is much less frequency of this occurring.



	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	numSpeeds	numSpeeds_ perMin	pilotTime_mean (s)	pilotTime_std (s)	MaintainError _RMS (s)
Mean	-1.08	91.78	-1.32	14.64	0.70	7.65	3.77	2.70
95% CI low	-2.16	81.88	-2.58	10.95	0.56	6.28	1.80	2.05
95% CI high	0.00	101.67	-0.07	18.32	0.83	9.02	5.73	3.35
Range	12.96	77.16	10.33	31.00	1.14	15.90	21.57	7.14
IQR	1.55	36.25	5.03	12.00	0.37	1.83	1.54	1.21

Figure 16: IM Performance - Time-Based MAINTAIN

The statistics show that the PTP delivery error is further from zero than the initial spacing error with larger spread. However, no sample of PTP delivery error was greater than ±10 s. The standard deviation of the delivery error is 2.84 s, and assuming the data is normally distributed, corresponds to a delivery error of 5.68 s at 95% probability, well inside the MOPS requirement. To understand why the delivery error spread at the PTP is larger than the initial error, we need to understand the variability in spacing error throughout the operation. MAINTAIN operations should also keep the spacing within the error tolerance for the entire maintain segment, not just at the PTP. A more representative metric of the MAINTAIN operation is the RMS value of the spacing error (MSI-ASG) throughout the IM operation. Data show that the system maintained the error to within less than 3 s throughout operations ranging from 40 to 110 nm. The 95% confidence interval for the RMS maintain error is between 2.05 and 3.35 s.

As noted in many pilot surveys, the number of speeds issued to realize this performance is large (median=15.5, IQR=12). In fact, the MAINTAIN operations have the largest number of IM speeds issued per minute of all operations flown (0.7 speeds per minute mean). This is a product of the state-based algorithm (CTD algorithm) being overly reactive to changes in the lead speed, discovered using history, and predicting deceleration regions.

A subset of the MAINTAIN operations (four runs) was performed at cruise level (A conditions). Those statistics are contained within the set shown in Figure 17 and do not represent outliers. The A runs exhibit less speed changes owing to the fact that the operations occur in Mach at level flight and thus there is less opportunity in the CTD algorithm deceleration identification to return more data.

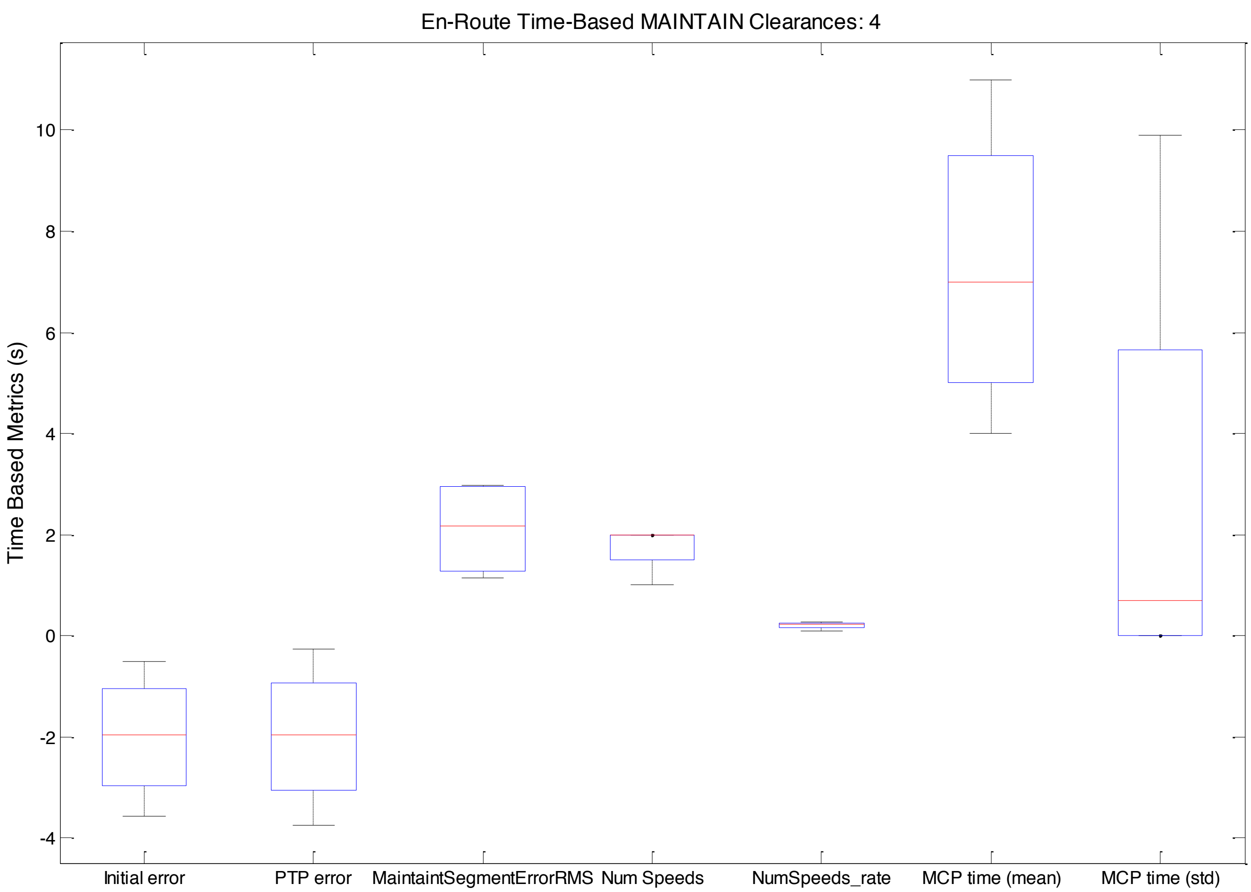
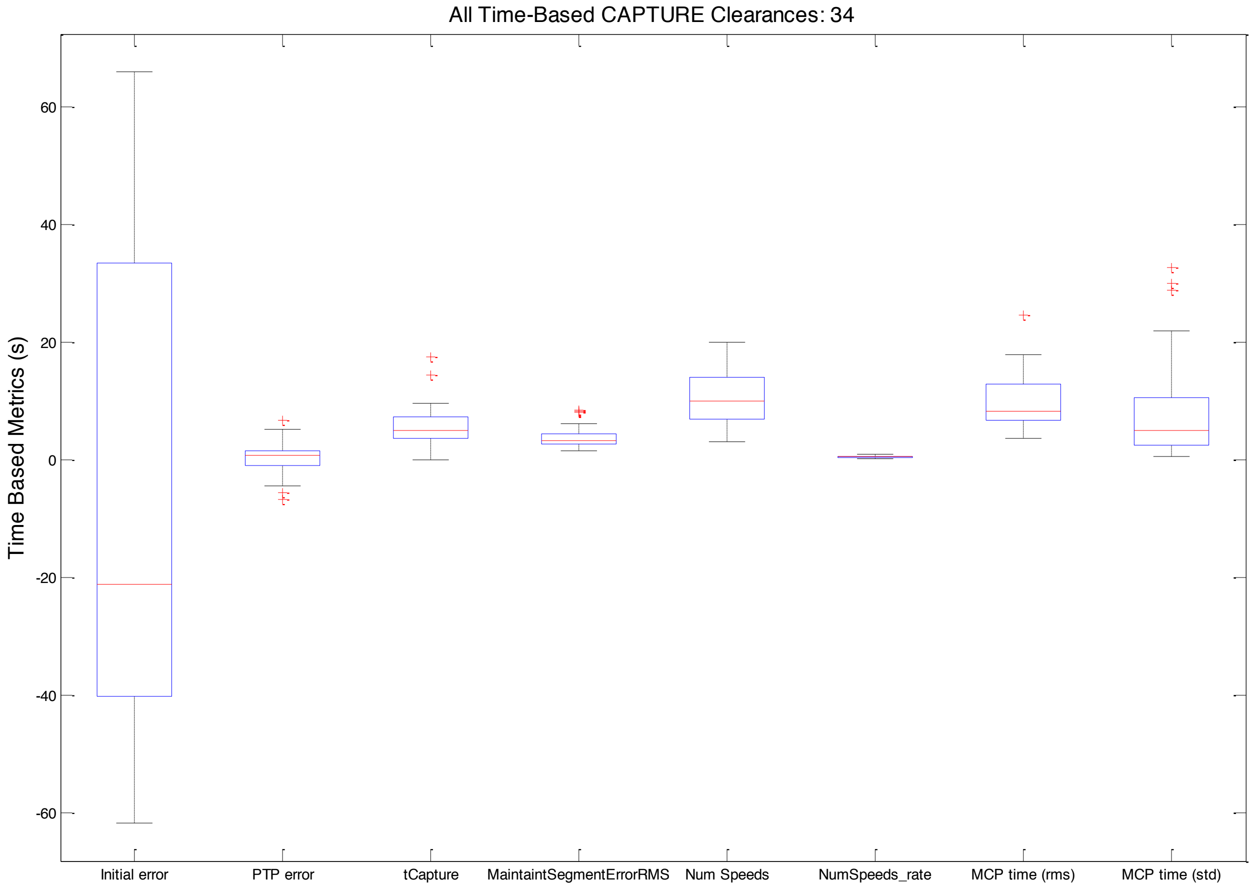


Figure 17: IM Performance - En Route Time-Based MAINTAIN

Time-Based CAPTURE Operations

The time-based CAPTURE statistics are shown in Figure 18. Time-to-capture (*tCapture*) in the boxplot is shown in minutes to match the scale of other time-based metrics that are in seconds. The delivery statistics at the PTP (median=0.7576 s, IQR=2.59 s) are very good relative to the initial spacing error (median=-21.43, IQR=73.83 s). The time-to-capture averages at 5.57 minutes (mean), with an IQR of 3.72 minutes. The MOPS metric for capture performance is based on a minimum capture rate of 3 seconds of error per minute of flight time. The capture rate for CAPTURE operations is computed by dividing the initial spacing error (reduced by 10 s) by the capture time in minutes. The mean capture rate for CAPTURE operations is 6.1 s, with only 4 out of the 34 CAPTURE operations below the 3-s threshold. Three of those four were for cases where the IM aircraft was the third in the chain, and all of them were for a delay case for the chain lead of at least medium (~10 kt below profile), all challenging cases for the algorithm.



	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	numSpeeds	numSpeeds_ perMin	pilotTime_mean (s)	pilotTime_std (s)	MaintainError _RMS (s)	tCapture (s)
Mean	-6.58	88.35	0.19	10.47	0.54	10.03	8.93	3.91	334.06
95% CI low	-21.99	80.90	-0.81	8.89	0.48	8.37	5.84	3.29	260.69
95% CI high	8.82	95.80	1.18	12.05	0.60	11.69	12.02	4.52	407.43
Range	127.95	79.75	13.60	17.00	0.69	20.93	32.16	6.91	1047.00
IQR	73.83	22.60	2.59	7.00	0.25	6.10	8.13	1.81	223.00

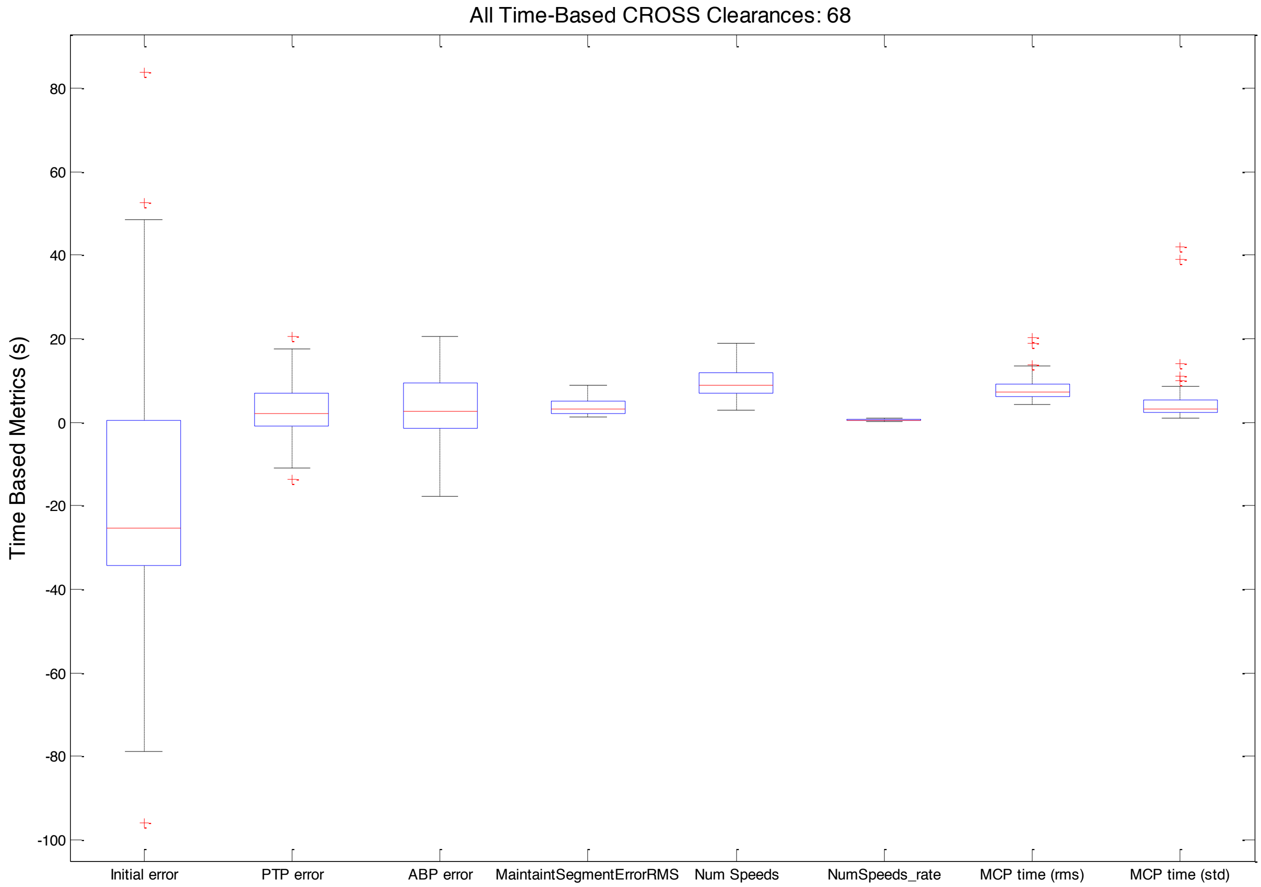
Figure 18: IM Performance - Time-Based CAPTURE

The number of speeds required to achieve this performance averages 10 (median) with an IQR of 7. The maintain segment of the operation has similar performance to equivalent MAINTAIN operations shown before (i.e., less than 4 s of RMS error).

Only two scenarios make up the portion of CAPTURE operations performed en route (A scenarios). One of those runs is, in fact, an outlier in Figure 18 (top outlier on PTP error).

Time-Based CROSS Operations

The CROSS statistics are shown in Figure 19. By far the largest number of IM operations performed during flight test are time-based CROSS operations. Sixty-eight such runs are part of this analysis. CROSS operations are more complex than either MAINTAIN or CAPTURE operations as they allow for merging geometries and large portions of the operation being on different routes. CROSS operations rely on a predictive algorithm rather than a state-based algorithm for the spacing signal on which the control is operated (PSI). CROSS operations attempt to achieve the desired spacing at the ABP, which may be upstream from the PTP. Between the ABP and PTP, the operation is performed on the same algorithm as CAPTURE and MAINTAIN operations, and that segment of the operation is labeled the "maintain segment." The flight test matrix includes many combinations of geometries and associated ABP and PTP placements. Some have no maintain segment; in particular, those with ABP and PTP at ZAVYO. Many of these operations were performed with a merging geometry with the lead on the SUBDY arrival and the FIM aircraft on the UPBOB arrival (late merge), but some were also performed with two aircraft on SUBDY having a prior merge at NALTE. Some CROSS operations with the merge at NALTE were performed with the ABP placed there.



	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	ABP error (s)	numSpeeds	numSpeeds_per Min	pilotTime_mean (s)	pilotTime_std (s)	MaintainError_ RMS (s)
Mean	-17.49	83.27	3.49	3.24	9.78	0.53	8.13	5.08	3.84
95% CI low	-25.22	79.56	1.71	1.16	8.91	0.48	7.38	3.45	3.00
95% CI high	-9.77	86.99	5.27	5.32	10.65	0.57	8.87	6.71	4.68
Range	180.00	72.49	34.22	38.25	16.00	0.80	16.20	41.05	7.80
IQR	34.63	18.67	7.82	10.87	5.00	0.22	2.94	2.94	2.82

Figure 19: IM Performance - Time-Based CROSS

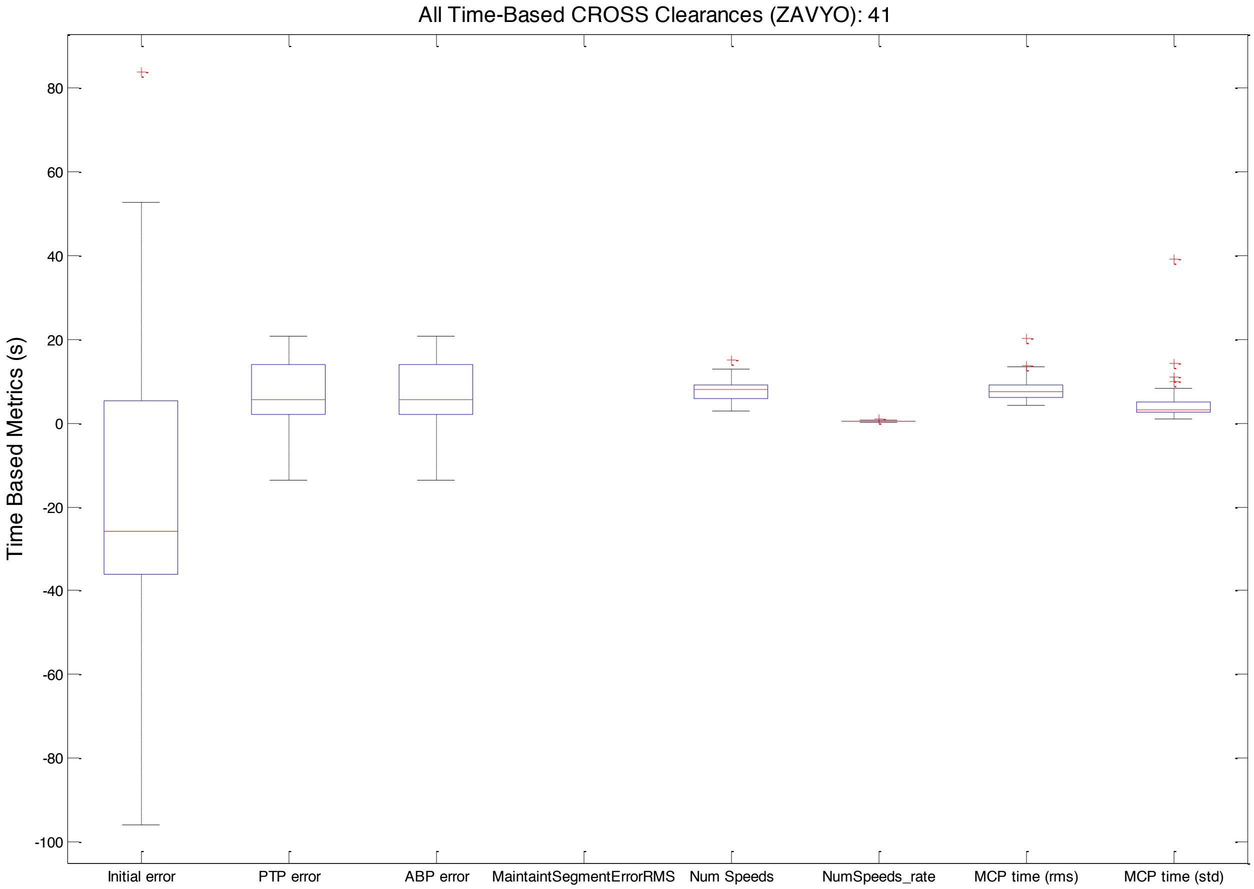
We first look at the totality of time-based CROSS operations (Figure 19). The delivery statistics at the PTP (median=2.0134 s, IQR=7.8206 s) are larger than for CAPTURE operations and biased more towards arriving late, but require on average about the same number of speed corrections. The standard deviation of PTP delivery error is 7.34 s, which would indicate a performance level that does not meet MOPS criteria.

Performance at the ABP is slightly better (in mean) than at the PTP (but with more spread). The standard deviation for ABP delivery error is 8.46 s, corresponding to performance that does not meet MOPS criteria.

There were two types of CROSS operations performed: those with no upstream merge at NALTE (ABP at ZAVYO), and those with the upstream merge (ABP at NALTE). The latter have a maintain segment between the ABP and PTP, which would serve to deliver better performance at the PTP. In fact, the PTP delivery of CROSS operations with ABP at NALTE has a standard deviation of 2.2 s, well within the MOPS performance. The PTP delivery of CROSS operations with merge near ZAVYO (ABP at ZAVYO, with SUBDY/UPBOB merge) has a standard deviation of 6.2 s outside of the MOPS standard. Some CROSS operations were performed with the ABP at ZAVYO but with the upstream merge at NALTE (thus no aircraft on UPBOB). Those operations have a PTP delivery standard deviation of 8.68 s, again outside of the MOPS standard.

In general, for those operations that had a maintain segment (ABP at NALTE), the maintain performance is similar to those of MAINTAIN operations and well within the MOPS targets for both PTP delivery and maintain segment performance.

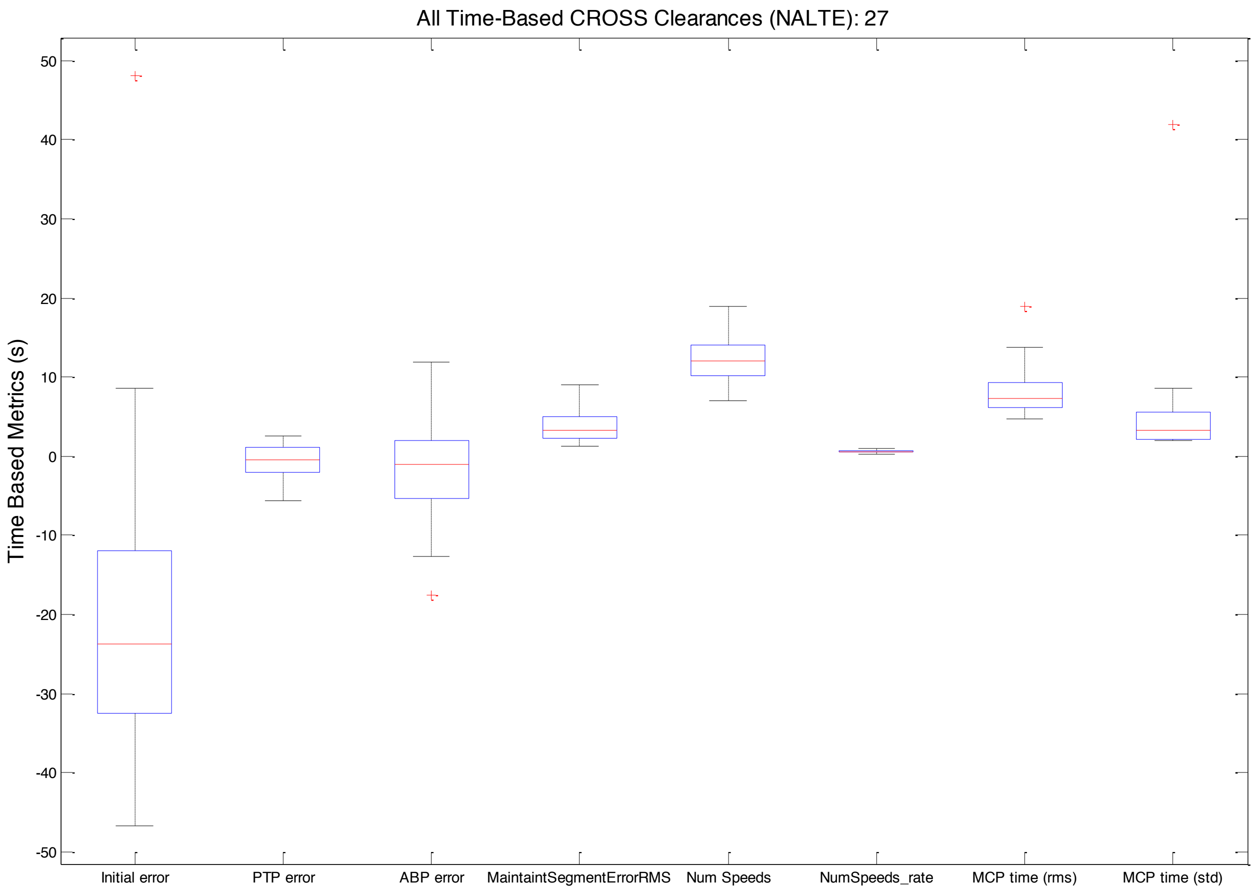
CROSS operations with no maintain segment (ZAVYO ABP and PTP) are displayed in Figure 20. As expected, the RMS value for Maintain segment error is zero and the delivery statistics at the ABP and PTP are the same. However, the delivery error is worse than for the overall CROSS operations, indicating that the NALTE operations tended to perform better, owing to their large maintain segment between NALTE and ZAVYO.



	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	ABP error (s)	numSpeeds	numSpeeds_per Min	pilotTime_mean (s)	pilotTime_std (s)
Mean	-15.69	78.56	6.20	6.20	8.07	0.45	8.14	4.99
95% CI low	-27.58	74.19	3.60	3.60	7.18	0.40	7.17	3.04
95% CI high	-3.80	82.93	8.80	8.80	8.97	0.50	9.11	6.93
Range	180.00	59.29	34.22	34.22	12.00	0.80	16.20	38.14
IQR	41.53	15.98	11.78	11.78	3.00	0.19	2.88	2.58

Figure 20: IM Performance - Time-Based CROSS (ZAVYO)

In fact, this is revealed looking at all CROSS operations with the ABP at NALTE as shown in Figure 21. The ABP delivery is worse than the PTP delivery, but overall the PTP delivery is better than for ZAVYO. The difference can be attributed to the late merging of the ZAVYO geometry, whereas all NALTE operations have a long maintain segment between NALTE and ZAVYO. In fact, the group of CROSS operations with the worst performance are those with the late merge just prior to ZAVYO when UPBOB and SUBDY merge as described earlier. This is attributable to several factors, including the lack of a maintain segment, route design and specifically the nominal vertical and speed profile, but also including the RF turn on the SUBDY route which has been shown to consistently have larger along-track wind forecast errors caused by the large change in track direction at altitudes corresponding to relatively unchanging forecast wind speed and direction. Lastly, the implementation of the TBO algorithm is known to have difficulties near the PTP in the time interval where the lead has crossed the ABP and the FIM aircraft is entering the segment of the trajectory that requires a nominal deceleration to the final stable approach speed.



	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	ABP error (s)	numSpeeds	numSpeeds_per Min	pilotTime_mean (s)	pilotTime_std (s)	MaintainError_ RMS (s)
Mean	-20.22	90.43	-0.63	-1.63	12.37	0.64	8.11	5.23	3.84
95% CI low	-28.41	84.53	-1.50	-4.27	11.14	0.58	6.88	2.21	3.00
95% CI high	-12.04	96.33	0.25	1.02	13.60	0.69	9.33	8.25	4.68
Range	94.98	60.17	8.26	29.57	12.00	0.58	14.21	40.07	7.80
IQR	20.60	23.47	3.16	7.32	3.75	0.19	3.14	3.42	2.82

Figure 21: IM Performance - Time-Based CROSS (NALTE)

Time-Based SPACE Operations

Lastly, we report statistics for time-based SPACE operations (Figure 22). There were only five time-based SPACE operations and thus the statistics are reported in tabular form only. All SPACE operations were performed with either the 757 or 737 as lead (no F900) on either merging or non-merging geometries with the lead on either in case of merges. Because of the very small number of experiments attempted, the statistics are not broken down by geometry. SPACE operations are special-case CROSS operations where the ABP and PTP are the same, and computed by the system at a distance of 6.25 nm from the runway threshold. No procedure is entered in the system; the geometry is assumed to be along the runway's extended centerline. When a FIM aircraft merges onto final approach, the merge point is part of the geometry and is computed by the system. Delivery statistics for SPACE operations are similar to those of CROSS, with slightly less speeds issued. Although within the MOPS performance targets, the sample size is small and thus the confidence interval for the delivery performance metric is larger than other clearance types.

	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	ABP error (s)	numSpeeds	numSpeeds_per Min	pilotTime_mean (s)	pilotTime_std (s)
Mean	-10.62	21.16	3.37	3.37	5.00	0.84	7.20	3.14
95% CI low	-38.44	12.62	-1.33	-1.33	3.76	0.42	-0.87	-2.88
95% CI high	17.19	29.69	8.08	8.08	6.24	1.27	15.27	9.16
Range	52.46	17.97	9.90	9.90	2.00	0.88	17.00	11.75
IQR	17.77	8.07	5.15	5.15	2.00	0.28	8.75	3.35

Figure 22: IM Performance - Time-Based SPACE (5 samples)

Distance-Based Operations by Clearance Type

Finally, we inspect the statistics for distance-based operations by clearance type. Because of the smaller sample size of those operations, the statistics are delivered in table form only (Figure 23 through Figure 26). No true comparison of delivery across distance and time-based operations can be performed without normalization caused by the difference in units. No normalization was attempted for this study. The majority of the distance - based operations performed were done en route, with the exception of the CROSS and SPACE clearances.

	InitialSpacing Error (nm)	IM Length (nm)	PTP error (nm)	numSpeeds	numSpeeds_ perMin	pilotTime_mean (s)	pilotTime_std (s)	MaintainError _RMS (s)
Mean	0.07	30.11	-0.31	2.67	0.90	6.78	0.96	0.14
95% CI low	-0.09	4.59	-1.01	-1.13	-0.76	0.45	-1.23	0.10
95% CI high	0.23	55.63	0.40	6.46	2.57	13.10	3.15	0.18
Range	0.12	18.84	0.50	3.00	1.34	5.00	1.73	0.03
IQR	0.09	14.13	0.38	2.25	1.00	3.75	1.30	0.03

Figure 23: IM Performance - Distance-Based MAINTAIN (Three Samples, all A Scenarios)

	InitialSpacing Error (nm)	IM Length (nm)	PTP error (nm)	numSpeeds	numSpeeds_ perMin	pilotTime_mean (s)	pilotTime_std (s)	MaintainError _RMS (s)	tCapture (s)
Mean	-0.62	31.09	0.52	3.00	0.73	10.37	3.70	9.52	285.00
95% CI low	-41.17	-24.20	-12.96	-9.71	-0.14	-38.86	-34.38		
95% CI high	39.94	86.38	13.99	15.71	1.61	59.61	41.79		
Range	6.38	8.70	2.12	2.00	0.14	7.75	5.99	0.00	0.00
IQR	6.38	8.70	2.12	2.00	0.14	7.75	5.99	0.00	0.00

Figure 24: IM Performance - Distance-Based CAPTURE (Two Samples, all A Scenarios)

	InitialSpacing Error (nm)	IM Length (nm)	PTP error (nm)	ABP error (nm)	numSpeeds	numSpeeds_per Min	pilotTime_mean (s)	pilotTime_std (s)
Mean	0.91	72.75	0.32	0.32	9.14	0.59	8.38	3.29
95% CI low	-1.62	54.51	-0.55	-0.55	6.45	0.41	6.69	2.18
95% CI high	3.45	90.99	1.18	1.18	11.84	0.77	10.06	4.41
Range	6.95	59.52	2.38	2.38	9.00	0.57	4.53	3.39
IQR	4.73	20.28	1.67	1.67	3.50	0.27	2.74	1.75

Figure 25: IM Performance - Distance-Based CROSS (Seven Samples, all B Scenarios)

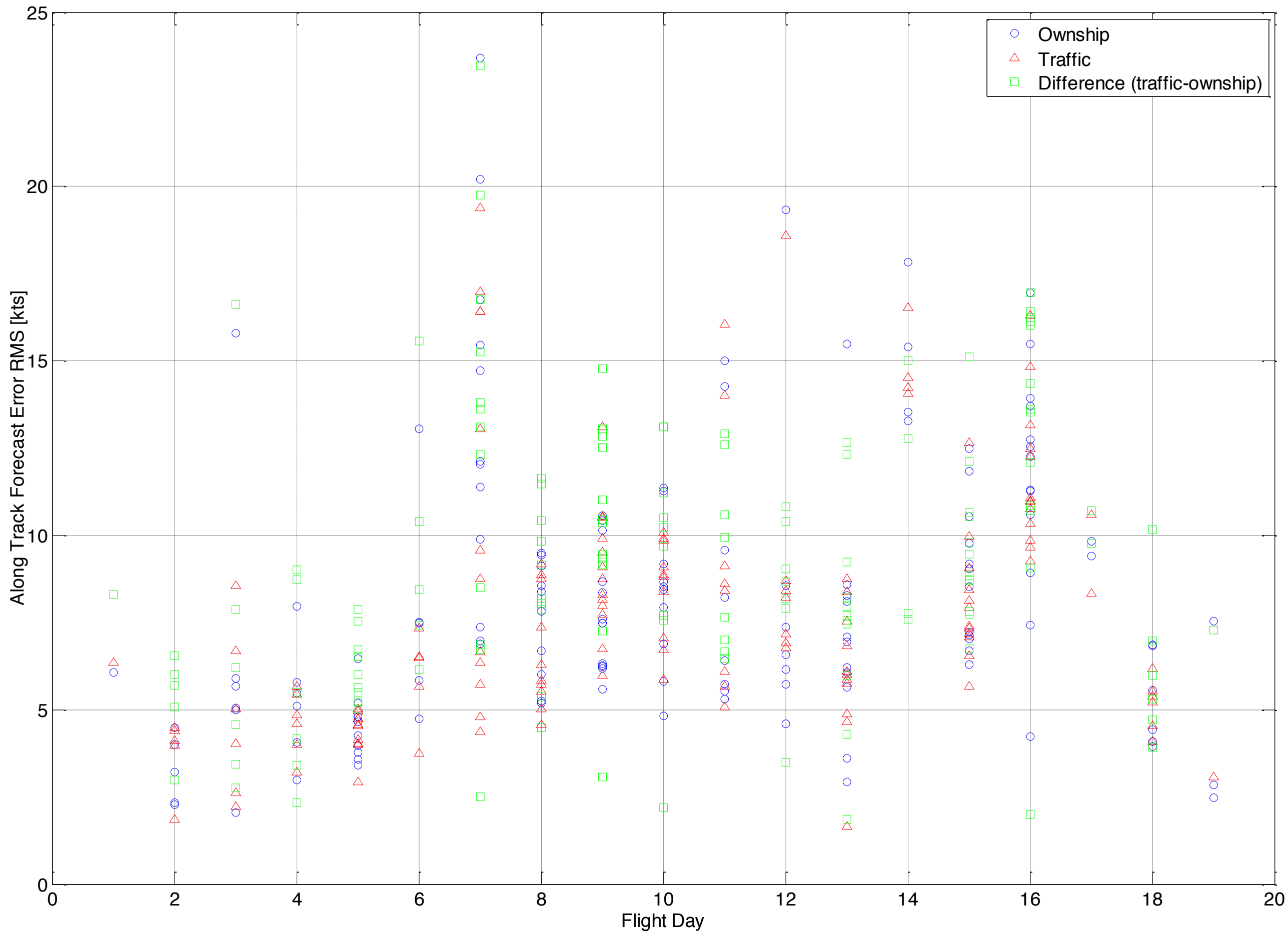
	InitialSpacing Error (nm)	IM Length (nm)	PTP error (nm)	ABP error (nm)	numSpeeds	numSpeeds_per Min	pilotTime_mean (s)	pilotTime_std (s)
Mean	-0.84	10.06	0.09	0.09	3.00	1.08	5.33	2.30
95% CI low	-2.61	5.96	-0.49	-0.49	0.52	-0.17	-3.39	0.39
95% CI high	0.94	14.16	0.68	0.68	5.48	2.33	14.06	4.21
Range	1.43	3.06	0.45	0.45	2.00	0.98	7.00	1.41
IQR	1.07	2.30	0.34	0.34	1.50	0.74	5.25	1.06

Figure 26: IM Performance - Distance-Based SPACE (Five Samples)

Along-Track Wind Forecast Error

Along-Track Wind Forecast Error (ATWFE) is computed for all flights for both ownship and traffic and the RMS values are computed individually and for their difference (traffic – ownship). Figure 27 reports the ATWFE metrics for each flight day. Blue squares are ATWFE computations for ownship, red triangles for traffic, and green squares for the difference between the two. In cases where ownship and traffic are on the same path, the differences in ATWE should be minor as the wind experienced by both aircraft may only be slightly different because of the actual flown altitude variations and a minor time difference between both aircraft being at equivalent 2-D positions. Thus, some green squares and red triangles are nearly superimposed in the figure.

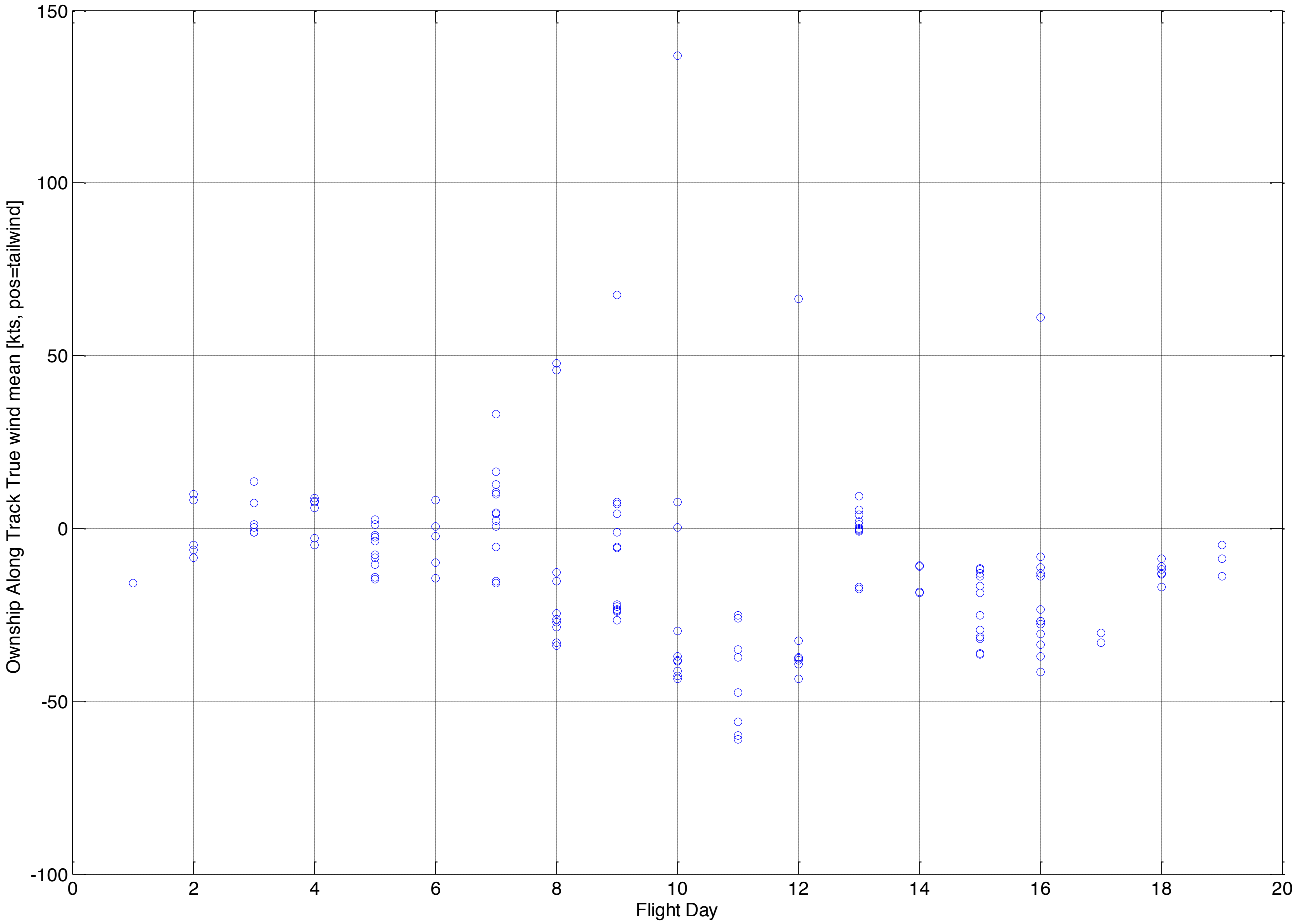
Clearly, ATWFE will vary by geometry and time of flight for a given experiment because the experienced wind changes. As the figure shows, there are even large variations in the ATWFE within a given day (e.g., Day 7 and Day 12 have large variability). The descriptive statistics for each of the three ATWFE metrics is shown in the table in Figure 27.



	ATWFE Ownship (kts)	ATWFE Traffic (kts)	ATWFE Diff (kts)
Mean	8.21	7.86	9.14
95% CI low	7.56	7.27	8.50
95% CI high	8.87	8.46	9.79
Range	21.64	17.72	21.60
IQR	4.47	4.43	4.91

Figure 27: Along-Track Wind Forecast Error

The experienced wind can have an effect on the IM Operation (headwind or tailwind). The along-track component of the actual wind is computed for all flights for both ownship and traffic and the mean of the experienced along track wind component is computed and shown for each day in Figure 28. Again, there is large variability within each day caused by the many different geometries flown and the four-hour time span of most daily campaigns.



	True wind along track Mean (kts) - Ownship	True wind along track Mean (kts) - Traffic
Mean	-10.83	-9.69
95% CI low	-14.95	-13.65
95% CI high	-6.71	-5.74
Range	197.87	194.69
IQR	27.44	23.34

Figure 28: Along Track True Wind (ownship)

Along-track wind forecast error does not appear to be strongly correlated to the mean of the along track experienced wind. To enable this comparison the mean of the experienced wind must be rendered positive (RMS values for along track wind forecast error are always positive) first by taking its absolute value. The correlation coefficient between ATWFE and along-track true wind (abs) is 0.27.

Fuel Burn

Average fuel burn rate statistics per clearance type is shown in Figure 29. Rates are comparable across operation type, except for the SPACE clearance which has a higher burn rate owing to its low-altitude, mostly level operational regime. Differences by other grouping variables are treated in the ANOVA section (Section 5).

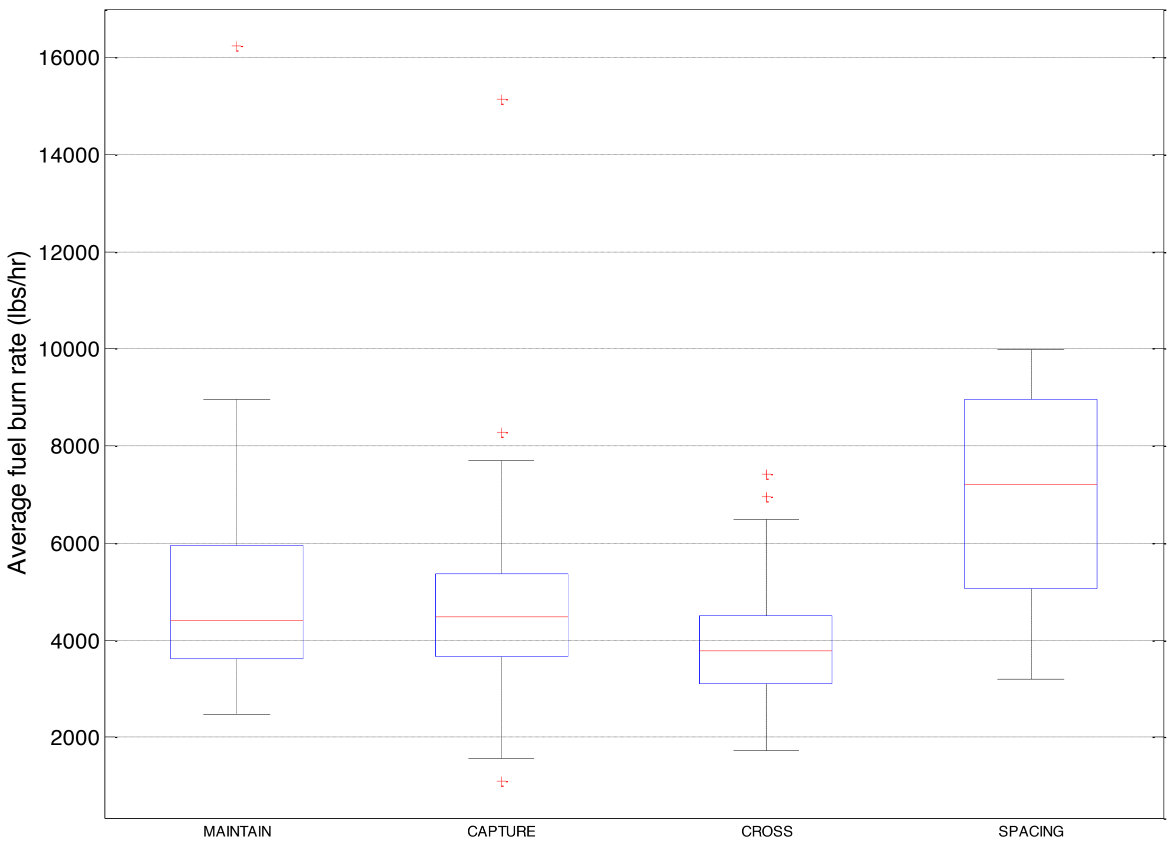


Figure 29: Average Fuel Burn Rate by Operation

Flight Technical Error

Flight Technical Error (FTE) is defined as the deviation of the aircraft (laterally and vertically) from its guidance path, embodied by a generated trajectory. The FMS and the FIM system both derive a generated trajectory for the basis of their control functions. Thus, four FTE metrics are computed:

- FMS Lateral deviation
- FMS Vertical deviation
- FIM Lateral deviation

- FIM Vertical deviation

As noted in Annex C, the actual generated trajectory changes throughout the flight and thus the FTE metrics represent the instantaneous deviation from the current generated trajectory. There can be some discontinuity in the FTE deviation data at times of trajectory generations. The FMS does not export its trajectory, only the instantaneous deviations. The FIM system does log its trajectory and the instantaneous deviations.

Lateral FTE is a measure of how close to the generated lateral path the aircraft actually flew. Given that none of the FIM operations have control in the lateral dimension, and that all flights in the flight test were performed in LNAV or ILS approach guidance (localizer), the lateral FTE metrics are not expected to be large or vary largely.

Vertical FTE is a measure of how close to the generated vertical path the aircraft actually flew. In FIM descent operations under the ATD-1 concept and associated FIM prototype, speed control is achieved mostly in the VNAV mode, in speed on elevator mode. Thus vertical deviations are expected in regions where speeds must be altered significantly from the assumed nominal speed profile. Pilots were instructed to try to remain close to the original vertical path and the vertical FTE metric is used to gauge that effort.

As noted in section 1 only the 737 recorded data for the FMS lateral and vertical deviations. Thus, the FMS FTE for the 757 contains no data. Figure 30 shows the statistics for FMS lateral FTE by path flown. The final approach path has larger means for FMS lateral FTE than the other paths. That is because the path is defined as a straight line along the extended runway centerline but some of the final approach spacing geometries had the aircraft approach from the right at a 30-degree intercept angle. Thus in the period prior to the intercept the aircraft was flying on heading or track, and the lateral deviation to the extended centerline is initially large. The en route path has a comparable mean to the descent paths but with more spread. This is likely caused by slop in the initial conditions where, in some cases, the FIM operation was started just before or just after ZIRAN, where a turn occurs. The rest of the geometry is straight.

Figure 30: FMS Lateral Deviation RMS by Path

By comparison, the FIM Lateral Deviation RMS by Path is shown in Figure 31. This data includes the 757. The en route path has larger deviations resulting from a flight test procedure. Crews were instructed to not enter SINGG in the flight plan in the FMS to protect the Military Operations Area (MOA) to the NW of the path. However, SINGG was the PTP for this path and thus the lateral FTE of the FIM system (which includes SINGG) grows larger as the aircraft approaches SINGG. The final approach path does not have significantly larger deviations than the other paths because the FIM system draws the complete path from FIM initiation to the runway (including an intercept if required) even when the aircraft may be flown in heading or track mode against the FMS path which only includes the runway extended centerline.

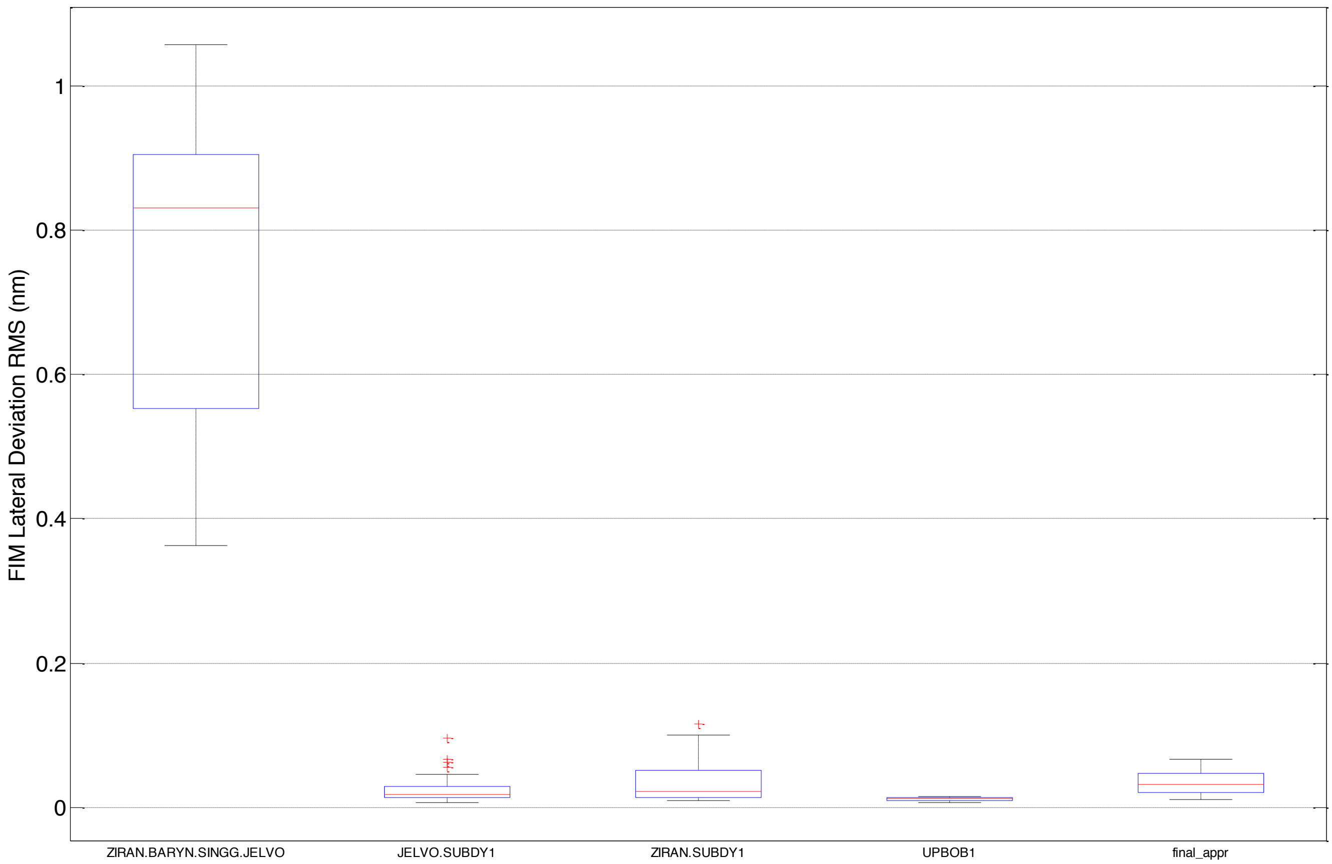


Figure 31: FIM Lateral Deviation RMS by Path

Vertical deviation FTE for the FMS is summarized in Figure 32. The en route path appears to have a consistent 4000 ft difference from the FMS nominal altitude. Given that this path is flown at level cruise altitude of 35,000 ft, the difference likely is caused by the FMS vertical altitude reference being the ECON altitude, not the actually flown altitude driven by the MCP. This is expected if the crews did not, in fact, enter the cruise altitude in the FMS VNAV path, but left it as an ECON cruise and flying the aircraft vertically using the MCP. Because no detailed FMS data is available for review, this theory cannot be confirmed. The average vertical deviation throughout the flight (RMS value) is similar for all three descent paths. This deviation is mostly caused by the aircraft deviating from the FMS guidance to execute FIM speeds using the MCP as detailed earlier. The fact that the deviation is generally not much larger than 2000 ft is promising and a product of the containment of the FIM speed control authority to within 15% of the nominal speed. The approach path has greater average deviations but again, this is caused by an artifact of the procedure where the vertical reference for the FMS is along the approach path with a glideslope by the portion of the IM operation outside of the runway centerline was conducted mostly level.

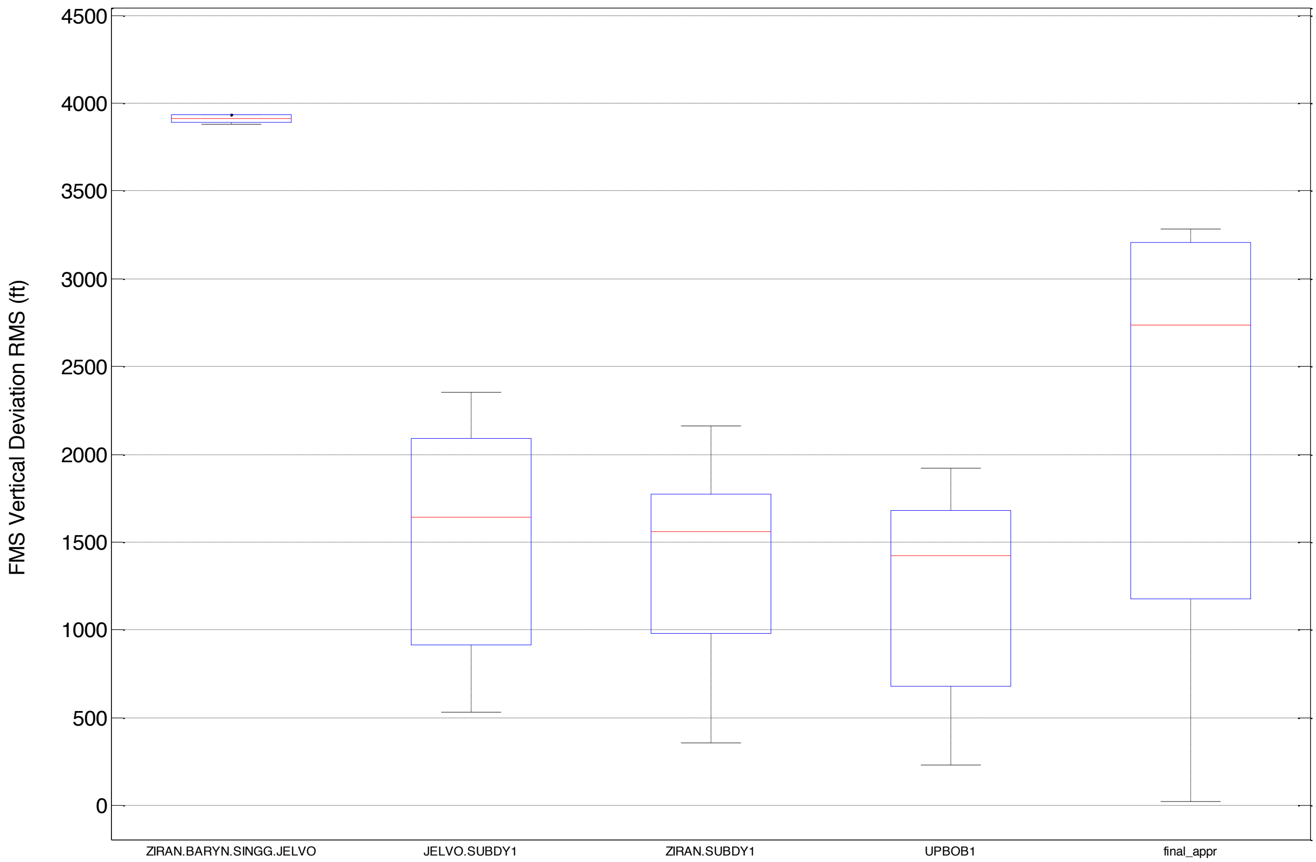


Figure 32: FMS Vertical Deviation RMS by Path

Vertical deviation FTE for the FIM system is summarized in Figure 33. In this case, the FIM system generates cruise and approach vertical paths based on IM operational inputs in the FIM system and corresponds more closely to the flown operation than the FMS path. The FIM system generates a vertical trajectory assuming a kinematic aircraft model whereas the FMS system has full aerodynamic and engine performance at its disposal. The fact that the FIM system generates vertical trajectories closer to what was flown is an artifact of the procedure design and the difference in fidelity between the FMS and FIM vertical trajectory construction models.

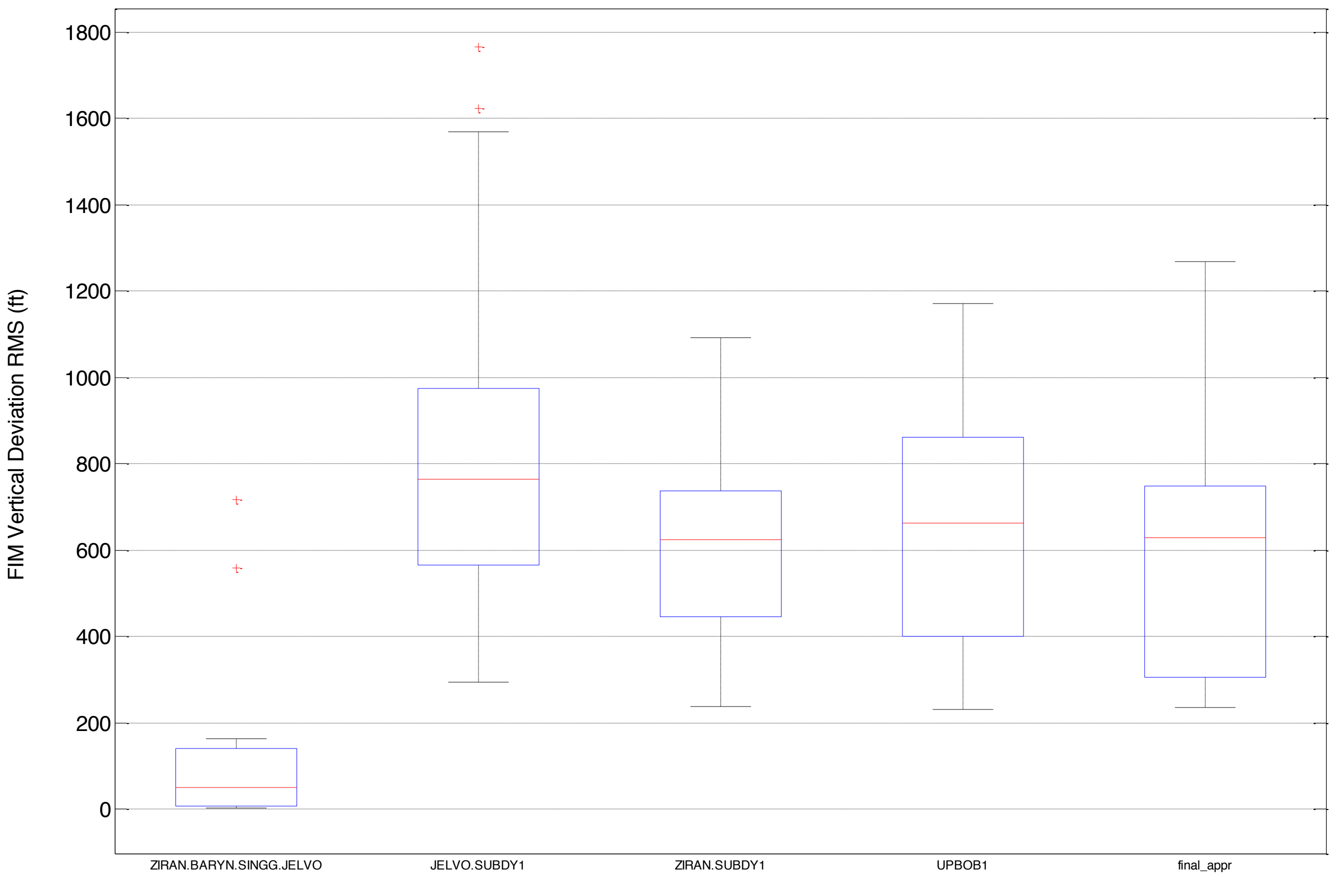


Figure 33: FIM Vertical Deviation RMS by Path

Path Definition Error

Path Definition Error (PDE) is defined as the difference between the FMS-generated trajectory and the FIM system-generated trajectory in the lateral and vertical dimensions. The FMS trajectory is not directly available for comparison, thus the PDE metric is based on the difference between the FMS-reported deviations and the FIM-reported deviations (lateral and vertical) as explained in Annex C of the Flight Test Plan. Again, because the 757 did not record data for FMS deviations, the PDE metric cannot be reported.

The summary statistics for lateral PDE by path are shown in Figure 34. The larger lateral PDE for the en route path is again caused by the difference in path entry between the FMS and FIM system, a procedure the pilots followed to avoid getting close the NW MOA near SINGG and the downstream turn through JELVO. All other paths have average lateral PDEs of very small value (less than an aircraft wingspan) with relatively small dispersion.

The summary statistics for vertical PDE by path are shown in Figure 35. Again, the en route path highlights a difference between the FMS programmed cruise altitude and the entered FIM system altitude. This difference did not have a bearing on the operation because the aircraft flew MCP altitude level at the FIM entered altitude. As discussed earlier, the final approach PDE is mostly caused by the FMS vertical profile generated along the runway extended centerline in operations that may have an intercept section or even a level flight segment at IM onset until approach path capture. The descent paths have average vertical PDE of less than 2000 ft, which is a relatively small number given the difference in fidelity between the FMS and FIM system vertical trajectory generators.

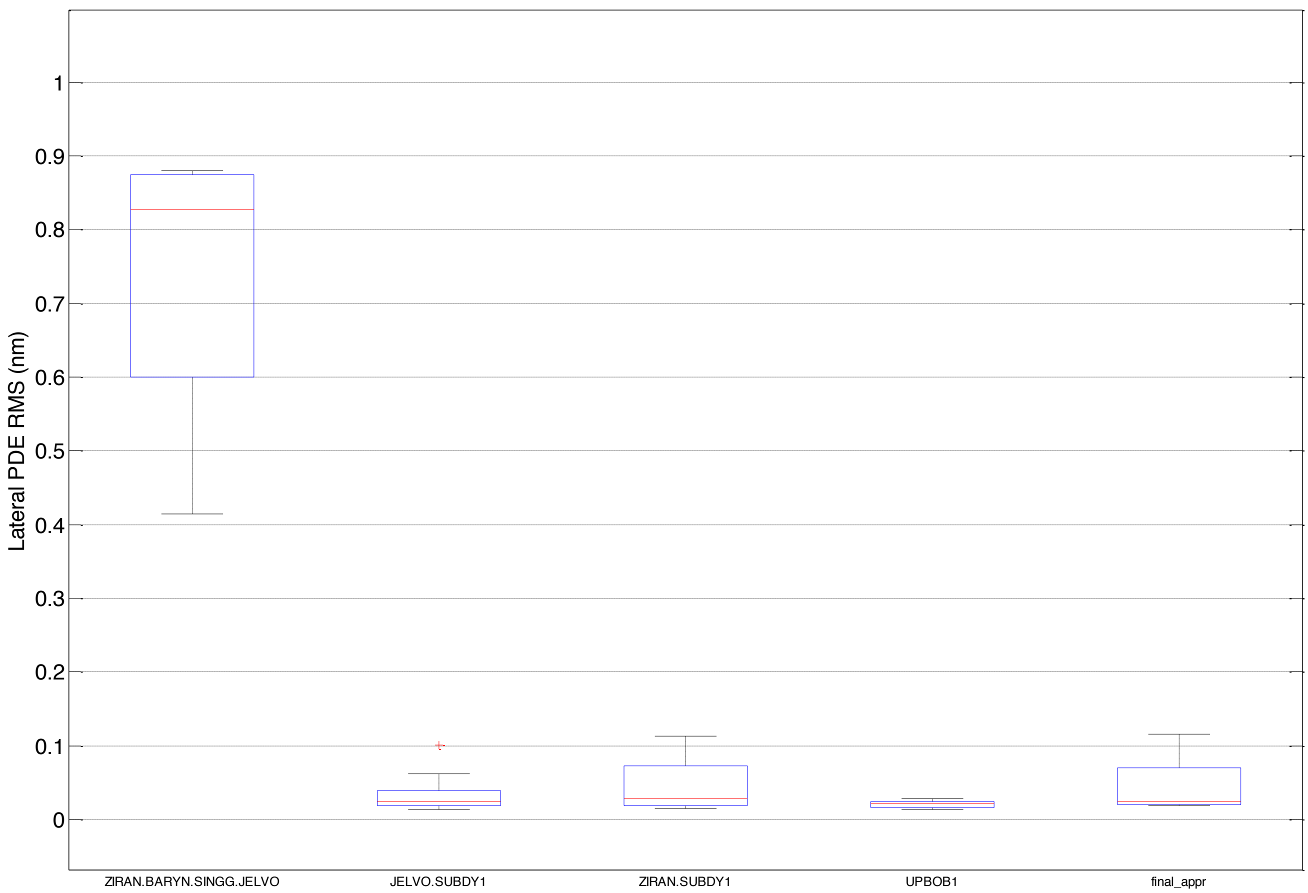


Figure 34: Lateral PDE RMS by Path

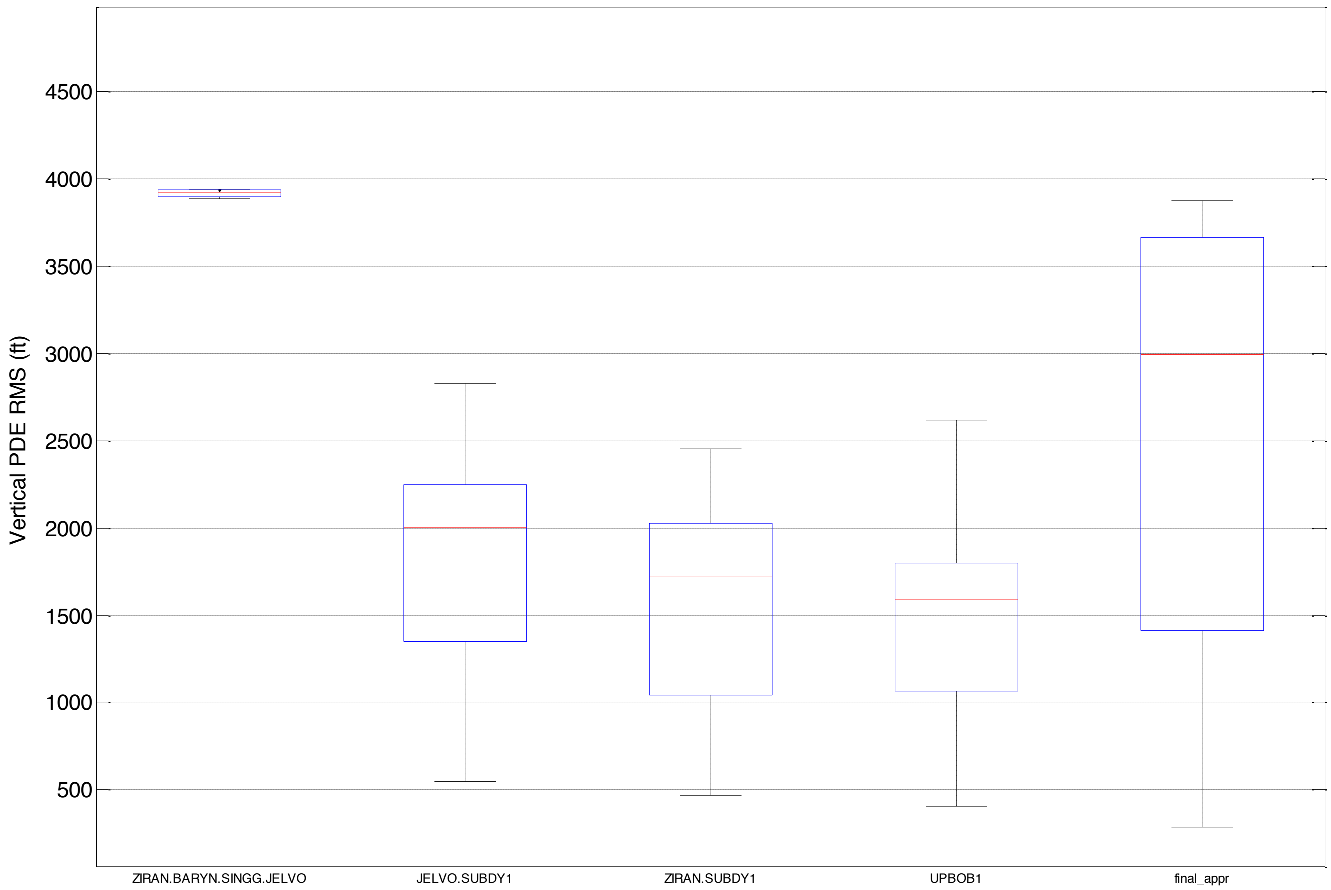


Figure 35: Vertical PDE RMS by Path

5. Analysis of Variance

The purpose of conducting ANOVA on the dataset is to identify statistically meaningful differences between groups in the data. It is important to realize that the flight test matrix in no way represents a full-factorial design and thus not all effects will possibly be discernable. This means that many of the interaction effects between the factors may not be captured. Thus, one-way ANOVA is considered exclusively in this report. Multiway ANOVA is not performed here, but linear regression models are attempted and reported in section 6; derivation of such models utilizes the same statistical techniques as performed using ANOVA.

Furthermore, because much of the data are not normally distributed, nonparametric means of performing ANOVA are sought, such as Kruskal-Wallis tests for comparing samples of unknown mean and variance and testing whether they may belong to the same distribution. All statistical tests are conducted at a significance level of 95% (alpha level of 0.05) and statistical significance is reported at that level.

Are there differences in ATWFE for ownship, traffic and their difference, between days and geometry?

ATWFE ownship

By day: (p value = 3.86E-9) Significant differences at 95% confidence level

By path: (p value = 0.0927) No significant difference at 95% confidence level

ATWFE traffic

By day (p value = 8.61E-12) Significant differences at 95% confidence level

By path (p value = 0.0007) Significant differences at 95% confidence level

ATWFE difference

By day (p value = 1.1e-5) Significant differences at 95% confidence level

Days 7, 14, and 16 have significant differences in ATWFE from all other days as shown in Figure 36.

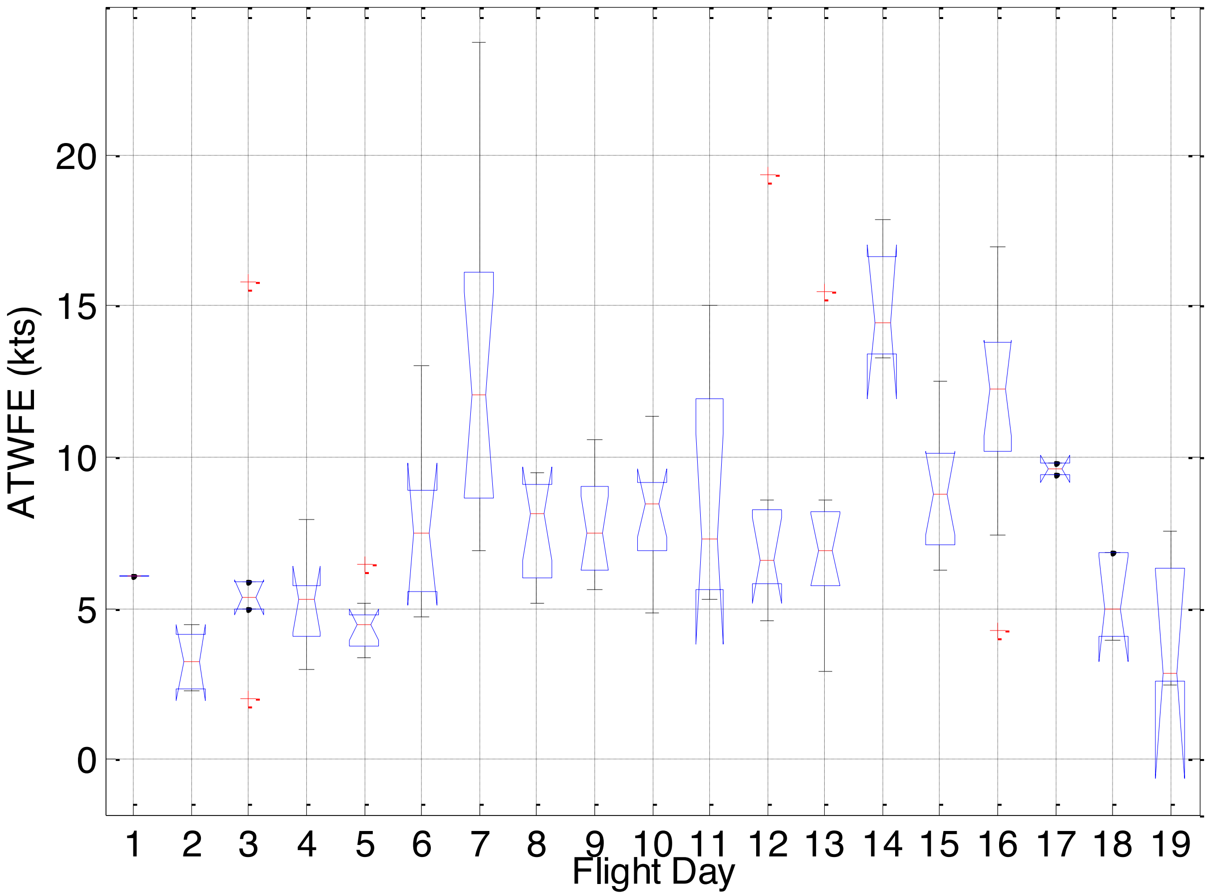


Figure 36: ATWFE By Flight Day

The final approach path (used on SPACE clearances) has significantly different ATWFE than the other paths (Figure 37). This is likely caused by the low altitude nature of this path and its much straighter nature. This path does not include the RF turns present in the transition to the final approach present in the other paths, and thus is subject to less forecast error observed for all other paths (see section 2) through those turns.

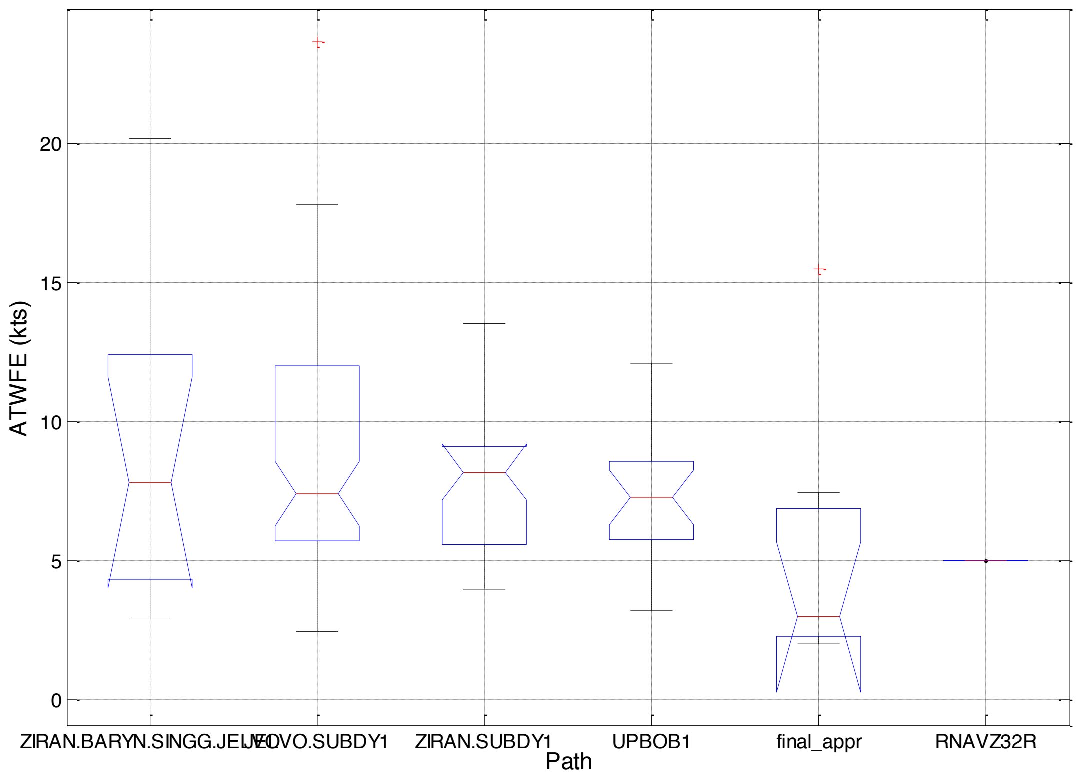


Figure 37: ATWFE By Ownship Path

Are there differences in Average Fuel Burn rate between operations, geometry, and aircraft type?

By operation units: (p value = 0.0067) <u>Significant differences at 95% level</u>

Distance-based operations have higher average fuel burn rate (Figure 38) likely caused by the higher IM Speed rate as will be seen later in this section.

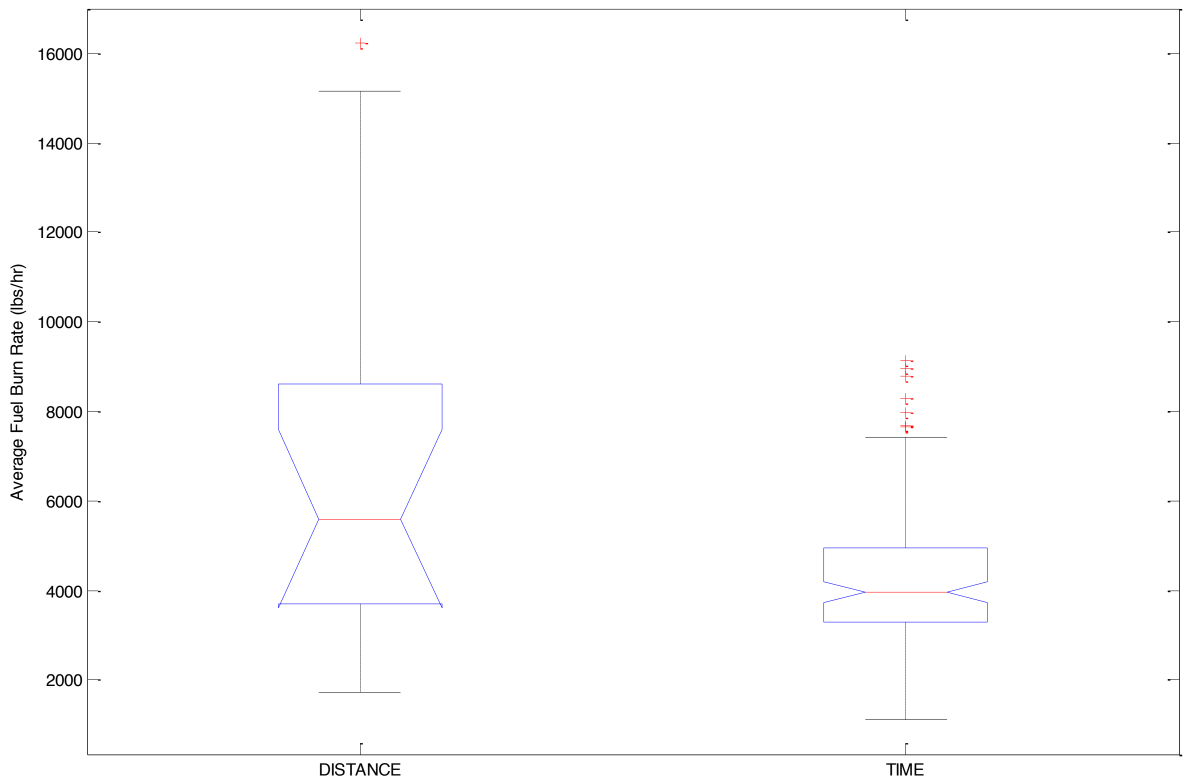


Figure 38: Average Fuel Burn Rate by IM Operation Units (time/distance)

By clearance type: (p value = 0.0012) <u>Significant differences at 95% level</u>

The main statistically significant difference is between CROSS and SPACING operations (Figure 39). SPACING operations are operated at low altitudes on generally level segments and thus are expected to burn more fuel.

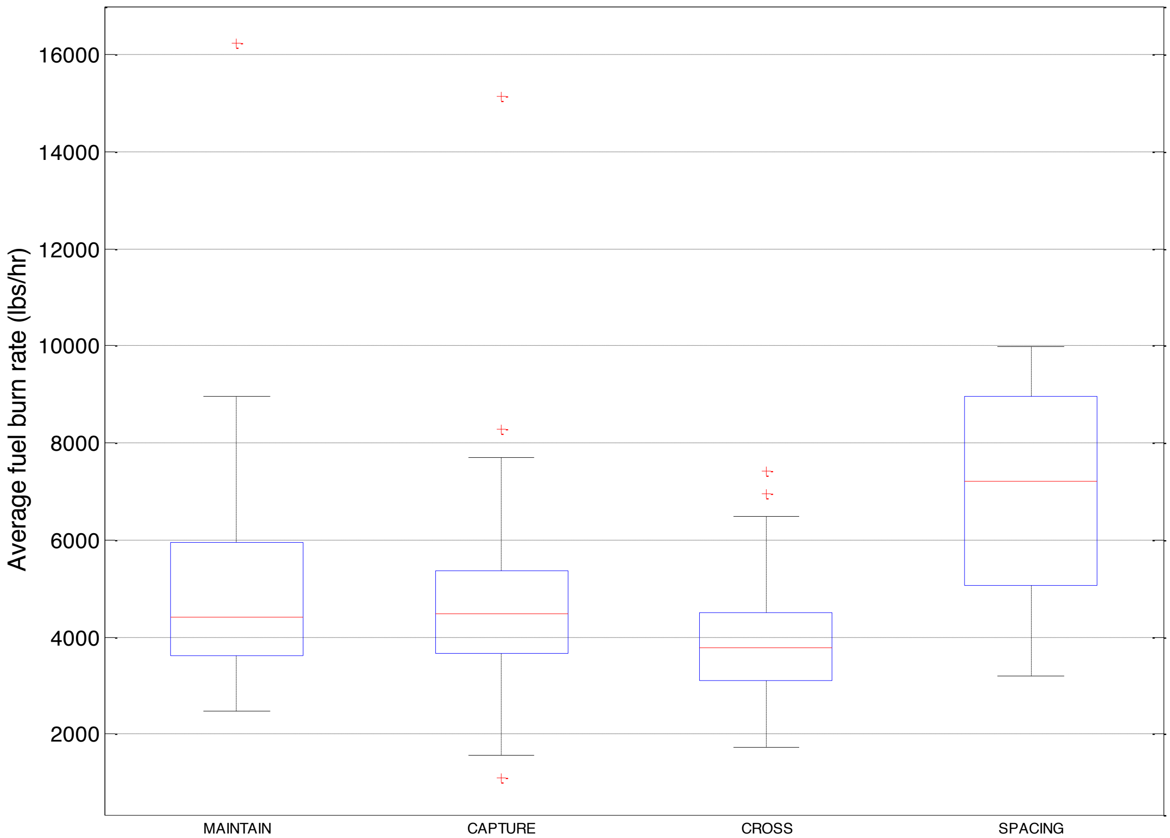


Figure 39: Average Fuel Burn Rate by Clearance Type

In general the 757 burns more fuel, as is expected because of the different weight class and age (generation) of aircraft (Figure 40 and Figure 41).

By aircraft type: (p value = 3.54E-06) <u>Significant differences at 95% level</u>

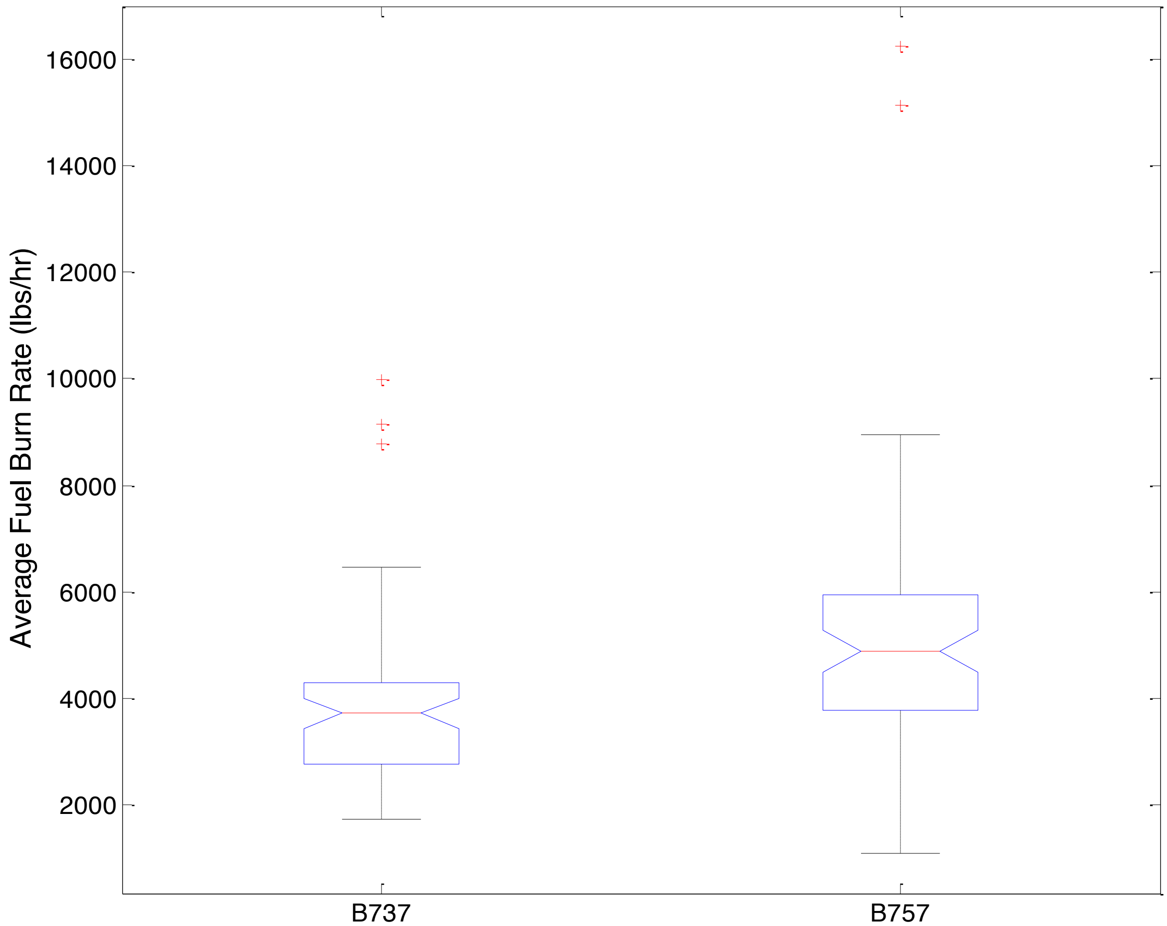


Figure 40: Average Fuel Burn Rate by Ownship Aircraft Type

By path: (p value = 1.86E-08) <u>Significant differences at 95% level</u>

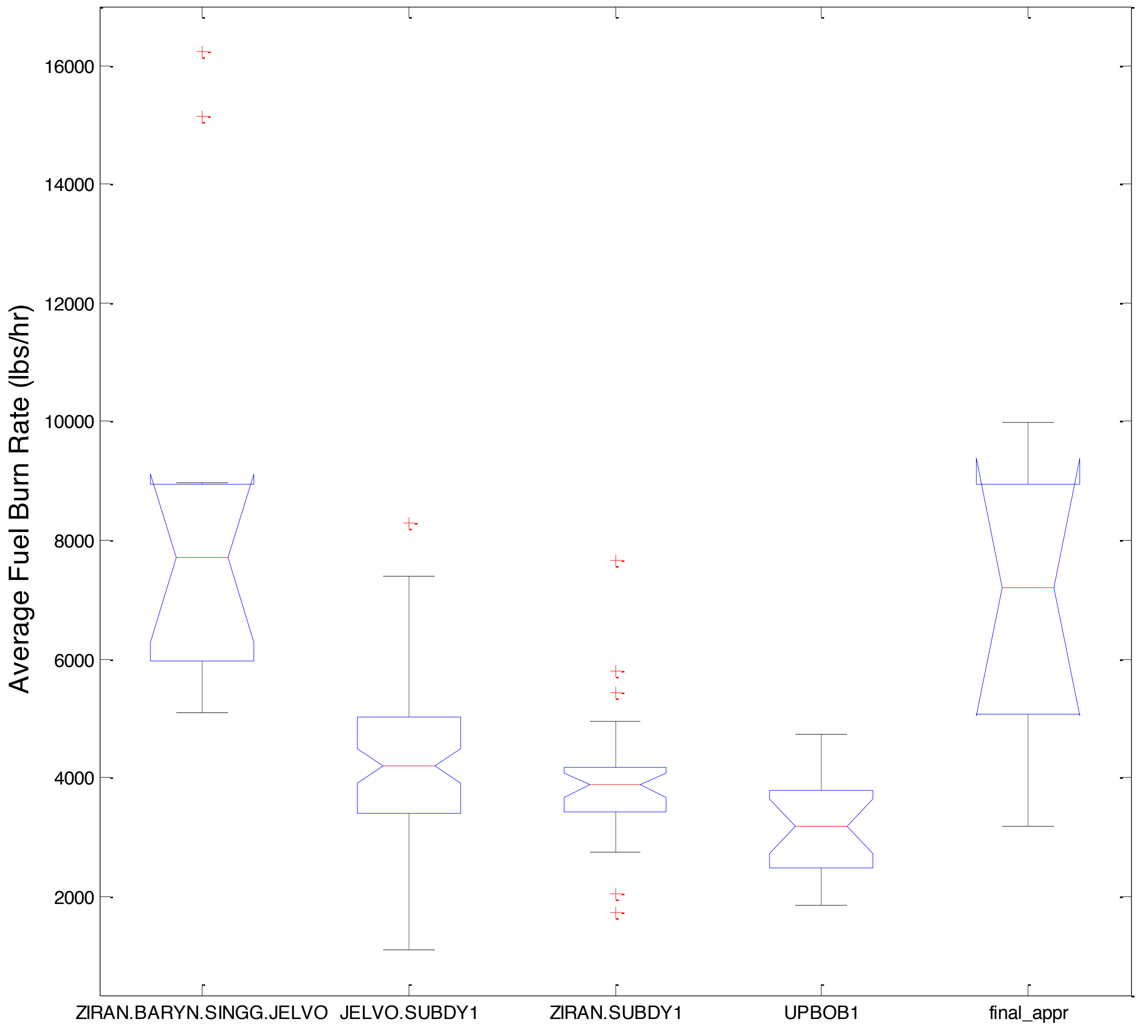


Figure 41: Average Fuel Burn Rate by Ownship Path

The en route and final approach paths have higher fuel burn rate, which is expected given that they are mostly level flight operations and thus will typically operate with speed on throttles. The other paths are used in descent operations in VNAV mode with speed on pitch, a more efficient way to modify speed. The UPBOB path appears to only have statistically significantly less burn than the JELVO path, because of the design of its nominal vertical and speed profile and generally shorter length during IM operations (Figure 42 and Figure 43).

A different view of the same effect is seen when looking at difference by operation types:

By operation type: (p value = 1.46E-07) <u>Significant differences at 95% level</u>

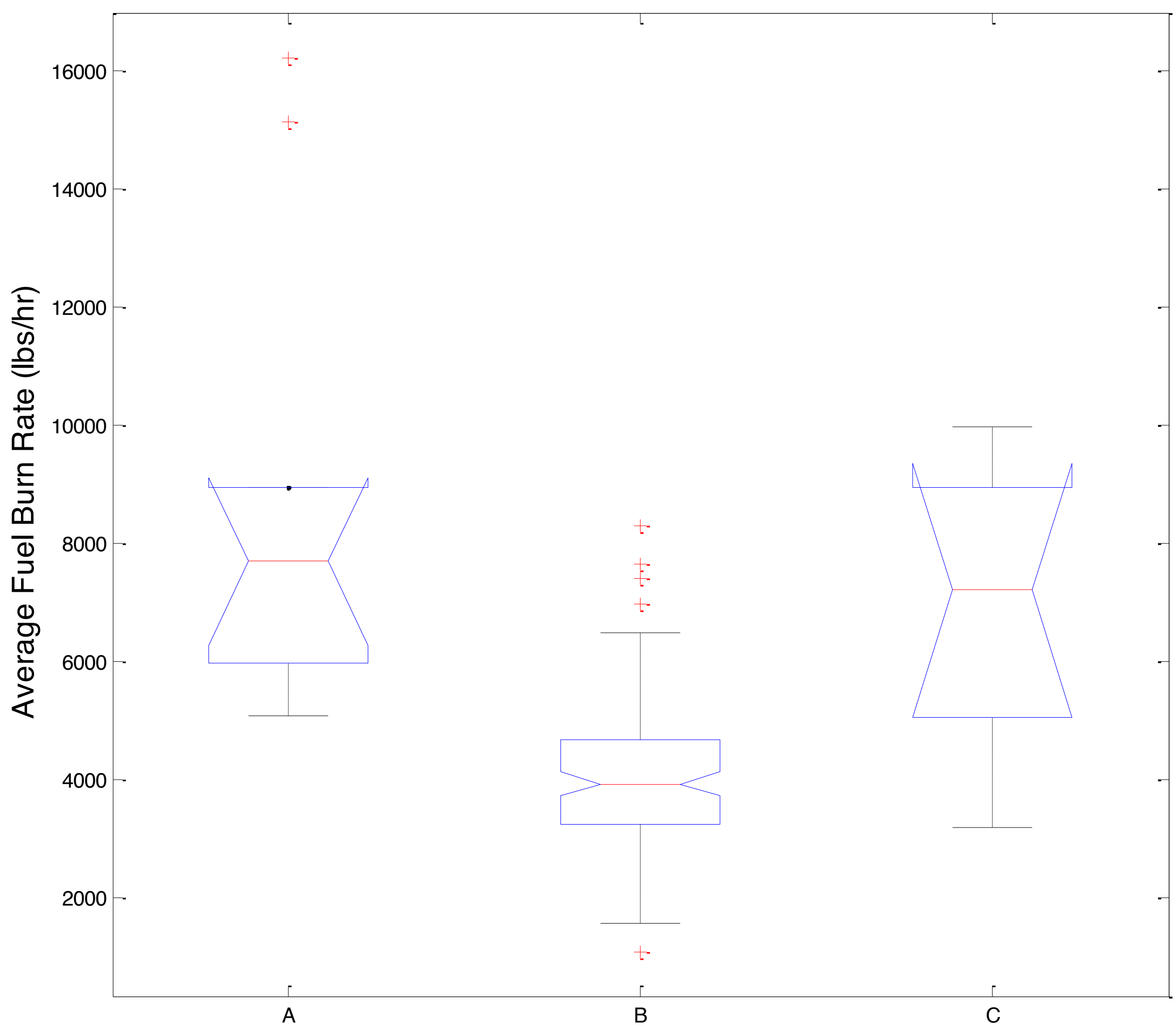


Figure 42: Average Fuel Burn Rate by Operation Type (A/B/C)

By chain position: (p value = 1.424E-7) <u>Significant differences at 95% level</u>

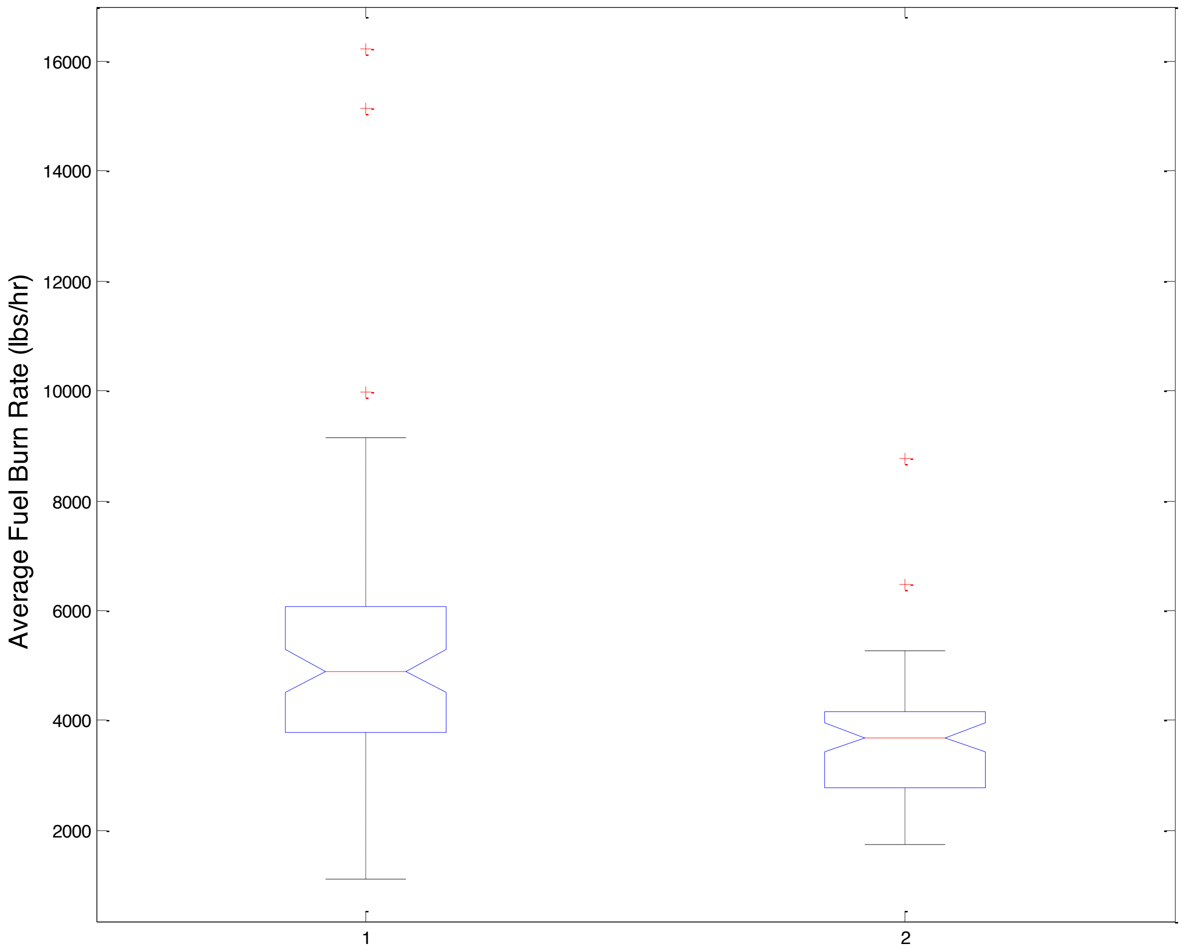


Figure 43: Average Fuel Burn Rate by Chain Position

There is significant difference in average fuel burn by chain position. Given that there is no statistically significant differences in IM Speed rate by chain position (see later section), this difference results from the fact that most second chain positions were flown by the 737, which has already been shown to burn less fuel.

Are there differences in FMS lateral FTE by day, path, or chain position?

By day: (p value = 0.5552) <u>No significant differences at 95% level</u>

By path: (p value = 0.0025) <u>Significant differences at 95% level</u>

By chain position: (p value = 0.075) <u>No significant differences at 95% level</u>

As discussed in section 4 there are differences in FMS lateral FTE across paths and the ANOVA reveals them to be statistically significant. However, the only pairwise statistical differences are between the en route and final approach paths compared to the descent paths, which were explained earlier. No statistically meaningful differences exist between the descent paths.

The lack of statistically meaningful difference by day is a testament to the performance of LNAV lateral control in presence of a wide range of wind conditions.

Are there differences in FMS vertical FTE by day, path, or chain position?

By day: (p value = 0.6457) No significant differences at 95% level

By path: (p value = 0.0022) Significant differences at 95% level

By chain position: (p value = 0.2231) No significant differences at 95% level

As discussed in section 4 there are differences in FMS vertical FTE across paths and the ANOVA reveals them to be statistically significant. However, the only pairwise statistical differences are between the en route and final approach paths compared to the descent paths, which were explained earlier. No statistically meaningful differences exist between the descent paths.

Are there differences in FIM lateral FTE by day, path, or chain position?

By day: (p value = 0.383) No significant differences at 95% level

By path: (p value = 1.03E-11) Significant differences at 95% level

By aircraft: (p value = 0.0016) Significant differences at 95% level

By chain position: (p value = 0.002) Significant differences at 95% level

As discussed in section 4 the difference in FIM lateral FTE across path is driven by the large differences in the cruise and approach paths that were explained. When comparing the FIM lateral FTE for only the B paths, the results indicate differences across the descent paths.

By path (B runs only):(p value = 5.2E-7) Significant differences at 95% level

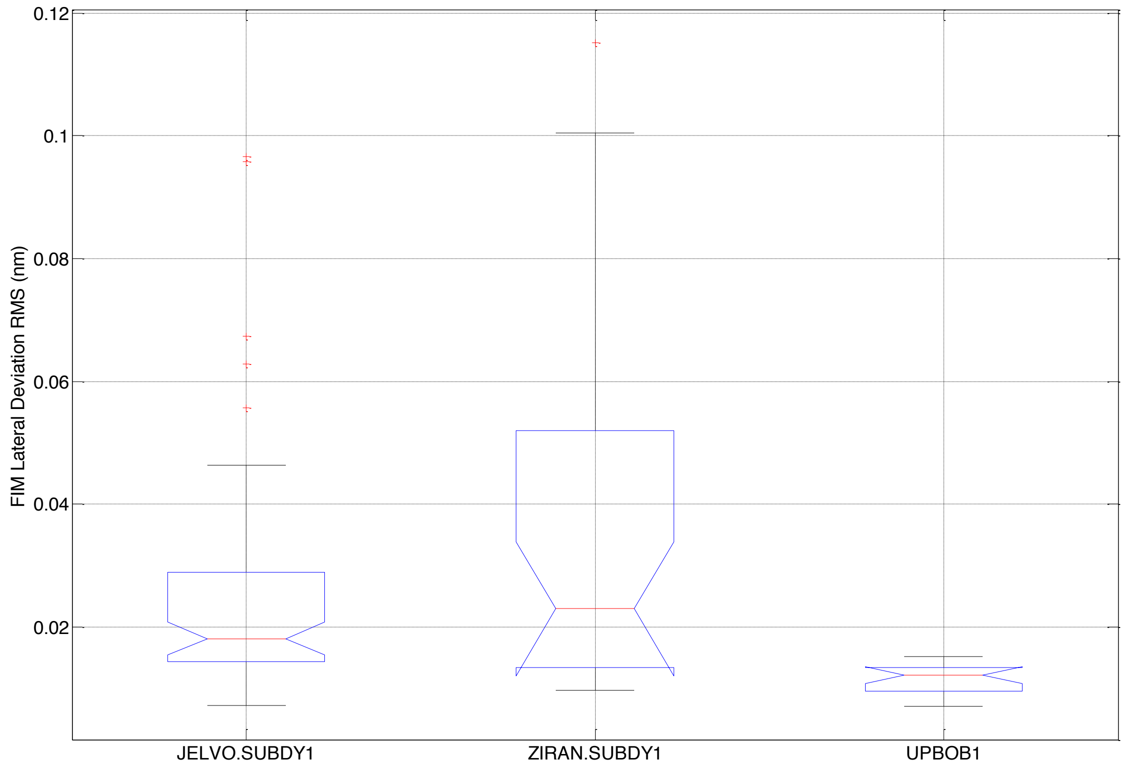


Figure 44: Lateral FTE RMS (FIM) by Descent Paths

The only pairwise meaningful difference is between UPBOB1 and the two other SUBDY paths. This difference is attributed to the relatively lower lateral complexity of the UPBOB path, especially because IM operations were started after the first large turn and the remainder of the path is generally straighter than either of the SUBDY paths, which have a general change of direction of more than 90 degrees in its upper portion, and RF turns in its latter portions. Possibly the statistics reveal differences between how the FIM system computes turns compared to the FMS because there were no observable differences in lateral FTE between the descent paths for the FMS (Figure 44) and the ANOVA reveals them to be statistically significant. However the only pairwise statistical differences are between the en route and final approach paths compared to the descent paths, which were explained earlier. No statistically meaningful differences exist between the descent paths.

There are differences in FIM Lateral FTE by aircraft but the difference is so small it is likely not contributing to any FIM performance (Figure 45).

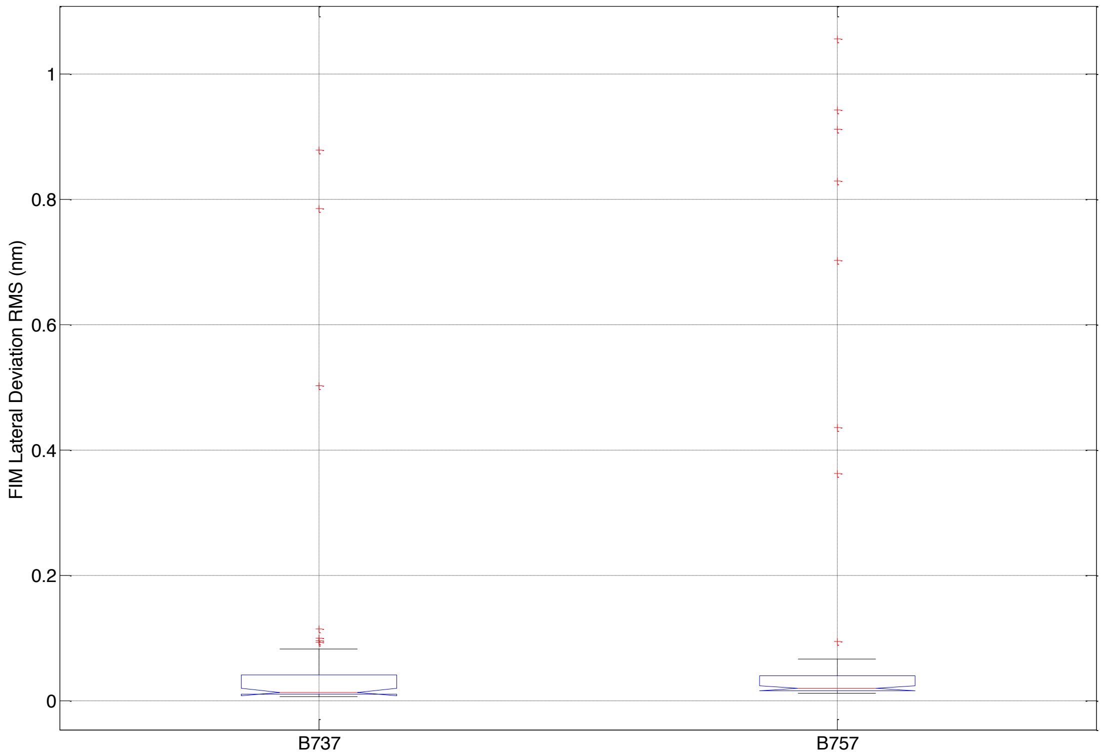


Figure 45: FIM Lateral FTE by Aircraft

Are there differences in FIM vertical FTE by day, path, or chain position?

By day:	(p value = 0.0005)	Significant differences at 95% level
By path:	(p value = 2.82E-6)	Significant differences at 95% level
By aircraft:	(p value = 0.014)	Significant differences at 95% level
By chain position:	(p value = 0.0522)	No significant differences at 95% level

There are differences in FIM Vertical FTE by day, which is expected given that the flight path angles flown by aircraft when in VNAV speed mode vary based on the experienced wind for the same CAS value (Figure 46).

The differences by path are dominated by the differences between the en route path and the approach paths that are described before. When comparing only among the descent (B) paths, the test still reveals statistical differences:

By path (B only): (p value = 0075) <u>Significant differences at 95% level</u>

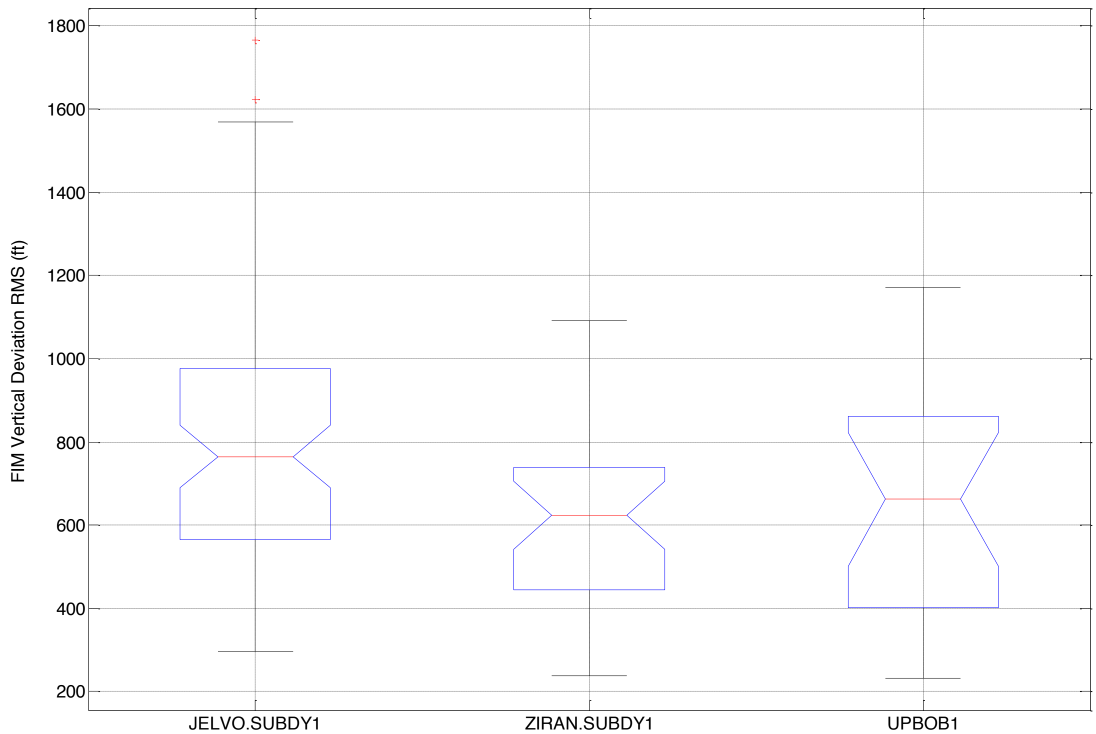


Figure 46: FIM Vertical RMS by Descent Paths

The JELVO and ZIRAN paths have differences among each other but not from UPBOB. Both SUBDY transitions have a common segment downstream of NALTE and thus the difference is expected to come from the portion upstream of NALTE. However the difference is small (less than 200 ft) and is not worth investigating further (Figure 47).

There are differences in FIM Vertical FTE by aircraft but the difference is so small it is likely not contributing to any FIM performance.

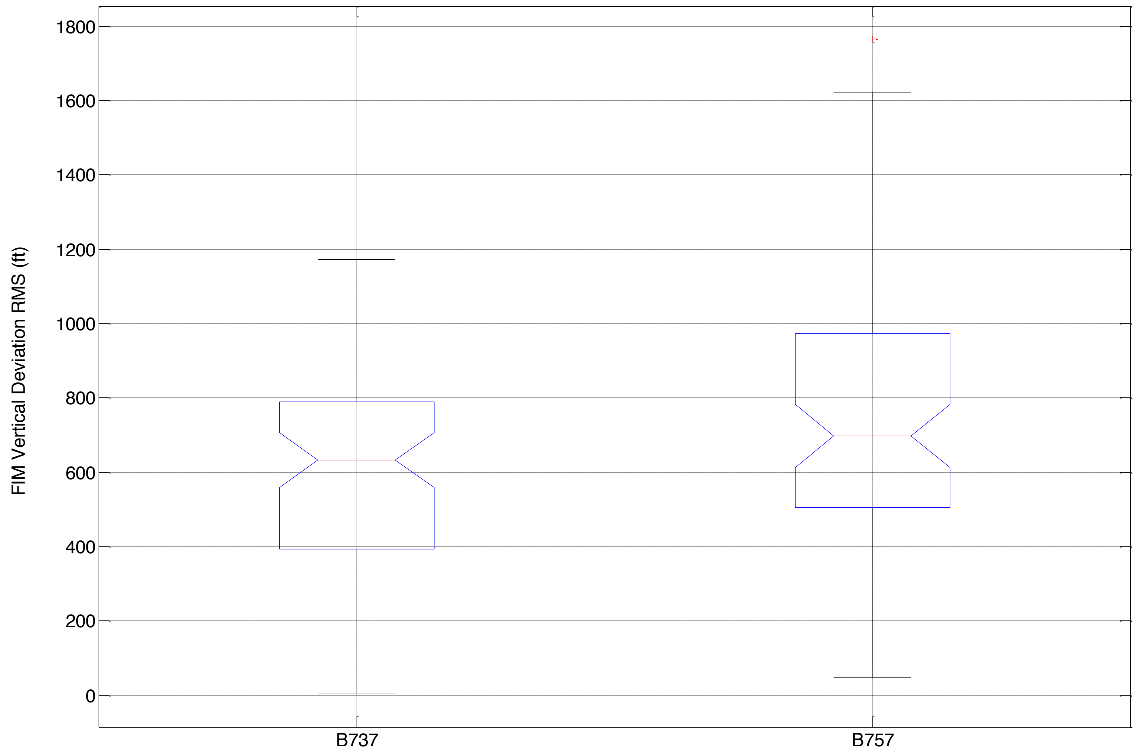


Figure 47: FIM Vertical FTE RMS by Aircraft

Are there differences in Lateral PDE by day, path, or chain position?

By day: (p value = 0.5362) <u>No significant differences at 95% level</u>

By path: (p value = 2.82E-6) <u>Significant differences at 95% level</u>

By chain position: (p value = 0.8367) <u>No significant differences at 95% level</u>

Again the path differences are dominated by the difference between the en route and approach paths (Figure 48). The difference across descent paths is statistically significant (p value = 0.0252) and shows more variability in PDE across the ZIRAN transition than the other paths.

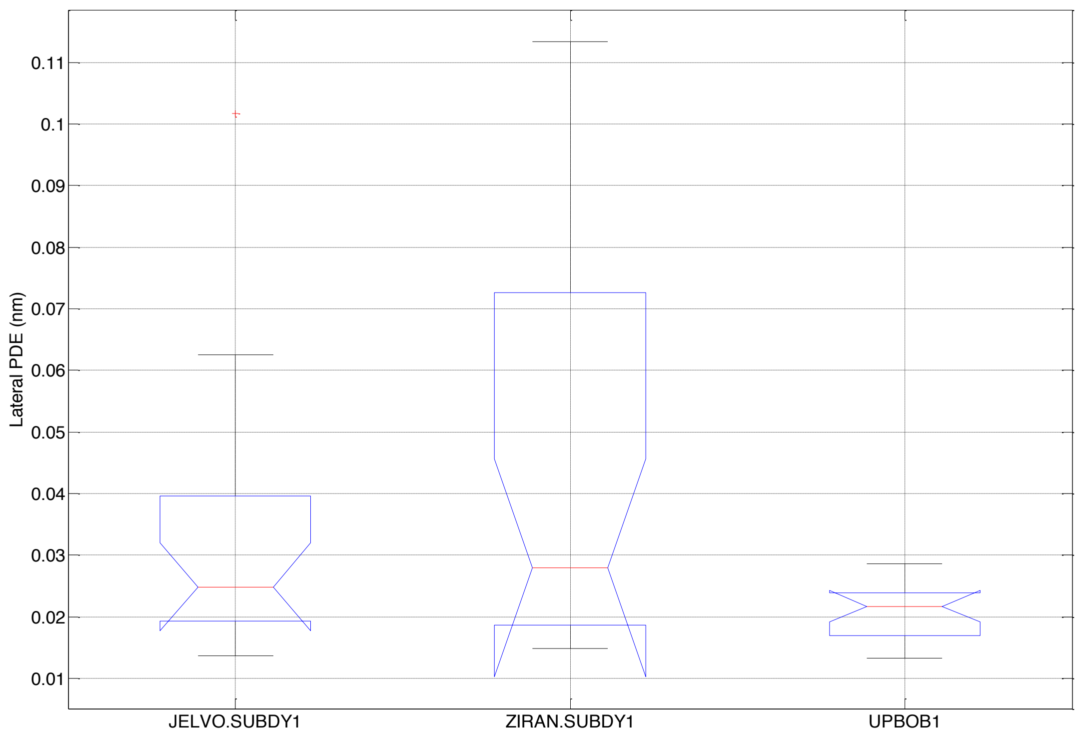


Figure 48: Lateral PDE by Descent Path

Are there differences in Vertical PDE by day, path, or chain position?

By day: (p value = 0.4071) <u>No significant differences at 95% level</u>

By path: (p value = 0..002) <u>Significant differences at 95% level</u>

By chain position: (p value = 0.3487) <u>No significant differences at 95% level</u>

Once again the difference by path is dominated by the difference between the en route and approach paths (Figure 48) There is no statistically significant difference across the descent paths (p value = 0.1027).

Are there differences in time-based PTP delivery across clearance types, geometries, and aircraft type?

PTP delivery (time)

By clearance type: (p value = 0.0022) Significant differences at 95% level

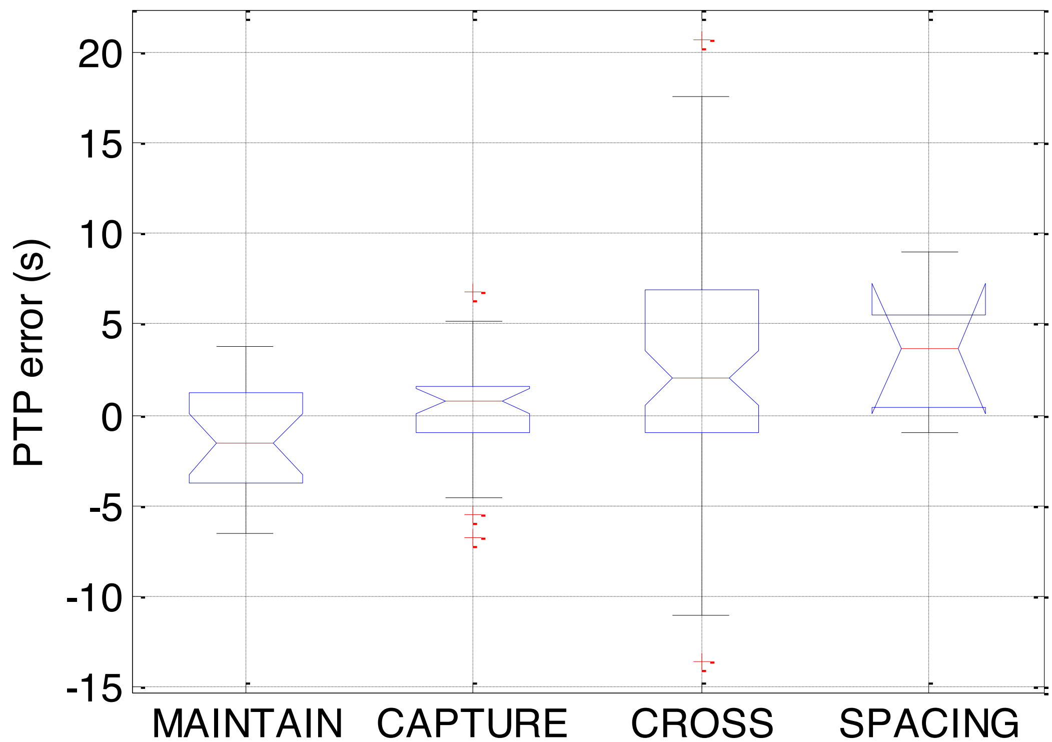


Figure 49: Time-Based PTP Error By Clearance Type

CROSS clearances have significantly worse performance at the PTP than MAINTAIN, and no other pairwise comparisons reveal statistically significant differences. It appears SPACING clearances have worse performance (Figure 49), but the low number of samples render this a visual artifact. The notches on the boxplot can be used to inspect pairwise differences. Overlap of notches indicates statistically meaningful pairwise difference. In the figure, onlt the notches of CROSS and MAINTAIN do not overlap.

By ownship path: (p value = 3.43E-07) <u>Significant differences at 95% level</u>

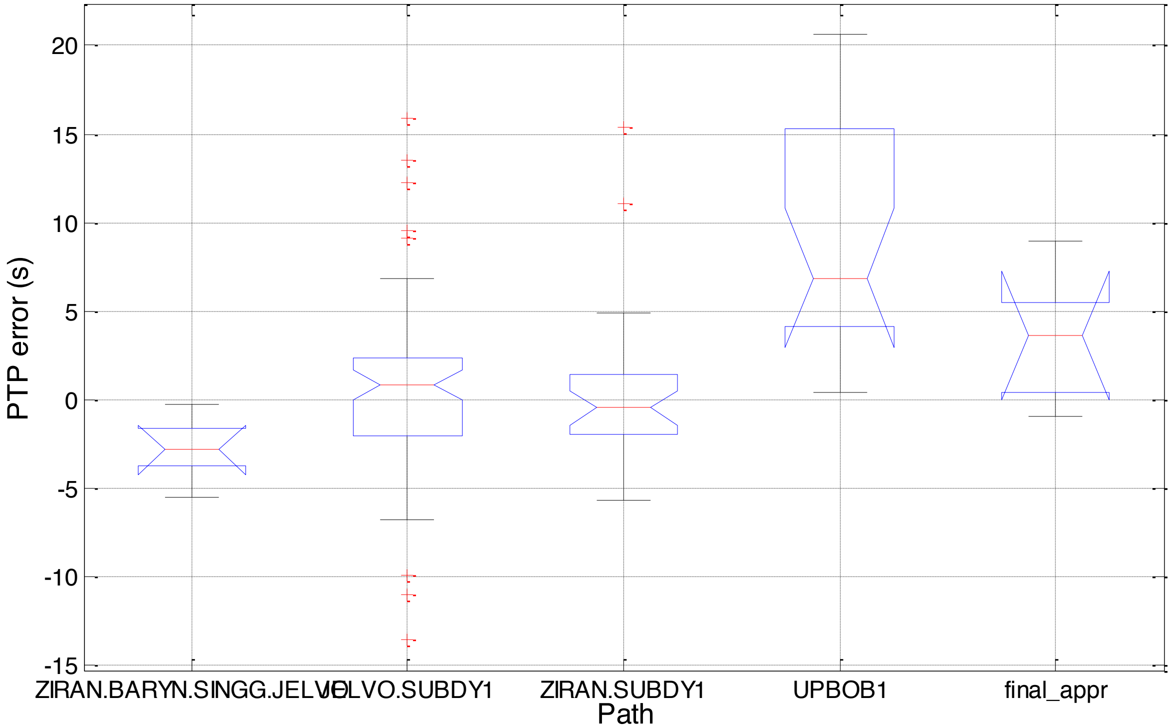


Figure 50: Time-Based PTP Error by Ownship Path

The UPBOB path flown by ownship has significantly worse performance than other geometries (Figure 50). It should be noted that UPBOB was never flown in-trail with another aircraft on UPBOB, thus all UPBOB performance is attributable to the exercise of a CROSS clearance, which has already been determined to have worse performance. UPBOB did not show significant difference in ATWFE (Figure 37) thus, the effect of the UPBOB path is not rooted in the wind forecast error, but likely in the design of the procedure itself (nominal vertical or speed profile), or its use predominantly in CROSS operations with a late merge near the PTP.

By traffic path: (p value = 0.0436) <u>Significant differences at 95% level</u>

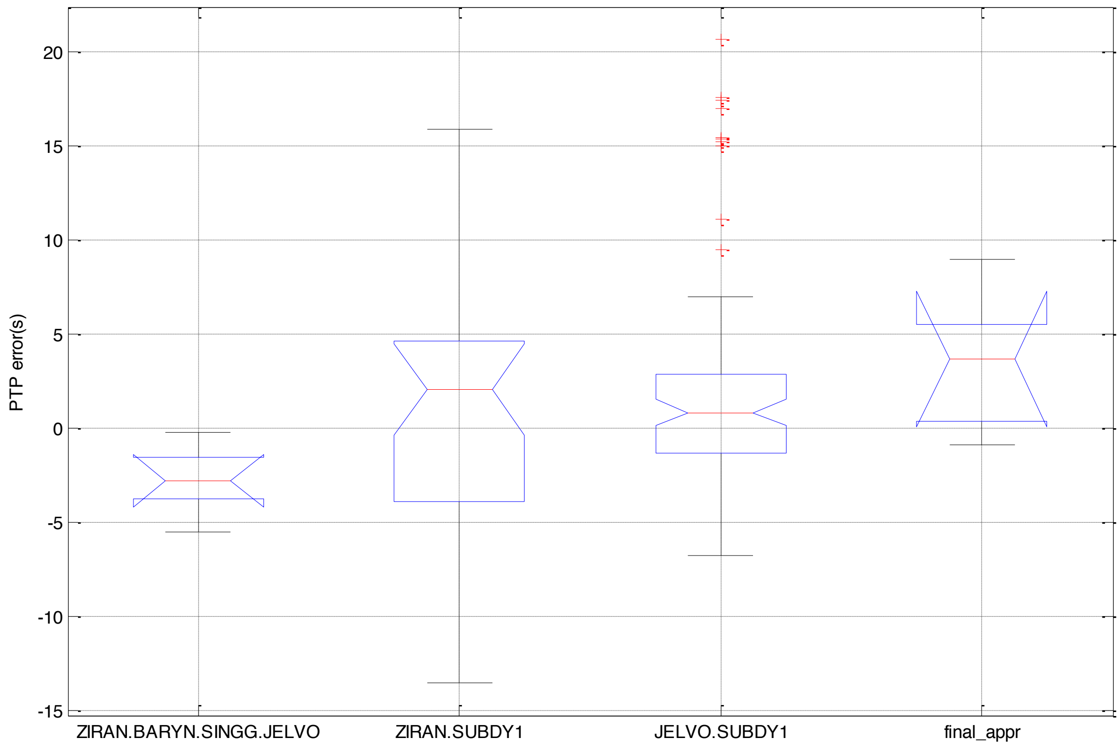


Figure 51: Time-Based PTP Error by Traffic Path

The delivery performance of pairs involving a lead on the en route path is significantly different. It should be noted that this should only happen when ownship is en route as well (no CROSS clearances flown en route) and thus the difference by lead path is 100% attributable to the difference by operation type as shown in Figure 51.

By scen. type: (A/B/C) (p value = 0.0189) Significant differences at 95% level

With A runs showing different performance than B or C runs (no difference between B and C runs).

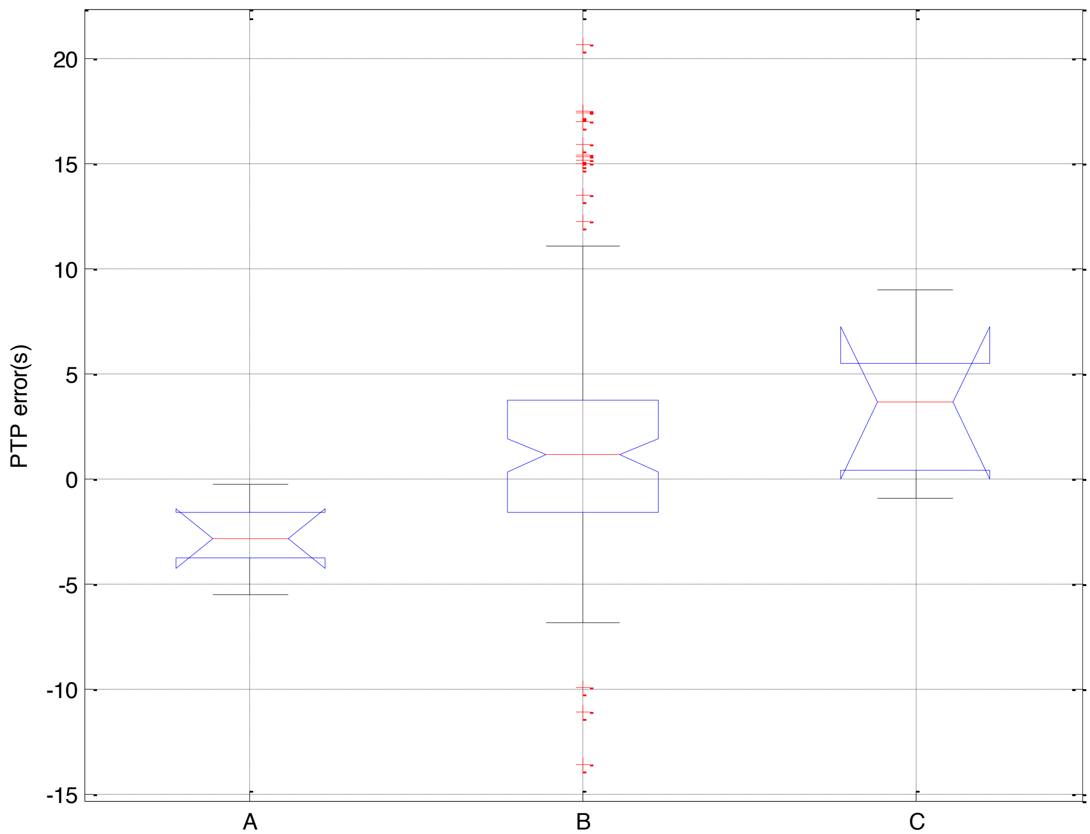


Figure 52: Time-Based PTP Error By Scenario Type

By ownship aircraft: (p value = 0.0523) No significant differences at 95% level

By traffic aircraft: (p value = 0.0521) No significant differences at 95% level

By chain position: (p value = 0.1925) No significant differences at 95% level

Given the small sample size of distance-based clearances, there are no statistically meaningful differences between distance-based PTP performance across clearance type, geometry, or aircraft type (Figure 52).

Are there differences in the IM speed rate across clearance types, geometries and aircraft type?

IM speed rate

By clearance type: (p value = 0.0016) Significant differences at 95% level

MAINTAIN operations have significantly more IM speeds issued per minute of IM operation than other clearance types (with the exception of SPACING, with a very small sample). This is due to a condition when the spacing error causes a speed error discretization oscillation, as is often the case when the non discretized speed error is on the boundary of the discretization value (e.g. 10kts). Hysterisis requirements exist in the system and its implementation is being reviewed in light of the observed behavior.

SPACING operations also have a higher average IM Speed Rate, although not statistically significant because of the low sample size and large spread (Figure 53). This is likely caused by the shorter nature of the operation, which tends to generate higher rates for mathematical reasons.

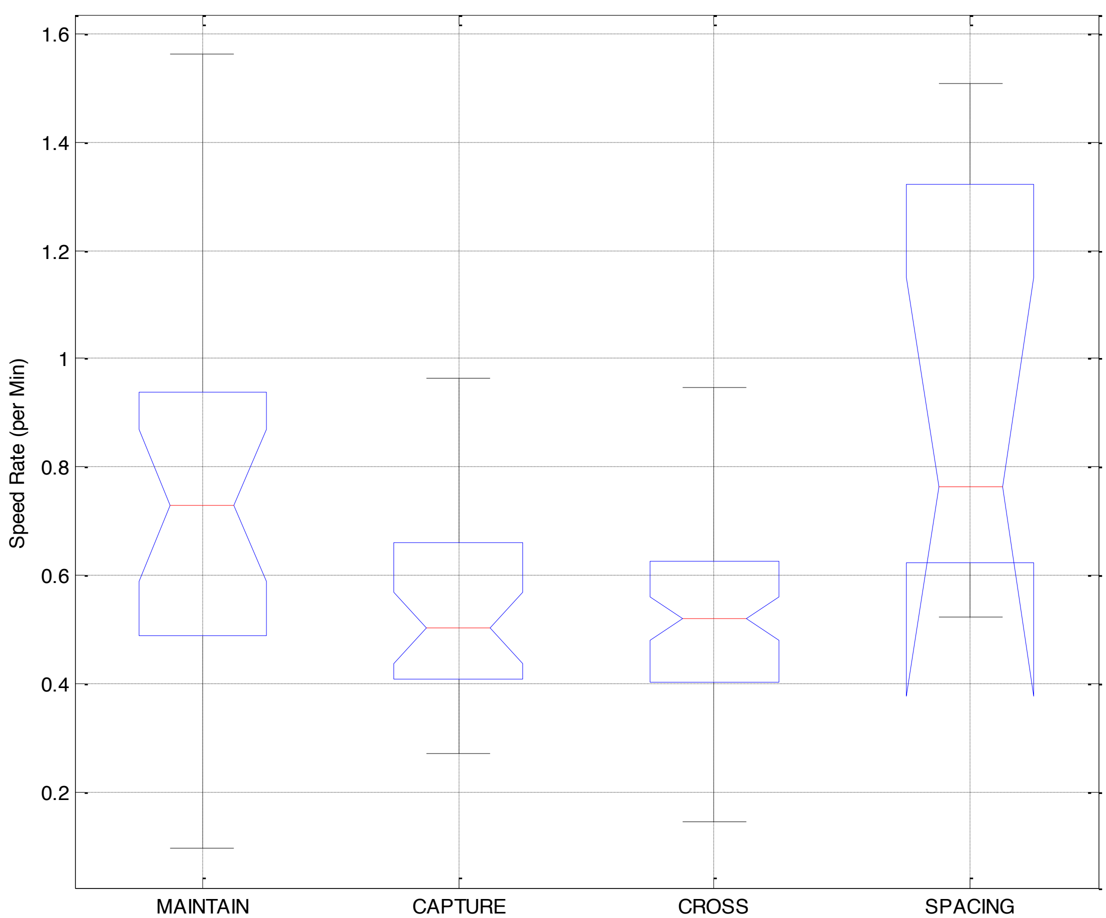


Figure 53: IM Speed Rate by Clearance Type

By chain position: (p value = 0.8533) <u>No significant differences at 95% level</u>

By units: (p value = 0.045) <u>Significant differences at 95% level</u>

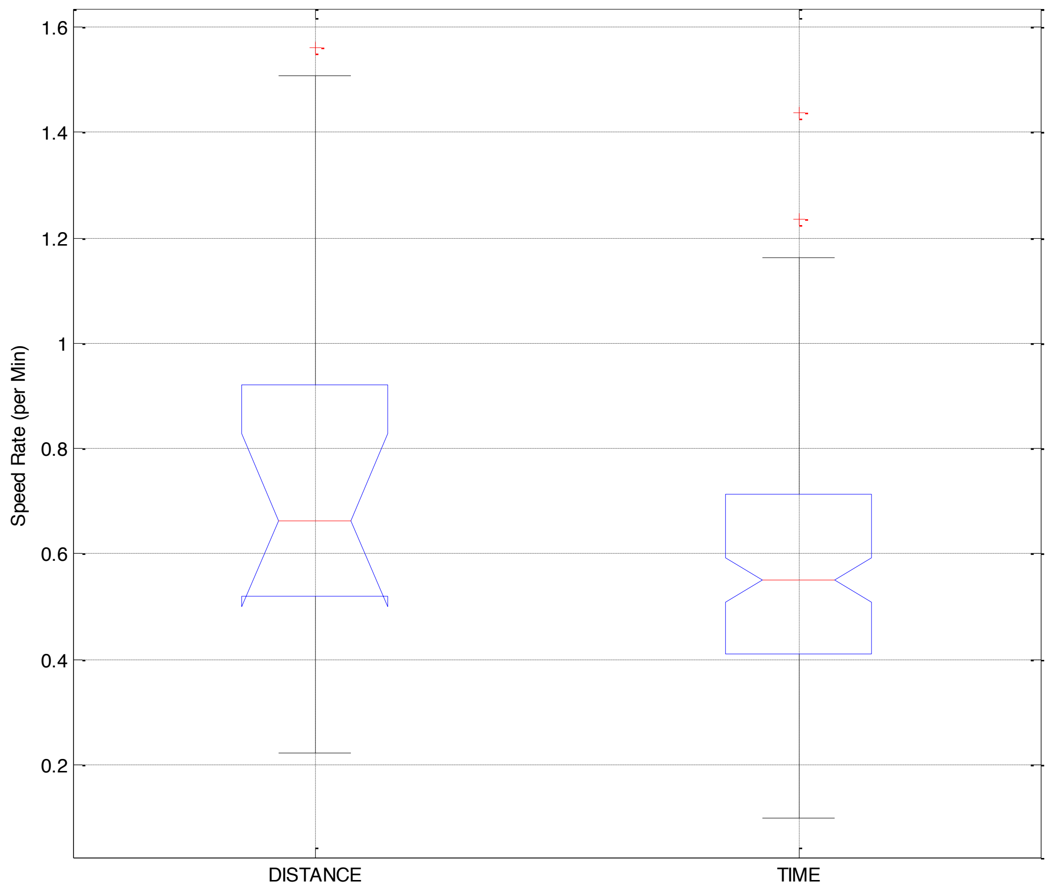


Figure 54: IM Speed Rate by Operation Unit Type (TIME versus DISTANCE)

Distance-based operations appear to have more IM speeds issued per minute than time-based operations (Figure 54). This is caused by the lack of decceleration estimation in the CTD implementation. In distance operations the CTD algorithm follows the traffic "on the string" and responds to its speed changes directly.

By ownship path: (p value=0.0002) <u>Significant differences at 95% level</u>

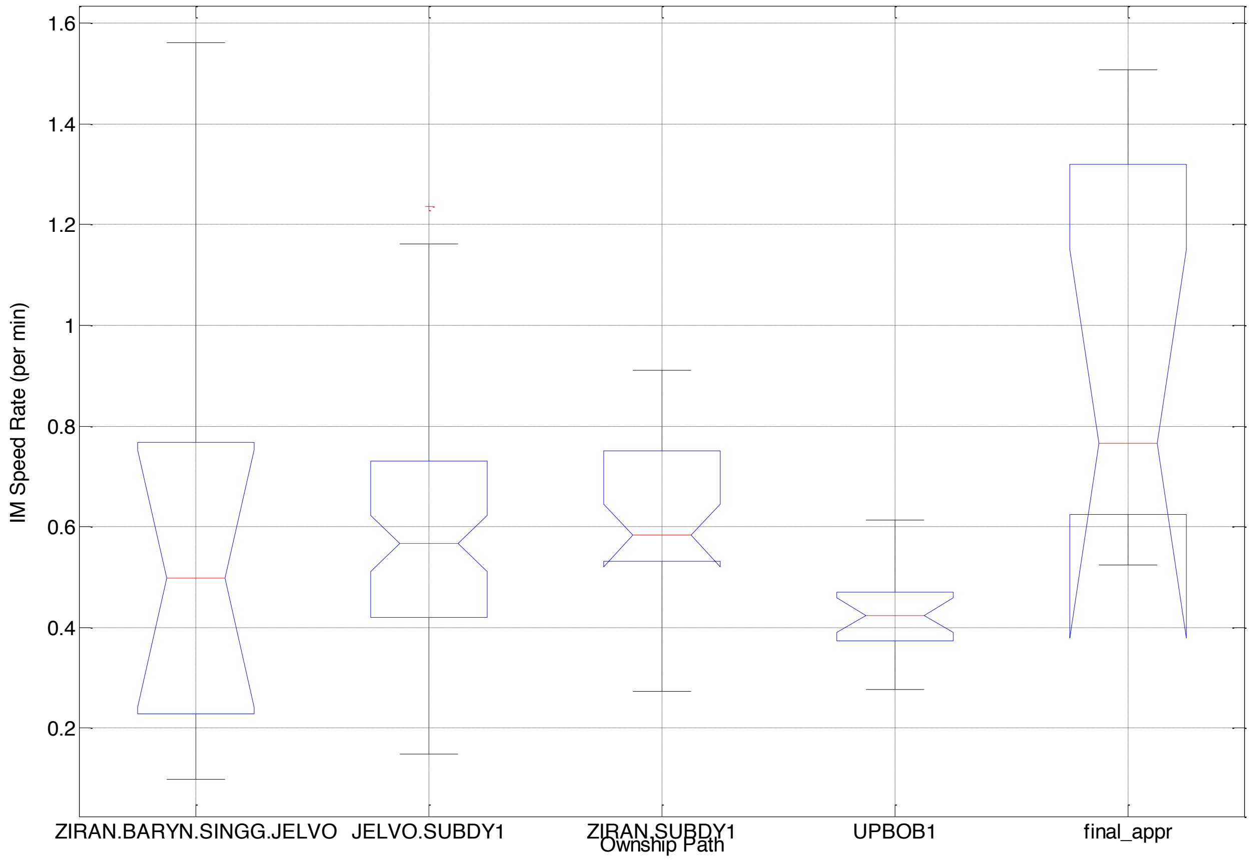


Figure 55: IM Speed Rate by Ownship Path

The UPBOB path has significantly less IM speed rate than other paths (Figure 55). This is attributable to the fact that it is used only in CROSS operations, while the SUBDY path is also used with MAINTAIN and CAPTURE operations, which tend to have higher IM speed rates as shown in Figure 55.

By traffic path: (p value=0.0178) Significant differences at 95% level

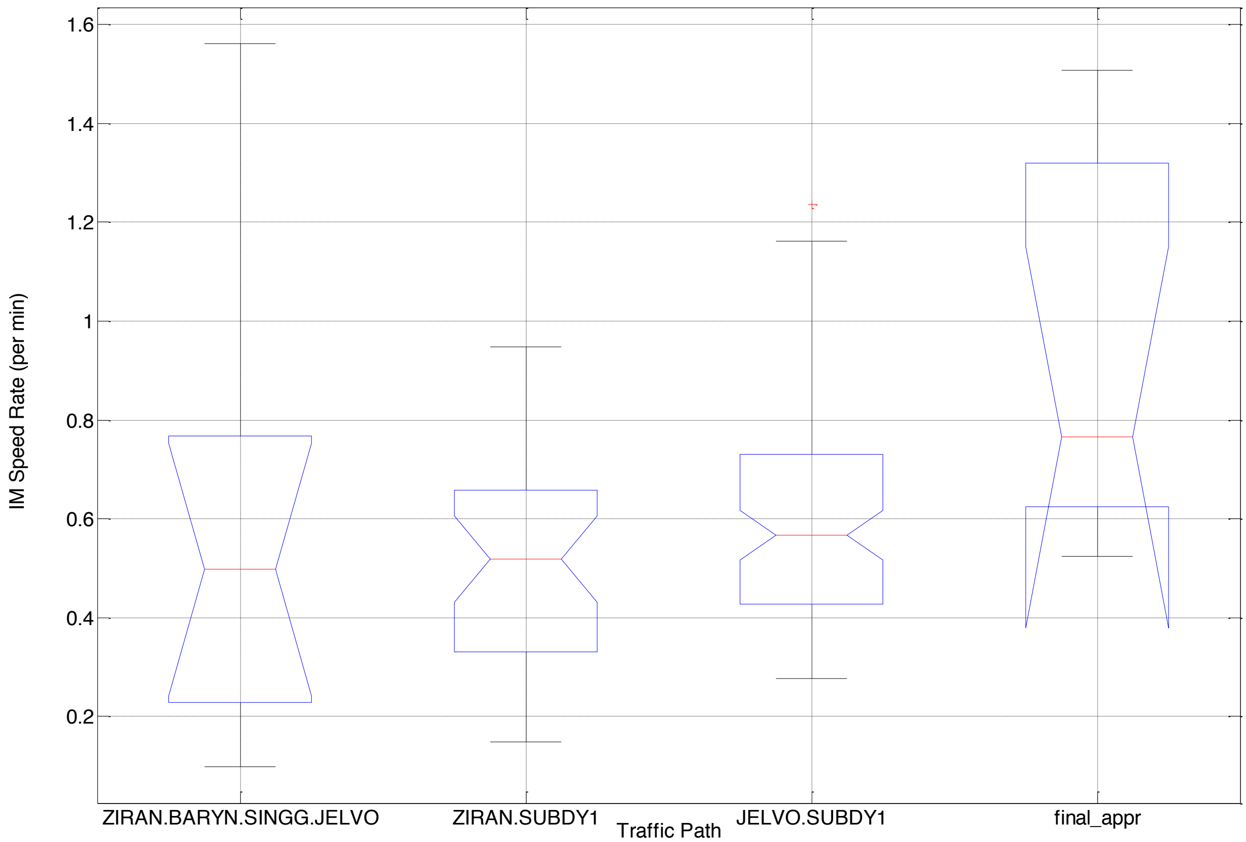


Figure 56: IM Speed Rate by Traffic Path

The only statistically significant pairwise difference involves the final approach path, which has a higher IM Speed Rate (Figure 56). This path is used only in SPACING operations, which has already been shown to have higher IM Speed Rates than other operations.

By aircraft type: (p value=0.503) No significant differences at 95% level

By lead aircraft type: (p value=0.258) No significant differences at 95% level

Are there differences in pilot implementation times (mean and std) between aircraft?

Pilot time mean (all): By aircraft (p value = 3.1e-5) Significant differences at 95% confidence level

Pilot time std (all): By aircraft (p value = 0.295) No significant differences

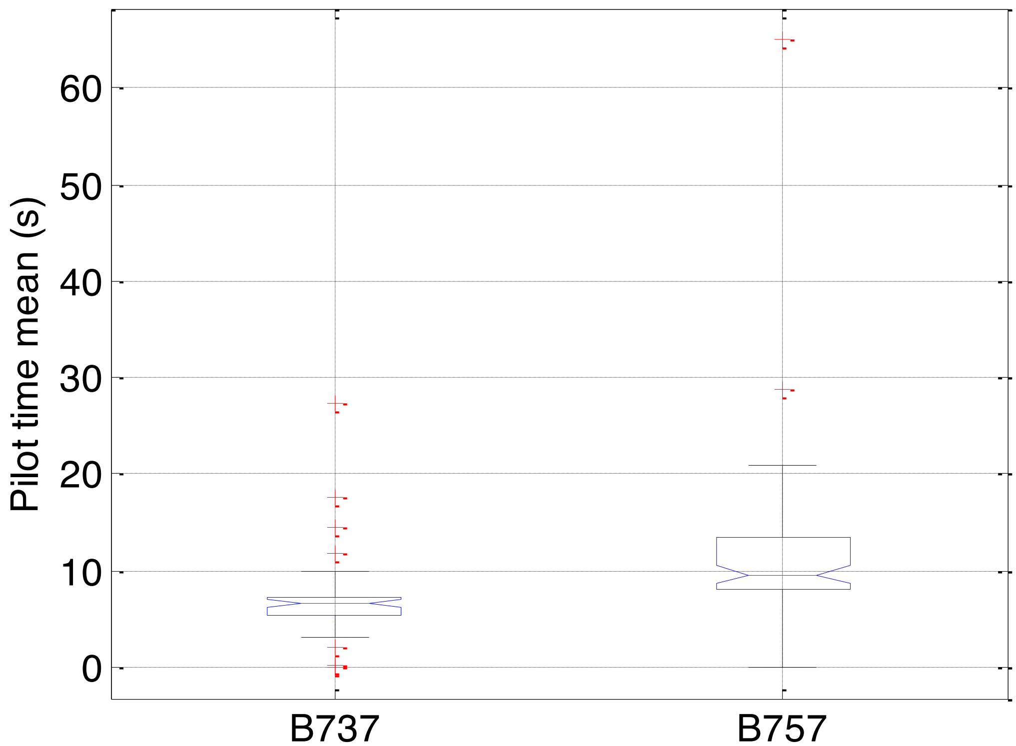


Figure 57: Pilot Implementation Time by Aircraft

The 757 took significantly more time than the 737 to implement IM clearances (on average 3 seconds longer) (Figure 57). This difference is difficult to attribute because it is rooted in individual pilot technique, which varies by crew, by day, and by affiliation. Note that the comparison of MCP time dispersion is done on the means of the MCP time standard deviations, computed for each run. Thus it is not direct comparison of variance, rather a comparison of means of a metric, that indicates the spread of speed implementation times across an individual run.

Among time-based CROSS operations, are there differences in performance by geometry, aircraft type, or chain position?

PTP delivery

By ownship path: (p value = 2.9E-05) <u>Significant differences exist at 95% level</u>

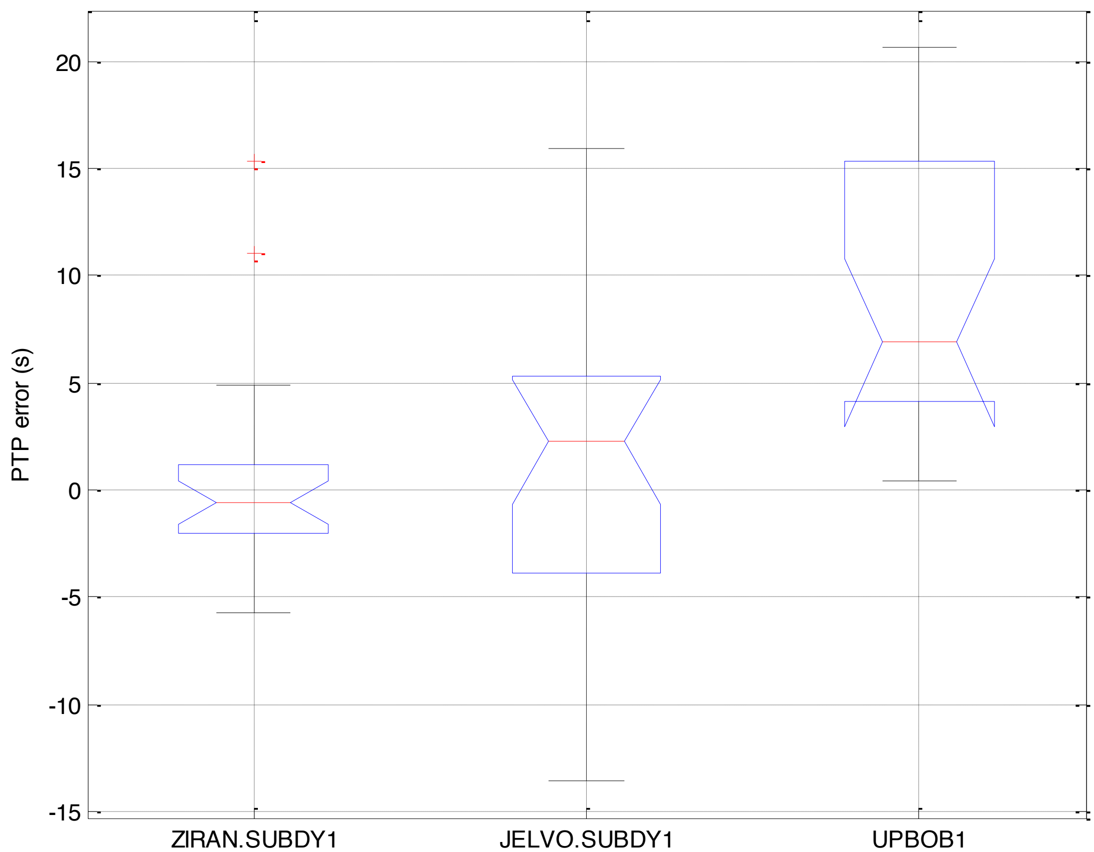


Figure 58: Time-Based CROSS, PTP Error by Ownship Path

Once again UPBOB displays worse performance (Figure 58). This was already seen and described in the overall PTP performance and caused by the UPBOB geometry design and the fact that it is always executed as pair number 2 in a late merge (at ZAVYO) situation.

By ABP placement: (p value = 4.91E-06) Significant differences at 95% level

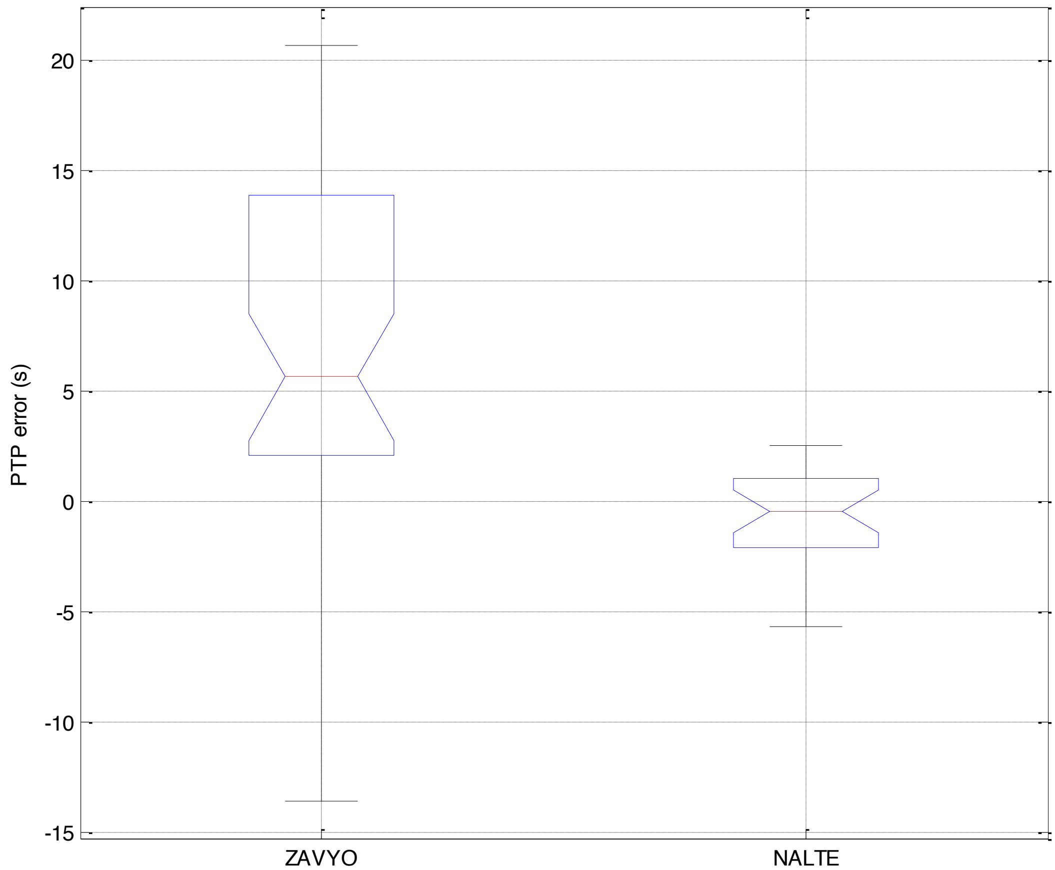


Figure 59: Time-Based CROSS, PTP Error By ABP Placement

At the PTP, performance is worse when the ABP is at ZAVYO and thus a late merge with no maintain segment (Figure 59). The maintain segment when the ABP is placed at NALTE helps reduce the variability and increase the delivery performance at the PTP.

By traffic path: (p value = 0.6908) No significant differences at 95% level

By ownship aircraft: (p value = 0.8583) No significant differences at 95% level

By lead aircraft: (p value = 0.4688) No significant differences at 95% level

By chain position: (p value = 0.63) No significant differences at 95% level

Some time-based CROSS operations were performed with the ABP at ZAVYO with two aircraft on SUBDY. Those operations had no maintain segment and performed statistically worse at the PTP than the same geometry with the ABP at NALTE. In general, again the performance at the PTP in cases where the ABP is at ZAVYO is worse for those pairs involving UPBOB, which also happens to always be in third position (second pair).

ABP delivery

By ownship path: (p value = 0.0001) Significant differences exist at 95% level

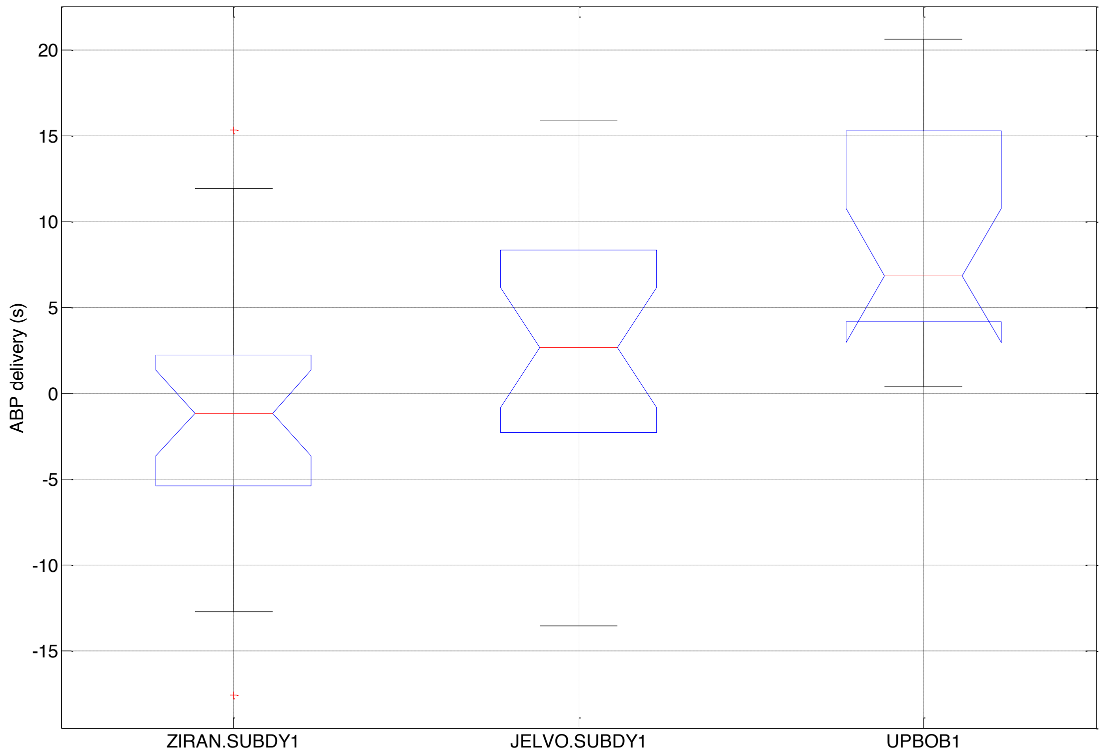


Figure 60: Time-Based CROSS, ABP Delivery by Ownship Path

Once again significant differences with UPBOB are displayed, which was only used in situations with ABP and PTP collocated at ZAVYO and thus reflects the same effect as that of PTP delivery performance (Figure 60).

By ABP placement:(p value = 4.54E-05) Significant differences at 95% level

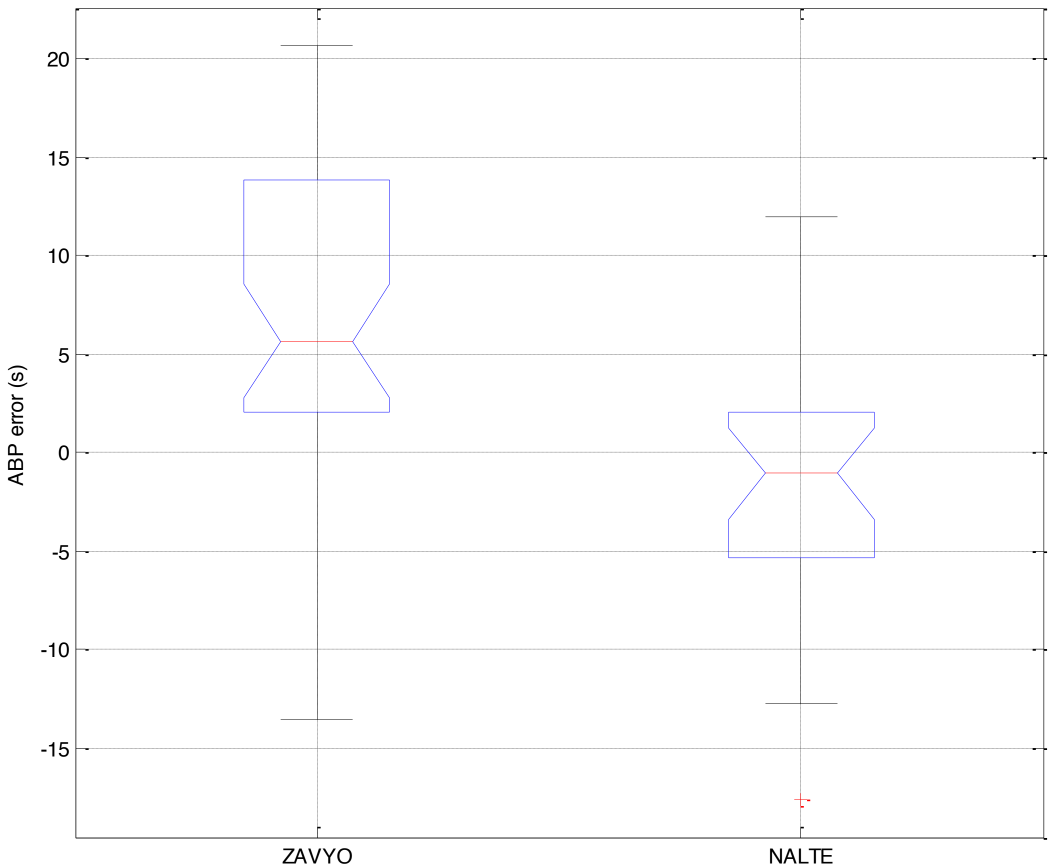


Figure 61: Time-Based CROSS, ABP error By ABP Placement

Performance at the ABP is worse in cases with a late merge (ZAVYO), likely also compounded by the poorer performance of the UPBOB path (Figure 61).

By traffic path: (p value = 0.8876) No significant differences at 95% level

By ownship aircraft: (p value = 0.7224) No significant differences at 95% level

By lead aircraft: (p value = 0.6152) No significant differences at 95% level

By chain position: (p value = 0.938) No significant differences at 95% level

IM Speed Rate

By ABP placement: (p value = 7.88E-06) Significant differences at 95% level

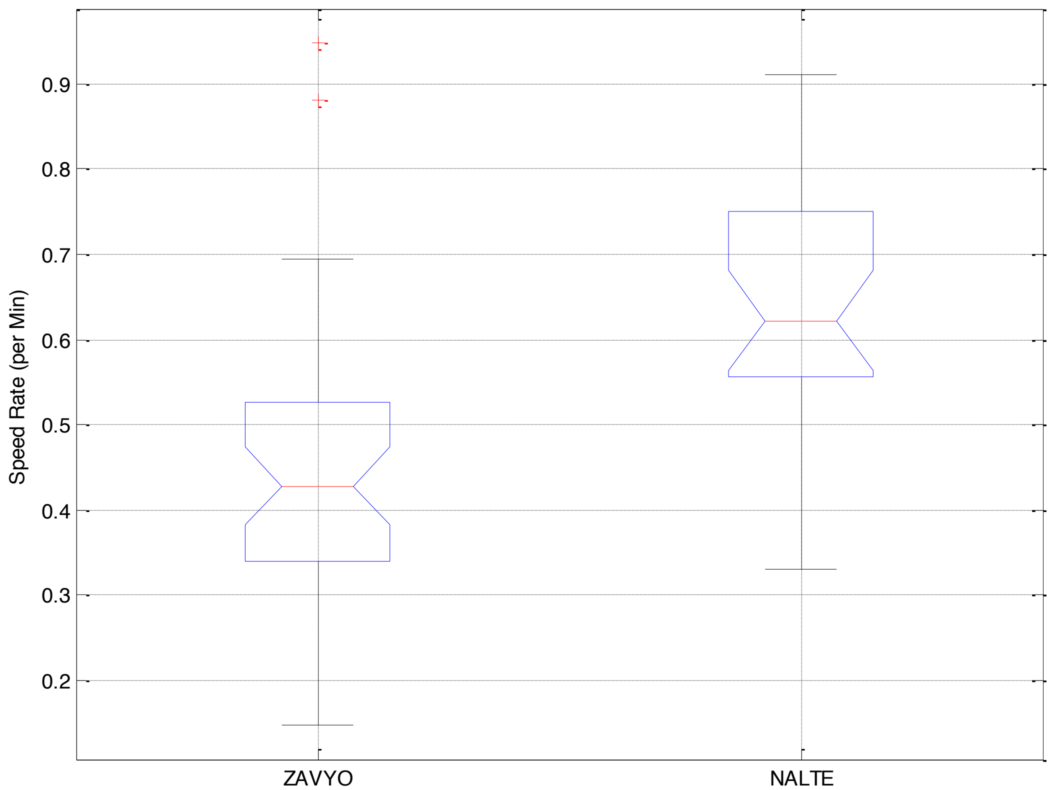


Figure 62: Time-Based CROSS, IM Speed Rate by ABP placement

CROSS operations with ABP placement at NALTE result in a higher speed rate, which is attributable to the maintain segment because the MAINTAIN operations have already been shown to have higher IM speed rates than other clearances (Figure 62).

By ownship path: (p value = 5.44E-05) Significant differences at 95% level

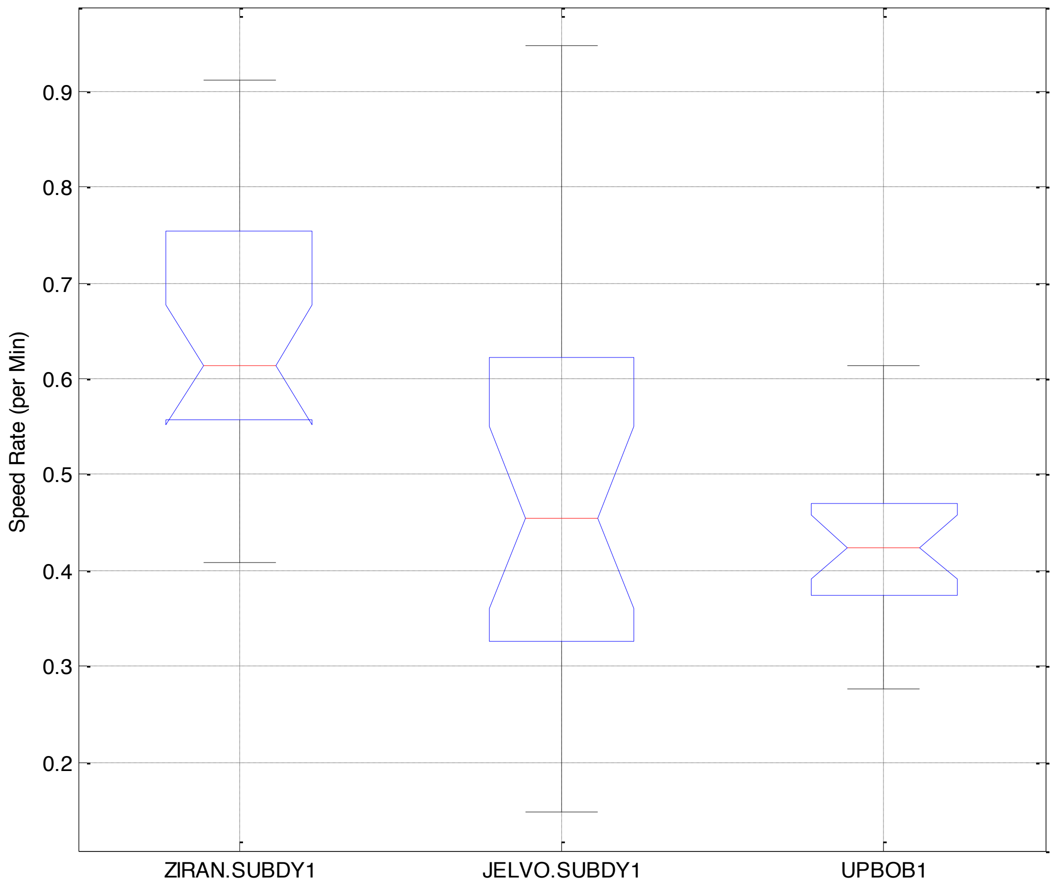


Figure 63: Time-Based CROSS, IM Speed Rate by Ownship Path

The ZIRAN transition of SUBDY seems to have consistently issued more speeds per minute than other paths (Figure 63). This is caused by the fact that 87.5% of the cases where ownship is on the ZIRAN path occurs for an operation with the ABP at NALTE and thus has a maintain segment, which will generate more IM speeds, as has been shown earlier.

By traffic path: (p value = 0.3759) No significant differences at 95% level

By ownship aircraft: (p value = 0.4271) No significant differences at 95% level

By lead aircraft: (p value = 0.2591) No significant differences at 95% level

By chain position: (p value = 0.63) No significant differences at 95% level

Among time-based CAPTURE operations, are there differences in performance by geometry, aircraft type, or chain position?

PTP delivery

By path: (p value = 0.1219) No significant differences at 95% level

By aircraft type: (p value = 0.0176) Significant differences at 95% level

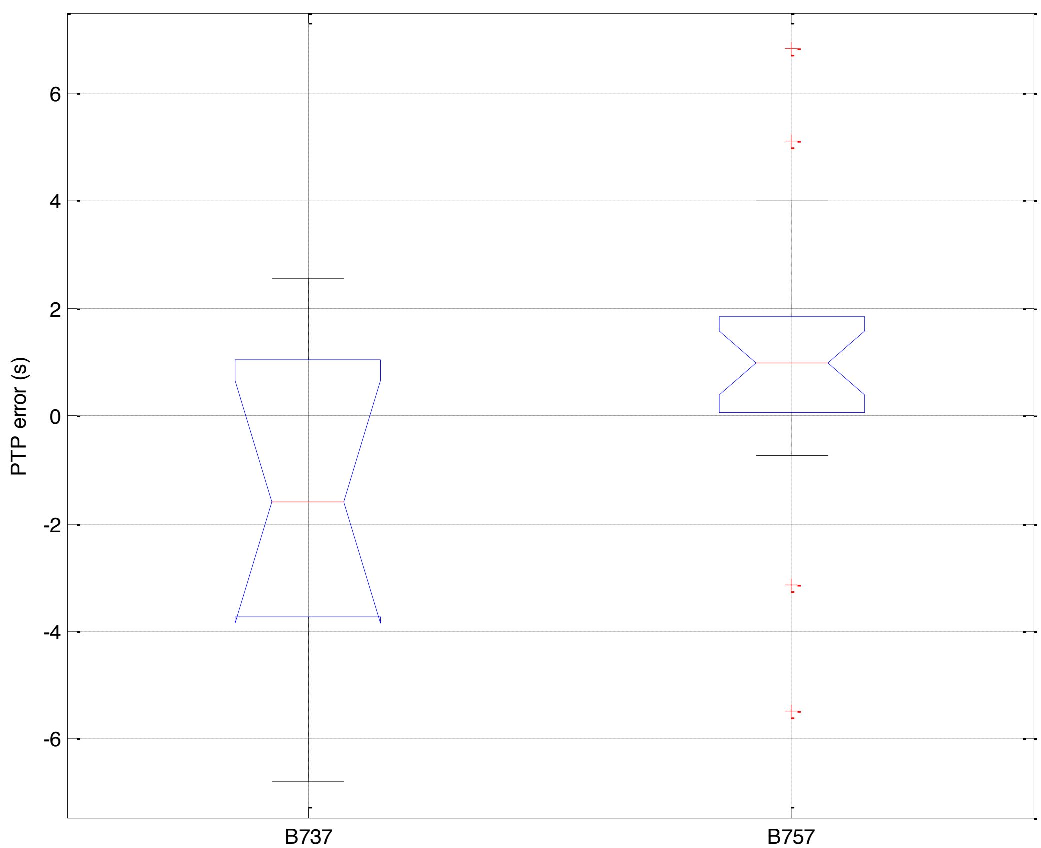


Figure 64: Time-Based CAPTURE, PTP Error by Aircraft Type

It is difficult to explain a difference in PTP delivery by aircraft type for the CAPTURE operation when no difference was observed by aircraft type among all time-based operations (Figure 64). No CAPTURE operations were performed on the UPBOB path and therefore the difference cannot be rooted in route design. There is no difference in the maintain segment performance between aircraft type, nor is there an observed difference in the time to capture. However, it is believed that in general the 757 has different acceleration and deceleration performance than the 737 resulting in this performance difference. In fact, later analysis shows that the capture rate of the 757 is higher than the 737.

By lead aircraft: (p value = 0.0928) No significant differences at 95% level

By condition (A/B): (p value = 0.0404) Significant differences at 95% level

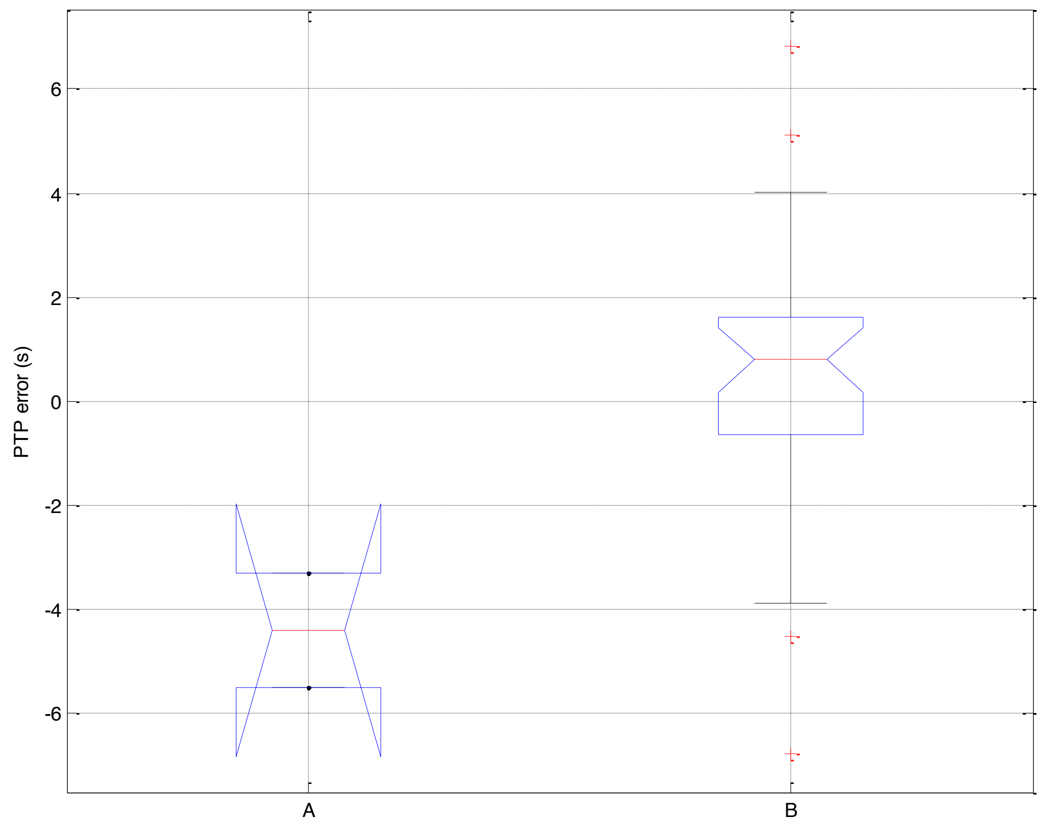


Figure 65: Time-Based CAPTURE, PTP Error by Scenario Type

Cruise operations are shorter in time and have less control authority than descent operations, resulting in operations that tend to arrive earlier (Figure 65).

By chain position: (p value = 0.133) No significant differences at 95% level

tCapture

The time to capture does not significantly differ across all variations of execution of the time-based CAPTURE clearance throughout the flight test.

By path: (p value = 0.5753) No significant differences at 95% level

By ownship aircraft: (p value = 0.5558) No significant differences at 95% level

By lead aircraft: (p value = 0.3456) No significant differences at 95% level

By chain position: (p value = 0.4773) No significant differences at 95% level

By condition (A/B): (p value = 0.3054) No significant differences at 95% level

Capture Rate

However, when looking at capture rate instead of the time to capture, there are significant differences among some of the groups. See section 4 for a defintion of how capture rate is computed. However, indendepent effects are difficult to attribute because more than half the observations for time-based CAPTURE operations are for the 757 on JELVO against the F900, thus in chain position 1. Each of those attributes in isolation has a statistically significant higher capture rate (Figure 66 through Figure 69). It should be noted that the attribution of aircraft to lead position is not symmetrical in the flight test and this could skew those results. For example, 45.8% of FIM pairs have a B757 lead, 10.42% have a B737 lead, and 43.8% have a F900 lead).

By ownship aircraft: (p value = 0.0203) Significant differences at 95% level

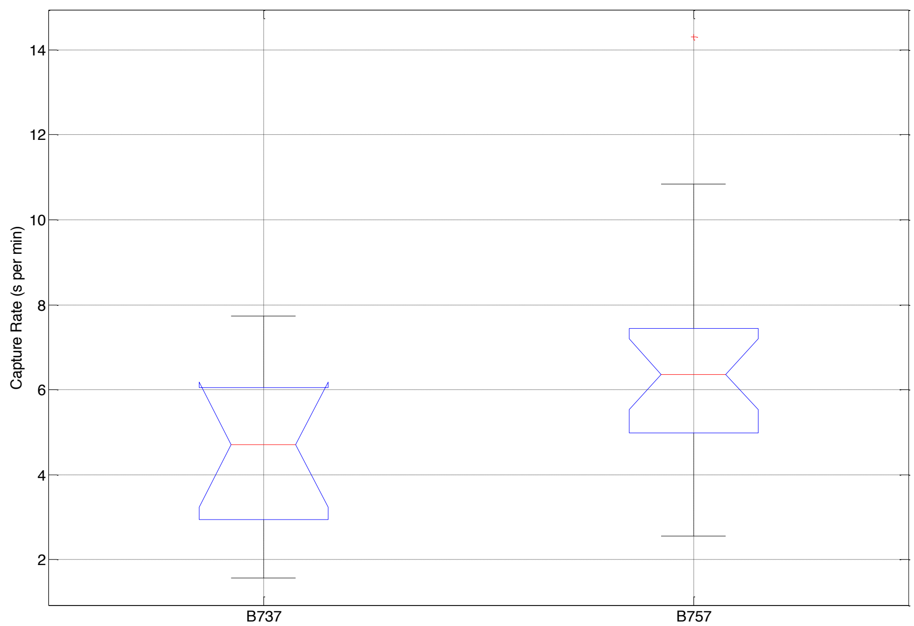


Figure 66: Capture Rate by Aircraft Type

By path: (p value = 0.0045) Significant differences at 95% level

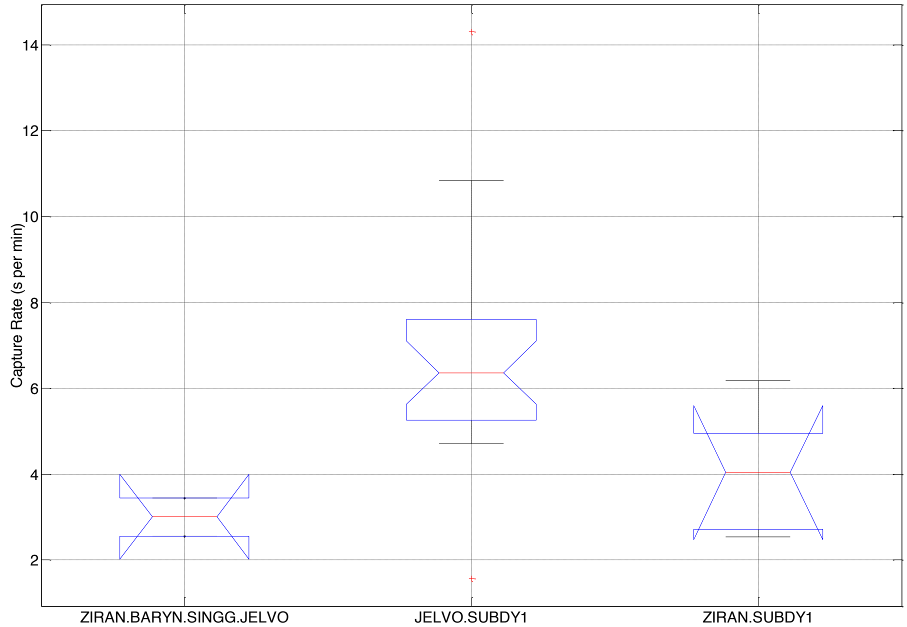


Figure 67: Capture Rate by Ownship Path

By lead aircraft: (p value = 0.0028) Significant differences at 95% level

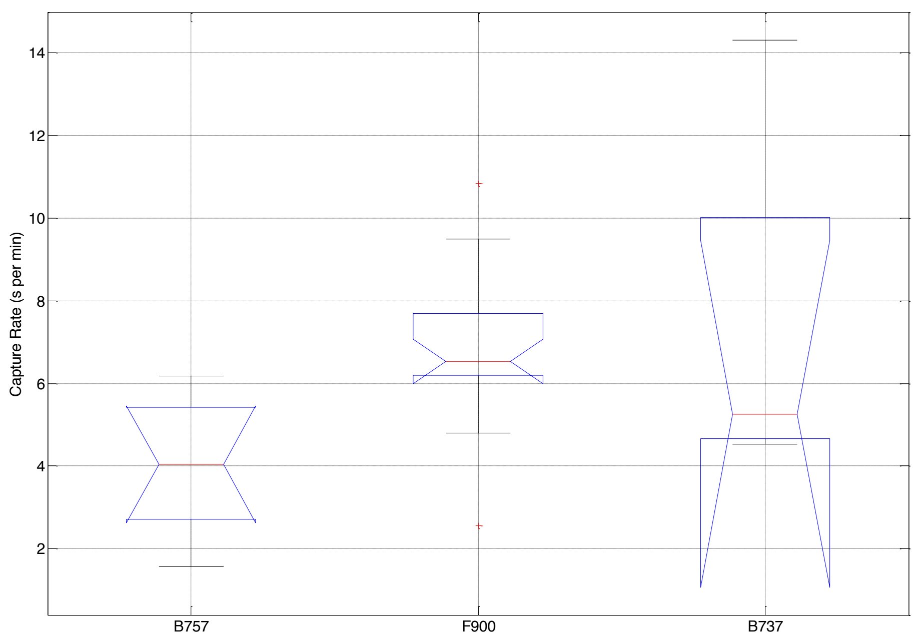


Figure 68: Capture Rate by Lead Aircraft Type

By chain position: (p value = 0.002) <u>Significant differences at 95% level</u>

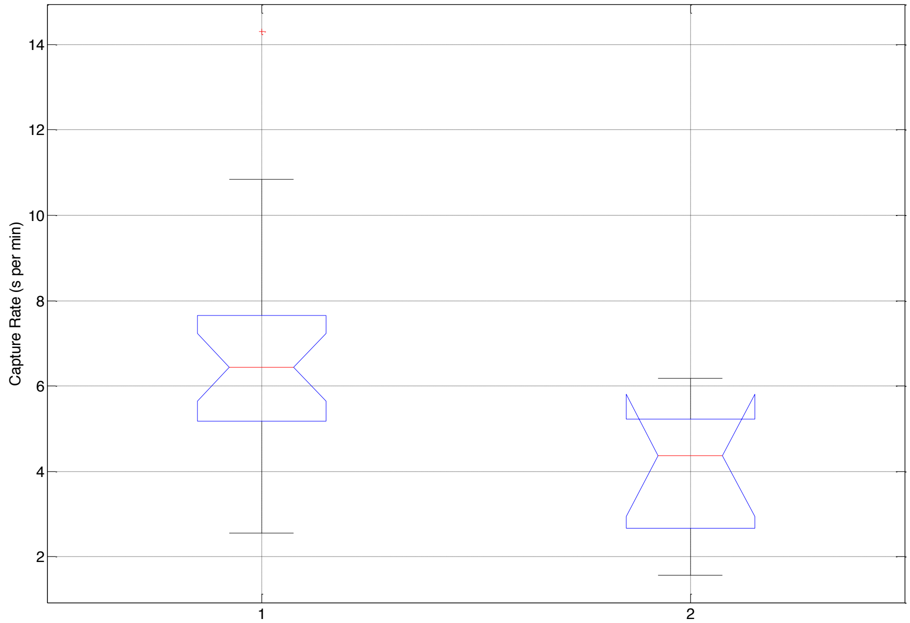


Figure 69: Capture Rate by Chain Position

By condition (A/B): (p value = 0.0516) <u>No significant differences at 95% level</u>

maintain_RMS

By path: (p value = 0.1063) <u>No significant differences at 95% level</u>

By ownship aircraft: (p value = 0.2175) <u>No significant differences at 95% level</u>

By lead aircraft: (p value = 0.1327) <u>No significant differences at 95% level</u>

By chain position: (p value = 0.0314) <u>Significant differences at 95% level</u>

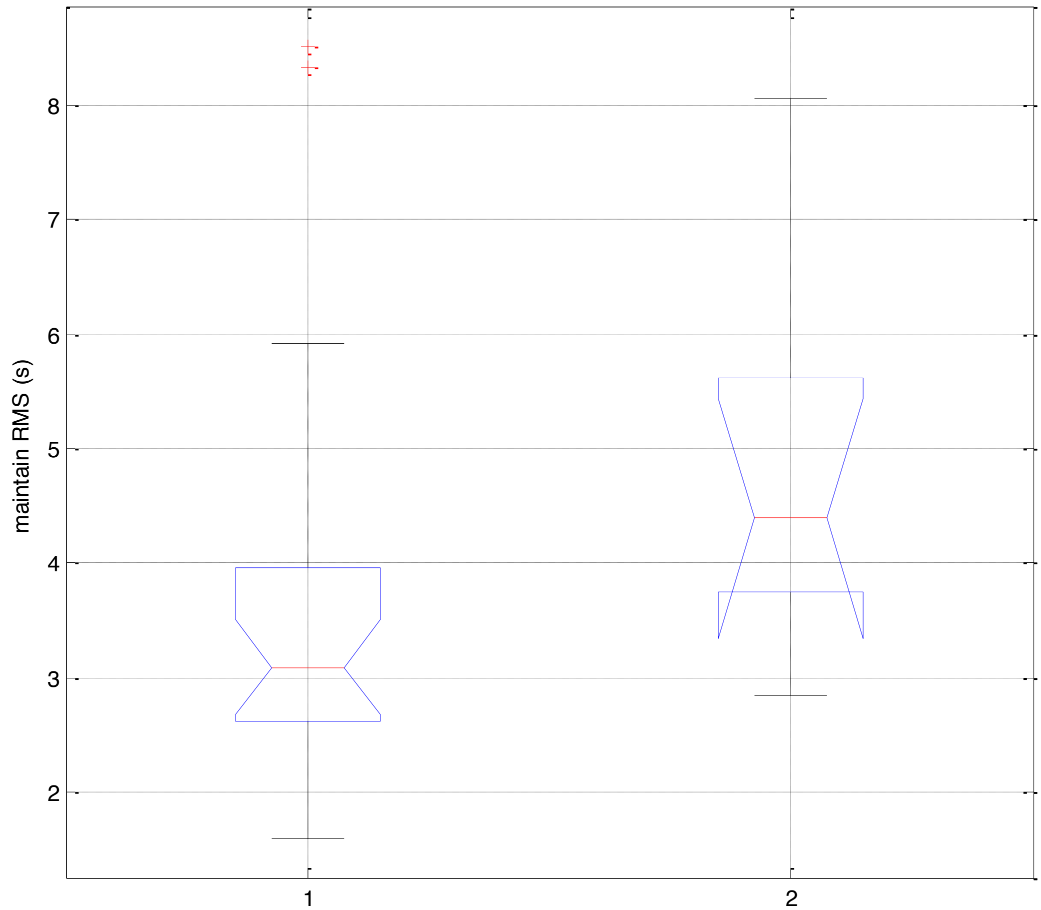


Figure 70: Time-Based CAPTURE, Maintain RMS by Chain Position

Operations at the last position in the chain have worse maintain segment performance (Figure 70). This can be attributed to the chain effect and associated accumulation of delay but, interestingly, does not translate to discernable differences in PTP delivery as was discussed earlier.

By condition (A/B): (p value = 0.0404) Significant differences at 95% level

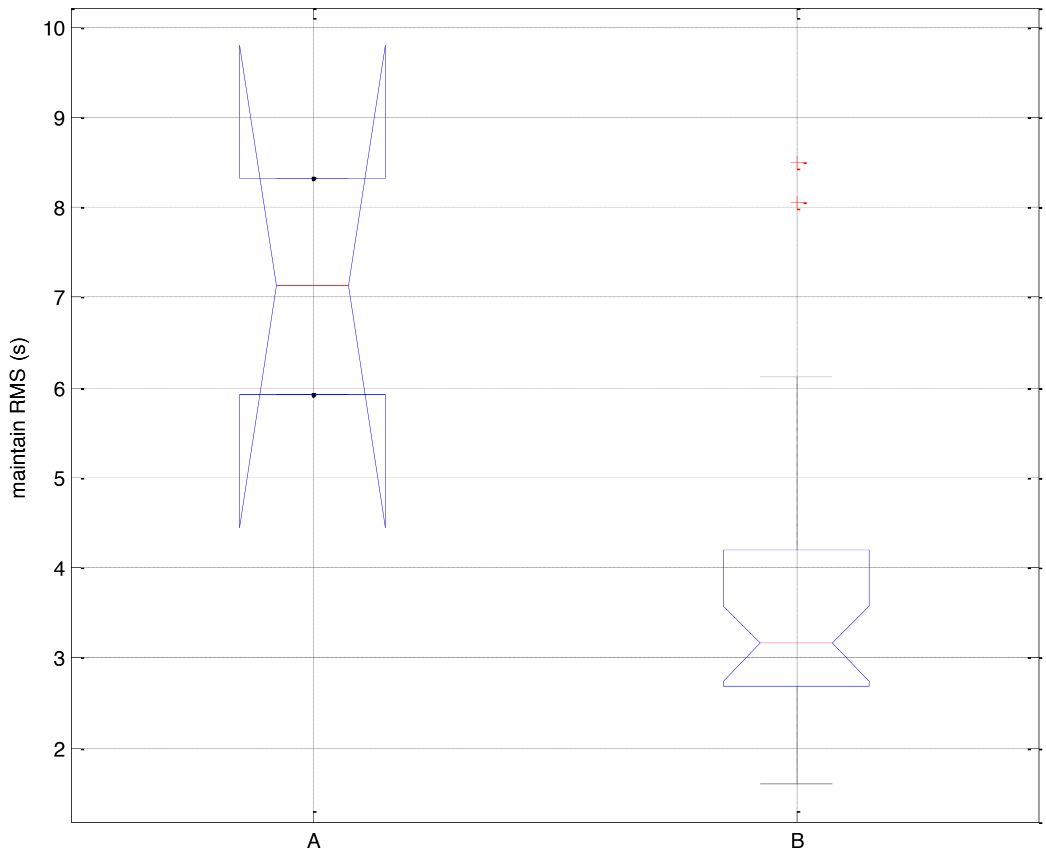


Figure 71: Time-Based CAPTURE, maintain RMS by scenario type

Cruise operations have worse maintain segment performance than descent operations (Figure 71). This is likely the same effect that was observed in PTP delivery performance.

IM Speed Rate

IM Speed Rate does not significantly differ across all variations of execution of the time-based CAPTURE clearance throughout the flight test.

By traffic path: (p value = 0.8994) No significant differences at 95% level

By ownship aircraft: (p value = 0.9267) No significant differences at 95% level

By lead aircraft: (p value = 0.579) No significant differences at 95% level

By chain position: (p value = 0.4405) No significant differences at 95% level

By condition (A/B): (p value = 0.7144) No significant differences at 95% level

Across time-based MAINTAIN operations, are there differences in performance by geometry, aircraft type, and chain position?

PTP delivery

By path: (p value = 0.6704) No significant differences at 95% level

By ownship aircraft: (p value = 0.0063) Significant differences at 95% level

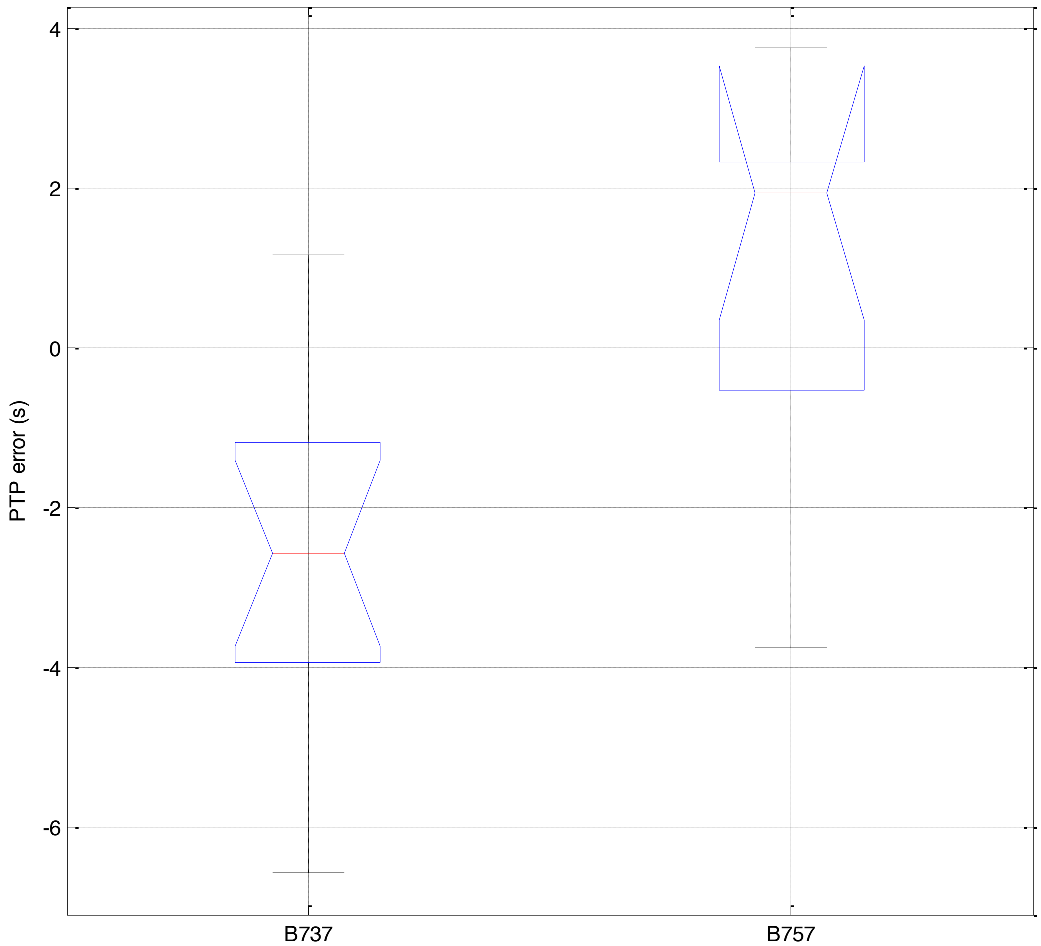


Figure 72: Time-Based MAINTAIN, PTP Error by Aircraft Type

PTP delivery differences between aircraft types is difficult to explain, especially because the maintain segment performance does not exhibit statistically significant differences (Figure 72 and Figure 73). This is likely the product of late adverse spacing evolution being too small to significantly affect the entire maintain segment performance. It has been shown that the along-track wind forecast error is consistently large through the operation of the RF turns present on the SUBDY path. Given the fact that MAINTAIN operations have predominantly been performed on the SUBDY path and that the RF turns occur late in the operation, likely near the time the lead aircraft reaches the PTP, this would tend to support that theory.

By chain position: (p value = 0.0068) Significant differences at 95% level

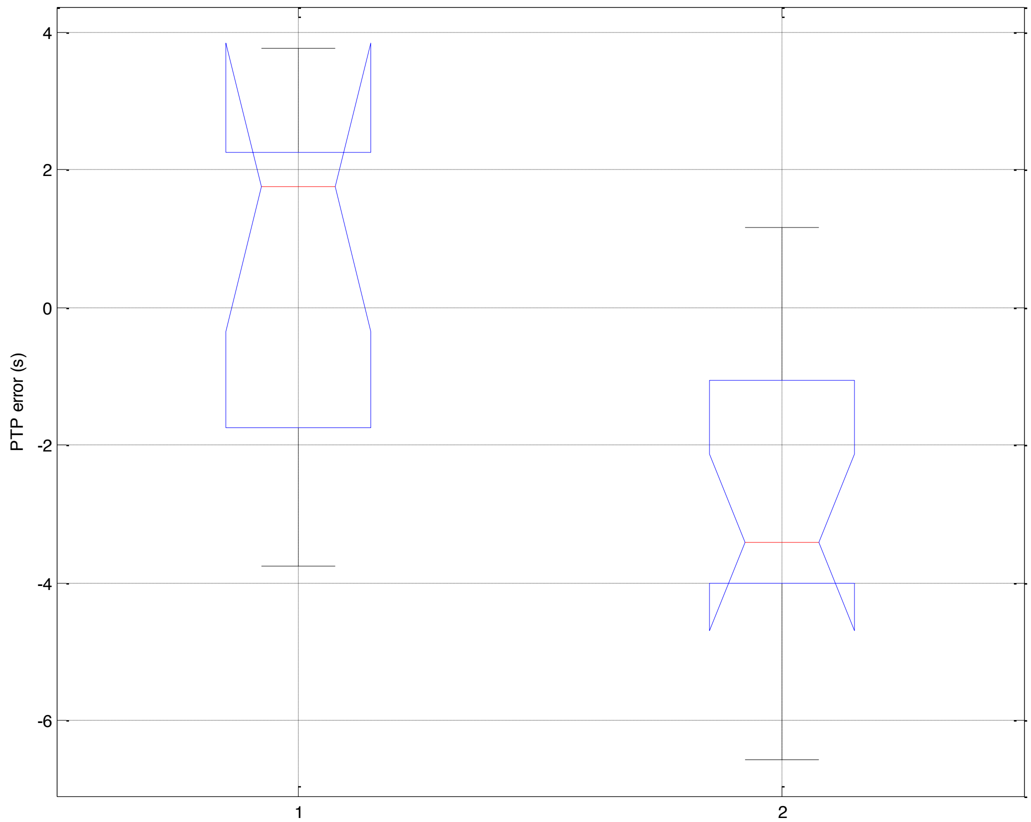


Figure 73: Time-Based MAINTAIN, PTP Error by Chain Position

By condition (A/B): (p value = 0.6704) No significant differences at 95% level

Maintain_RMS

Maintain segment performance does not significantly differ across all variations of execution of the time-based MAINTAIN clearance throughout the flight test.

By path: (p value = 0.3491) No significant differences at 95% level

By ownship aircraft: (p value = 0.4528) No significant differences at 95% level

By lead aircraft: (p value = 0.4528) No significant differences at 95% level

By chain position: (p value = 0.2167) No significant differences at 95% level

By condition (A/B): (p value = 0.3491) No significant differences at 95% level

IM Speed Rate

By path (p value = 0.0022) Significant differences at 95% level

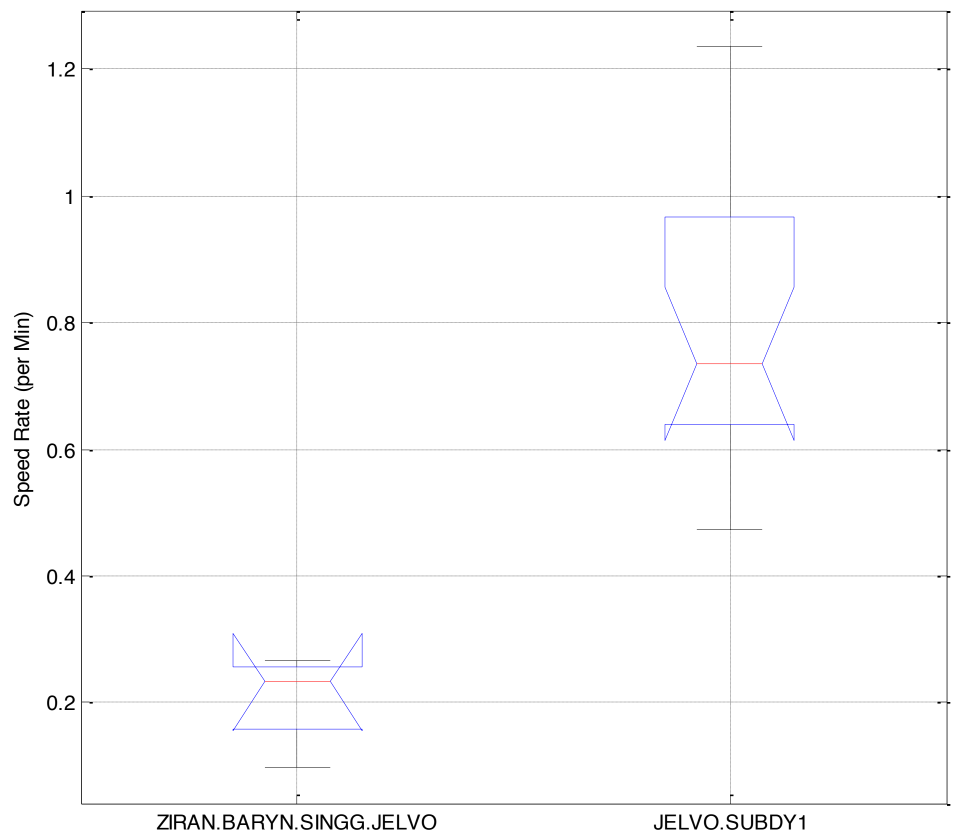


Figure 74: Time-Based MAINTAIN, IM Speed Rate by Path

The difference in IM speed rate by path is attributable to late operation along-track wind forecast errors through the RF turns of the SUBDY path (Figure 74). Also, given that the en route path is level and shorter and has less discretization of available IM speeds (operations in Mach rather than CAS), it should be expected to generate less IM speeds and worse performance, as has been seen.

By ownship aircraft: (p value = 0.088) No significant differences at 95% level

By lead aircraft: (p value = 0.088) No significant differences at 95% level

By chain position: (p value = 0.1018) No significant differences at 95% level

By condition (A/B)   (p value = 0.0022)   <u>Significant differences at 95% level</u>

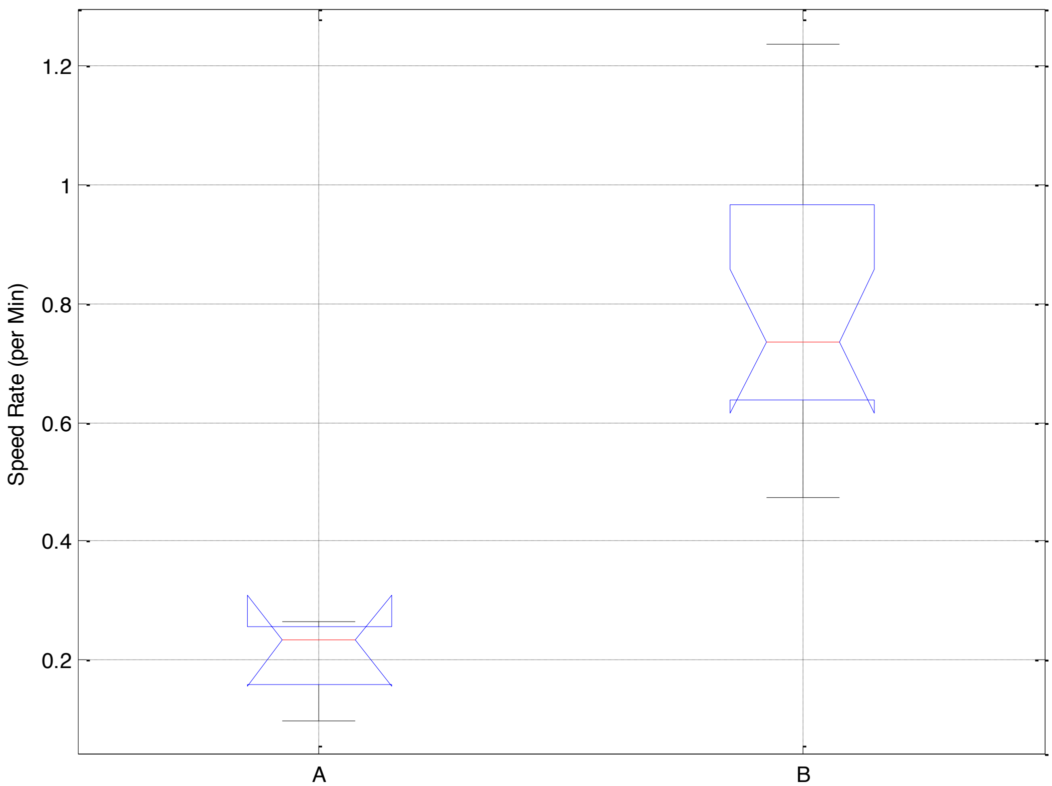


Figure 75: Time-Based MAINTAIN, IM Speed Rate, by Scenario Type

This difference describes the same effect described earlier by ownship path between the SUBDY and en route paths (Figure 75).

6. Generalized Regression Models

Objective

The objective for generating regression models out of the flight test data is to get a deeper understanding of how operational parameters at the onset of the operation affect IM performance. Understanding and describing what operational conditions contribute to each IM performance aspect is an important step in gaining confidence in the operation observed through the use of the prototype in the flight test.

The set of regressors used in all regression analysis consists of the following:

- Clearance Type (MAINTAIN, CAPTURE, CROSS, SPACE)
- Intial Spacing Error (nm or s)
- Initial Altitude (ft)
- IMlength (nm)
- Aircraft Type [ownship] (737, 757)
- Lead aircraft type [traffic] (737, 757, F900)
- Chain Position (1 or 2)
- Ownship Path
- Traffic Path
- Ownship along track actual wind component mean
- Traffic along track actual wind component mean
- Chain lead (non-FIM aircraft) nominal speed profile deviation mean [delay condition] (kt)

Several metrics were attempted for this regressor. The first being the test card condition, which includes three delay conditions for the non-FIM aircraft (no delay, medium delay, and high delay, see Flight Test Plan for further details). However, in many instances, the actual profile flown by the non-FIM aircraft did not match the desired condition. When used as a regressor, its inclusion tended to worsen the model or not be strong enough to warrant inclusion.

The second metric attempted was based on the actual flown CAS as compared to the nominal CAS profile. A mean value of that difference between tStart and tEnd is reported for each run. A first attempt to match the discrete test card delay conditions was made by clustering the resulting mean error into three clusters. The cluster analysis revealed three clusters for the error (-15kts, -5kts and 0 kts), but when the discrete cluster index was used in the regression no significant improvement was discernable. Thus the variable retained for this regressor in this analysis is the continuous error signal mean with continuous positive and negative values in kts.

- Distance to go to the ABP at onset (CROSS only) (nm)

Note that the along-track wind forecast error is not included in the list of regressors as it is unlikely to be known accurately as an operational input, even though it is likely to be a contributor to performance. The actual wind experienced is included separately from the forecast quality as it is likely estimable and is expected to have some impact on the performance separate from the forecast quality. In fact, several of the flown days were for high wind conditions that, even in the presence of a decent forecast, tended to exhibit worse performance. It is expected that the quality of models increases if the forecast errors are used as regressors, but this was not attempted.

Regression models are attempted for this set of regressors for each of the performance metrics described in the ANOVA section:

- Achieved PTP spacing error (nm or s)
- Achieved ABP spacing error (nm or s) [CROSS only]
- IM Speed Rate (number of IM speeds per minute of operation)
- Time to capture (s) [CAPTURE only]
- Maintain segment RMS error (s or nm)
- Fuel Burn Average Rate (lbs/hr)

Methodology

Standard regression techniques assume normality of the input and output data to the model. As described in section 5, the data collected is not necessarily normally distributed because of both the experiment design and the uncontrollable and non-normal nature of some of the input conditions (e.g., wind conditions). Thus, generalized regression techniques are used, that are less sensitive to the normality assumption. These techniques can deal with data of different distributions such as Poisson (for positive integer responses such as the number of IM speeds) and Gamma (for positive continuous responses such as the IM speed rate or the maintain segment RMS response).

In addition, rather than specifying a given model a priori, fitting the data to it, and then evaluating the fit (a process that can take a long time), stepwise model search techniques are employed. Matlab provides many different techniques for the construction of generalized linear regression models by stepwise effect inclusion. This report focuses on the methods that start with a simpler model and trend towards a complex model by iteratively adding and removing terms until the model no longer offers statistically meaningful improvement.

The Matlab function used is `stewiseglm` with its default search convergence criterion based on Deviance, with is related to the statistical significance of the added term. Terms are added to the model if the p-value of the F or chi-squared statistic is smaller than 0.05, and terms are removed to the model if the p-value of the F or chi-squared statistic is greater than 0.05. Terms are added in order from linear to interaction terms and quadratic. The search thus favors simpler models, starting with purely linear terms, and ending with purely quadratic terms. In cases where such searches result in models with poor fit, a reverse search is attempted (start at the complex model and remove terms).

The quality of the resulting model is evaluated based on the adjusted R squared value, related to the fit quality to a line, much like in standard regression, but adjusted for the number of terms in the model. R squared values range from 0 to 1, where 1 indicates a perfect fit. Regression models are reported in this document if their adjusted R squared value is greater than 0.7. Models with excessively high adjusted R squared values (>0.95) are inspected and not reported if they contain too few remaining error degrees of freedom. After all, it is always easy to fit a perfect line through two data points.

Regression Models

All Time-Based Operations

The first models attempted were for all time-based operations, with the clearance type part of the list of included terms. As will be shown later, typically better submodels were found for each separate IM operation type.

No overall models of time-based PTP performance were of sufficiently good quality to report.

A model for the number of IM speeds with R=0.73 is described as

```
Generalized Linear regression model:
    numSpeeds ~ [Linear formula with 10 terms in 7 predictors]
    Distribution = Poisson , Link = Log


Estimated Coefficients:
                                              Estimate        SE        tStat      pValue
                                             __________   __________   _______   __________
```

(Intercept)	-1.2077	0.49176	-2.4559	0.014054
hAtStart	4.3983e-05	9.2036e-06	4.7789	1.7626e-06
ownship_path_JELVO.SUBDY1	2.5732	0.38245	6.7283	1.7164e-11
ownship_path_ZIRAN.SUBDY1	2.69	0.40293	6.6761	2.4538e-11
ownship_path_UPBOB1	2.1487	0.41522	5.1747	2.2825e-07
ownship_path_final_appr	2.5989	0.50943	5.1017	3.3666e-07
clearanceType_CAPTURE	-0.3597	0.091246	-3.9421	8.0782e-05
clearanceType_CROSS	-0.28139	0.10281	-2.7371	0.0061981
windAlongTrackComponents_mean	-0.018866	0.0077476	-2.435	0.01489
windAlongTrackComponents_traffic_mean	-0.0089389	0.0038443	-2.3252	0.020059
chain_positionSTR_2	0.18182	0.08033	2.2634	0.023613
traffic_speedProfileDev_mean_lead1	-0.0098503	0.0046306	-2.1272	0.033402
hAtStart:windAlongTrackComponents_mean	9.9573e-07	2.7943e-07	3.5635	0.00036594
windAlongTrackComponents_mean^2	0.00021282	5.5598e-05	3.8279	0.00012923

```
116 observations, 102 error degrees of freedom
```

Reports of regression models included herein will take this form and are explained in the next paragraph through an example. The actual model and associated data is delivered in an accompanying Matlab data file and associated scripts for reproduction and validation by NASA.

To exercise the model, the *Estimate* column is used, which includes the value of the regression term for the factor in question. The other columns are used to report on the statistics of the inclusion of this term and are not used here. Because many of the regressor variables are categorical in nature, their terms are for specific values of those variables, with the nominal value built into the Intercept term. Thus in the above example, the nominal values for ownship path is the en route path (ZIRAN.BARYN.SINGG.JELVO), the nominal value for clearanceType is MAINTAIN, and the nominal value for chain position is 1. To exemplify the description of the model and its use, let us determine the estimated number of IM speeds for a CAPTURE operation, with ownship on the JELVO.SUBDY1 transition, in second chain position, starting at 23,000 ft, with a chain lead speed deviation of -10 knots and along track winds of -15 knots (for both ownship and traffic).

log(numSpeeds) = -1.2077 (Intercept Term) +

4.3983E-5 * 23,000 (hAtStart Term) +

2.5732 (ownship_path Term) +

-0.3597 (clearance type Term) +

-0.018866 * -15 (ownship wind Term) +

-0.0089389 * -15 (traffic wind Term) +

0.18182 (chain position Term) +

-0.0098503 * -10 (lead speed error Term) +

9.9573e-07 * 23,000 * -15 (hAtStart*wind interaction) +

0.00021282 * (-15)^2 (wind ^2 Term)

= 2.4192

The log term comes from the specific distribution forced on the generalized regression, which for a response expected as a positive integer (as is numSpeeds) defaults to Poisson, thus using a log-based link function. Thus the number of IM speeds expected for this example would be exp(2.4192) = 11.24.

Inspection of the model reveals interesting insight by way of the terms that are missing from the model (thus were not added as significant contributors). For example, it appears that the number of IM speeds is not affected by the length of the IM operation or the initial spacing error. It is mosly affected by the type of operation, wind condition, and lead delay condition. The initial altitude term likely serves as a surrogate for the type of operation (A, B, or C) because, by design, en route (A) conditions were run at FL350, while descent (B) conditions were started at FL230.

Interestingly, no good model can be found for the IM speed rate (numSpeeds per min, R never more than 0.5) even though a good model for numSpeeds (R=0.73) was derived. No phyiscal explanation for this has yet surfaced and the author believes this to be a mathematical artifact of the technique used and the relatively few data samples.

All Distance-Based Operations

PTP performance for all distance-based operations generates a good model (R=0.9999) but is an example of an instance of a model with no degrees of freedom left and thus not a very representative model. The number of leftover degrees of freedom for such a model is 1 based on 14 initial observations and a model with 9 terms. Forcing a simpler model may generate more degrees of freedom with a worse fit model. A reportable model can thus be generated by forcing the search to not include quadratic terms.

The resulting model for PTP performance for all distance-based operations is (R=0.71):

```
Generalized Linear regression model:
    achievedSpacingError_PTP ~ [Linear formula with 7 terms in 5 predictors]
    Distribution = Normal

Estimated Coefficients:
                                                Estimate       SE         tStat       pValue
                                               __________    _________    ________    ________

    (Intercept)                                   2.3439      0.60345      3.8842     0.011593
    traffic_path_JELVO.SUBDY1                     2.3578       1.0754      2.1924     0.079851
    traffic_path_ZIRAN.SUBDY1                   -0.65848      0.70623    -0.93239      0.39393
```

```
    traffic_path_final_appr                            -3.1473        0.80223      -3.9232      0.011146
    IMlength                                         -0.051403       0.015419      -3.3336      0.020696
    windAlongTrackComponents_mean                     -0.15433        0.04205      -3.6702      0.014441
    windAlongTrackComponents_traffic_mean                0.154        0.04213       3.6553      0.014667
    traffic_speedProfileDev_mean_lead1                 0.10289       0.031514       3.2647      0.022328
  IMlength:windAlongTrackComponents_traffic_mean -0.00060412     0.00014685       -4.114     0.0092282


14 observations, 5 error degrees of freedom
```

Matlab includes a utility to graphically depict and evaluate the model (`plotSlice`). The following figure examplifies this utility for the above model (distance-based PTP error). The utility is interactive and allows for exploration of the model. For each included regressor (columns), the user can select values either manually (by entering or selecting values), or graphically (by moving each vertical blue line). The model output for the selected values is shown on the left of the y axis, including confidence intervals. Green lines in each regressor areas show the estimated response (confidence bounds as red dotted lines) for that regressor throughout its envelope.

The shape of the green lines represent a useful graphical way to estimate the contribution to each regressor on the response independent of scale (because the y axis is common).

Thus, from Figure 76, one can quickly graphically infer that the true wind along track components have the larger impact on PTP error performance (larger slopes) than the path or IM length. The fact that ownship and traffic true wind component factor slopes have opposite signs may be an artifact of the model because it is created for all distance-based operations, which include a mix of same route operations (CAPTURE, MAINTAIN, SPACE) and merging route operations (CROSS). In same route operations the traffic true wind component should be similar to ownship's. However in merging operations they may be much different. Thus a better model for distance-based PTP performance should be obtained by segregating operation types because the wind components look predominent but have different effects depending on the operation type.

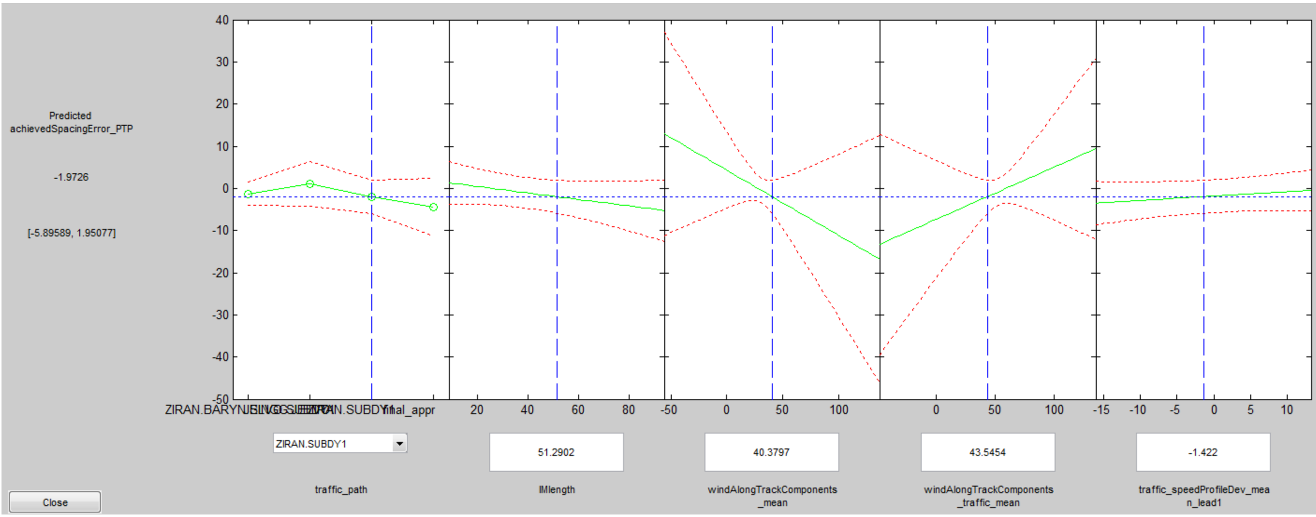


Figure 76: plotSlice Output for PTP Error Model (Distance-Based Operations)

A simple model for numSpeeds can be found for all distance-based operations with relatively good quality (R=0.79) and leftover degrees of freedom

```
Generalized Linear regression model:
log(numSpeeds) ~ 1 + IMlength + windAlongTrackComponents_traffic_mean +
traffic_speedProfileDev_mean_lead1


Estimated Coefficients:
                                             Estimate       SE         tStat       pValue

                                            __________   _________   _______    __________

    (Intercept)                                 1.1995     0.28519    4.2059    2.6006e-05
    IMlength                                  0.011589   0.0043131    2.6869      0.007211
    windAlongTrackComponents_traffic_mean   -0.0057008   0.0029095   -1.9594       0.05007
    traffic_speedProfileDev_mean_lead1       -0.026081    0.015264   -1.7087      0.087503


14 observations, 10 error degrees of freedom
```

This model has three linear terms of generally the same scale and thus the estimates can be numerically compared for effect strength. Since IM length takes values up to 100nm but the wind components and speed errors take values between ~ -25 to +25 (half the range of IM length) all three components of the model have similar strength effects.

A model for the IM Speed Rate can be derived (R=0.8) when constraining to linear terms to increase the number of leftover degrees of freedom:

```
Generalized Linear regression model:
reciprocal(numSpeeds_perMin)~1 + traffic_path + chain_positionSTR + traffic_speedProfileDev_mean_lead1
    Distribution = Gamma


Estimated Coefficients:
                                         Estimate        SE          tStat         pValue
```

(Intercept)	0.92623	0.10388	8.9165	1.9844e-05
traffic_path_JELVO.SUBDY1	-3.0217	0.99707	-3.0305	0.016296
traffic_path_ZIRAN.SUBDY1	1.1257	0.23235	4.8447	0.0012804
traffic_path_final_appr	-0.98787	0.24441	-4.0419	0.003726
chain_positionSTR_2	3.6934	0.96292	3.8357	0.0049778
traffic_speedProfileDev_mean_lead1	0.0642	0.015903	4.0369	0.0037518

14 observations, 8 error degrees of freedom

This model does not include IM length as numSpeeds does (because it represents a rate per operational time, strongly correlated to IM length) and thus the term likely became insensitive. Interestingly, the terms retained include traffic path and chain position, which were not part of the model for numSpeeds. Again, this is difficult to explain and is currently attributed to the small sample size and mathematical artifact of the two different distributions imposed on the model as a result of the different nature of their responses (positive integers for numSpeeds, implying a Poisson distribution and log link funtion; positive continuous numbers for speed rate, implying a Gamma distribution and inverse link function).

To obtain models for other IM performance metrics, we need to start building more specific models for each clearance types.

Time-Based MAINTAIN Operations

PTP error for time-based MAINTAIN operations results in a good model (R=0.8014) with only one interaction term.

```
Generalized Linear regression model:
    achievedSpacingError_PTP ~ 1 + hAtStart + IMlength + chain_positionSTR + ownship_path*own_aircraft


Estimated Coefficients:
                                                   Estimate         SE         tStat       pValue
                                                  __________    __________    _______    __________

    (Intercept)                                      -11.692        2.8247    -4.1392     0.0011644
    hAtStart                                      0.00042514    9.7666e-05      4.353    0.00078266
    ownship_path_JELVO.SUBDY1                         4.4175        1.9912     2.2185      0.044942
    own_aircraft_B757                                -5.3393        1.8976    -2.8137      0.014641
    IMlength                                       -0.064419      0.025742    -2.5025      0.026466
    chain_positionSTR_1                                2.834         1.381     2.0521      0.060867
    ownship_path_JELVO.SUBDY1:own_aircraft_B757       8.5106        1.4832     5.7381    6.8436e-05


20 observations, 13 error degrees of freedom
```

hAtStart is a surrogate for condition type (A/B/C). When we instead use condition type as a categorical variable in the model, the model is poorer and the term is absent. It appears to be a strong term in the model, even though technically the data is clustered mostly near two values (23,000 ft and 35,000 ft). However, because several runs were truncated beyond the initial start, some values exist below 23,000 ft. Also, in some instances, aircraft were kept lower than FL230 on B runs. The 757 aircraft appears to decrease the quality of the PTP delivery and has an interaction term with the JELVO path. It can be concluded that the data reveals poorer MAINTAIN performance for the 757, especially on the en route path (it should be noted that ownship_path in this subset only takes two values [en route path is nominal], as no time-based MAINTAIN operations were flown with ownship on either UPBOB or ZIRAN.SUBDY). This corroborates the ANOVA results reported in the previous section, with this model now including strength of terms, with the ownship path being the strongest term, followed aircraft type and chain position.

A good model for numSpeeds can be obtained for time-based MAINTAIN operations (R=0.76)

```
Generalized Linear regression model:
    log(numSpeeds) ~ 1 + ownship_path + IMlength + windAlongTrackComponents_mean


Estimated Coefficients:
                                      Estimate        SE         tStat        pValue

                                     __________    _________    ________    __________

    (Intercept)                        -0.20471      0.45035    -0.45455       0.64943
    ownship_path_JELVO.SUBDY1            1.7231      0.41509      4.1512    3.3076e-05
    IMlength                           0.010767    0.0040359      2.6679     0.0076333
    windAlongTrackComponents_mean    -0.0095997    0.0036042     -2.6635     0.0077338


20 observations, 16 error degrees of freedom
```

This model has three terms of relatively equal strength, revealing better performance for the (nominal) en route path.

The best model that can be obtained for IM speed rate has a R value of 0.61, not good enough for reporting. Several attempts were made at looking for better models, including replacing the hAtStart variable with the condition type (A/B/C), adding both, removing IM length, etc., to no avail. Again, the fact that a good model can be had for numSpeeds but not for IM Speed rate is attributed to the mathematical artifacts of the techniques used.

A model for the spacingError RMS value of the maintain segment can be reported (R=0.7).

```
Generalized Linear regression model:
    reciprocal(spacingErrorMaintainSegment_rms) ~ 1 + hAtStart + ownship_path + IMlength + IMlength^2
    Distribution = Gamma


Estimated Coefficients:
                                  Estimate          SE         tStat       pValue

                                 ___________    __________    _______    __________

    (Intercept)                       2.8341       0.55244     5.1302    8.3527e-05
```

```
    hAtStart                    -2.8374e-05    6.3803e-06    -4.4471    0.00035364
    ownship_path_JELVO.SUBDY1       -0.50912       0.13545    -3.7588     0.0015647
    IMlength                        -0.03745      0.012057    -3.1062      0.006419
    IMlength^2                      0.000245    6.6417e-05     3.6888     0.0018216


22 observations, 17 error degrees of freedom
```

To obtain this model, the lead aircraft speed error (delay condition) had to be removed from the list of regressors to search. When including it, the resulting model does not include the term but excludes a lot more terms and is much poorer. The reported model includes the initial altitude variable as a surrogate for condition type. When including both, the model does not improve and includes both terms revealing the B condition (descent) as having slightly better maintain performance than the level (A) condition. However the simpler model is reported above, excluding the condition type term. IM length appears both as a linear and quadratic term. The presence of the quadratic term can be explained by the fact that the RMS metric is dependent on the length of the operation (better performance for longer operation) and is quadratic in nature (square root of a squared term).

Time-Based CAPTURE Operations

A model for PTP error for time-based CAPTURE operations can be reported (R=0.79) but is relatively more complex than reported models so far (nine terms with two interaction terms).

```
Generalized Linear regression model:
    achievedSpacingError_PTP ~ [Linear formula with 9 terms in 6 predictors]
    Distribution = Normal


Estimated Coefficients:
                                               Estimate        SE         tStat       pValue
                                               _________    _________    _______    __________
    (Intercept)                                 -6.5604       1.9018    -3.4495     0.0022843
    ownship_path_JELVO.SUBDY1                    2.1576       1.7563     1.2285       0.23225
    ownship_path_ZIRAN.SUBDY1                    5.1184       1.8408     2.7806      0.010906
    own_aircraft_B757                            2.3624      0.69007     3.4234     0.0024313
    IMlength                                     0.036663     0.019123     1.9172      0.068291
    windAlongTrackComponents_mean                0.0093661     0.015102     0.6202        0.5415
    chain_positionSTR_2                         -4.4288       1.0596    -4.1798    0.00038888
    traffic_speedProfileDev_mean_lead1          -1.4018      0.26442    -5.3016    2.5462e-05
    IMlength:traffic_speedProfileDev_mean_lead1  0.013445    0.0026819     5.0132    5.1032e-05
 windAlongTrackComponents_mean:chain_positionSTR_2 -0.17907     0.039066    -4.5837    0.00014499


32 observations, 22 error degrees of freedom
```

Graphical review of the model reveals that the term with the strongest effect is the true wind along track component, followed by path and chain position. The IMlength is a weak component, likely helping delineate the capture from the maintain segment of the operation (longer IM lengths are likelier to have a longer maintain segment). The aircraft type effect has been seen in the ANOVA analysis, but that analysis also revealed a difference in performance across operation types, and yet neither hAtStart nor the condition type regressors are found in the resulting model.

A model for tCapture can be derived (R=0.73) only when removing the lead delay condition regressor from the search, and including quadratic terms. Two quadratic terms are present: initialSpacingError and hAtStart. Thus, it would appear that the time to capture is strongly influenced by the altitude at the start of the operation (two terms) and initial spacing error (two terms). When attempting a model with condition type (A/B/C) instead of hAtStart, the resulting model is worse, indicating that altitude truly has an effect. The author believes this is a result of the effect of altitude on the estimated CAS decceleration segments that are derived and used by the CTD algorithm based on ground speed history, and transformed to airspeed using altitude and interpolated forecast winds at those altitudes.

```
Generalized Linear regression model:
    reciprocal(tCapture) ~ 1 + initialSpacingError + hAtStart + chain_positionSTR +
initialSpacingError^2 + hAtStart^2
    Distribution = Gamma


Estimated Coefficients:
                              Estimate         SE         tStat        pValue
                             __________    _________    ________    _________

    (Intercept)               -0.001392     0.0047546    -0.29277       0.77185
    initialSpacingError       5.1354e-06    4.5997e-06     1.1164       0.27372
    hAtStart                  7.8547e-07    3.8461e-07     2.0422       0.05065
    chain_positionSTR_2       -0.0025772    0.00047388    -5.4385    8.3746e-06
    initialSpacingError^2    -1.3324e-06    2.2232e-07    -5.9933    1.8633e-06
    hAtStart^2               -1.7001e-11    7.2086e-12    -2.3584       0.02557


34 observations, 28 error degrees of freedom
```

A model for IM speed rate can be derived (R=0.84) but is fairly complex (13 terms, including 2 quadratic terms). Attempts at deriving simpler models of equivalent quality have failed, thus the complex model is reported here.

```
Generalized Linear regression model:
    numSpeeds_perMin ~ [Linear formula with 13 terms in 7 predictors]
    Distribution = Gamma
Estimated Coefficients:
                                                    Estimate         SE         tStat        pValue
                                                   __________    _________    _______    _________

    (Intercept)                                       -4.1214        1.4968    -2.7535     0.013075
    initialSpacingError                            -0.0099237     0.0019638    -5.0533   8.2745e-05
    hAtStart                                       0.00062461    0.00012863     4.8558   0.00012696
    ownship_path_JELVO.SUBDY1                         -1.4023        0.5469    -2.5641     0.019516
```

```
    ownship_path_ZIRAN.SUBDY1                           -1.1872       0.57737    -2.0562      0.054558
    IMlength                                           0.013612     0.0048363     2.8145      0.011475
    windAlongTrackComponents_mean                      0.083951       0.01444     5.8138     1.654e-05
    chain_positionSTR_2                                 -1.1778       0.17714    -6.6491    3.0663e-06
    traffic_speedProfileDev_mean_lead1                 0.065325      0.010926     5.9791    1.1764e-05
 initialSpacingError:windAlongTrackComponents_mean -0.00016399    6.1314e-05    -2.6746      0.015463
 hAtStart:windAlongTrackComponents_mean           -2.5841e-06    4.8408e-07    -5.3382    4.4921e-05
 chain_positionSTR_2:traffic_speedProfileDev_mean_lead -0.17243      0.027696    -6.2258    7.1214e-06
    initialSpacingError^2                            0.00012426    4.6235e-05     2.6876      0.015041
    hAtStart^2                                       -1.376e-08    2.4345e-09    -5.6522    2.3154e-05


32 observations, 18 error degrees of freedom
```

Interestingly, in this instance, no good model for numSpeeds can be derived, exhibiting opposite output from the MAINTAIN regression models. This is likely a result of the more complex nature of the CAPTURE operation, including a capture and maintain segment, where the maintain segment is known to generate more speeds. Thus when looking at the IM speed rate, the number of speeds are averaged and the differentiated effect of the number of speeds between the capture and maintain segments is minimized.

A model for the RMS error of the maintain segment can be found (R=0.95), but includes 12 terms in 8 predictors, including 3 interaction terms. An initially better model was found with quadratic terms as well but was simplified at a small reduction in fit. It is expected that initial spacing error and IM length affect maintain performance, as well as the wind and lead delay condition. It is surprising to find terms related to the path and aircraft type because ANOVA analysis at the same alpha level revealed no statistical differences in those groups for this metric.

```
Generalized Linear regression model:
    spacingErrorMaintainSegment_rms ~ [Linear formula with 12 terms in 8 predictors]
    Distribution = Gamma


Estimated Coefficients:
                                                  Estimate         SE         tStat       pValue

                                                 ___________    __________    _______    __________

    (Intercept)                                      1.7429       0.17861      9.758    1.3003e-08
    initialSpacingError                          0.00029001    0.00014951     1.9397      0.068245
    hAtStart                                    -5.1298e-05    6.7166e-06    -7.6375    4.7134e-07
    ownship_path_JELVO.SUBDY1                      -0.61875      0.070122    -8.8239    5.9049e-08
    ownship_path_ZIRAN.SUBDY1                      -0.52171       0.06294    -8.2889    1.4732e-07
    own_aircraft_B757                              -0.11934      0.033053    -3.6106     0.0019995
    lead_aircraft_F900                              0.11528      0.034054     3.3852     0.0032977
    lead_aircraft_B737                              0.13542      0.042584     3.1802     0.0051831
    IMlength                                     -0.0083808     0.0012343    -6.7899    2.3296e-06
    windAlongTrackComponents_mean                -0.0034083    0.00032258    -10.566    3.8033e-09
    traffic_speedProfileDev_mean_lead1             0.017474     0.0028012      6.238    6.9471e-06
 initialSpacingError:traffic_speedProfileDev_mean_lead1   -8.8419e-05    2.8454e-05    -3.1074
0.0060797
```

```
    hAtStart:IMlength                                  4.8386e-07    6.0305e-08     8.0235    2.3504e-07
own_aircraft_B757:traffic_speedProfileDev_mean_lead1  -0.022233     0.0028524    -7.7944    3.5434e-07


32 observations, 18 error degrees of freedom
```

Time-Based CROSS Operations

Models for CROSS operations include more regressors in the stepwise search. This is because we must account for the FIM pair to be on different paths, thus introducing the effect of traffic path and traffic wind components. Also, the ABP placement (NALTE and ZAVYO) and the DTG to the ABP at IM start are included in the search. hAtStart is included in the initial list of regressors even though only B scenarios were run for CROSS to determine whether altitude at start is an individual component of performance. As a result, the models reported are generally more complex than previous models.

A model for PTP performance can be found although just below the reporting threshold (R=0.69). This model was manually arrived at after finding a better fit at the reporting threshold but with a term left with a pValue beyon 0.05 (DTG_ABP). Although the fit reduces to 0.69 after removal of the term, the model is shown anyway in this case.

```
Generalized Linear regression model:
    achievedSpacingError_PTP ~ [Linear formula with 8 terms in 7 predictors]
    Distribution = Normal


Estimated Coefficients:
                                                    Estimate         SE          tStat       pValue
                                                   _________    __________    _______    __________

    (Intercept)                                       10.323        2.0295     5.0863    5.7506e-06
    ownship_path_JELVO.SUBDY1                        -3.5819        2.0137    -1.7788       0.08148
    ownship_path_UPBOB1                               10.546         2.221     4.7485    1.8221e-05
    lead_aircraft_B737                                3.1199        3.2125    0.97116       0.33624
    lead_aircraft_B757                                 10.63        4.5345     2.3442      0.023166
    ABP_NALTE                                        -5.4998        1.7124    -3.2118     0.0023317
    chain_positionSTR_2                              -13.059        4.8407    -2.6978     0.0095452
    traffic_speedProfileDev_mean_lead1               0.50215       0.11725     4.2829    8.5751e-05
    DTG_ABP:windAlongTrackComponents_traffic_mean  0.0042044    0.00065859     6.3839    5.9754e-08
    ABP_NALTE:traffic_speedProfileDev_mean_lead1    -0.39176       0.16745    -2.3396      0.023423


59 observations, 49 error degrees of freedom
```

This model again shows than when UPBOB is used, in large part with the 737 following the 757, the performance will be degraded by at least 7 s (10.546 s additional error for UPBOB, 10.63 s additional error for 757 lead and -13.059 s additional error for the second chain position). Initial Spacing Error and hAtStart are dropped terms. Only the traffic wind components are retained and included in the model when the ABP is at NALTE, suggesting the non-coincident route portion at altitude (prior to NALTE) has an effect.

A model for ABP performance can also be found at the reporting threshold (R=0.7) at about the same level of complexity. It should be noted that this is expected because the set of time-based CROSS operations includes 41 (out of 68) operations with ABP at ZAVYO, where the ABP performance is the same as the PTP performance. Independent models for ZAVYO and NALTE CROSS operations were sought and are reported later.

```
Generalized Linear regression model:
    achievedSpacingError_ABP ~ [Linear formula with 9 terms in 6 predictors]
    Distribution = Normal


Estimated Coefficients:
                                                      Estimate         SE         tStat       pValue
                                                     __________    __________    ________    __________

    (Intercept)                                        15.819        6.6818      2.3674      0.021991
    hAtStart                                         -0.0007307    0.00030278     -2.4133      0.019677
    ownship_path_JELVO.SUBDY1                          -1.4601        2.3894    -0.61107       0.54403
    ownship_path_UPBOB1                                13.663        2.1114       6.471    4.7642e-08
    windAlongTrackComponents_traffic_mean            -0.33685       0.15082     -2.2335      0.030209
    chain_positionSTR_2                              -6.6658        2.4974     -2.6691      0.010344
    traffic_speedProfileDev_mean_lead1                0.37932      0.099676      3.8055    0.00040084
    hAtStart:DTG_ABP                                 5.425e-06    1.7486e-06      3.1024     0.0032124
    DTG_ABP:windAlongTrackComponents_traffic_mean     0.01039     0.0023235      4.4715    4.7463e-05
windAlongTrackComponents_traffic_mean:chain_positionSTR_2  -0.2144      0.098713      -2.172
0.034831


58 observations, 48 error degrees of freedom
```

No model for numSpeed can be reported for time-based CROSS operations (best model is R=0.64), but a model for IM Speed Rate is just above the reporting threshold (R=0.71). This model has only five predictors but includes two quadratic and two interaction effects. ABP placement is not retained in the model even though the ANOVA analysis revealed a statistically significant difference among the NALTE vs ZAVYO ABP placement scenarios.

```
Generalized Linear regression model:
    numSpeeds_perMin ~ [Linear formula with 9 terms in 5 predictors]
    Distribution = Gamma


Estimated Coefficients:
                                              Estimate         SE         tStat       pValue
                                             __________    __________    _______    __________

    (Intercept)                                 0.85872       0.25063     3.4262     0.0012476
    ownship_path_JELVO.SUBDY1                   0.60095       0.16892     3.5577    0.00084191
    ownship_path_UPBOB1                         0.89083       0.28296     3.1483     0.0027952
    DTG_ABP                                    0.019597     0.0040067     4.8909    1.1234e-05
    windAlongTrackComponents_mean              -0.05254      0.011331    -4.6367    2.6554e-05
    chain_positionSTR_2                         0.74213       0.38219     1.9418      0.057925
    DTG_ABP:windAlongTrackComponents_mean    0.00043781    0.00015934     2.7477     0.0083761
```

```
    DTG_ABP:chain_positionSTR_2              -0.016455     0.0072127    -2.2814      0.026905
    windAlongTrackComponents_mean^2         -0.0012137     0.0001978    -6.1362    1.4431e-07
    traffic_speedProfileDev_mean_lead1^2     -0.0025499    0.00065815    -3.8744    0.00031743


59 observations, 49 error degrees of freedom
```

A submodel for ABP performance for the time-based CROSS operations with ABP at NALTE is better than the general model (R=0.78). The model is simpler as well (four predictors) but with both degrees (linear and quadratic) of the chain lead delay profile effects. The model reveals that the performance is worse when the traffic aircraft is on the ZIRAN transition. Interestingly, DTG_ABP is not retained but IMlength acts as a surrogate. This is strange because, for all NALTE operations, the maintain segment is fixed in length equal to the along track distance from NALTE to ZAVYO on the common segment.

```
Generalized Linear regression model:
    achievedSpacingError_ABP ~ [Linear formula with 6 terms in 4 predictors]
    Distribution = Normal


Estimated Coefficients:
                                             Estimate        SE         tStat       pValue

                                            __________    _________    _______    __________

    (Intercept)                                 165.77       35.461     4.6748    0.00029923
    hAtStart                                -0.0079594     0.001667    -4.7748    0.00024575
    traffic_path_ZIRAN.SUBDY1                    6.565       1.4777     4.4428    0.00047453
    IMlength                                   0.13269     0.053818     2.4656      0.026226
    traffic_speedProfileDev_mean_lead1         0.26685       0.0807     3.3067     0.0047928
    traffic_speedProfileDev_mean_lead1^2      0.026087    0.0071128     3.6676     0.0022859


21 observations, 15 error degrees of freedom
```

No other models for NALTE operations have been found at or above the reporting threshold. The maintain segment performance (R=0.68) and the IM speed rate (R=0.58) come the closest but are not fitting well enough to inspect.

The ZAVYO only PTP performance model for time-based CROSS is better than the general model (R=0.72)

```
Generalized Linear regression model:
    achievedSpacingError_PTP ~ [Linear formula with 10 terms in 7 predictors]
    Distribution = Normal


Estimated Coefficients:
                                               Estimate         SE         tStat       pValue

                                              __________    __________    _______    __________

    (Intercept)                                   86.388         20.38     4.2389    0.00025012
    initialSpacingError                         0.093816       0.02357     3.9803    0.00049219
    hAtStart                                   0.0021475    0.00072167     2.9757     0.0062421
```

```
    ownship_path_JELVO.SUBDY1                  -8.2759        4.2296    -1.9567      0.061207
    ownship_path_UPBOB1                         9.9294        3.6162     2.7458      0.010806
    traffic_path_ZIRAN.SUBDY1                     6.73        3.8951     1.7278      0.095887
    IMlength                                   -3.3773       0.79199    -4.2643    0.00023399
    windAlongTrackComponents_mean              -1.0064       0.53438    -1.8833      0.070898
    traffic_speedProfileDev_mean_lead1         0.74927       0.13713     5.4641    9.9158e-06
    hAtStart:windAlongTrackComponents_mean  6.5203e-05     2.518e-05     2.5895      0.015541
    IMlength^2                                 0.02311     0.0052582     4.3949    0.00016595


37 observations, 26 error degrees of freedom
```

No other models for ZAVYO operations have been found at or above the reporting threshold.

Distance-Based CROSS Operations

MAINTAIN, CAPTURE, and SPACE operations each have less than five operations flown in distance and thus are not inspected for regression modeling. CROSS operations have seven operations conducted in distance.

A simple model for PTP spacing can be found with enough error degrees of freedom left over to be of some significance (R=0.8652). The model has two terms: the wind effect (for ownship only) and the chain lead delay condition. Initial spacing error and IM length are dropped as terms as well as all geometric components (path and hAtStart).

```
Generalized Linear regression model:
    achievedSpacingError_PTP ~ 1 + windAlongTrackComponents_mean + traffic_speedProfileDev_mean_lead1
    Distribution = Normal


Estimated Coefficients:
                                          Estimate        SE         tStat      pValue
                                         _________    _________    _______    _________

    (Intercept)                           -0.38386      0.18026    -2.1294      0.10027
    windAlongTrackComponents_mean        -0.035632    0.0056817    -6.2714    0.0032995
    traffic_speedProfileDev_mean_lead1    0.057501     0.019673     2.9228     0.043123


7 observations, 4 error degrees of freedom
```

All distance-based CROSS operations were performed with ABP at ZAVYO and thus ABP performance should be no different than PTP performance and thus no independent regression model for ABP performance is sought. By the same token, no regression model for maintain_RMS is sought because there was no maintain segment in those operations.

The models derived for numSpeeds and IM Speed Rate are simple and of good fit, but have only 2 degrees of freedom left over and thus are not reported.

Summary of Regression Analysis

Regression models for key IM performance metrics as functions of IM operational input type regressors were sought. Sixteen models have been derived with a fit better than 0.7 when using the adjusted R squared metric for fit quality. Most models retain between three and five predictors in linear, interaction, and quadratic terms. The simplest model has two predictors and the most complex model has eight predictors. The best fit model is the most complex (R=0.95). A summary table of the models attempted and those reported is in Figure 77.

	All Time Based Opearations	All Distance Based Operations	Time Based MAINTAIN	Time Based CAPTURE	Time Based CROSS	Distance Based CROSS
PTP Performance	No Model Found	R=0.71, 5 predictors	R=0.8, 5 predictors	R=0.79, 6 predictors	R=0.69, 7 predictors	R=0.87, 2 predictors
ABP Performance	N/A	N/A	N/A	N/A	R=0.7, 6 predictors	N/A
numSpeeds	R=0.73, 7 predictors	R=0.79, 3 predictors	R=0.76, 3 predictors	No Model Found	No Model Found	No Model Found
IMspeedRate	No Model Found	R=0.8, 3 predictors	No Model Found	R=0.84, 7 predictors	0.71, 5 predictors	No Model Found
tCapture	N/A	N/A	t=0.7, 3 predictors	R=0.73, 3 predictors	N/A	N/A
maintainSegment_RMS	N/A	N/A	R=0.7, 3 predictors	R=0.95, 8 predictors	No Model Found	N/A

Figure 77: Regression Model Search Summary

In general, the initial spacing error is not present in the delivery performance models, indicating that the algorithms implemented have enough control authority to deal with the conditions they faced during flight test with no impact on performance. Delivery performance is affected more by wind conditions and IM length, as well as path (as ANOVA analysis demonstrated). Capture performance is influenced more by the initial spacing error as is expected. The overall takeaway from this exercise is the extent of the influence of the path (and thus its associated design) on all aspects of performance.

7. Summary and Conclusions

The ATD-1 flight test program resulted in a body of 144 FIM operations to be analyzed for performance. In general, the observed performance is within or slightly outside of the MOPS performance criteria for a wide variation of input conditions designed to cover the spectrum of realistic operations in a typical airspace. The major performance criteria inspected include

- PTP delivery.
- ABP delivery (CROSS operations only).
- Maintain Segment Error.
- Capture time and Capture Rate (CAPTURE operations only).
- Number of IM speeds, and IM speed rate.

When taken in aggregate, time-based operations delivered at the PTP slightly worse than the MOPS criterion of 10 s of error at 95%. The empirical probability of an error less than 10 s is 88.3%. This is driven mostly by CROSS operations which, in aggregate, have a probability of delivering less than 10 s of error at the PTP of 78%, whereas no instances of errors greater than 10 s were seen for MAINTAIN, SPACE, or CAPTURE operations.

The slightly worse PTP performance of CROSS operations is attributed to instances with a late merge including the UPBOB route for the trail aircraft. Executions of CROSS operations with an upstream merge have significantly better performance. It is believed that a different design for the UPBOB1 STAR, with a better-matched nominal altitude and speed profile, would improve performance. A different design for the UPBOB1 STAR altitude and speed profile was drafted and a few operations were performed to enable comparisons that will be carried out by NASA at a later date.

As a general conclusion from the observed data, it would seem that better PTP performance for CROSS operations should be sought operationally by placing the ABP upstream of the PTP at or downstream of route merges, thereby creating a maintain segment. Route design with late merges near the PTP are not conducive to good PTP delivery performance.

Similar effects are observed at the ABP. Overall, time-based CROSS operations have an empirical probability of ABP errors of less than 10 s of only 69%. However, operations with the ABP at NALTE have 78% observed errors below 10 s, and when excluding a number of conditions where the operation started with insufficient control authority (distance to ABP too short for the initial spacing error), that probability increases to 88%. It is believed that, with better design of the nominal altitude and speed profile at NALTE for both the ZIRAN and JELVO transitions of the SUBDY1 STAR, the ABP performance would meet the MOPS criterion.

Maintain segment performance for MAINTAIN, CAPTURE and CROSS (NALTE) operations has a mean of 3.6 s using the RMS error metric. Although the MOPS does not define maintain performance in this way, it is believed that, in aggregate, the flight test demonstrated acceptable maintain performance.

Thirty of the 34 (88%) CAPTURE operations had capture rates better than the MOPS criteria of 3 s or error per minute of operation. The majority of the cases that did not meet this level of performance are attributed to extreme cases at the back of the chain with medium to large delay at the front of the chain.

This level of overall performance is achieved with an average rate of 0.57 IM speeds per minute (one IM speed command every two minutes). Pilots have nominally indicated in surveys that the number of IM speeds was acceptable, but it has been observed that MAINTAIN operations tend to issue more speeds than other clearances, as well as include more reversions. This has been attributed to the design of the CTD algorithm and the lack of hysteresis in cases where the speed error is near the discretized speed action threshold.

This performance is achieved (1) through a wide variety of initial spacing errors (96 s too close to 84 s too late); (2) on three different routes; (3) for descent, cruise, and final approach operations; (4) two different aircraft; and (5) 19 different days of experienced wind conditions (from 61 kt of average headwind to 67 kt of average tailwind) and associated forecasts and errors (from 2 kt to 19 kt of average RMS along-track forecast error).

The Fuel Burn analysis performed compared only fuel burn across operations in the flight test and have no comparative basis to a non-FIM OPD operation. In general, the analysis revealed expected differences between aircraft types and correlated to the number of FIM speeds issued; the more speeds issued, the more fuel burned.

The PDE analysis performed revealed overall small values for PDE, including less than 2000 ft average vertical difference among the descent paths between the FMS and FIM computed vertical trajectories. This is an excellent result given the difference in fidelity of the two system trajectory generators.

The along track wind forecast error analysis revealed a large variation of forecast errors throughout the 19 flight days. In general, the forecast error tended to go through a large variation near the RF turns on the SUBDY procedure. This is expected because the forecasts were generated from a column of air over the Grant County airport for the low altitude forecast breakpoints (surface, 6,000 ft, 12,000 ft) and the trajectory geometry changes direction significantly through the RF turns in the 6,000 ft to 12,000 ft altitude band.

Overall, the Flight Test effort was a success, delivering data for realistic FIM operations on the first prototype of a FIM system that revealed a majority of the operations to be within MOPS standards. The prototype is based on an implementation of the NASA ASTAR algorithm with additions to fit the demand of the flight test, namely a distance-based adaptation, an implementation of final approach spacing, and a Mach/CAS transition implementation. The analysis performed reveals that minor changes and finalization of the control algorithms should lead to system performance that meets or exceeds the MOPS standards. In particular, improvements in the CTD algorithm during maintain operations should lead to fewer issued IM speeds with no loss of performance.

The flight test also revealed the impact of route design on FIM performance, in particular the altitude and speed profile information embedded within the design in the form of altitude and speed constraints at waypoints. Given that the route design establishes the baseline profile for the FIM system, a design that seeks smoother nominal speed transitions along the route would lead to less drastic speed changes during IM operations.

Acronyms

ABP	Achieve-By Point
ANOVA	Analysis of Variance
ASG	Assigned Spacing Goal
ATA	Actual Time of Arrival
ATD-1	Air Traffic Management Technology Demonstration - 1
ATWFE	Along-Track Wind Forecast Error
CAS	calibrated airspeed
CI	Confidence Interval
CTD	Constant Time Delay
DTG	Distance To Go
ETA	Estimate Time of Arrival
FAF	Final Approach Fix
FIM	Flight Deck Interval Management
FMS	Flight Management System
ft	feet
FTE	Flight Technical Error
ICD	Interface Control Document
IM	Interval Management
IQR	Inner Quartile Range
Kt	knots
LNAV	Lateral Navigation Guidance Mode
M	Mach
MCP	Mode Control Panel
MOA	Military Operations Area
MOPS	Minimum Operation Performance Specification
MSI	Measured Spacing Interval
NASA	National Aeronautics and Space Administration
nm	nautical mile
PDE	Path Definition Error
PSI	Predicted Spacing Interval
PTP	Planned Termination Point

RMS	Root Mean Square
s	seconds
SOW	Statement of Work
STD	Standard Deviation
TBO	Trajectory-Based Operations
TCP	Trajectory Change Point
TG	Trajectory Generation
UTC`	Coordinated Universal Time
VNAV	Vertical Navigation Guidance Mode

Revision Record

Release/Revision	**NEW**
Contract Number (if required)	NNL13AA03B-NNL15AB46T, Contract Deliverable 4.26
Limitations	
Description of Change	New document
Authorization for Release	

AUTHOR:	Signature on File	1116132
	Scharl, Julien	BEMSID
	66-CB-E111	May 10, 2017
	Organization Number	Date
APPROVER:	Signature on File	83438
	Rein-Weston, Karl J.	BEMSID
	9M-PW-ERCS	May, 10, 2017
	Organization Number	Date
DOCUMENT RELEASE:	Signature on File	115298
	Withers, Barbara L.	BEMSID
	9M-PW-ERCS	May 10, 2017
	Organization Number	Date

Release/Revision	**A**
Contract Number (if required)	NNL13AA03B-NNL15AB46T, Contract Deliverable 4.26
Limitations	
Description of Change	Updates throughout the document to address NASA's comments received on 16 May 2017
Authorization for Release	

AUTHOR:	Signature on File	1116132
	Scharl, Julien	BEMSID
	66-CB-E111	May 31, 2017
	Organization Number	Date
APPROVER:	Signature on File	83438
	Rein-Weston, Karl J.	BEMSID
	9M-PW-ERCS	May, 31, 2017
	Organization Number	Date
DOCUMENT RELEASE:	Signature on File	115298
	Withers, Barbara L.	BEMSID
	9M-PW-ERCS	May 31, 2017
	Organization Number	Date

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01- 07- 2017

2. REPORT TYPE
Contractor Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
ATD-1 Avionics Phase 2: Post-Flight Data Analysis Report

5a. CONTRACT NUMBER
NNL13AA03B

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Scharl, Julien

5d. PROJECT NUMBER

5e. TASK NUMBER
NNL15AB46T

5f. WORK UNIT NUMBER
330693.04.10.07.09

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA-CR-2017-219645

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 03
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES Langley Technical Monitor: Densie K. Scearce

14. ABSTRACT
This report aims to satisfy Air Traffic Management Technology Demonstration–1(ATD-1) Statement of Work (SOW) 3.6.19 and serves as the delivery mechanism for the analysis described in Annex C of the Flight Test Plan. The report describes the data collected and derived as well as the analysis methodology and associated results extracted from the data set collected during the ATD-1 Flight Test. All analyses described in the SOW were performed and are covered in this report except for the analysis of Final Approach Speed and its effect on performance. This analysis was de-prioritized and, at the time of this report, is not considered feasible in the schedule and costs remaining.

15. SUBJECT TERMS
ATD-1; Airspace Management; Aviation; FIM

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	26	STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)* (757) 864-9658

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18