NASA/CR-2017-219626

Flight Deck Interval Management Flight Test Final Report

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Boeing, Seattle, Washington

June 2017

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Flight Test Final Report

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Table of Contents

List of Figures

List of Tables

Acknowledgments

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Executive Summary

In the process of implementing a Flight Deck-Based Interval Management Spacing (FIM-S) algorithm-based on the National Aeronautics and Space Administration (NASA) Airborne Spacing for Terminal Arrival Routes (ASTAR) trajectory based solution, this Air Traffic Management Technology Demonstration-1 (ATD-1) Avionics Phase 2 flight test team (Figure 1) learned how Interval Management (IM) operations can perform in the field. The prototype system was installed on the avionics of two commercial airplanes and tested during 19 flying days to assess ASTAR's implementation and performance. The flight test program has very successfully demonstrated FIM operations on 56 merging and in-trail spacing flights using a chain of three airplanes. The merging chain of airplanes tested a new set of air traffic control (ATC) voice clearances directing flight crews to achieve and maintain a given time-based or distance-based longitudinal spacing behind a target airplane. It enables new operations in either a voice or data link environment with new types of ATC advanced arrival procedures that reduce fuel burn and airport noise on arrival [1].

Figure 1. NASA ATD-1 Flight Test Team

This NASA led effort involved collaboration between Boeing, the Federal Aviation Administration (FAA), Honeywell, and United Airlines. The FAA and NASA aim was to predictably achieve FIM-S inter-arrival precision of less than 10 seconds in-trail spacing error during the arrival phase of flight. Overall the FIM-S system and procedures show potential for consistent inter-arrival precision improvement across a wide range of operating environments and FIM-S clearance types. In practice controllers today achieve an average spacing error of 18 seconds in in-trail spacing without ATC ground tools. United is optimistic that NASA and FAA can further improve the spacing accuracies by combining FIM-S with new ATC ground tools [2] and provide a considerable boost for airport capacities.

The essence of these flight test statistics clearly show the power of the FIM-S system that takes large initial spacing errors at the FIM-S initiation point and delivers a much smaller spacing error at the Planned Termination Point (PTP). On 198 unique FIM-S operational runs, the NASA ASTAR algorithm implementation corrected airplane speed on average every couple of minutes with the pilot taking less than 10 seconds to execute the speed command. FIM-S was flown for both time-based and distance-based operations and the clearances tested included: 1) Achieve by then maintain (CROSS); 2) Capture then maintain (CAPTURE); 3) Maintain current spacing (MAINTAIN) and 4) Final approach spacing (SPACE) clearance types.

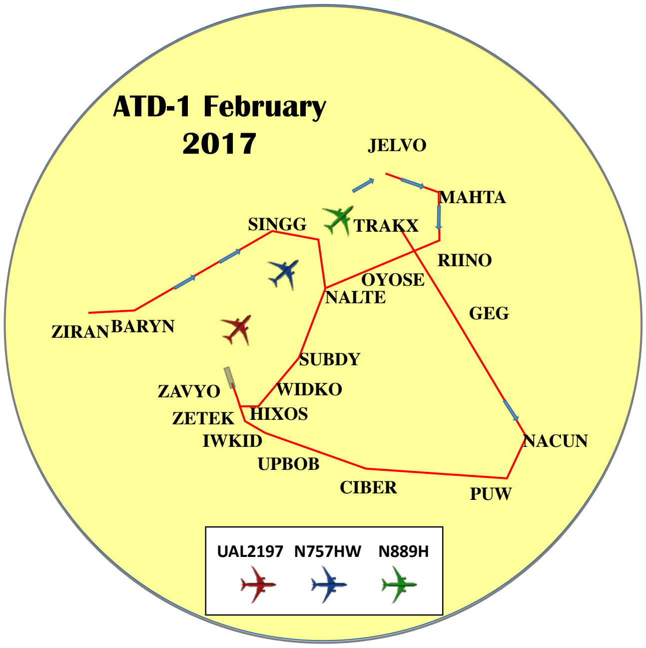


Figure 2. FIM-S Flight Test Procedures

This avionics architecture implemented was one of the first Automatic Dependent Surveillance–Broadcast In (ADS-B In) spacing applications for arrival operations using a chain of three airplanes. It used the Electronic Flight Bag (EFB) to host NASA’s ASTAR algorithm, which could ultimately be available to retrofit airplanes favoring early fleet availability. By building prototype equipment without following all the processes of a fully certified development and test program, the Boeing, Honeywell, and United team was able to more quickly develop the FIM-S prototype to demonstrate a unique capability for in-trail spacing operations. The ADS-B In capability allows the pilot to execute the controller instructions in an effort to improve delivery accuracy while keeping the spacing appropriate for the particular phase of flight. This is not to say that the pilot assumes separation responsibility, but rather executes the controller spacing interval instructions, while flying the prescribed route, arrival, or departure procedure in the clearance. For this flight test program, ATC ground system personnel, assisted by the flight test director, were used to deliver airplanes to points on final cruise legs or on arrival procedures at spacing values that enabled high success rates for FIM-S operations to the runway. The arrival procedures were developed with the support of FAA Air Traffic and Flight Standards Organizations (see Figure 2). Transition into a Required Navigation Performance (RNP) Authorization Required (AR) approach procedure was utilized with the intent of allowing efficient decent profiles (3 degrees) while providing appropriate speed authority to participating flight crews. Procedures included speed and altitude constraints. The Flight Test Director communicated on a non ATC frequency directly with each of the participating flight crews as well as a designated flight test base station Telemetry Room at Boeing Field. This capability allowed the flight test director to assist in the setup of the scenarios reviewed at the morning preflight briefing. Additionally the flight crews communicated with controllers at all five air traffic facilities on normal ATC frequencies, and current day pilot-controller roles, responsibilities, and phraseology were used. The Flight Test Director commanded the crew to enter Achieve-by and Termination Points. It should be noted minimum ATC separation was not stressed in favor of the accuracy of the Assigned Spacing Goal (ASG). Furthermore, it should be noted the efficiency of the overall flight operations could not have been accomplished without the daily support of the air traffic facilities involved.

The NASA ATD-1 flight trial clearly demonstrated the feasibility of FIM as a means to maintain arrival capacity during low ceiling and visibilities or high winds by precisely controlling inter-arrival spacing. Although more development work is necessary for operational implementation, the FIM-S system tested during the ATD-1 flight trial met all but one of its design goals. It was remarkable to have the first prototype FIM-S system perform as well as it did. The one design goal not met was very close to being achieved, and is for one particular geometry and clearance type. The reason for not meeting this design goal is under study, and there is very high confidence that this clearance type and geometry will be corrected prior to any future FIM flight testing.

1 Introduction

This report describes a prototype system built for experimental flight evaluations and research, and not intended for revenue flight. To understand how the team planned this Cost Plus Fixed Fee (CPFF) contract, it helps to know a little about the prior research and context for the contract. The Flight-deck Interval Management-Spacing (FIM-S) algorithm flown in Air Traffic Management Technology Demonstration-1 (ATD-1) Phase 2 (P2) had been integrated into various simulators at National Aeronautics and Space Administration (NASA), Boeing and other simulation facilities prior to the initiation of this second phase of the ATD-1 program. The system was integrated into the Boeing 737 Engineering Flight Simulator with hardware LRUs within the umbrella of ATD-1 Phase 1 [1]. It demonstrated the use of ASTAR as a FIM-S merging and in-trail spacing application in a series of realistic FIM-S operational scenarios on a pair of arrivals to KPHX. The intent was to gain insight into real-world avionics implementations where ASTAR was hosted within the traffic processing functions. Honeywell has considerable experience with Airborne Basic Situation Awareness (AIRB) technology and the in-trail procedure (ITP) surveillance application hosted on an EFB architecture. The cockpit display of traffic information (CDTI) used in their ITP demonstration came from a system that had been certified for AIRB per DO-317A. ITP was developed for oceanic operations on 12 United 747 airplanes flying Pacific routes.

These precursor activities provided much of the system requirements and served to mitigate risks of the flight test program. Under Phase 1, the following major tasks provided insight for IM applications: (1) FIM Feasibility Assessment during the NextGen midterm time frame (2016 to 2020) in forward-fit and retrofit options, (2) Trade Studies of 28 architectures for both the 787-8 (i.e., an advanced avionics platform) and the 737NG (i.e., a significant US fleet for retrofit), (3) Concept Engineering Prototypes, and (4) Prototype Recommendations [3]. The final task resulted in Boeing's recommendations of a prototype FIM-S system that led to the flight test program. In addition, a laptop running ASTAR was flown on the Boeing 787 2015 ecoDemonstrator as a proof of concept. The data from these flights helped to shape the P2 program and flight test.

The airborne FIM architecture should fit into a broader air and ground (i.e., end-to-end) architecture. NASA already developed and turned over to the FAA the technology and elements of this integrated architecture during the past 20 years that help better manage portions of the nation's air traffic control system (Figure 3). For example "Traffic Management Advisor" (TMA) was introduced in the NAS to assist with the flow of air traffic from the en-route to the terminal arrival airspace. Although TMA has been an effective tool to allow controllers to understand the traffic demand at selected airports on a quarter-hour basis it does not provide the desired level of accuracy to support significantly increased throughput. ATD-1 technology provides the future capabilities that will expand TMA to "Traffic Management Advisor with Terminal Metering" (TMA-TM). The new system will rely on enhancements to TMA by adding IM and Controller Managed Spacing (CMS). Collectively this technology is expected to provide controllers with the tools necessary to improve delivery accuracy to the destination runway.

These ATD-1 FIM-S flight test demonstrate how more-frequent trajectory adjustments are made by the airborne system than is possible with TMA or other ground system tools alone so that increased levels of spacing precision on final approach can be achieved. The FAA continues to develop, test, and certify for operational use in the field these tools

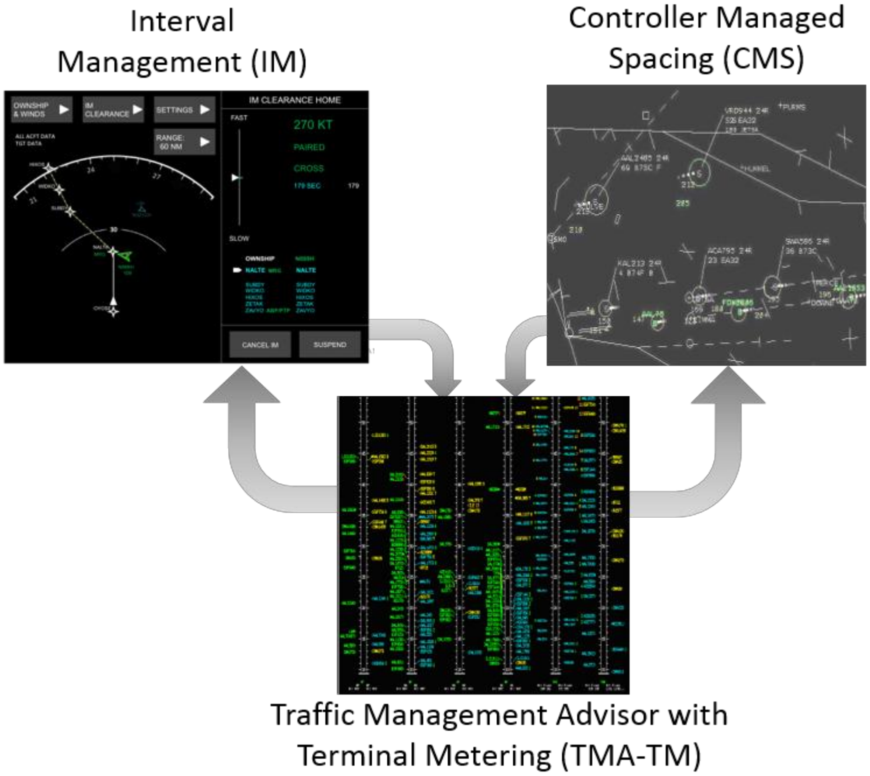


Figure 3. ATD-1 Goals and Technologies for Integrated (End-to-End) Arrival Operations

before agency implementation and improve the level of spacing precision on final approach. While in practice controllers today achieve an average spacing error of 18 seconds without metering tools (e.g., without TMA), Human-in-the-Loop experiments have shown average spacing errors of 12 seconds (e.g., TMA-TM, Ground-based Interval Management-Spacing).

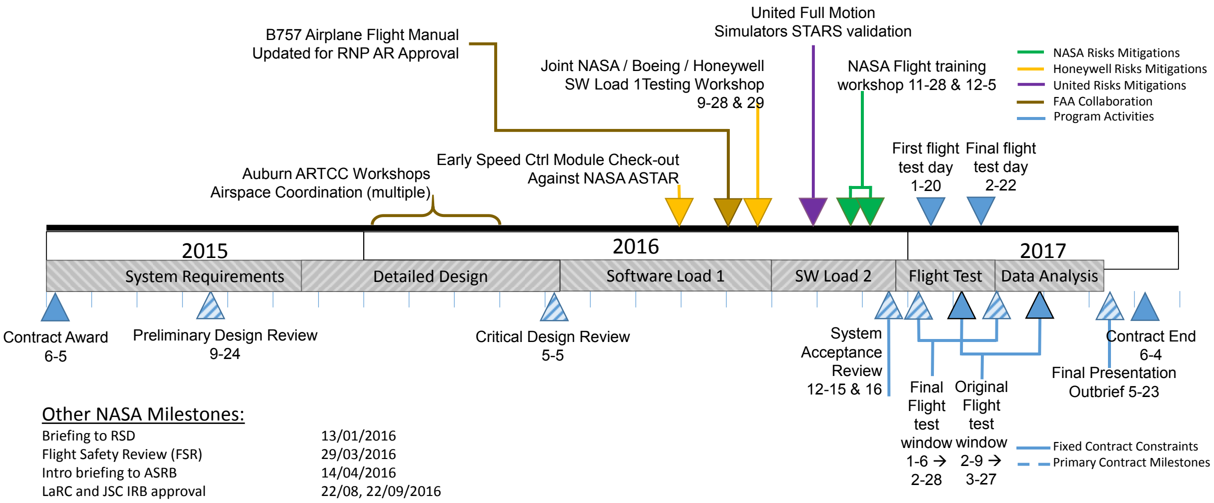
The FIM-S flight test results show that further improvements in spacing precision are still possible. For an on-time airline such as United Airlines, to whom arrival and departure rates are key to schedule reliability, such spacing improvements are directly translatable into economic benefits [1].

1.1 Scope, Schedule, Risk Mitigation Steps

The Flight Test proposal included a FIM-S prototype development and flight test effort for up to three airplanes scheduled within 22 months from contract award (see the proposal Statement of Work [SOW]). This proposed schedule was driven by the availability of the United Airlines 737-900, which was not available during the holiday seasons (November – December and Spring Break) owing to the need for it to be returned to service to support United Airlines flight operations at these times. The 737 was also not available during the busy summer season. The two airplane constraints compressed the flight test into a window between January and March. This compression imposed firm schedule constraints and program cost risk from the start.

Therefore, Boeing had to vigorously manage program scope and its team members rigorously abided by its contractual milestones to stay within the compressed schedule and CPFF cost constraints. Contract award determined the start of requirements allocation and design activities and therefore set one bound on the schedule, the other was set by the United Airlines 737-900 availability. Scope was set by the need to faithfully execute on the number of contractual flight test days (e.g., lost days for bad weather, poorly designed procedure, airspace availability) while managing risks of any impact on performance of bad or unusable data (e.g., system anomalies, hardware or instrumentation failures[1]) Within these, the team was laser focused on eliminating flight test risks by leveraging previous work (e.g., ATD-1 Phase 1) and executing contracted tasks effectively, using a fixed software testing schedule with no margin for additional software build spirals and little margin for extra test cycles prior to flight test. As seen in Figure 4, the schedule did not allow for extended hardware-in-the-loop bench testing, ASTAR enhancements (e.g., those not defined in the allocated system requirements) or Human Machine Interface (HMI) evaluations.

The resulting contract phases can broadly be divided into six areas as illustrated in the hashed gray bar at the bottom of the Figure 4 timeline. They were framed by contract deliverables and include requirements, design development, implementation, ground and flight testing, and data analysis phases. It was clear early on that only time was available for two software loads subjected to the system test plan formal testing prior to flight test. The effects of the compression did not leave margin for additional ground check out of the hardware to refine speed commands and alert annunciations, to optimize data entry or to conduct pilot focus groups to review the usability of the software.



Other NASA Milestones:

Briefing to RSD	13/01/2016
Flight Safety Review (FSR)	29/03/2016
Intro briefing to ASRB	14/04/2016
LaRC and JSC IRB approval	22/08, 22/09/2016
Operational Safety Review (OSR) to ASRB	08/12/2016
Flight Safety Release (FSR)	12/2016
Flight Readiness Review (FRR)	19/12/2016

Figure 4. ATD-1 Avionics Development and Flight Test Contract Compressed Schedule

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[1] The number of contractual flight test days was 18; there are 19 flying days in the data collection set attributed to the additional flying day terminated early due to a mechanical event.

Load 1 had to be completed to enable the start of system testing that ran in parallel to Load 2 development. The lack of spirals was mitigated by a joint NASA/Boeing/-Honeywell/United workshop to accelerate the discussions about hardware-in-the-Loop testing and the active NASA involvement in these tests as well as the software progress reviews. At the end of Load 2, a number of test issues, not critical for flight test, were left open for future work (Appendix A). Attributed.

The success of the program is attributed to a very unique team, with all members very focused on the program testing needs, using additional in-house resources and investing considerable effort to ensure success within the above contract schedule constraints. ATD-1 Phase 1 precursor activities and related steps were vital risk reduction opportunities. They included the following steps:

- Honeywell was selected for the Boeing ATD-1P2 avionics design tasks after an earlier ATD-1 phase 1 supplier was removed.
- Flight test airplanes and test crews were competitively selected after ATD-1 phase 1.
- Airline team members were competitively selected after ATD-1 phase 1.
- The Boeing 787 eco-Demonstrator was flight tested with the ASTAR algorithm on board in March 2013, outside of the ATD-1 Phase 1 contractual deliverables.
- Software development and testing was competitively bid.
- Moses Lake was selected as test site over Denver International Airport. This allowed the team to decrease the proposed costs and assumed risks potentially ensuing from interrupted runs caused by ATC intervention. It allowed the team to minimized assumptions for time lost in transit, assumptions for airplane fixed-base operational costs and extended setup times, personnel travel costs, etc.
- To emulate future navigation capabilities special Standard Terminal Arrival Routes (STAR) were developed connecting to Required Navigation Performance (RNP) Authorization Required (AR) Approaches. Although this created challenges in the development of the STARs and the certification of airplanes and flight crews, it did provide the desired navigational accuracy.
- Simulator validation of the Jeppesen-developed navigation database and procedures were performed by United Airlines in a 737 full motion simulator at their Houston Training Facility. The simulator validation was attended by FAA AFS-460 specialists.

Early in the project the risk of conducting three airplane experiments without conflicts with other traffic within the National Airspace System (NAS) was identified. To mitigate these risks, coordination with the air traffic facilities involved began one year prior to flight and included briefings on ADS-B IN, and FIM-S. The facilities participated in the procedure design and experiment execution. Daily “test cards” were developed for use at the operational positions with facility representatives attending pre- and post-flight briefings on a daily basis.

ATD-1 program scope was always limited by the flight test performance objectives and the need for accelerated development. For all the risk mitigation and schedule constraint reasons cited previously, the program scope could not allow time for unplanned tasks. Risk and cost rational processes (e.g., those from the above schedule and funding perspective) had to be deployed at every gate to ensure ATD-1 success.

2 Summary of Design and Evaluation Activities

The following sections summarize the sequence of ATD-1 P2 Avionics design, implementation and design evaluation activities (e.g., software testing, hardware in-the-loop bench testing) as actually executed.

The Speed Control & Trajectory Generation (Spd Ctrl), Human Machine Interface (HMI) and System Engineering (SE) Working Group (WG) teams managed these tasks with everyone willing to participate in multiple WG meetings as necessary to achieve the essential milestones. The Spd Ctrl WG leaders were responsible for the ASTAR implementation, and the software development and unit testing. The SE WG leaders managed requirements and system level testing. The HMI and Hardware WG leaders insured that all the crew entry, display design features and hardware was ready for testing and installation.

2.1 NASA ASTAR Algorithm Implementation

NASA has developed an FIM-S algorithm, ASTAR, which constantly calculates the airspeed required to position the FIM aircraft at the Achieve by Point (ABP), at the assigned spacing goal (ASG) behind the target aircraft. ASTAR version 13 (revision 7) is the basis for the implementation of FIM-S in this program [4].

ASTAR contains both trajectory-based and state-based mechanisms for calculating the speeds required to achieve or maintain a precise spacing interval. The trajectory-based capability allows for spacing operations prior to the airplane being on a common path. ASTAR builds a 4-D trajectory flight path for both a target airplane and the FIM airplane based on the clearance assigned to each. It then employs ADS-B In messaging and onboard sensors to determine current position along the respective trajectories and calculates an estimated time of arrival (ETA) for each airplane to cross a common point (known as the Achieve-By Point – ABP). The difference between the ETAs (e.g., 97 seconds) minus the desired time spacing goal (e.g., 90 seconds) is the spacing error (e.g., 7 seconds) the algorithm attempts to drive to zero with speed guidance displayed to the crew of the FIM airplane. The desired spacing goal is required to be met no later than when the trailing airplane crosses the ABP, which helps to keep speed guidance close to constraints found in published procedures.

No NASA software was used under this program. The implementation process started with the System Requirements Definition Document (SRDD) [5] and ASTAR Description Document [4], to formalize FIM-S system and software requirements that were reviewed at the Critical Design Review (CDR — See section 2.4). The implementation of ASTAR in the prototype FIM-S system differs from the ASTAR version implemented in simulation at NASA in the following areas:

- Final Approach Spacing control algorithm implementation: The ASTAR Description Document did not include treatment of this operation.
- Distance-based operation adaptations: [4] includes time-based operations only.
- Mach operations and Mach/CAS transition: [4] inhibited the generation of speed commands until both the Traffic to Follow (TTF) and ownship passed the first CAS constrained waypoint on their respective routes.

The Mach/CAS operational limitations, were considered a program flight test risk item early in the program. The following partial list of refinements or modifications in support of Mach operations where developed in the prototype to mitigate the flight test risks:

- Refinements to the trajectory generation to handle implicit speed and altitude constraints.
- Changes to the deceleration estimation process to account for differences in Mach and CAS regions.
- Changes to the speed limit calculations.
- Changes to the speed command quantization.
- Development of a discovery algorithm for traffic cruise parameters.

Figure 5 shows a functional block diagram of the FIM-S prototype implementation based on ASTAR. Honeywell implemented NASA's ASTAR in the Speed Control software block in Figure 5.

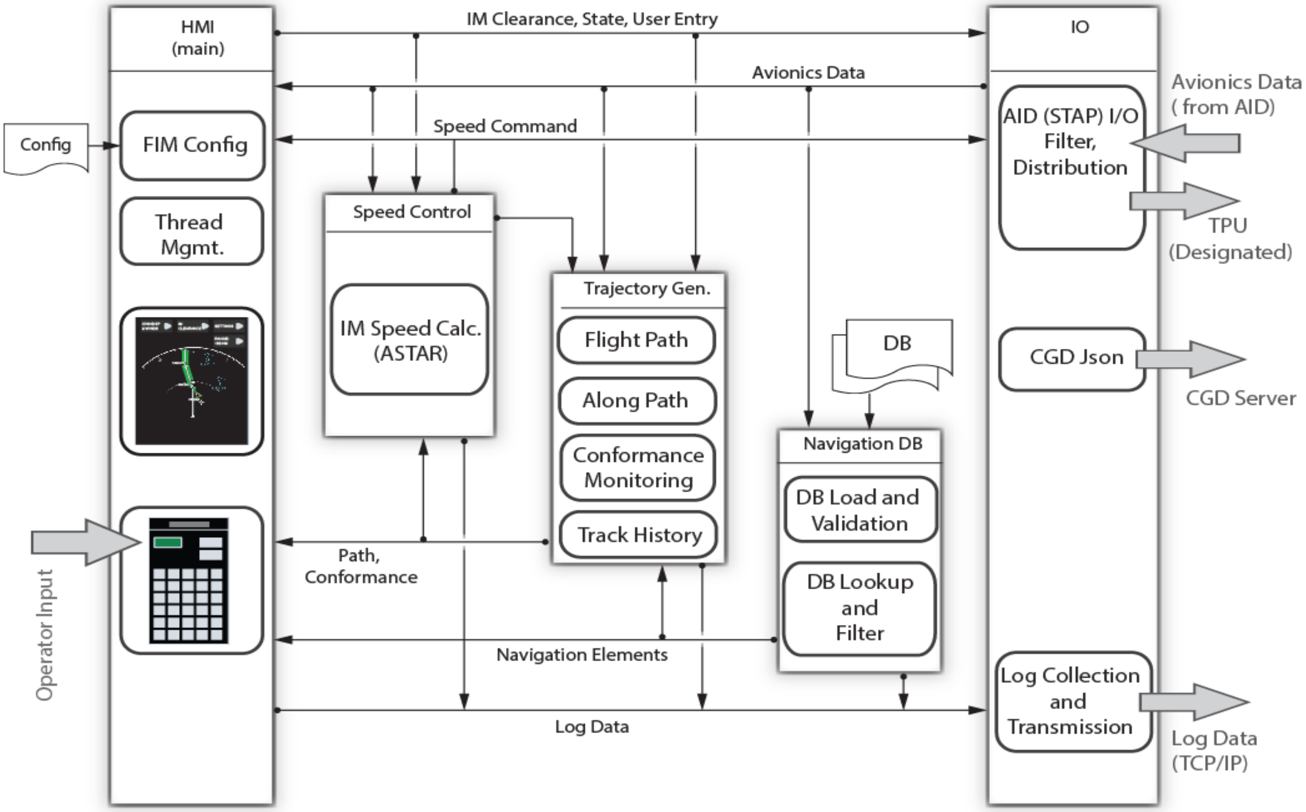


Figure 5. EFB FIM-S Software Functional Block Diagram

Figure 5 illustrates the Honeywell main FIM-S software application hosted on the UTC Aerospace EFB hardware platform, which comprises the main application, along with libraries that implement the Speed Control module implementing ASTAR, the Trajectory

Generator and Navigation Database functionality. It also contains the Input /Output (I/O), CDTI, data logging and thread management functions. The design and implementation of the software and CDTI are based on previous Honeywell ADS-B In / CDTI efforts, modified for the needs of ATD-1. The CDTI user interface appearance reflects both typical Honeywell human interfaces adapted to the guidance from NASA cockpit display and interfaces guidance documents [6] and Boeing's design guidance. Further Honeywell software design details are found in ATD-1 Technical Reference manual [7].

2.2 Flight Test Airplanes and Equipment

The flight trials demonstrated the FIM-S avionics system in an airspace environment that is characteristic of a commercial airport with a variety of instrument arrival and approach procedures. The team equipped two transport category airplanes (757, 737) and a business jet with compatible surveillance and flight deck capabilities. The Boeing team used the Honeywell 757 Flying Testbed airplane and its associated crew as one FIM airplane. It was modified to meet both the operational and data-gathering requirements for the program. United Airlines supplied the second FIM airplane and its crews, a 737-900 transport category airplane also modified with the FIM-S equipment. Honeywell also provided the designated traffic airplane, a Dassault Falcon 900 business jet; it served as the target airplane. It was equipped with ADS-B Out technology (DO-260B compliant) but did not have the FIM equipment installed and had limited data gathering capabilities. The three airplanes capabilities are summarized as follows:

- Commercial transport category airplanes (757-200 and 737-900) and a regional business jet (Falcon 900 flown to follow a 737 flight profile).
- 757-200 and 737-900 equipped with an ARINC 735B (DO-317A compliant) TPU that included the ADS-B In functionality.
- 757-200 and 737-900 equipped with transponders providing ADS-B Out functionality (DO-260B compliant). Falcon 900 equipped with ADS-B Out only (DO-260B compliant).
- All equipped with GNSS
- 757-200 and 737-900 equipped with a Flight Management System (FMS) and other avionics capable of sourcing all required FIM data.
- LNAV/VNAV and RNP AR capable or equivalent.
- 757-200 and 737-900 capable of speed intervention through the Mode Control Panel (MCP).

The FIM-S software is implemented in dual, UTC Aerospace Class 3 EFBs that are mounted as side displays on the flight decks of a 737-900 and a 757-200 airplane. In addition, two prototype configurable graphics displays (CGD) that provide speed advisories and other FIM situational awareness information to the pilots are installed in their primary fields of view. A Honeywell DO-317A-compliant Traffic Alert and Collision Avoidance System (TCAS) Traffic Processing Unit (TPU) provides the ADS-B In track processing capability, and this feeds the FIM-S application running in the EFBs. The EFBs provide the following capabilities:

- FIM-S application

- Touchscreen data entry and application control functions
- Display of FIM-S application entered and processed data
- Traffic situational awareness through a Traffic Display
- Output of speed guidance and situational information to the CGD.

On FIM-S system initialization, one of the EFBs was designated as the Master, and used received and input data to perform the computations resulting in the provision of speed guidance and FIM situational awareness information. The Master EFB fed both CGDs. In case of EFB failure, the slave EFB must be restarted to allow it to be assigned the Master role and to provide information to the CGDs. Both Master and Slave EFBs can be used simultaneously for data entry and display selections are independent. Crew procedures were defined prior to flight test to ensure that a single data-entry field is not being addressed simultaneously by both pilots.

Provision was made for the display, once sufficient data had been made available, of either current Measured Spacing Interval or Predicted Spacing Interval, depending on the type of operation planned, so that a suitable ASG could be entered for use in the test condition. This display was solely for engineering and flight test convenience and would not be part of a "production" system.

Figure 6 shows the components of the FIM-S system (yellow) and the existing avionics

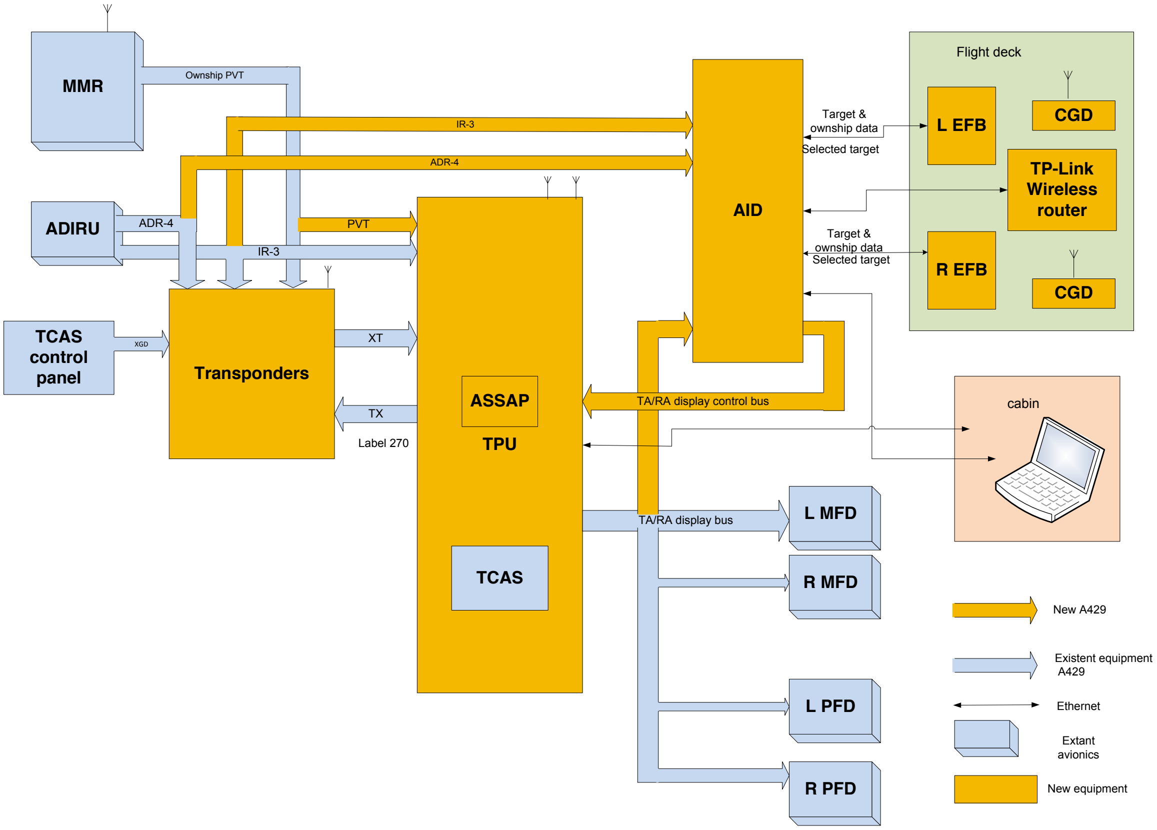


Figure 6 - FIM-S System Hardware/Software Configuration

that provide data to the FIM-S system (light blue). These data are partly FIM-S aircraft data and partly data from the target received via ADS-B. The DO-317A compliant TPU is largely production standard; most importantly, the TCAS function that resides in the TPU is fully production standard, and regression testing has been carried out to ensure that TCAS capabilities are unimpaired.

Data identifying the designated airplane are fed back from the EFB's Aircraft Interface Device (AID) to the TPU to ensure that the target airplane data are always available to the Traffic Display regardless of how many ADS-B equipped airplanes are providing data that are being processed by the TPU.

The success of this flight test relied on extra communication capabilities including a Remote Communications Air Ground (RCAG) station at MWH, to enable communications from the airplane to the Boeing flight test operations center at Boeing Field. Satellite communications on the B757 allowed for the transmission of telemetry data, and airborne internet connectivity on all three airplanes for the reception of extensive telemetry data. An extra VHF communication radio was dedicated for flight test operations and was monitored in real time at the Boeing Field Telemetry Room. L-Band SATCOM was very useful as it is less susceptible to data loss during turns. GXa SATCOM was available to send and receive data that was not time critical. The Atmosphere Planet Software was critical in the surveillance of the flight test area, providing multiple airplanes progress and situational awareness off other test airplanes and traffic. Such communication capabilities should be available to all participating airplanes and monitoring rooms. Cell phones were utilized for the coordination of morning engine start, taxi and takeoff times.

2.3 Prototype Hardware/Software Platform

The cockpit hardware suite is composed of two side-mounted UTC Aerospace Systems EFBs linked to the avionics data buses through the UTC AID and loaded with the Honeywell-built FIM-S software. Two model SE iPhones are mounted in the forward field of view and serve as speed command indicators for each of the crew members. Figure 7 illustrates the layout of both the EFB (left) and the iPhone (right).

The primary job of the FIM-S system is to provide speed commands and status information to the crew when performing IM procedures under Instrument Flight Rules (IFR). Figure 7 shows a FIM-S CROSS clearance in paired mode; it illustrates the four FIM-S display items: An indication of whether the airplane is paired to the target airplane, the commanded speed (in knots or Mach) and two indicators. The first indicator shows whether the airplane is fast or slow relative to the target (FAST/SLOW Indicator — FSI) and the second shows whether the airplane will be early or late to a fix relative to the target ahead (Progress Indicator — PI) which, in Figure 7, was 68 seconds early. The EFBs show route, nearby traffic, and other information to illustrate movement along the intended clearance within the IM arrival stream. Finally, Figure 7 illustrates a status message where IM SPEED LIMITED indicates that the commanded speeds exceed the profile performance bound (i.e., control authority) embodied in the design. Further details of the avionics interfaces used on the two FIM-S equipped airplanes is shown in Figure 6.

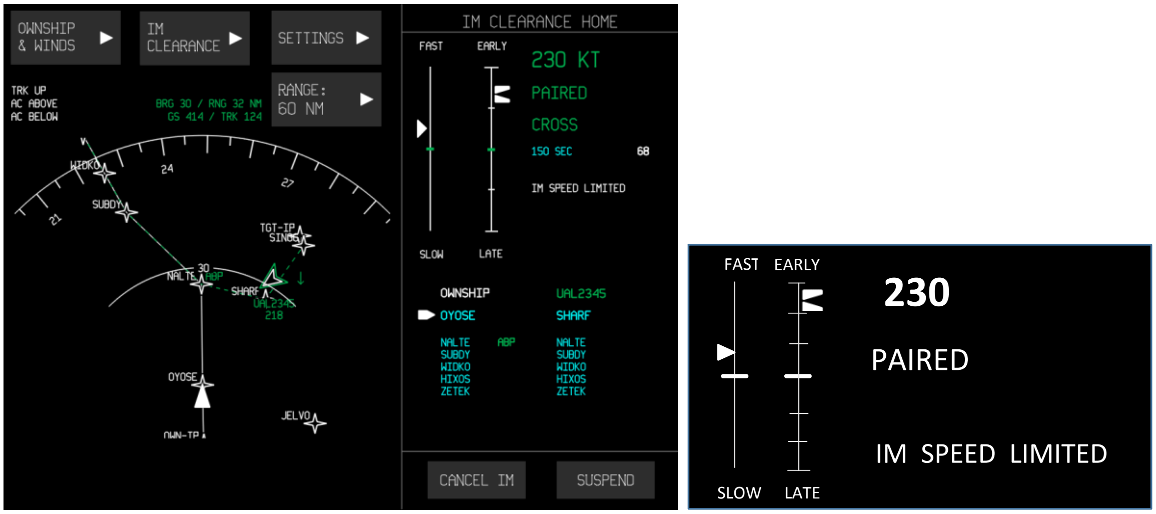


Figure 7. FIM-S Active Cross Clearance in Paired State

Each of the crew members uses a side mounted EFB in landscape mode where the information entered by one crew member is cross-fed to the other display. This display device hosts the IM application, the IM data entry and display of traffic information. The EFB also computes the information displayed on the CGDs. Only a subset of the IM information needed information needed in the Primary Field of View (PFoV) is indicated on the CGD (speed, alert messages, etc.). Figure 8 illustrates the equipment location on the 757.

Figure 8. IM System -- Equipment Location (757)

2.4 A Brief Overview of the Development and Test Process

Despite the considerable ATD-1 Phase 1 precursor activities (see risk reduction activities and related events listed in section 1.1), significant systems engineering effort was required to review NASA's proposed revisions to the FIMSRD [8] and ASTAR limitations at the start of the compressed contract schedule. It took several weeks to analyze and consolidate the FIMSRD in preparation for the Preliminary Design Review (PDR) meeting. Revisions to existing requirements were only made known after contract award and resulted in a month delay in the contract SOW's scheduled PDR meeting.

Once a complete system level requirements specification document was agreed on [5], the ATD-1 P2 program moved ahead to PDR and recorded an acceptable number of change board design items. The completed system requirements enabled quick allocation of flight test relevant requirements to the prototyped architecture, efficient development of software and hardware articles, and as much test verification as possible before the fixed start date for flight test. It was based on NASA's prior ATD-1 work at various simulators facilities available to the government; industry work at RTCA, Inc. on the Minimum Operational Performance Standards (MOPS) developed in collaboration with the FAA, avionics suppliers and the airlines and Boeing's Phase 1 and Honeywell prior work. The PDR focused on allocation of requirements to architectural design elements, review and recording of implementation notes for later detailed design consideration and the capture of implementation attributes (e.g., testing methodology assignment, testing notes). Strict management of the implementation steps flowed from these efficient processes consistent with a prototype development effort and insured the project's ability to stay within cost and schedule constraints. Five working groups (WG) were assigned detailed design activities around the time for PDR. Their detailed design and implementation analysis activities each focused on the allocated requirements established by the early SE work. The weekly WGs meetings produced multiple design and test documents. The complete set of required documentation is loosely mapped against the five WGs' activities as follows (only final document versions are listed in the references):

- Speed Control WG [9]
- Human Machine Interface WG [9]
- System Engineering WG [5], [10]
- Flight Test WG [11]
- Data Collection and Analysis WG [11], [14]

The primary testing objective was to assess the Honeywell software integrated with the installed avionics systems to ensure that the NASA ASTAR 13 algorithm was implemented correctly on the flight test hardware. The testing approach included a capability to execute a subset of the MOPS performance tests, those that were critical for flight test execution (see System Test Plan report approach and road map [10]). For example, to stay within time and cost constraints, system-level testing relied on the previous NASA testing to ensure that ASTAR 13 met the performance requirements of the MOPS. In areas were the ASTAR 13 algorithm did not meet the performance as defined in the MOPS or additional functionality was required, the team was not always in a position to refine the algorithm or add functionality prior to flight test. Some changes to the ASTAR 13 algorithm were outside the scope of the testing scope and can only be referred to test recommendations and change impact assessments outside this program. The testing approach relied primarily on a subset of MOPS test vectors, procedures and the pass/fail system test criteria tailored to the program objectives and conditions expected to be encountered during flight test at Moses Lake. The performance requirements in the MOPS were not the primary testing objective for ATD-1 and there is no guarantee the flight procedures tested meet all the MOPS requirements.

The primary means of testing was using software unit testing (i.e., preliminary software load) of integrated software items as defined by the joint WGs and performed by individuals or on actual hardware integrated with the Honeywell test environment. These tests were for items that required more explicit testing (i.e., software Load 1 and Load 2). Each development team performed these unit tests as part of the prototype development process; the detailed description of the overall process is provided in the System Test Plan (STP). The STP further describes our approach and overall test road map as follows:

- Software Unit Testing Approach – high level description of how individual software modules were tested
- Test Operations – high level description and description of the Honeywell simulated integrated software and actual hardware test environment
- Integrated System Test – high level description and list of MOPS and other integrated system tests (e.g., CGD)
- Other system tests including analysis/demonstrations/inspection, TPU testing, review of flight test procedures.

The FIM-S development and testing phase was essentially concluded at System Acceptance Review (SAR), which was conducted over two sessions at Honeywell's Redmond, WA, facility. Version 1.0 of the FIM-S software was reviewed three months earlier with attendance by NASA and other personnel to mark the start of integrated testing jointly with personnel from NASA/Boeing/Honeywell. This was focused collaborative integrated testing of the ASTAR algorithm implementation and refinement of MOPS and integrated testing scenarios. Existing Honeywell test equipment was used to generate traffic signals and ownship state data to fully exercise all aspects of the FIM-S system. The airplane model used for SAR and integrated testing was based on a version being developed for future MOPS testing. The complete system connected the FIM components (TPU, EFBs, CGDs, AID, Wireless Components and supporting equipment (e.g., engineering laptop used in flight)). Version 2.0.2 was reviewed in a second SAR session at the time when hardware installation test results on the airplanes became available and focused on successful completion of simulated flight test scenarios (e.g., setups and transitions between clearance types that would be used in the actual flight test rather than strictly following the MOPS test vectors.

Throughout the program, the team maintained traceability between initial design requirements, mapped implementation verification definitions, and test artifacts at the system level using configuration controlled relational database tools (i.e., IBM Rational Dynamic Object Oriented Requirements System (DOORS) and other tools – see tables in Appendix A). System level traceability and documentation was maintained and consistently updated throughout the review phases: PDR, CDR and SAR. The integrated software items (see the software unit testing approach in the STP for a detailed description) had been defined and allocated prior to PDR.

2.5 FIM-S Software Description

The FIM-S software was hosted across multiple physical devices following the allocation in the selected architecture by the SE WG. The selected architecture was initially proposed in the ATD-1 P2 proposal based on the ATD-1 Phase 1 architectural studies of feasible options that allowed the project to stay within the considerable cost and schedule constraints.

The software functions, hosted on the avionics hardware, provide the following:

- FIM-S Speed Control and Trajectory Generation functions hosted on the EFBs
- HMI data entry and control functions hosted by the EFB
- Speed guidance, speed/state changes, and crew alerts in the forward field of view displayed by the CGD
- Traffic information from legacy hardware and traffic interface functionality computed on the DO-317A compliant TPU
- Navigation database services and input/output control functions hosted by the EFB

Figure 9 illustrates the software functional architecture with the two EFBs (captain and first officer) and two CGD displays (captain and first officer). Further, it depicts wireless, wired, Ethernet, and 429 connectivity between the various devices. The ASTAR algorithm is hosted on the EFBs by the speed control software function. The AID ensures that all aircraft bus data is transferred to the FIM-S application.

The DO-317A-compliant TPU IO function has been modified to provide additional FIM-specific data but otherwise uses the existing Honeywell TPA-100B baseline software. Once the traffic to follow has been identified by the FIM-S application, the TPU ensures the target data is provided. Auxiliary functions such as data logging are further described in the reference documentation.

The EFB-based FIM-S application was very complex and achieved excellent results soon after the start of the flight test program. Among the most challenging aspects of the software development were porting the speed control algorithm from a lab implementation to an avionics implementation, extending the algorithm to the clearance types not implemented in the current ASTAR release and developing an aircraft independent trajectory generator.

The speed control development activity needed to address issues of real time performance of the EFB computers, master/slave operations for redundancy and synchronization of the HMI between the dual EFBs. There was also a significant amount of work involved in developing software requirements and designs to cover en-route operations and the final approach spacing clearance that had limited functionality in ASTAR 13. In particular, augmenting the algorithm for real time execution in the en-route

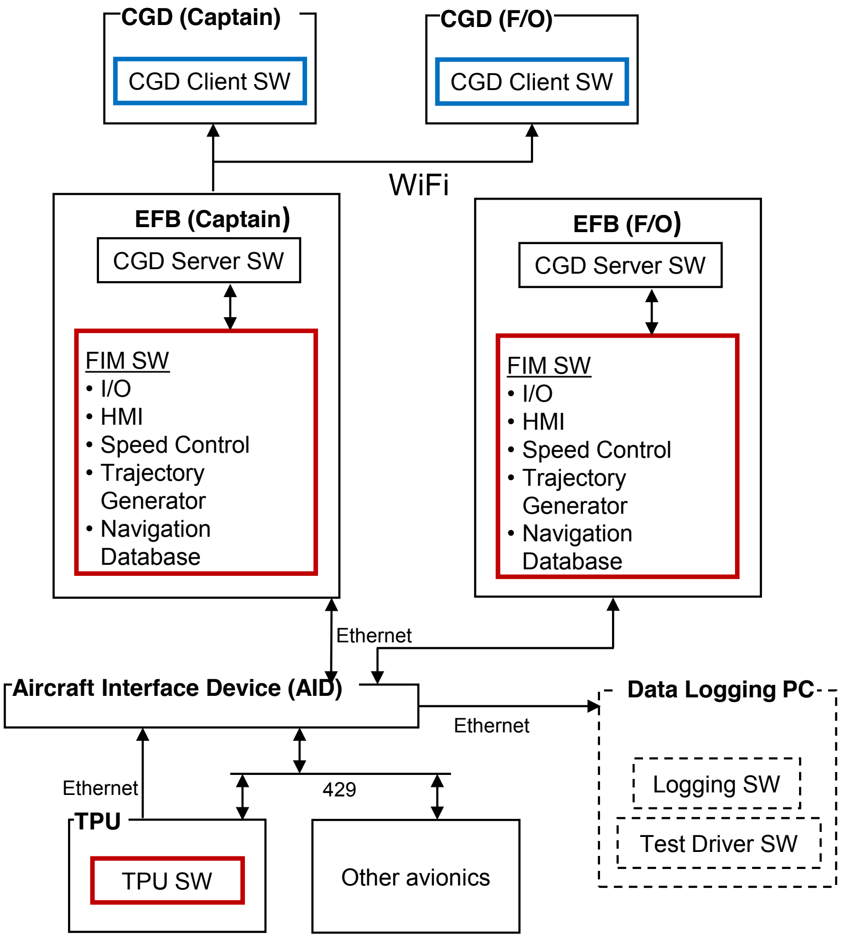


Figure 9. FIM-S Software Functions Allocation

regime (Mach) was especially challenging and, as indicated in the open test issues listed in the appendix (see FIM open test issue #274), is still not completely satisfactory.

Developing the trajectory generator (TG) was also somewhat challenging. Part of the challenge was to develop a completely aircraft independent TG. By definition, an aircraft independent TG does not use aircraft performance data but, in this case, this even includes such basic parameters as cruise speed and cruise altitude, so a special algorithm was developed to discover these parameters for the target aircraft. Another challenging aspect of TG development were all the ancillary functions assigned to this component. Although not strictly “trajectory generation” functions, to maintain functional coherence the design allocated the traffic history database and many of the time/distance calculations to the TG component. As a result, the actual TG component was a fairly complex piece of software.

The accelerated pace of this project did not allow time for additional test cycles or added engineering flight tests before the scheduled FIM-S flight tests. A few aspects of the system did not work as well in flight as they had in lab testing as a result. Also, before the flight test began, and even early in the development phase, some issues were found in the lab testing that were deemed to not impact the performance of the system in flight and were recorded as deferred items to be fixed later in a future version of the system.

These items are listed in Table A-1 in Appendix A. Items noted at SAR and during the actual flight test are listed in Table A-2 and Table A-3, respectively.

These issues required a few workarounds in the early days of the flight test. Over time, most of the issues requiring workarounds were corrected, resulting in the introduction of two operational software upgrades during the flight test. Each software change was analyzed to make sure that it would not invalidate previous quantitative results; runs that were affected by issues that were corrected in later software updates were excluded from the formal data analysis.

In addition to the two software upgrades during the formal runs, a third software update was made that included an updated Nav DB with additional speed constraints on selected arrival procedures. This software version was used for qualitatively evaluating FIM-S performance on procedures with improved speed profiles better tailored to IM operations.

The CGD design was kept very basic to minimize logic processing on the display device and to simplify the data flows with the EFB. All display information is provided through the EFB and no crew input is required during IM operations. The CGD leverages existing and emerging network and communication designs based on Ethernet, Internet Protocol (IP), and Wi-Fi capabilities built into the host device using standard software interfaces, protocols and device drivers. In fact, no resident software is hosted or executed on the CGD display hardware, only the commercial HTTP Browser is. This minimizes the latency, ensures same information is displayed on both the CGD display devices at the same time, and reduces display drawing complexity, latency, and jitter. This allows the flight test to focus on the display of airplane speed guidance and deviation indications in the flight crew's PFoV with the necessary information to safely conduct airborne IM spacing.

A timeline of the software versions and the flight test days they were used on is included in Appendix A The appendix also provides a complete list of the remaining open software issues.

The chief CGD observation from 19 flying days is the CGD PFoV trend information (and identical EFB side display cues) provided throughout the merging and spacing maneuvers by the FSI and PI cues were not usable at all times. They did not provide accurate information regarding the airplane state following an assumed deceleration profile. Despite thorough testing during the implementation phase (no CGD jitter, latency, or drawing faults were reported during flight test or SAR) this usability performance aspect could not be further evaluated with available hardware in the loop ground tests and MOPS test vectors. MOPS guidance is silent on these design specification details for trend information; the HMI design was not finalized at the start of the program. The HMI WG lacked prior usability advice and could not finalize the implementation details (e.g., symbology, font sizes, scales) until shortly before integrated system testing (i.e., start of software Load 2 integrated testing). MOPS test vectors are not adequate on this issue. Placing the CGD in the PFoV was also challenging, particularly on the 737 owing to the small size of the flight deck. This required numerous discussions with Boeing SMEs and United crews to reach consensus on the best options for the flight test. Thanks to people's skills and willingness to overcome testing challenges during an otherwise thorough implementation and testing phase, only valid CGD alert messages were observed during SAR and flight. All the off-route messages that were observed during flight were correct. There were some IM speed-limited messages that were a little hard to understand but, after analysis, we determined they were calculated correctly. No additional issues were raised for misleading or hazardous CGD information.

2.6 Design, Test, and Operations References

NASA's need to ensure technology transfer to the FAA can be assisted by the following design, test and operations descriptions of the primary aspects of the prototype. Details of FIM-S Avionics System's design are split between the Boeing and Honeywell deliverables. Select documentation tasks where led by Boeing and resulted in Boeing documents (e.g., system requirements, CGD design, system tests, hardware documentation, data collection); others where led and documented by Honeywell (e.g., technical reference and operations/pilot manual, EFB design, HMI design, software unit tests) according to the team members work breakdown structure and their respective areas of design responsibility (i.e., Honeywell TPU, EFB, etc., and Boeing CGD and 737 hardware). All documents were reviewed by the team members as part of the WG activities and the technical reviews; final document deliveries were done jointly. The highlight of primary documents further described is as follows:

- Software Design Description [9] (Deliverable 4.4)
- FIM-S Avionics Technical Reference Manual [7] (Deliverable 4.16)
- FIM-S Flight Test Plan [11] (Deliverable 4.22)
- FIM-S Avionics System Test Plan [10] (Deliverable 4.15)
- FIM-S Avionics Operations Manual [13] (Deliverable 4.17)
- Post-Flight IM Data Analysis report [14] (Deliverable 4.26)
- System Requirements Definition Document [5] (Deliverable 4.8)

This documents list, although extensive, was instrumental in maintaining documentation traceability as well as a disciplined and concise SE approach. The team strove to achieve the best fit for the various tasks through PDR, CDR, and SAR milestones with documentation updates as time and budget allowed. The disciplined approach paid dividends in the testing phases where it provided as much verification as possible within the constraints of the contract and minimized the risk of implementation errors or omissions that might have affected the flight test program. Consistent with a prototype development effort and to stay within cost constraints of the ATD-1 project, the testing and formal documentation traceability was limited to system requirements and focused on observations and recommendations relative to the MOPS (section 4.1.1). It did not provide the level of formal traceability or the depth as would be required for certified avionics but rather analyzed the System Requirements Definition Document (SRDD) to determine the best method to verify requirements. The verification methods, where defined in the SRDD and used in the System Test Plan (STP); further details are provided in the STP. A brief description of the key documents is provided in the following paragraphs.

The Honeywell [9] and Boeing Software Design Documents (SDD) [12] capture the architecture of the EFB and CGD software system, subsystems and components respectively. Specifically, the SDDs describe aspects of each software component and the surrounding context and interfaces.

The FIM-S Avionics Technical Reference Manual [7] provides an overview of the technical design, operation, and performance of the FIM-S application and FIM-S avionics system.

The Flight Test Plan [11] describes procedures for conducting FIM-S operations with the FIM-S Avionics Systems installed in two test airplanes.

The STP [10] documents the procedures and the pass/fail system test criteria applied to the Honeywell and Boeing FIM-S software items in preparation for SAR. The test plan describes the testing approach and the expected test results at the system level for those Software Design Description (SDD) requirements that necessitate testing of integrated software items. The actual test results, exercised with hardware in the loop, where presented at SAR and documented in Table 2 of this report.

The FIM-S Avionics Operational Manual [13] describes the operation and use of the FIM-S Application installed on an EFB. Specifically, this document includes (1) screen layouts for each page of the interface; (2) step-by step instructions for data entry, data verification, and input error correction; (3) algorithm state messages and error condition alerting messages; (4) airplane speed guidance and deviation indications; and (5) graphical display of the spatial relationships between the Ownship airplane and the Target airplane.

The post-Flight Data Analysis Report (FDAR) [14] serves as the mechanism by which analysis of collected flight test data was delivered. It describes the data collected or derived as well as analysis methodology. Finally it includes associated results extracted from the data set collected during the ATD-1 P2 Flight Test and is summarized in section 3 of this report.

The SRDD [5] contains the actual allocation of requirements to architecture elements and associated implementation verification methods derived from the NASA system level requirement specifications [8]. The original document was based on the initial analysis products of the Boeing/Honeywell ATD-1 collaboration and was released to support PDR in September, 2015. The requirements were the basis for subsequent implementation efforts by the WGs. These requirements were accepted prior to FIM PDR and included associated attributes and supporting notes. Revision A was released after PDR and included changes identified during and shortly after the CDR. Revision B is the final version and includes findings from the pre-flight software implementation testing activities and the December, 2016, SAR. It supports the release of the companion ATD-1 Phase II STP document.

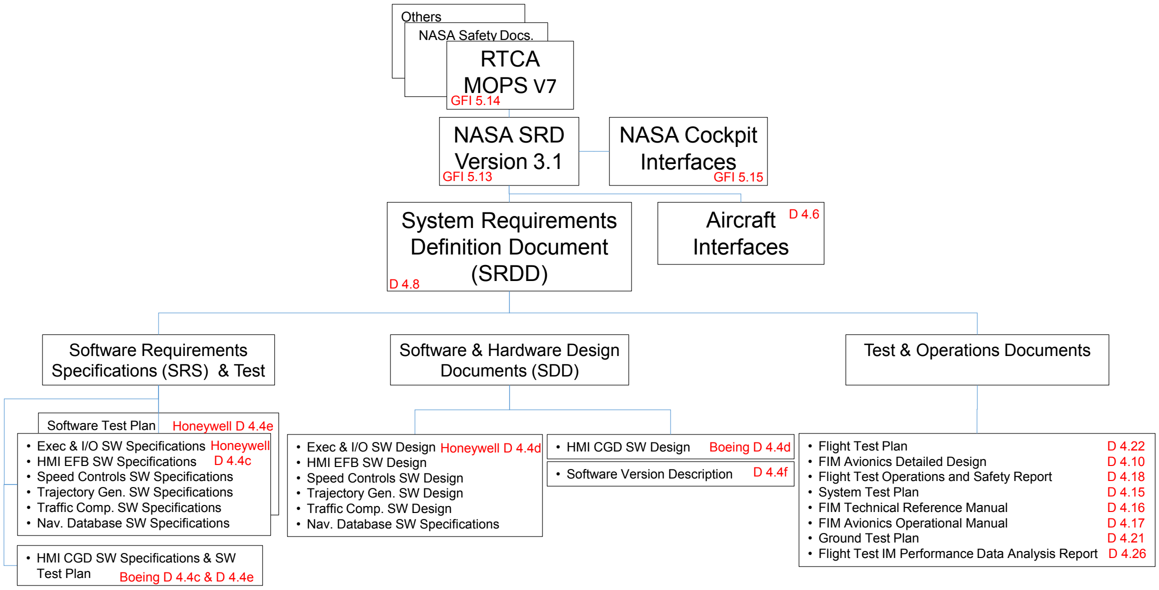


Figure 10. ATD-1 Project Documentation Tree

The full design and flight test documentation was more extensive and was developed progressively throughout the program. A complete overview listing the requirements, design, test and operations documents for the program is provided in Figure 10. It provides a hierarchy tree centered on the Government Furnished Items (GFI) used to guide the implementation of ASTAR. The document tree, from the earliest contract deliverable (the Boeing SRDD and an initial Interfaces Control Document [ICD]), is branched from left to right into requirements related documents, software and hardware design focused documents, and, finally, Test and Operations related documents (i.e., those following the program milestones time-line). The tree includes references to the GFI used to guide the FIM system implementation; it also lists the Contractual Deliverable Requirements List (CDRL) numbers under which the final document versions were delivered. Where proprietary information from the team members was used, documentation was provided in two versions: one limited version included proprietary materials (e.g., for internal use by government civil servants) and one unlimited to allow broader distribution with proprietary details simplified.

3 Summary of Flight Test and Data Analysis Activities

The January 20 to Feb 22, 2017, ATD-1 flight test program was the result of considerable preparation activities designed to ensure success. The following sections summarize those accomplishments as well as describe the actual flight test results. The Flight Test and Data Collection WGs teams generated this material with everyone willing to participate with multiple WG meetings as necessary to achieve the essential milestones. The Flight Test WG leaders were responsible for the Design of Experiment materials and the Arrival and Approach procedures design described in the following paragraphs. The Data Collection WG leader assembled the data collection, and analysis results described in sections 3.3 and 3.4.

3.1 Design of FIM-S Flight Test Experiment

The experiment was set up for a merging chain of three airplanes – the Falcon first, followed by the 757 and the 737 in trail – executing high- and medium-altitude merges and in-trail trajectory-based operation, on RNAV routes coupled to precision RNP approaches to Runway 32R at the Grant County International Airport, near Moses Lake, WA.

The flight test matrix is provided in Table 1 and describes the flight test conditions that were executed. The types of FIM-S clearances that were tested include the following:

- Achieve by then maintain (CROSS)
- Capture then maintain (CAPTURE)
- Maintain current spacing (MAINTAIN)
- Final approach spacing (SPACE)

For the **CROSS** clearance type, the objective is to achieve a controller-ASG by the ABP, then maintain the spacing interval until the PTP. This clearance type uses the trajectory-based speed control law prior to the ABP, and a state-based speed control law after the ABP. The ABP and PTP for the **CROSS** clearance can be specified as the same waypoint or different waypoints.

For the **CAPTURE** clearance type, the objective is to capture the spacing goal at or greater than a minimum closure rate, then maintain the spacing interval to the PTP. Because both airplanes are on the same route, knowledge of the target airplane’s trajectory is not required. Therefore the state-based speed control law is used throughout the operation.

For the **MAINTAIN** clearance type, the objective is to maintain the initial spacing interval between the FIM-S and target airplane until PTP. Both airplanes are on the same route, the target’s trajectory is not required, and state-based speed control law is used. This is the only FIM-S operation where the spacing goal is not provided by the air traffic controller.

Table 1. ATD-1 FIM-S Flight Test Matrix

Scenario	Tgt Route	Tgt Delay (see TgtRts)	FIM1 Clnc Type	FIM1 T/D	FIM1 Route	FIM1 SpErr	FIM1 ABP	FIM1 PTP	FIM2 Clnc Type	FIM2 T/D	FIM2 Route	FIM2 SpErr	FIM2 ABP	FIM2 PTP
A1	en route	0 (.78M)	CROSS	Time	en route	+20 sec	JELVO	MAHTA	CROSS	Time	en route	-15 sec	JELVO	MAHTA
A2	en route	0 (.78M)	CROSS	Distance	en route	+3 NM	JELVO	MAHTA	CROSS	Distance	en route	-2 NM	JELVO	MAHTA
A3	en route	0 (.78M)	CAPTURE	Time	en route	+20 sec	na	JELVO	CAPTURE	Time	en route	-15 sec	na	JELVO
A4	en route	0 (.78M)	CAPTURE	Distance	en route	+3 NM	na	JELVO	CAPTURE	Distance	en route	-2 NM	na	JELVO
A5	en route	0 (.78M)	MAINTAIN	Time	en route	na	na	JELVO	MAINTAIN	Time	en route	na	na	JELVO
A6	en route	0 (.78M)	MAINTAIN	Distance	en route	na	na	JELVO	MAINTAIN	Distance	en route	na	na	JELVO
B1	JELVO.SUBDY	No Delay	CROSS	Time	ZIRAN.SUBDY	-20	NALTE	FAF	CAPTURE	Time	ZIRAN.SUBDY	+30	na	FAF
B2	ZIRAN.SUBDY	No Delay	CROSS	Time	JELVO.SUBDY	0	PTP	FAF	MAINTAIN	Time	JELVO.SUBDY	na	na	FAF
B3	ZIRAN.SUBDY	No Delay	CROSS	Time	JELVO.SUBDY	+60	PTP	FAF	CROSS	Time	TRAKX.UPBOB	+30	PTP	FAF
B4	JELVO.SUBDY	No Delay	CAPTURE	Time	JELVO.SUBDY	-60	na	FAF	MAINTAIN	Time	JELVO.SUBDY	na	na	FAF
B5	JELVO.SUBDY	No Delay	CAPTURE	Time	JELVO.SUBDY	+60	na	FAF	CROSS	Time	TRAKX.UPBOB	+30	PTP	FAF
B6	JELVO.SUBDY	No Delay	MAINTAIN	Time	JELVO.SUBDY	na	na	FAF	CROSS	Time	ZIRAN.SUBDY	+15	NALTE	FAF
B7	JELVO.SUBDY	Med Delay	CROSS	Time	ZIRAN.SUBDY	-20	NALTE	FAF	CAPTURE	Time	ZIRAN.SUBDY	+30	na	FAF
B8	ZIRAN.SUBDY	Med Delay	CROSS	Time	JELVO.SUBDY	0	PTP	FAF	MAINTAIN	Time	JELVO.SUBDY	na	na	FAF
B9	ZIRAN.SUBDY	Med Delay	CROSS	Time	JELVO.SUBDY	+60	PTP	FAF	CROSS	Time	TRAKX.UPBOB	+30	PTP	FAF
B10	JELVO.SUBDY	Med Delay	CAPTURE	Time	JELVO.SUBDY	-60	na	FAF	MAINTAIN	Time	JELVO.SUBDY	na	na	FAF
B11	JELVO.SUBDY	Med Delay	CAPTURE	Time	JELVO.SUBDY	+60	na	FAF	CROSS	Time	TRAKX.UPBOB	+30	PTP	FAF
B12	JELVO.SUBDY	Med Delay	MAINTAIN	Time	JELVO.SUBDY	na	na	FAF	CROSS	Time	ZIRAN.SUBDY	+15	NALTE	FAF
B13	JELVO.SUBDY	High Delay	CROSS	Time	ZIRAN.SUBDY	-20	NALTE	FAF	CAPTURE	Time	ZIRAN.SUBDY	+30	na	FAF
B14	ZIRAN.SUBDY	High Delay	CROSS	Time	JELVO.SUBDY	0	PTP	FAF	MAINTAIN	Time	JELVO.SUBDY	na	na	FAF
B15	ZIRAN.SUBDY	High Delay	CROSS	Time	JELVO.SUBDY	+60	PTP	FAF	CROSS	Time	TRAKX.UPBOB	+30	PTP	FAF
B16	JELVO.SUBDY	High Delay	CAPTURE	Time	JELVO.SUBDY	-60	na	FAF	MAINTAIN	Time	JELVO.SUBDY	na	na	FAF
B17	JELVO.SUBDY	High Delay	CAPTURE	Time	JELVO.SUBDY	+60	na	FAF	CROSS	Time	TRAKX.UPBOB	+30	PTP	FAF
B18	JELVO.SUBDY	High Delay	MAINTAIN	Time	JELVO.SUBDY	na	na	FAF	CROSS	Time	ZIRAN.SUBDY	+15	NALTE	FAF
B19	ZIRAN.SUBDY	No Delay	CROSS	Time	JELVO.SUBDY	+20	NALTE	FAF	CROSS	Time	ZIRAN.SUBDY	+15	NALTE	FAF
B20	ZIRAN.SUBDY	Med Delay	CROSS	Time	JELVO.SUBDY	+20	NALTE	FAF	CROSS	Time	ZIRAN.SUBDY	+15	NALTE	FAF
B21	ZIRAN.SUBDY	High Delay	CROSS	Time	JELVO.SUBDY	+20	NALTE	FAF	CROSS	Time	ZIRAN.SUBDY	+15	NALTE	FAF
B22	ZIRAN.SUBDY	No Delay	CROSS	Distance	JELVO.SUBDY	+2 nm	PTP	FAF	CROSS	Distance	ZIRAN.SUBDY	+1 nm	PTP	FAF
B23	ZIRAN.SUBDY	Med Delay	CROSS	Distance	JELVO.SUBDY	+2 nm	PTP	FAF	CROSS	Distance	ZIRAN.SUBDY	+1 nm	PTP	FAF
B24	ZIRAN.SUBDY	High Delay	CROSS	Distance	JELVO.SUBDY	+2 nm	PTP	FAF	CROSS	Distance	ZIRAN.SUBDY	+1 nm	PTP	FAF
C1	Str-in	No Delay	FINAL	Time	Str-in	+15 sec	PTP	6.25						
C2	Str-in	No Delay	FINAL	Distance	Str-in	+1 NM	PTP	6.25						
C3	Str-in	No Delay	FINAL	Time	Turn	+15 sec	PTP	6.25						
C4	Str-in	No Delay	FINAL	Distance	Turn	+1 NM	PTP	6.25						
C5	Turn	No Delay	FINAL	Time	Str-in	+15 sec	PTP	6.25						
C6	Turn	No Delay	FINAL	Distance	Str-in	+1 NM	PTP	6.25						
C7	Str-in	High Delay	FINAL	Distance	Turn	+1 NM	PTP	6.25						
C8	Turn	High Delay	FINAL	Distance	Str-in	+1 NM	PTP	6.25						

The **SPACE** clearance type is a special subset of the **CROSS** operation. It is designed to be initiated within TRACON airspace. To use trajectory-based control laws, the FIM-S avionics make assumptions when determining FIM-S and target trajectories, and the PTP is defined as 6.25 nmi from the runway threshold. The **SPACE** clearance type can begin when one airplane is established on final and the other airplane is also established on final or on a vector less than 45 degrees to the final course.

The tests have been designed to evaluate FIM-S system performance while allowing the test conditions variables that affect the operation and its performance to be isolated as much as possible so that their effects can be assessed individually. It is not possible to control some of the variables (e.g., effects of wind vector, latency in crew response to speed guidance) and, because there are many independent variables, total isolation was not expected. Therefore the distribution of combinations of variables in Table 1 allowed close examination of the target delay, type of algorithm (trajectory-based or constant-time delay), and early and late ABP placement. The structure of test scenarios is organized to examine the following independent variables:

- Spacing error (airplane position relative to the location desired by the schedule)
- Spacing type (time in seconds or distance in tenths of nautical miles)
- Lead airplane delay (none, medium, or high; speed aligned to ground schedule)
- ABP location (merge point or final approach fix)
- Airplane route geometry (for the Final Approach Scenario only)

Based on this design, the definition of delay is a positive value that indicates the IM operation aims for the airplane to speed up (decrease spacing); a negative value aims for the airplane to slow-down (increase spacing). Further detailed variable definitions can be found in the Post-Flight Data Analysis report [14].

3.2 Arrival and Approach Procedures Design

The flight test WG leaders along with the Air Traffic Facilities involved designed the arrival and instrument approach procedures with considerable help from Jeppesen, Inc., FAA, ANM-200, AFS-460 and United Airlines who completed the Simulator Validation Flights in their 737 full motion simulator. The instrument approach procedures depicted in the approach plates were released for the public and published as procedures for both runways 32R and 14L at Moses Lake. RNAV (RNP) Z AR approaches were selected because they contain RF legs which will satisfy testing requirements of the FIM-S system algorithm.

Figure 11 is an example flight test run where the operations overlay the map of the procedures. The Honeywell Dassault Falcon 900 is shown as the red icon in the center (N889H); the Honeywell Boeing 757 is shown as the black icon at the right (NWH) and the United 737 is shown as a red icon at the left (UAL2197). This was a low altitude test case started at flight level 230 with merging at NALTE and the PTP at ZAVYO. The 757 was assigned a CROSS clearance with the Falcon 900 as the target; the 737 was assigned a CROSS clearance with the 757 as the target: NALTE had been the ABP for both FIM-S airplanes.

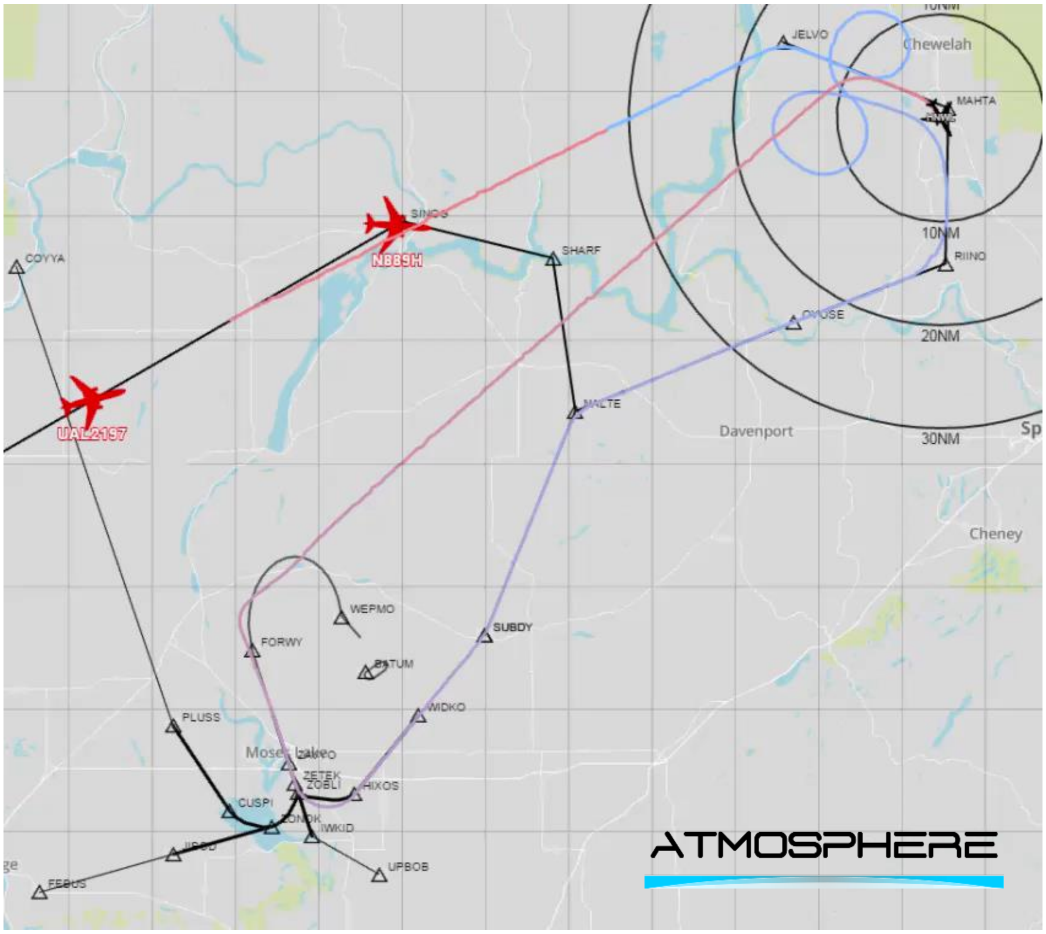


Figure 11. Example FIM-S Operations and Arrival and Approach Procedures

The arrival procedures had been developed by the NASA ATD-1 P2 team. The procedures have many of the features found in recently implemented arrival procedures at busy airports in the US in that they have speed and altitude constraints at a number of the defining waypoints. The FIM-S system requires these constraints to define the vertical and speed profiles for both target and executing airplanes. Because the flight tests were carried out under IFR, the procedures were subjected to normal development and approval processes, and were published as Special procedures for use only by Honeywell and United Airlines during tests.

The SUBDY RNAV STAR has en-route transitions (ZIRAN and JELVO start points) converging from west and east and thus providing arrival direction diversity allowing examination of the differing effects of wind components. The transitions merge at waypoint NALTE at 17,000 ft. msl., provide opportunity for a merge between traffic streams part-way down the descent, but with control space to allow correction of initial spacing error from both high altitude initiations (FL350) and medium altitude initiations (FL230). The STAR terminates at SUBDY, which is also a transition waypoint to the RNAV (RNP) Z AR approach to Moses Lake runway 32R.

The NALTE RNAV STAR is similar to the SUBDY STAR in form and function. The STAR terminates at NALTE, a common initial point with an approach transition to the RNAV

(RNP) Z AR instrument approach to Moses Lake runway 14L. (Note: only the STARs and IAPs to runway 32 were flown during the flight test.)

The UPBOB RNAV STAR provides more arrival direction diversity by bringing the user to Moses Lake from the southeast. The STAR terminates at UPBOB, a common initial point with approach transitions to the RNAV (RNP) Z AR instrument approaches to Moses Lake runways 32R and 14L.

All STARs, therefore, provide simple linking between arrival and approach procedures as needed by the FIM-S system functions. When selecting the procedures in the FMS per flight test card instructions, see the flight test plan for more detail [11], flight crews will close any discontinuities ensuring that all procedure points remain.

3.3 Data Collection

The Data Collection and Analysis WG started its work by tracing the requirements in the NASA FIMSRD, SOW and Boeing SRDD to the corresponding airplanes participating in the flight test and their respective recording systems. NASA submitted to the Data Analysis WG a data request list in early summer 2016 from which to record and deliver flight test data and IM performance metrics in the SOW. This NASA document became the basis for data recording requirements and traceability to recording systems, procedures and data artifacts provided in Appendix C of the Flight Test Plan.

Data collection was performed on-board the airplane using the following systems:

- EFB recording system:
    - All FIM-S system parameters, including HMI entries, airplane states (ownship and traffic), trajectories, and control system details.
- TPU recording system:
    - All TPU system data used during flight test to troubleshoot some issues. None of the TPU data was used as a primary source for computing IM Performance data and analysis based thereupon.
- Airplane recording system:
    - Airplane parameters, including airplane state, configuration, and fuel. FMS lateral and vertical deviations where available.
    - Private systems on-board 757 and F900, and flight data recorder in the 737.

Video recordings of the cockpit environment and EFBs were collected on the 757 and used during flight test to troubleshoot some HMI and other system issues. The videos were not otherwise used and were delivered directly to NASA from Honeywell on conclusion of each flight.

All sources of data included GPS-sourced, UTC timestamps for data correlation. The process for collecting and delivering data under the flight test program is depicted in Figure 12. EFB and TPU data was available daily during post-flight for analysis and troubleshooting, per flight condition. Airplane data was available within 24 hours and not

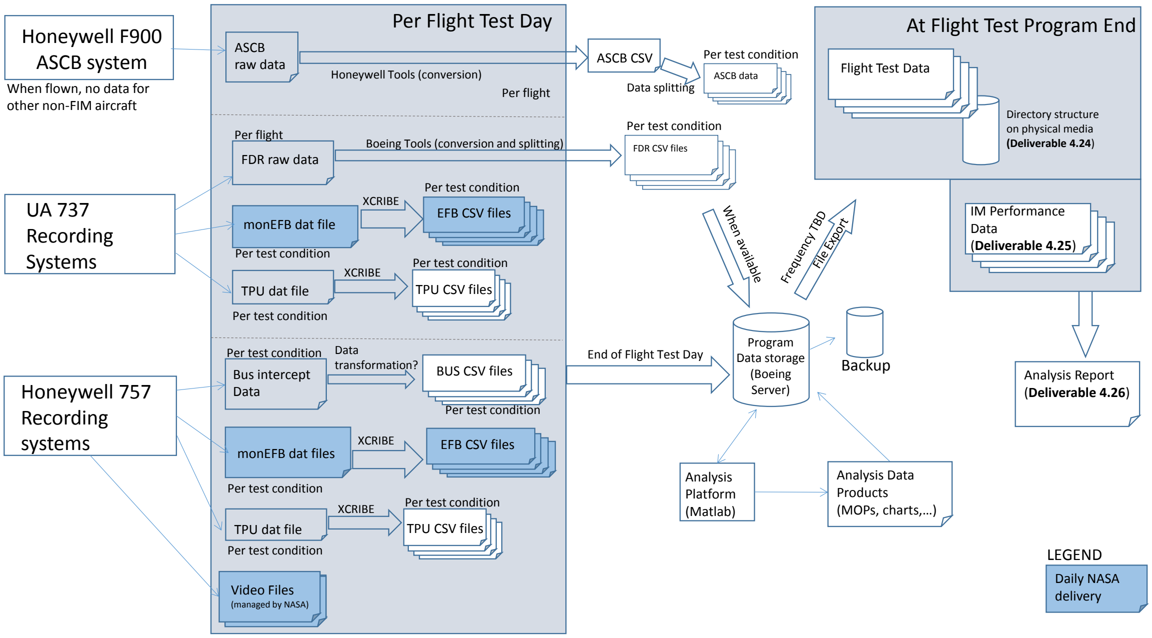


Figure 12. FIM Flight Test Program Data Flow

used directly during flight test but was the primary source for some of the data analysis (e.g. fuel, lead airplane airspeed).

Raw data from all systems on all airplanes are archived in a Flight Test Data Repository. Daily handoff of the data to NASA occurred during flight test. The entire set of raw data collected makes up Deliverable D4.24 and was delivered to NASA on March 29, 2017.

The data set considered consists of data collected on three airplanes during the flight test conducted Jan 20-Feb 22 2017 in the Seattle area. For more details about the flight test and data collected consult the Flight Test Plan document. The dataset contains data for a total of 19 flying days and 198 unique FIM-S operations flown.

The Flight Test Data was delivered 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.

3.4 Data Analysis

The first task in data analysis was to define and derive the IM Performance data from the raw flight test data collected. A total of 34 metrics were derived from the Flight Test Data, for each of the analyzed conditions. They fall in the following categories:

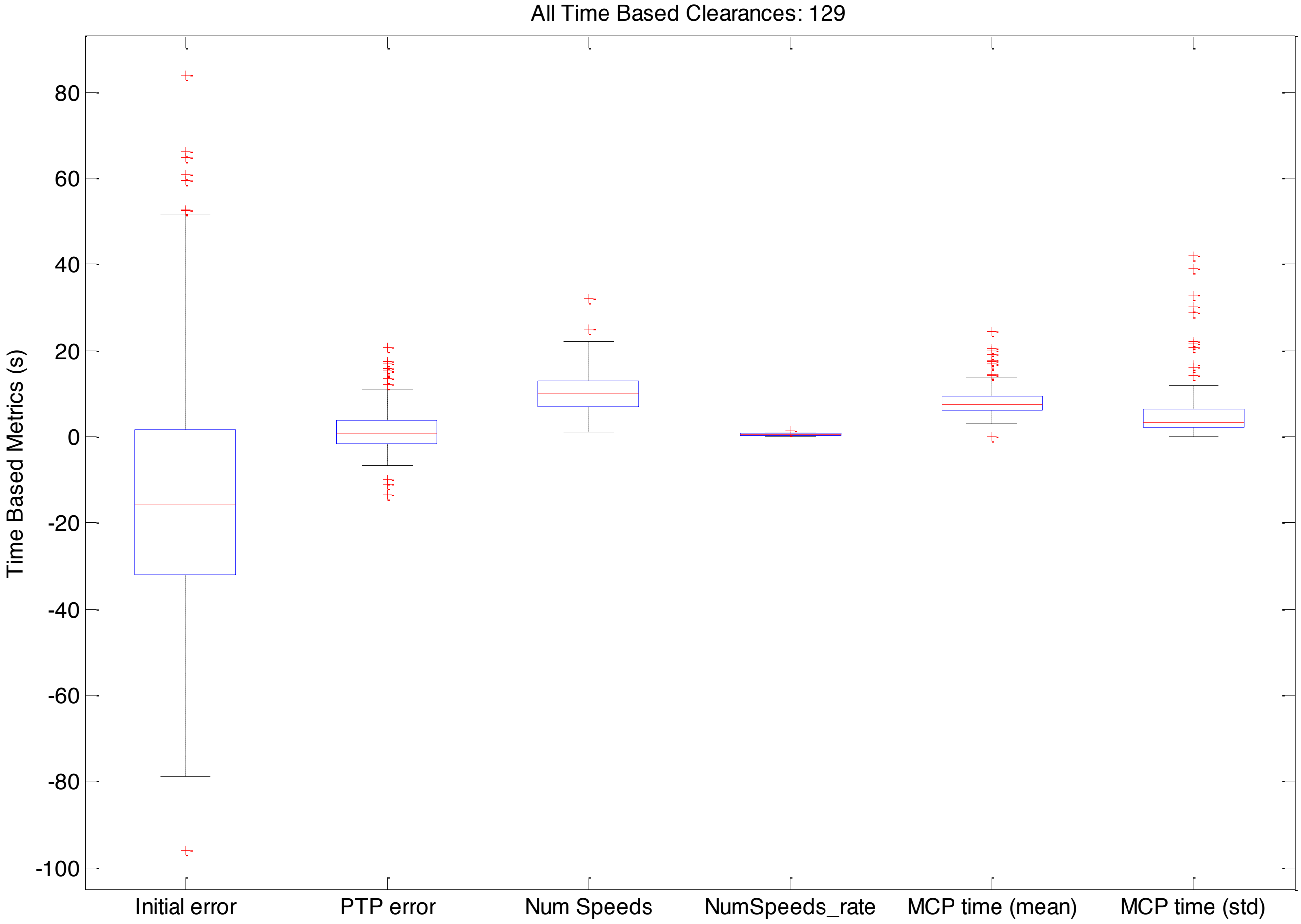
- IM Operation Performance, including initial conditions (initial spacing error, altitude and airplane state), and key system performance:
    - PTP delivery performance
    - ABP delivery performance
    - FIM Speed issue performance
- Winds observed and forecast
- Fuel burn
- Flight Technical Error, from FMS deviations where available.

Approximately 11% of the experiments were discarded due to bad or unusable data for a variety of reasons that include operator error, software errors, and scenario setup difficulties. Of the good data, 80% was retained for performance and other analysis reported herein; 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-S 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-S system can handle, the data set contains 25 MAINTAIN, 36 CAPTURE, 75 CROSS, and 8 SPACE operations. Fifteen (15) of the operations were done using a distance-based spacing goal and 129 using a time-based spacing goal.

The summary statistics for each category of IM operation is shown in a series of figures (Figure 13 through Figure 24) using box plots, spanning from the general (e.g., all time-based operations) to the specific (e.g., time-based CROSS operations with ABP at NALTE). Box plots are standardized statistic graphical representation of slices of the data set depicting the median, lower, and upper quartiles and outliers for each metric. Boxplots are shown only for slices of the experiment matrix with sample size of seven or more. Below each boxplot (when shown) is a table with the full data. Note that the standard deviation is not included in each table as the data is not necessarily normally distributed and use of the standard deviation is typically tied to analyses that assume normality.

Displayed measures of performance computed from the raw set include:

- Initial Spacing Error (seconds [s] or nmi): Spacing error at beginning of FIM-S operation
- PTP achieved spacing error (s or nmi)
- ABP achieved spacing error (s or nmi) [CROSS operations only]

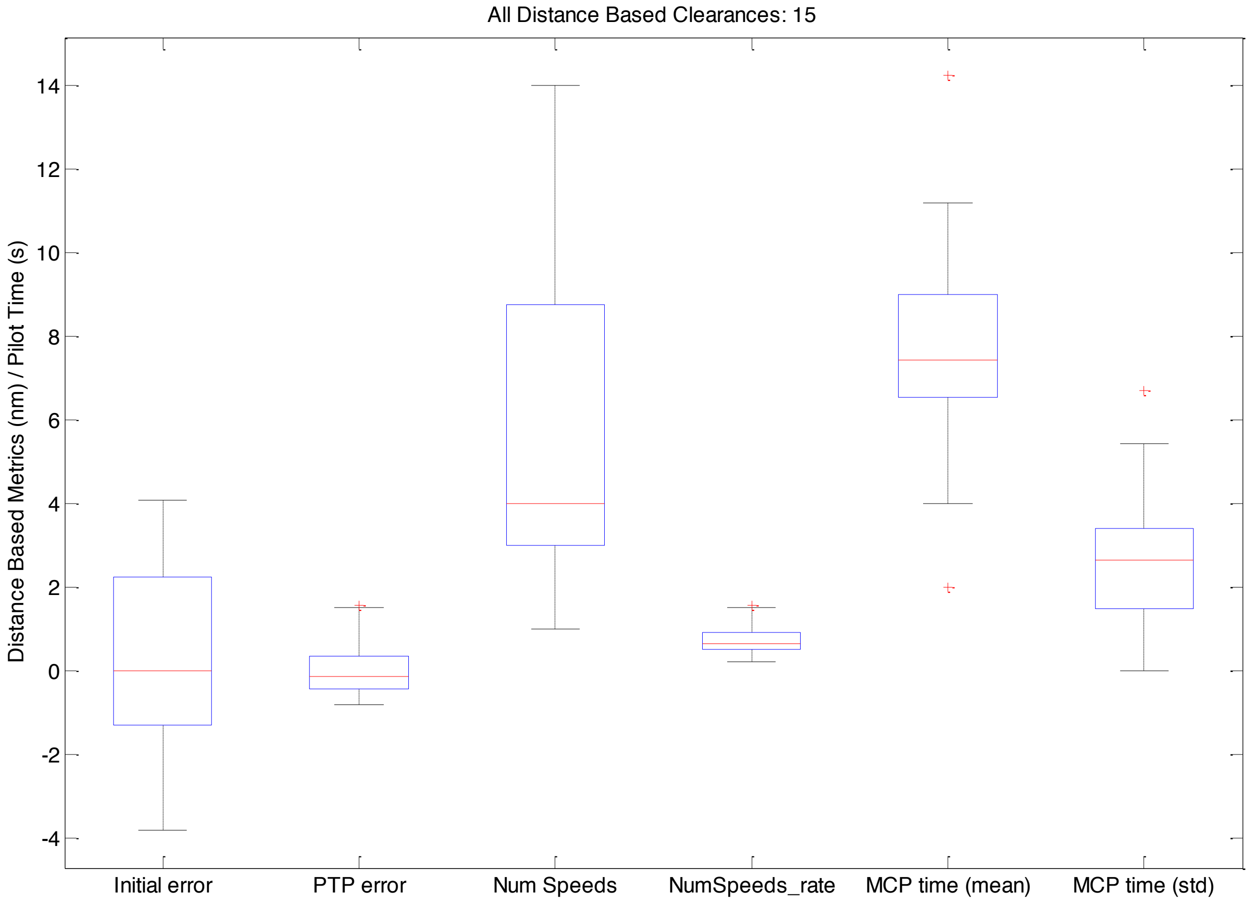


	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	numSpeeds	numSpeeds_ perMin	pilotTime_mean (s)	pilotTime_std (s)
Mean	-11.55	83.65	1.79	10.60	0.57	8.51	5.80
95% CI low	-17.32	79.78	0.75	9.69	0.53	7.85	4.54
95% CI high	-5.78	87.53	2.84	11.52	0.61	9.18	7.05
Range	180.00	114.03	34.22	31.00	1.34	24.60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

Figure 13. IM Performance - All Time-Based Clearances

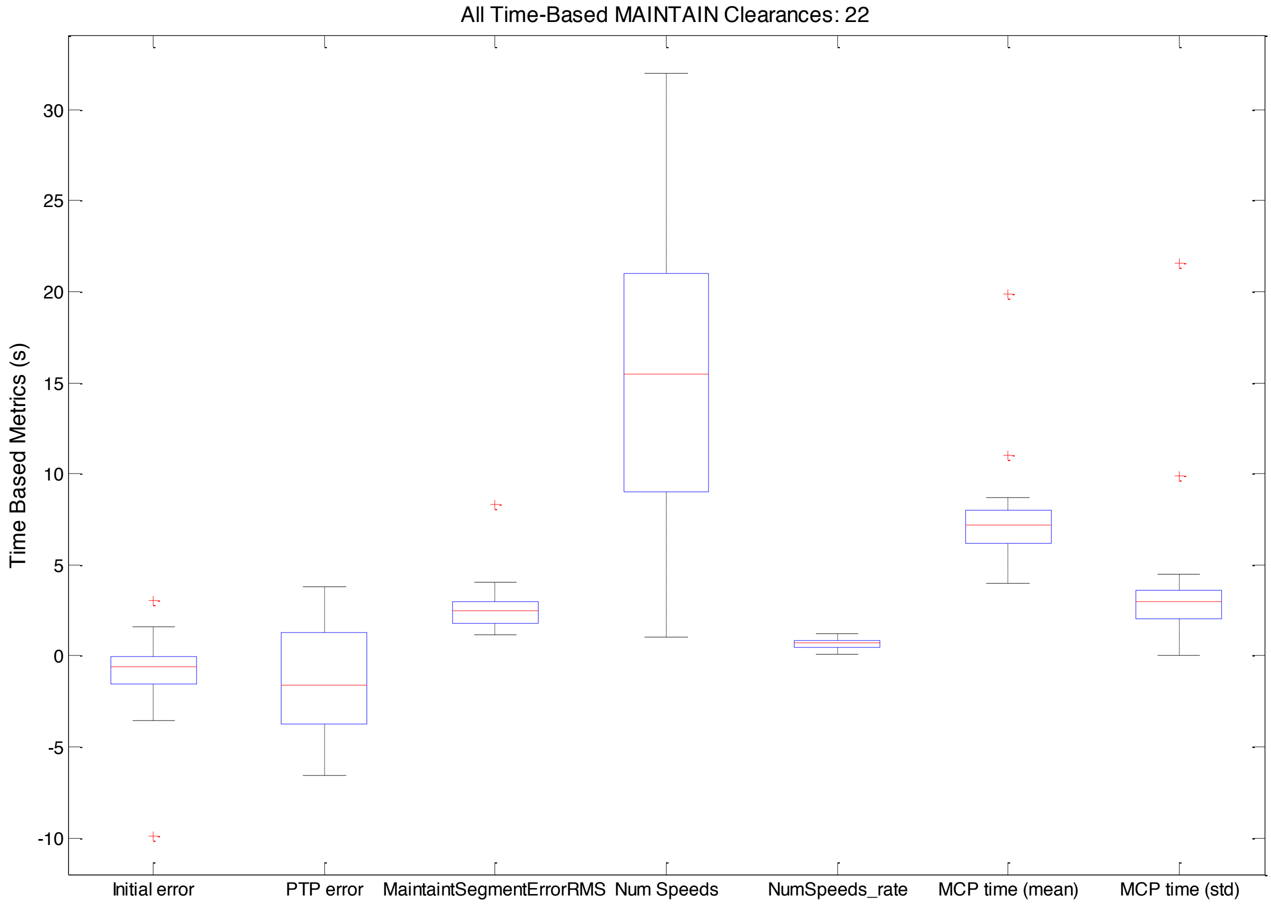
- ABP achieved spacing error (s or nmi) [CROSS operations only]
- Number of IM speeds issued (NumSpeeds)
- Number of IM speeds issued per minute of IM operation (NumSpeeds_rate)
- Pilot implementation time (MCP time) – mean and standard deviation
- Time to capture (minutes) [CAPTURE operations only]
- RMS error of maintain segment (s)

More information on the definition and computation for each metric can be found in the Post-Flight Analysis Report (D4.26).



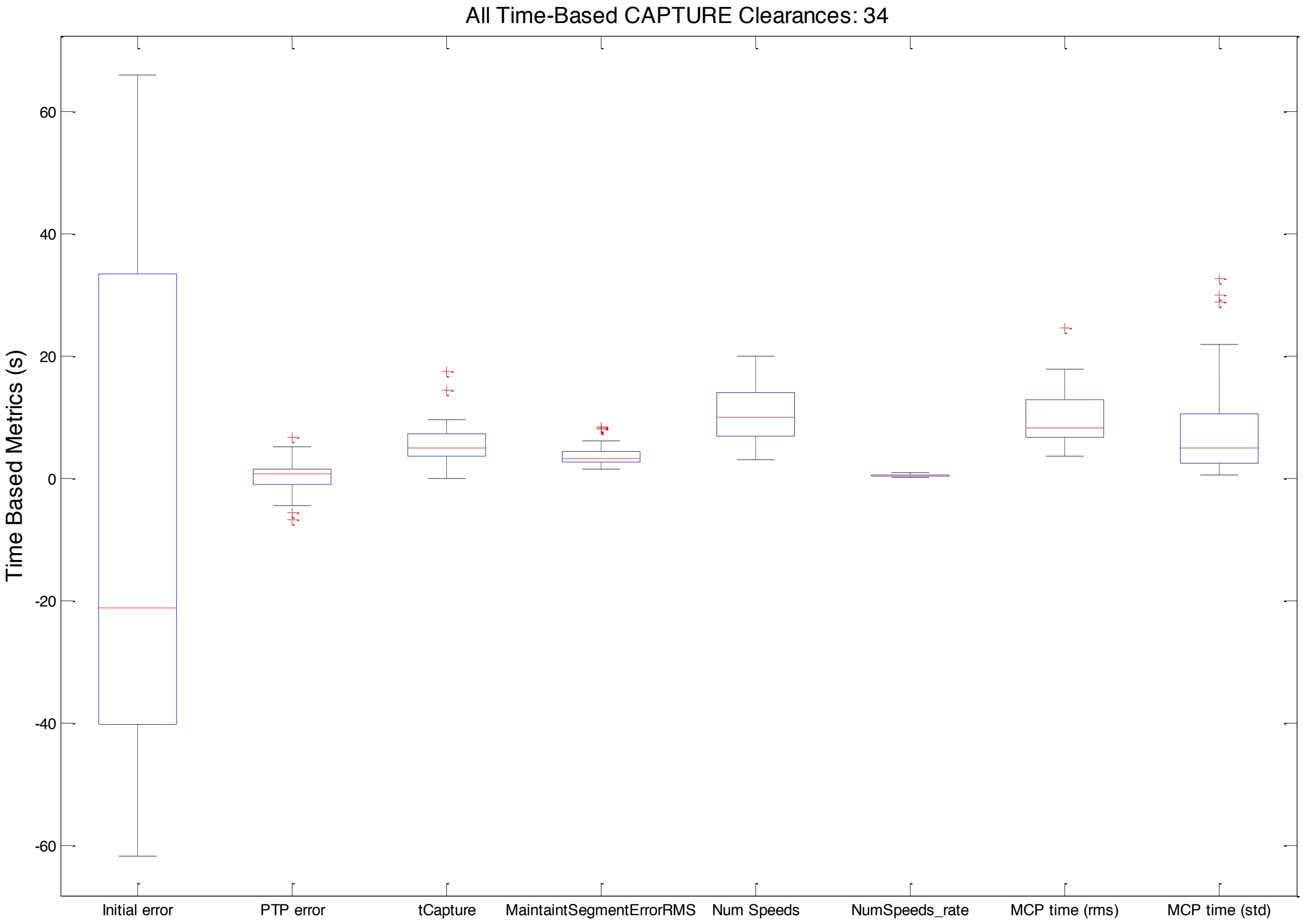
	InitialSpacing Error (nm)	IM Length (nm)	PTP error (nm)	numSpeeds	numSpeeds_ perMin	numSpeeds_GS_S egment	pilotTime_mean (s)	pilotTime_std (s)
Mean	0.19	46.13	0.18	5.80	0.77	2.07	7.71	2.68
95% CI low	-1.09	29.47	-0.27	3.67	0.55	1.03	6.06	1.71
95% CI high	1.47	62.79	0.62	7.93	0.99	3.10	9.37	3.66
Range	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 14. IM Performance - All Distance-Based Clearances



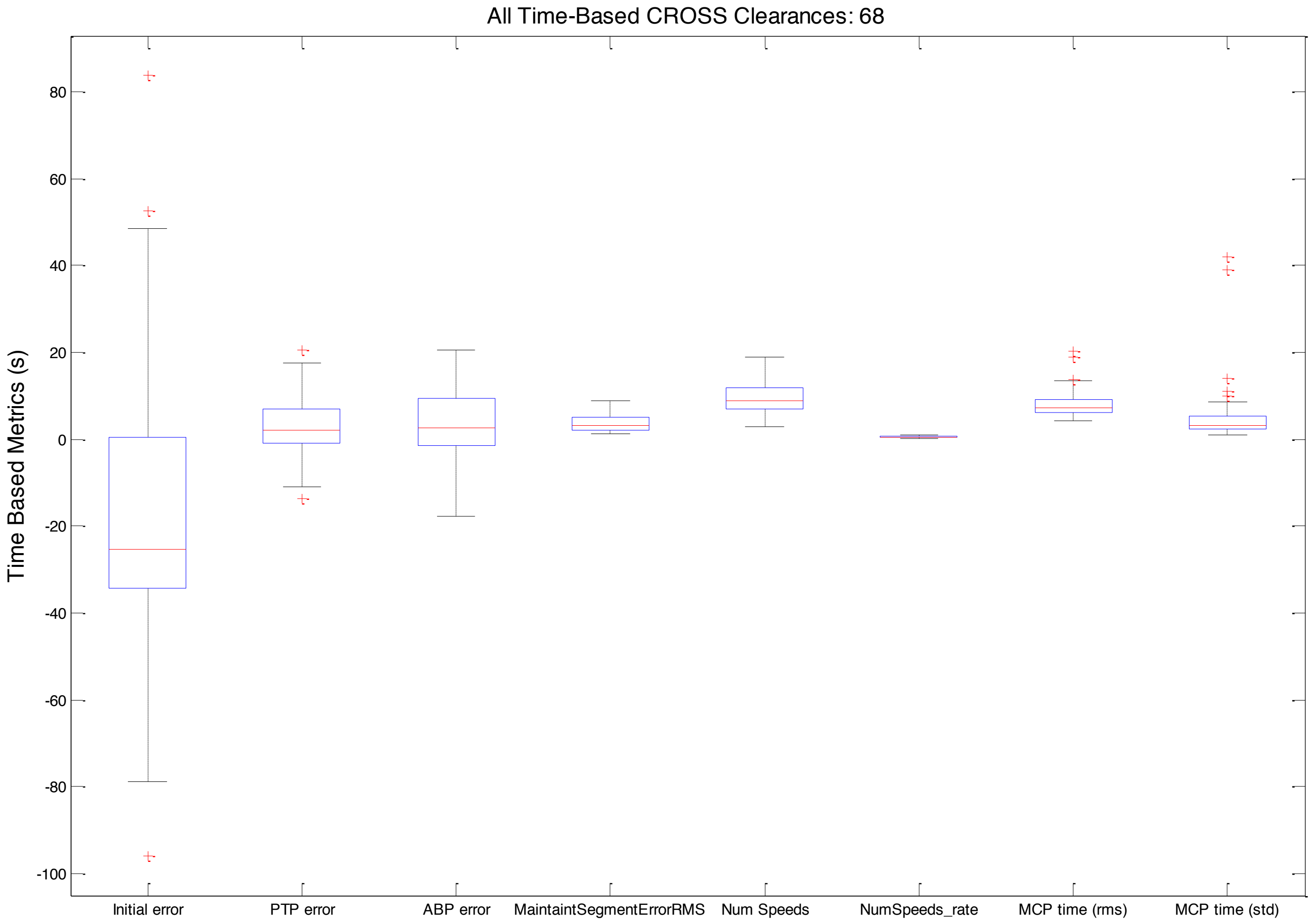
	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	numSpeeds	numSpeeds_ perMin	pilotTime_mean (s)	pilotTime_std (s)	MaintainError _RMS (s)
Mean	-1.08	91.78	-1.32	14.64	0.70	7.65	3.77	2.70
95% CI low	-2.16	81.88	-2.58	10.95	0.56	6.28	1.80	2.05
95% CI high	0.00	101.67	-0.07	18.32	0.83	9.02	5.73	3.35
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 15. IM Performance - Time-Based MAINTAIN



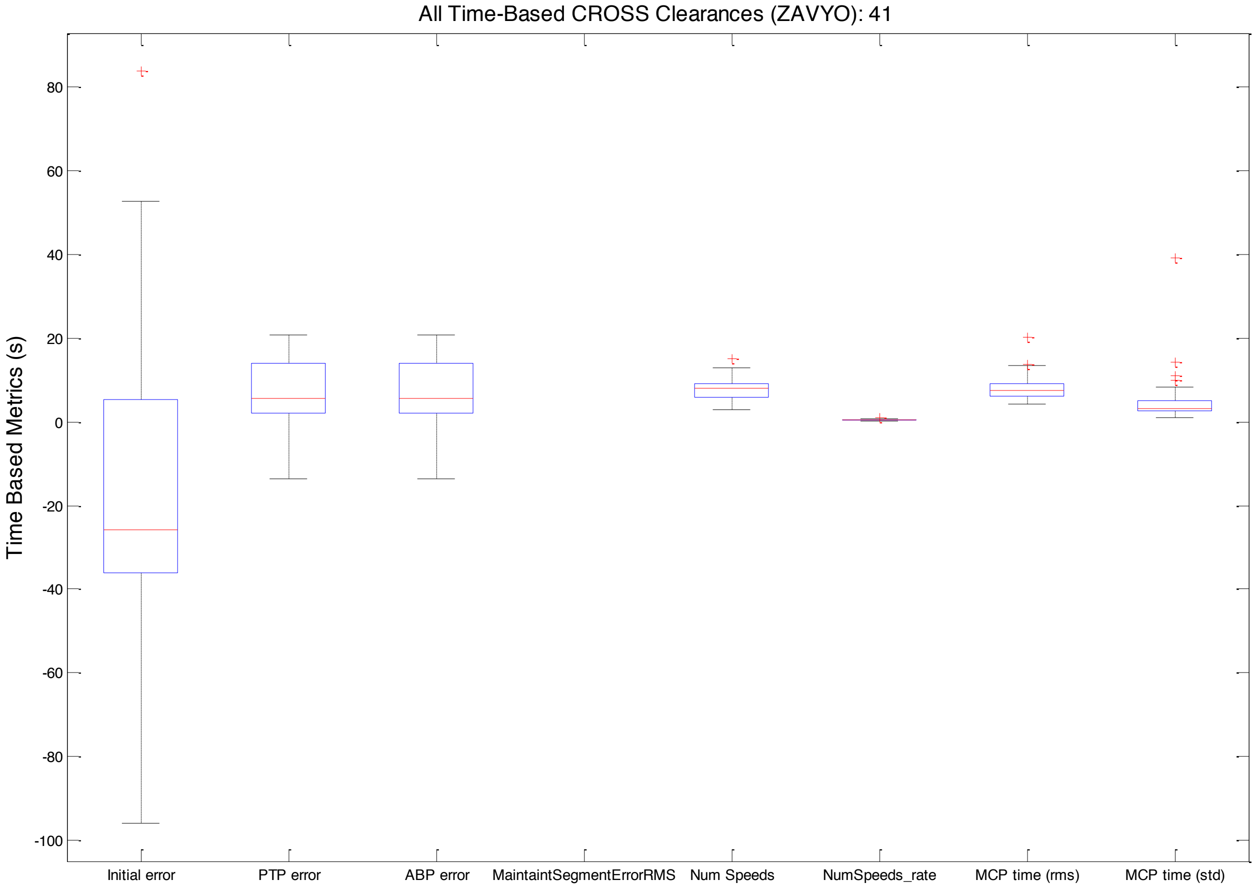
	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	numSpeeds	numSpeeds_ perMin	pilotTime_mean (s)	pilotTime_std (s)	MaintainError _RMS (s)	tCapture (s)
Mean	-6.58	88.35	0.19	10.47	0.54	10.03	8.93	3.91	334.06
95% CI low	-21.99	80.90	-0.81	8.89	0.48	8.37	5.84	3.29	260.69
95% CI high	8.82	95.80	1.18	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 16. IM Performance - Time-Based CAPTURE



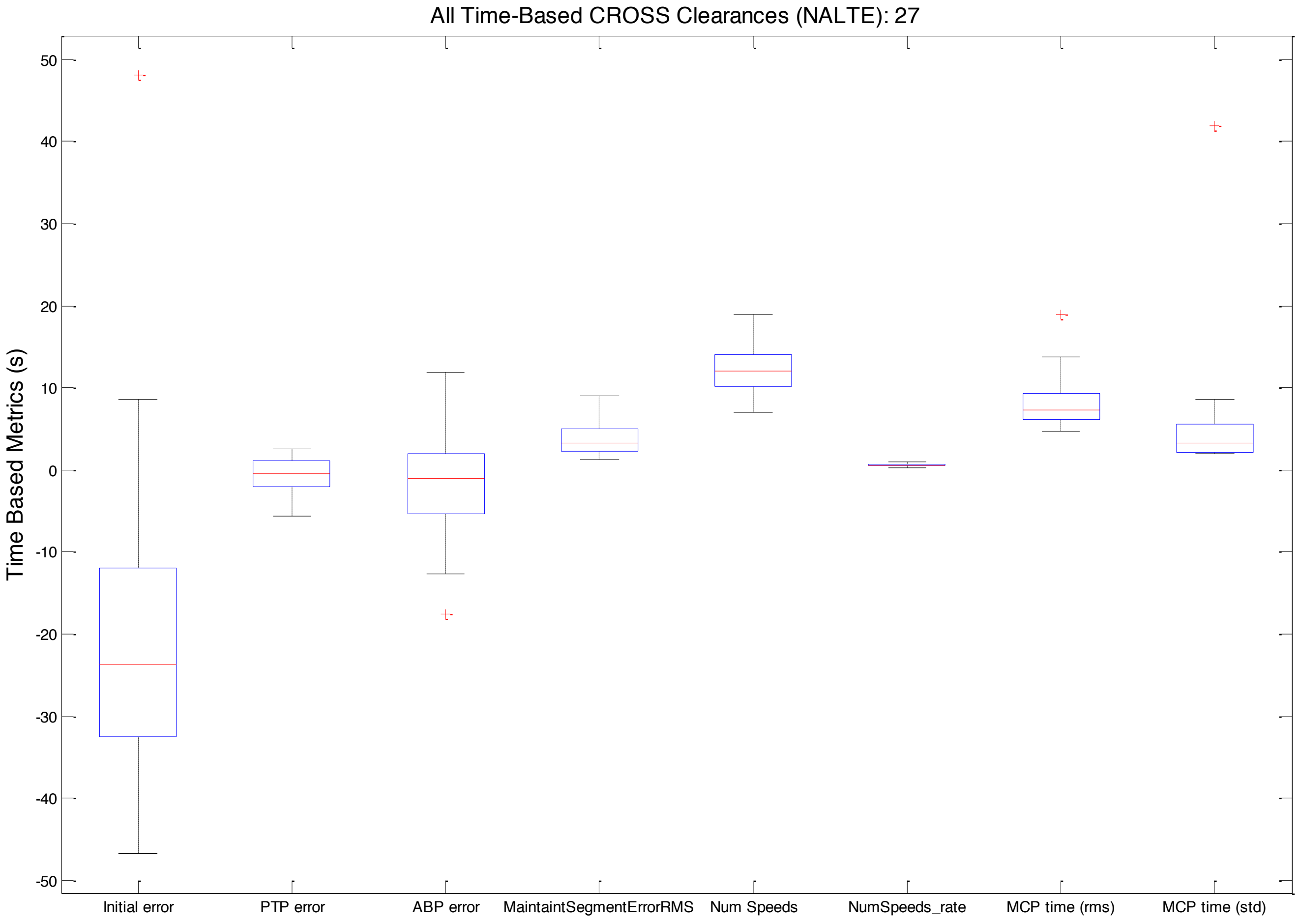
	InitialSpacing Error (s)	IM Length (nm)	PTP error (s)	ABP error (s)	numSpeeds	numSpeeds_per Min	pilotTime_mean (s)	pilotTime_std (s)	MaintainError_ RMS (s)
Mean	-17.49	83.27	3.49	3.24	9.78	0.53	8.13	5.08	3.84
95% CI low	-25.22	79.56	1.71	1.16	8.91	0.48	7.38	3.45	3.00
95% CI high	-9.77	86.99	5.27	5.32	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 17. IM Performance - Time-Based CROSS



	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 18. IM Performance – Time-Based CROSS (ABP at ZAVYO)



	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 19. IM Performance - Time-Based CROSS (ABP at NALTE)

	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 20. IM Performance - Time-Based SPACE (5 samples)

	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 21. 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 22. 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 23. 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 24. IM Performance - Distance-Based SPACE (Five samples)

When taken in aggregate, time-based operations delivered at the PTP slightly worse than the MOPS criterion of 10s of error at 95%. The empirical probability of an error less than 10s is 88.3%; the detailed descriptions are found in the Post-flight Data Analysis Report [14] under the summary and conclusions section as well as the discussions related to Figure 13. This is mostly driven by CROSS operations, which in aggregate have a probability of delivering less than 10s of error at the PTP of 78%, whereas no instances of errors greater than 10s were seen for MAINTAIN, SPACE or CAPTURE operations.

The slightly worse PTP performance of CROSS operations has been attributed to instances with a late merge including the UPBOB route for the trail airplane. 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 eliminate the observed poorer performance. A different design for the UPBOB1 STAR was drafted and a few operations were performed to enable comparisons, but this fell outside the scope of the contractor’s analysis. 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.

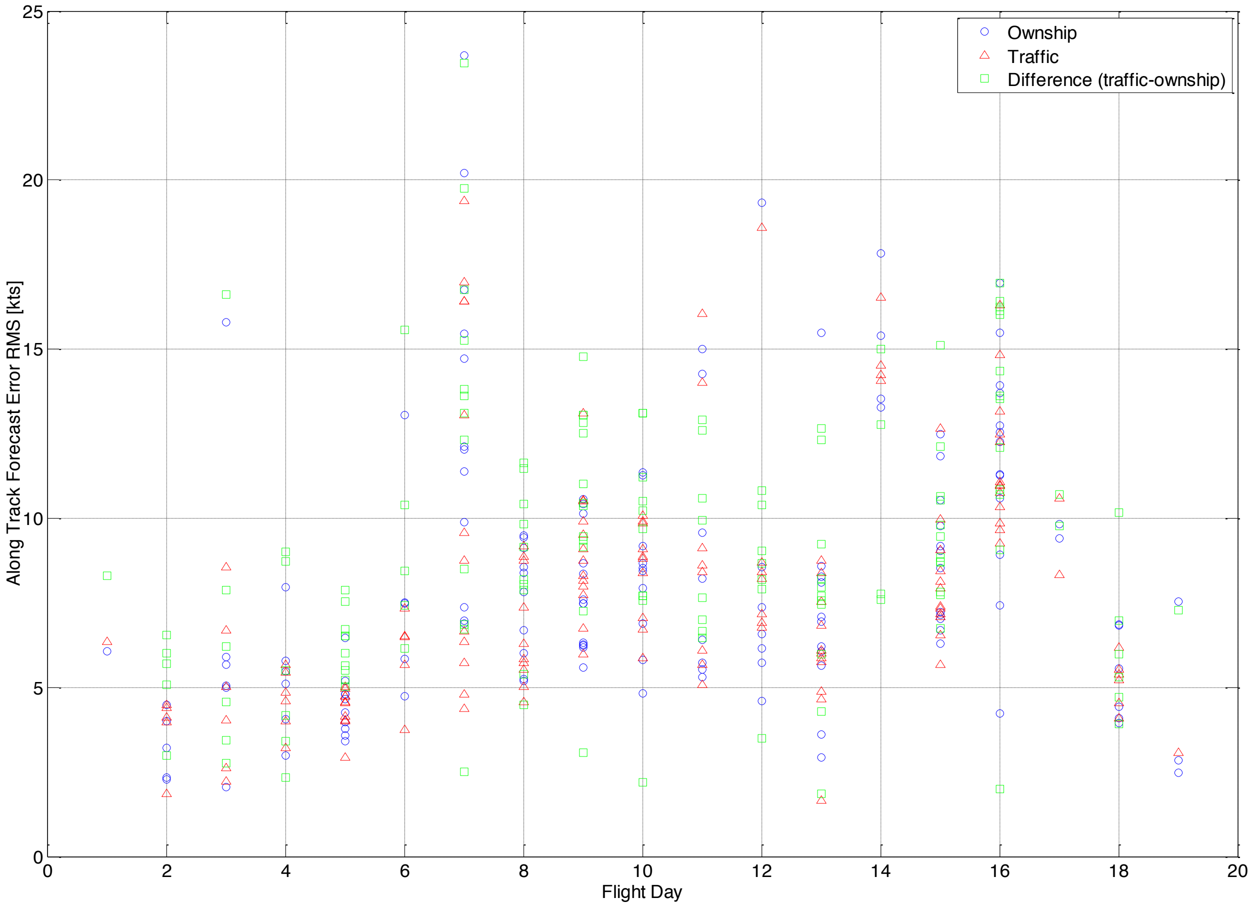
Similar effects are observed at the ABP. Overall, time-based CROSS operations have an empirical probability of ABP errors of less than 10s of only 69%. However, operations with the ABP at NALTE have 78% observed errors below 10s, and when excluding a number of conditions where the operation started with 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 3.6s 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 3s per minute. 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 2 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 through a wide variety of initial spacing errors (96s too close to 84s too late) on three different routes, for descent, cruise and final approach operations, two different airplanes, and 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).



	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 25. Along Track Wind Forecast Error

Wind forecast errors for each flight day is reported in Figure 25. The metric used is the Along-Track Wind Forecast Error (ATWFE) which is the wind forecast error (forecast – truth) laid against the track in RMS aggregate.

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, and 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. A correlation analysis between the PTP delivery performance and IM speed rate reveals very low correlation between ATWFE and performance.

The Fuel Burn analysis performed only compared 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 airplane types and correlated to the number of FIM speeds issued. The descriptive statistics for the fuel burn are shown in Figure 26.

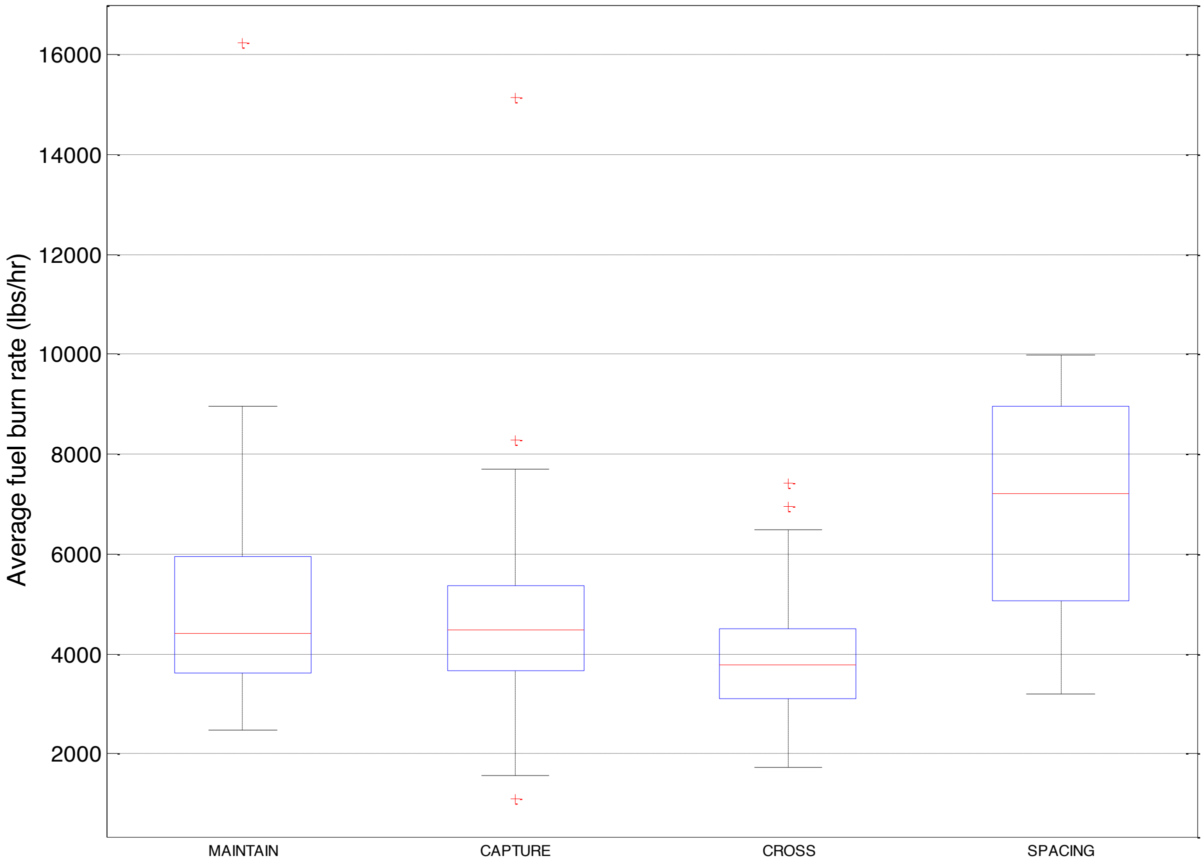


Figure 26. Average Fuel Burn Rate by Operation

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

4 Lessons Learned, Conclusions, and Recommendations

This section documents the issues and organizes them into lessons learned, conclusions, and recommendations. It is the hope that they will guide the stakeholders as they contemplate the next step in further development efforts. The subsections reference the design and evaluation activities as well as flight test activities described in sections 2 and 3.

4.1 Lessons Learned

The following list is organized by areas of potential impact on future design and testing steps. Included is the full text from written comment requests submitted by individual team members that participated in the flight test. When individuals submitted comments, they were preceded by the name of the organization authoring the comment and numbered C3 – C47. Some comments (without the organization name) are findings from the WG team members representing several team member organizations (e.g., C1, C2, etc.) Summary recommendations in section 4.3 are derived from the significant comments listed, and include references to help trace to the paragraph content.

4.1.1 Minimum Operational Performance and Other Standards

Displays/Human Machine Interface

Basic airborne situation awareness display (AIRB) is a prerequisite for all airborne surveillance applications, including FIM-S. The CDTI used in this demonstration came from a system that had been certified for AIRB per DO-317A. A regression analysis was performed against the current MOPS (DO-317B) and it was determined there were no significant differences between the standards for CDTI that would impact performance during the demonstration.

Other aspects of the HMI, in particular the FIM-S data entry screens and FIM-S outputs, including speed commands and annunciations, were developed from previous NASA work on FIM [8]. The final implementation was then checked for compliance with the FIM MOPS. While there was extensive discussion in the HMI WG leading up to the final HMI design, there was not enough time to conduct pilot focus group reviews and usability studies typically used to verify certified avionics equipment. Therefore, the HMI used in this demonstration should be considered *minimally* compliant to the MOPS but not *optimized* for cockpit use (e.g., minimizing crew workload)

Algorithms

The primary speed control algorithms for FIM-S in this demonstration came from NASA's Airborne Spacing for Terminal Arrival Routes version 13 (ASTAR13) 7th Revision [4]. ASTAR compliance to the FIM MOPS (DO-361) was assumed based on previous NASA work. Other algorithms, such as final approach spacing and conformance monitoring were developed to meet the FIM MOPS[2] requirements.

Because of the compressed schedule and testing risks, the complete suite of FIM MOPS verification tests were not performed as part of this demonstration; however, basic speed control performance was checked using a subset of the MOPS tests. The results of these tests are included in Table 2. See the System Test Plan [10] for details on the rest of the system verification that was performed.

Table 2 summarizes the subset of MOPS performance tests that were run against the FIM-S software developed for this project. The pass/fail criteria in this table are from the MOPS, however as described in the system test plan, this project had less stringent pass/fail criteria for the system tests based on the assumption that the ASTAR algorithm was fully tested in previous work at NASA. Except for the final approach spacing clearance which was not extensively tested at NASA for ASTAR13 that assumption appears to be valid.

Based on these results presented at SAR, the demonstration implementation of ASTAR13 performance was deemed acceptable for flight test. Further investigation of the algorithms performance on distance-based final approach spacing clearances is warranted however, as well as more validation of the MOPS test vectors for this clearance.

FIM MOPS Requirements Observations

The NASA System Requirements Document (NASA FIMSRD) [8] included directly or by reference the FIM MOPS requirements as they existed at the time the NASA FIMSRD was released. The FIMSRD was extensively reviewed at the start of the program by the entire SE team. This review included engineers, managers and pilots drawn from all the participating organizations – NASA, FAA, Boeing, Honeywell and United. The results of this review were captured in the NASA FIMSRD revision 3.1, released on August 27, 2015.

The NASA FIMSRD revision includes a notation on each MOPS requirement considered for this project indicating if the requirement was accepted as-is, modified or deleted. The details captured in the SRD will not be repeated here, however the highlights of differences/findings are listed below:

1. Aural alerting was not implemented for this demonstration.
2. IM Turn was not implemented for this demonstration.
3. IM Procedural Limit requirements were modified/added compared to the MOPS.
4. Departure Intended Flight Path Information (IFPI – SID, SID En Route Transition) were not implemented. This is a MOPS requirement, but current Concept of Operations (CONOPS) does not include departure operations.

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[2] Because this project started before RTCA DO-361 was released, compliance was ensured by including the relevant MOPS requirements from a mature draft of the MOPS directly into the project System Requirements Document, GFI 5.13.

Table 2. Speed Control Performance Test Summary

CROSS	time		ASG: 120s initial spacing: 37s	w/in 9.4s at own crossing	passed at 4.17 vs. 9.4s
				maintain w/in 9.4s of ASG > 95%	passed at 100%
	distance		ASG: 3 NM initial spacing: 2 NM	w/in 9.4s * own nom ground speed at Traffic To Follow (TTF) crossing	passed at 0.05 vs. 0.485 NM
				maintain w/in 9.4 * (max ground speed) > 95%	passed at 100%
CAPTURE	time	JET1	ASG: 160s initial spacing: 123s	capture phase: @3s/min	pass
				maintain w/in 9.4s of ASG > 95%	pass at 100%
		JET6	ASG: 90s initial spacing: 120s	capture phase: @3s/min	pass
				maintain w/in 9.4s of ASG > 95%	passed at 100%
	distance	JET1	ASG: 7.5 NM initial spacing: 5.35 NM	capture @ 0.125 NM/min	pass
				maintain w/in 9.4 * (max ground speed) > 95%	pass at 100%
		JET6	ASG: 7.5 NM initial spacing: 5.32 NM	capture @ 0.125 NM/min	pass
				maintain w/in 9.4 * (max ground speed) > 95%	fail at 94.84%
SPACE	time	test1	ASG: 120s initial spacing: 182s	w/in 9.4s at own crossing	passed at 0.68 vs. 9.4s (but at last moment)
		test3	ASG: 120s initial spacing: 156s		passed at 0.45 vs. 9.4s (but at last moment)
		test5	ASG: 120s initial spacing: 82s		passed at 3.25 vs 9.4s (but at last moment)
	distance	test2	ASG: 5 NM initial spacing: 11.17 NM	w/in 9.4s * own nom ground speed at TTF crossing	failed at ~60% over tolerance
		test4	ASG: 5 NM initial spacing: 9.35 NM		passed
		test6	ASG: 5 NM initial spacing: 4.57 NM		failed at ~35% over tolerance
MAINTAIN	time	JET1	N/A	maintain w/in 9.4s of ASG > 95%	passed at 100%
	distance	JET1	N/A	maintain w/in 9.4 * (max ground speed) > 95%	passed at 100%

5. Additional requirements for wind/temperature processing were included.
6. Speed control requirements were included by reference to the ASTAR description document [4].
7. Several “hard” requirements in the MOPS were made configurable in this implementation, including IM speed profile limits, conformance bounds, and ground speed matching. However, at the conclusion of system testing and SAR it was decided to use the standard MOPS values for each of these parameters in the flight test.
8. Minimum Safe Speed monitoring (FRAC.235/236) was not implemented in the FIM-S equipment for this demonstration because all airplanes involved included this monitoring in other onboard systems.
9. The IM feasibility check was not implemented. However an engineering display of anticipated Measured Spacing Interval (MSI)/Predicted Spacing Interval (PSI) and initial speed command was implemented so that pilots and the flight test director could assess the feasibility of any given clearance during the flight test.
10. The MOPS PI requirements were supplemented with requirements from the NASA HMI PI implementation [6].
11. The MOPS speed command indication requirements were supplemented with requirements from the NASA HMI fast/slow indicator implementation [6].
12. The CDTI state descriptions used in this implementation were based on the NASA HMI rather than the generic state descriptions in the MOPS. The detailed HMI requirements in MOPS section 2.3.5 and subsections were included in the SRD, however there were enough modifications to the requirements to match the NASA HMI that these MOPS requirements cannot be considered fully validated in this implementation.
13. Additional requirements were provided for pre-populating and clearing selected clearance information. This was done both to improve the HMI for standard FIM-S operations as well as to support the specific conditions of flight test (e.g., performing multiple clearances in a row without landing/resetting the system between runs).

In addition to the items listed, there were many requirements included in the NASA FIMSRD that were not related to MOPS requirements (tagged as “MOPS Status: New” in the FIMSRD). Most of these requirements were included to support this specific flight test program and should not be interpreted as indicating the MOPS were in any way incomplete.

At the conclusion of the NASA FIMSRD review, all the requirements from the FIMSRD were captured in the System Requirements Definition Document (SRDD, deliverable 4.8 [5]). This document was updated and maintained throughout the duration of the project.

As the detailed design and implementation proceeded it was found that some MOPS level requirements were problematic or required further clarification. These items were noted that could be reviewed for future updates to the MOPS:

1. The default PTP (FRAC.024/025) requirements did not work out well for cruise operations. In the demonstration FIM-S equipment, all clearances included a destination airport (so the airplane could determine which direction the airplane was flying in cruise and to select which arrival and approach procedures to display for arrival operations) but this created a PTP and associated constraints that were not always appropriate. Cruise clearance IFPI requirements should be clarified based on real CONOPS scenarios. There was a similar problem with default altitude limits (FRAC.027) where inappropriate constraints could be generated depending on when the clearance was executed.

2. All requirements for FIM-S operation in the Mach regime were problematic. Because most of the previous work with ASTAR was in the arrival and approach phases, this was identified as a risk early in the program and although the design was extended to operate in the Mach regime, the resultant implementation should not be considered a complete Mach solution. Therefore, this project cannot be used to claim the Mach requirements in the MOPS have been validated.

3. Final Approach Spacing requirements were also problematic. This was another area where ASTAR13 had not been tested extensively and it was also identified as a risk early in the program. Requirements for this operation were developed in discussion in several WGs (HMI, Speed Control, and Flight Test) but the need for this much discussion would indicate the MOPS requirements in this area were also not fully developed.

4.1.2 Procedures Design

<u>Boeing Comments</u>

C1. The set of arrival procedures used in this program were developed and designed exclusively to support the flight test program needs. The design was based on the needs of the flight test program, balanced with the airspace needs. The goal was to arrive at procedures that resemble modern Optimal Profile Descent (OPD) procedures in use throughout the NAS today. OPD procedures include altitude information to support “descend-via” operations but have little or no speed information. FIM-S operations require a smooth nominal speed profile embedded within the procedure design as the nominal basis for the control algorithm.

Pilot feedback and data analysis revealed correlations between FIM performance and the nominal altitude and speed profile embodied in the design of each procedure flown in the flight test. Given that the route design establishes the baseline speed profile for the FIM-S system, a design that seeks smoother nominal speed transitions along the route would lead to less drastic speed changes during IM operations and a positive effect on performance.

4.1.3 System Engineering

Boeing and Honeywell Comments

C2. The SE tasks benefited from vital precursor activities performed prior to ATD-1 P2, yet faced the difficulty of managing a fixed software testing schedule from the start (i.e., two software release cycles). The precursor activities enabled the team to focus SE on the critical system level challenges within the conditions expected to be encountered during flight test at MWH. All ATD-1 concept of operations, architecture design tasks were performed prior to this contract and no refinements (e.g., integrated air-ground concept of operations SE analysis) were included in this already compressed detailed design phase for ATD-1 P2.

The Boeing team members insisted on the firm allocation of all NASA requirements at the start of the program (i.e., prior to PDR). Once a stable set of requirements was agreed to, the ATD-1 P2 program could move ahead to PDR. This insistence on minimizing traveled risks (e.g., ASTAR implementation limitations – see Section 2.1) and managing scope risk issues, enabled thorough requirements understanding and reviews as well as accurate allocation of requirements to architecture elements. The use of formal configuration control tools and processes greatly enhanced communication and NASA, Boeing, Honeywell and United's wiliness to collaborate.

To enable accelerated testing yet test as much as possible within the detailed design phase, SE focused on minimizing traveled risks from implementation errors or omissions of the agreed PDR requirements. The team maintained traceability between initial design requirements, mapped implementation verification definitions, and test artifacts at the system level to minimize traveled risks and by relied on two precursors: 1) the previous NASA testing to ensure that ASTAR 13 met the MOPS performance requirements and 2) Honeywell's ability to execute a subset of the MOPS performance tests on their hardware-in-the-loop test equipment to maintain the compressed schedule.

Based on the results presented at SAR and the post-flight data analysis results, the implementation verification approach was deemed very successful. The prototype equipment was built without following all the processes of a fully certified development and test program. It is expected that the air navigation services provider (ANSP) and their certifying authorities will want to use these lessons learned to further guide testing of a FIM-S system that can be integrated with ground system capabilities (e.g., GIM, TBFM). The approach used in the program should allow them to follow similar risk reduction processes to integrate air and ground capabilities while in parallel test these components separately using industry standards and processes (e.g., DO-178C) in their respective implementations.

United Airlines' Comments

C3. Final [hardware][3] design needs to be completed/frozen much earlier in the process to better meet airline engineering and installation timeframes. Changes were still being [exchanged between United and] Boeing while the airplane was being modified.

C4. The format/type of design documents also needs to be reviewed and agreed on during the contracting phase. Boeing did not provide the type of documents (service bulletins, etc.) that United's engineers are used to receiving from Boeing/Airbus/vendors [for in-production systems]. This caused additional work for both United and Boeing.

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[3] Editorial comments by the final report author to clarify lessons learned comments submitted by individual team members that participated in the flight test.

4.1.4 Operational Use

United Airlines' Comments

C5. The FIM-S algorithm should not cause the number of airspeed changes as we experienced during the flight test.

C6. FIM-S algorithm should not permit airspeed changes of 30-50 knots near the FAF like we experienced during the flight test. This causes large airplane configuration changes in a short period of time. It may also cause the airplane to be outside of the ±75 ft. vertical profile required inside the FAF to fly a RNP approach.

C7. The speed commands given by the FIM-S algorithm, especially when within 10 miles of the termination point, need to be smaller (100-knot speed reductions are not acceptable).

C8. FIM-S algorithm will need to consider different airplane type speed requirements (e.g., 737-900 flies higher approach speeds when compared to a 757 or an A320).

C9. The FIM-S algorithm needs to take more account of the energy profile being flown; the airplane can't be expected to descend and slow down at the same time.

C10. For something like FIM-S to be able to be considered for airlines in the future, it would need to be able to be run on the airline's existing EFBs (in United's case it is iPads). United is not going to install a permanent EFB with FIM-S if we already have EFBs. This should be considered when developing the hardware and software. It would have been much more time and cost effective if we could have installed FIM-S on our United EFBs/iPads—this should be a goal for future projects—and use what is already in the airplane when possible.

C11. Another option would be to use different, uncertified tablets—again, not using class 3 EFBs.

C12. The trend information provided by the "fast-slow" cue needs to be usable at all times to provide information regarding the accuracy of the airplane following the assumed deceleration profile.

How did the FIM-S system work from an operational (pilot/crew) perspective?

C13. The pilots used four different FIM-S software loads during the 19 flying days (see Table A-1).

C14. The first two loads were plagued with instability and required the crews to utilize several programing workarounds. The third load, which was used starting with the eighth flight, was much more stable. With pilot compensation, the FIM-S software was very capable of producing consistent spacing errors of 5 seconds or less. The final software load, which was used for the final two flights, optimized the actual STAR profiles, which reduced the amount of pilot compensation needed. This load provided the best overall results. On the final day of flight testing, each of the four runs had a spacing error of 1 second. As a comparison, the average spacing error currently achieved by ATC is approximately 18 seconds. Improving to 5 seconds or less of error, would result in 11 more landing slots per hour to the same runway.

What improvements need to be made for the next version of FIM/ATD?

C15. While this phase of testing proved that the FIM-S algorithms do work, continued development of the algorithm is needed. An algorithm that maintains string stability but more proactively corrects for errors would be an improvement. The vertical path and autothrottle performance of different airplanes using the system also needs to be incorporated.

C16. Another round of flight tests, that would demonstrate a more mature FIM-S algorithm, along with the ground components of time-based flow management that were not demonstrated during NASA ATD-1 (Ground Interval Management - Spacing and Traffic Sequencing And Spacing) should be considered. Optimized STARs are also needed.

What is the future of FIM-S from United's/airline's perspective?

C17. The next step for FIM-S is for the industry to advocate for FIM capability within the RTCA NextGen Advisory Committee (NAC). FIM could be an important component of the northeast airspace initiative, improving operations in the northeastern US. There are no other concepts that allow for maintaining VMC arrival rates during periods of lower ceilings and visibilities, when visual approaches are not possible. To implement FIM-S, either a mandate is needed or those who choose to equip should receive preferential treatment.

4.1.5 Hardware Installation

United Airlines' Comments

C18. The airline/flying partners need to be more involved in the equipment selections/specifications during the planning phases of the project.

C19. For something like FIM-S to be able to be considered for airlines in the future, it would need to be able to be run on the airline's existing EFBs (in United's case it is iPads). United is not going to install a permanent EFB with FIM-S if we already have EFBs. This should be considered when developing the hardware and software. It would have been much more time and cost effective if we could have installed FIM-S on our United EFBs/iPads—this should be a goal for future projects—and use what is already in the airplane when possible.

C20. Another option would be to use different, uncertified tablets—again, not using class 3 EFBs (duplicate comment with C11 for added emphasis).

4.1.6 Flight Test

Planning

Boeing Comments

C21. The SOW used the term “Flight Test Readiness Review” to refer to what industry would normally call a Test Readiness Review. While the test ultimately was a flight test or series of flight tests, there was also bench and ground testing required. The term caused a lot of misunderstanding among industry participants. Ultimately, the program went with a test readiness review to ensure all the parts were ready to start formal on-airplane testing and then conducted flight readiness reviews prior to the start of flight test sequences to ensure all the details were complete to run the individual flight tests.

C22. Integrated simulators with Human-in-the-Loop was not done because of both cost and schedule constraints. The traveled risk was successfully mitigated with expertise and schedule padding but could have gone very wrong.

C23. A specific example was Falcon pilots having difficulty meeting lead times and engaging military SUA along the flight path. Extra coordination with the ATC and support from the test directors ultimately mitigated the risks but a lesson was learned—include the target pilots in the training simulations even if they only observe.

Execution

Boeing and Honeywell Comments

C24. No pre-training of the Falcon pilots was mitigated by having backup flight test director ride jump-seat on the Falcon.

C25. Rotating Falcon pilots required the backup test director to stay on the Falcon to help work ATC issues.

C26. Workload for the Falcon pilots was high between loading the FMC speeds for the next approach, maneuvering to adjust the arrival times, and working ATC. In this case issue with the Falcon added to that workload as well as poor weather early in the flight test. Having the extra pilot on board was used by some crews to help reduce that workload.

C27. The many settings on the Falcon FMS proved problematic in the beginning. Examples include the limit on bank angle at altitude, and frequency settings. Once these were worked out, the FMS ETAS proved very accurate as long as it was set up correctly and the Falcon was inbound on the FMS course.

C28. Having the Embraer 170 as backup was a very helpful provision that Honeywell provided at no additional program cost.

C29. Situational Awareness is extremely critical for this kind of multi-airplane flight test. The ability for the Test Director to see the full big picture proved to be the difference between success and failure. When the Planet displays were working, the SA was very good and allowed an efficient flight test.

C30. Good, effective risk management mitigated the most challenging risks and made the program a success.

C31. Good communication proved essential.

C32. Organizational communication allowed the many team members to work effectively to solve problems as they came up.

C33. Technical communication, including dissimilar paths was critical; VHF, Cell Phone, IM on planet, telephone, and email.

Professionalism of all the team members, examples include:

Boeing and Honeywell Comments

C34. Honeywell pilots figuring out how to get the flight plans filed, including United flight plans, even though the national flight plan filing system rejected them because of the STARS not being published in the ATC database.

C35. Pilots collaborated each evening to find workarounds to software issues (see Table A-1).

C36. The airplanes FMS' ETAs were used to set up the sequences and "substitute" for GIM-S tools. This worked with some issues. On the Falcon FMS, the ETAs only read out in minutes. The accuracy needed to set up the test sequences required seconds resolution. The ETAs, while only reporting in minutes, were accurate to within seconds and, after some trial and error, a workaround was devised for the Falcon. As the Falcon was coming onto course or into the speed range, the ETA change could be tracked and, when it was crossing a minute boundary, to point could be noted. This allowed resolving the ETA down to 10 seconds and proved quite accurate. As could be expected, when maneuvering or off the planned path, including speed, the ETA was not accurate. The 737 FMS proved very good at ETAs even when challenged with path changes, but that was influenced by pilot technique.

Program Management

United Airlines' Comments

C37. Develop a draft flight test schedule prior to the beginning of flight test. Any known no-fly days should be communicated to everyone prior to flight test beginning. For example, NASA knew there would be one Friday or Monday off to accommodate their people needing travel back to Virginia per the NASA travel policy. This was not made known to the rest of the flight team until the week prior to the no-fly day. United (and Honeywell) had people traveling to Seattle, and the schedule impacted us a lot more than Boeing or NASA.

C38. Streamline planning calls; there was a lot of duplication between the flight test WG, data collection WG, bi-weekly PM calls, etc. during the planning phases of the project.

United Airlines' Comments

C39. All crews should train together, as opposed to training be split into multiple groupings.

C40. Pilot training should be completed with the FIM-S software that will be used during flight test.

C41. Having both pre- and post-flight briefings after every flight did not seem necessary. Especially once we got past the first few flights, it seems like we could have had pre-flight briefings on a daily basis and then had post-flight briefings on an as-needed basis.

C42. FIM-S is operationally feasible, but needs to be integrated into the FMC and not used on a standalone EFB setup.

C43. FAA needs to apply FIM-S logic to the design of STARS and transitions to approaches, especially to airspeed and altitude windows.

Boeing Comments

C44. Coordinating a complex flight test like this one, including 3 vehicles interacting, and required a well-informed flight test director. Placing the flight test director on the middle airplane, especially the one with good situational awareness was critical. Originally the plan was to have the flight test director at Boeing field. With the addition of the Planet software for situational awareness, moving the flight test director to the 757 proved a very good move. It allowed good SA, good communications with the other airplanes, and two paths to communicate with the 757 crew, VHF radio for messages that needed to be shared with the other flight crews, and intercom for those that did not.

C45. The simulator training that was done at NASA Langley was very valuable for working out operating concepts and coordination techniques. It also allowed refining the operating procedures.

C46. Lead airplane crews understanding the role and criticality of the lead airplane in the flight test setup. The simulator facility at Langley did not have a Human-in-the-Loop simulator for the Falcon, to the simulations were done using a computer surrogate. This was okay but left a large issue both with working out procedures for the lead airplane and training the Falcon crews. In hindsight, the program should have had the Falcon crews, at least a couple of pilots, train on the Langley simulation as Test Directors. This would have allowed them to see the “big picture” and better understand the role of the lead airplane.

C47. Have all the constraints to flight profiles on one diagram rather than expecting the crews assimilate data from several sources. The STARS, military special use airspace, and civilian ATC sector information were depicted on different information sources. While the Falcon pilots had a multidisplay cockpit and additional iPads and paper charts, not one of the various tools showed all of the constraints. The STARs and Special Use Airspace (SUA) were shown on the cockpit displays and the iPads but the Civil ATC sectors and what turned out to be a keep-out zone for other civilian flight testing were not. This required the pilots to keep track of several different restrictions, which proved very difficult and resulted in several frustrations from the ATC controllers. An example was that the military SUA was depicted but the controllers wanted a 3 mile buffer from the SUA—just keeping out of the SUA was not sufficient.

4.2 Conclusions

The NASA ATD-1 ASTAR algorithm clearly demonstrated the promise of IM operations using the Boeing, and Honeywell jointly developed FIM-S avionics in the 19 flying days test program.

During the February 2017 flight testing at Moses Lake, WA, FIM-S avionics on Honeywell and United Airlines commercial airplanes flew for 19 flying days to assess a FIM-S algorithm based on the NASA ASTAR solution and performance. The flight test program has very successfully demonstrated IM operations on 144 merging and in-trail spacing runs using a chain of three airplanes. In general, the flight trial clearly demonstrated the feasibility of FIM operations as a means to maintain arrival capacity during low ceiling and visibilities or high winds by precisely controlling inter-arrival spacing. The FIM-S system tested during the ATD-1 flight trial met all but one of the MOPS criterion, a remarkable achievement given this was the first prototype FIM-S system.

The FIM-S prototype overall showed good performance through: 1) 19 uniquely different flight days (winds, multiple United and Honeywell crews); 2) a variety of realistic initial spacing errors (see Table 1); 3) cruise, descent and approach regimes; and 4) several off-profile conditions for the lead airplane in the chain (see Table 1). The goal was not to confirm if the prototype passes MOPS but to evaluate its performance through flight test. The data collection effort confirmed that: 1) delivery performance is close to the MOPS at the PTP and ABP throughout; 2) IM speed rate is acceptable although some algorithm improvements could make it better, especially for MAINTAIN operations, and 3) the capture rate is close to the MOPS criterion, except in extreme conditions. In aggregate, time-based operations delivered at the PTP were slightly worse than the MOPS criterion. This is mostly driven by CROSS operations. MAINTAIN, SPACE, or CAPTURE operations all met the MOPS criteria.

FIM operations require a smooth nominal speed profile embedded within the procedure design as the nominal basis for the control algorithm. Pilot feedback and data analysis revealed the impact of route design on FIM-S 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-S system, a design that seeks a smoother nominal speed transition along the route would lead to less drastic speed changes during IM operations.

The SE WG made several difficult risk-reduction decisions (and, in hindsight, correct decisions) in managing the program to avoid implementation errors and omissions. The results produced flight test data for performance and other analysis from well over 80% of the recorded data. The accelerated, yet risk- and cost-rational SE steps used configuration controlled relational database tools (i.e., DOORS and other tools) throughout their SE processes and testing to assess the collected data on 144 Flown FIM-S experiments (runs). The team built a successful prototype without following all the traditional processes of a fully certified development and test program, yet the team maintained traceability of system level design features to the MOPS. MOPS findings and flight test data interpretations were documented to be leveraged in future flight test planning and/or design activities. This report provides a list of those requirements that were not implemented or required additional clarification to support future reviews. The software version documentation in Appendix A includes a detailed list of resolved and open test issues. The accelerated SE development processes were successful in that they maintained systematic system level requirements traceability throughout the documentation hierarchy; this will allow readers to find needed evidence to support MOPS standards findings and clarifications.

Although more development work is necessary for operational implementation, the FIM-S system tested during the ATD-1 flight trial met all but one of the MOPS performance metrics during flight test. It is remarkable to have the first prototype FIM-S system perform as well as it did. The one design goal not met is very close to being achieved, and was for one particular geometry and clearance type. There is very high confidence that this clearance type and geometry will be corrected prior to any future FIM testing. To achieve arrival operations that are integrated with the ATC ground systems end-to-end is the ultimate goal and will require solving several issues. Section 4.1 of this report describes the lessons learned that illustrate the issues; the next section provides recommendations based on the ATD-1 lessons learned to support potential future testing.

4.3 Summary Recommendations

The 19 flying days testing a FIM-S algorithm based on the NASA ASTAR solution, led to productive discussions on the recommendations for future FIM-S testing. The recommendations fall into two main categories: (1) expansion of the ATD-1 flight test processes and steps to improve and increase the number of successful FIM experiments (runs) and (2) future testing to expand the spectrum of realistic IM operations. To further decompose the recommendations and improve readability, each of these two areas are divided in two subordinate areas: (1a) expand ATD-1 FIM-S flight test planning; (1b) enhance ATD-1 FIM-S procedures design and operations; (2a) future prototypes development processes (i.e., focused on design cycles); and (2b) accelerated, yet affordable, risk planning for future end-to-end flight or other types of testing.

It should be mentioned that to ensure successful end-to-end flight testing as recommended in section 4.3.4, the recommendations in sections 4.3.1 – 4.3.3 should be taken into account in the planning of end-to-end testing.

4.3.1 Expand ATD-1 FIM-S Flight Test Planning

The report's lessons learned discussed a number of situations associated with the ATD-1 flight test. From these observations, the following recommendations are made:

- Improved training of flight test personnel (see comments C22-C23):
    - Captain and First Officer: all crews should train together so as to develop common/harmonized FIM-S flying techniques. Include training for lead/target airplane crew who need to apply the same flying techniques (see comments C24—C27, C46).
    - Captain and First Officer: train with the actual software used for flight test (see comments C39—C40).
    - Test engineers: harmonize the flying procedures awareness among all support personnel such as flight test engineers and others. (see comment C44)

    - ATC personnel: Multiple ATC coordination briefings were performed for this flight test. Simulator training would be critical for future air and ground integrated testing of IM operations (see comment C23).
    - Flight test directors: The NASA simulator training was done with the flight test directors and this was very beneficial to the execution of the flight test. This training should be a model for training other personnel (e.g., ATC, test engineers – see comment C45).
- Involve ATC personnel in the experiment design to include criteria for IM operations set up (e.g., static and dynamic situations) and real-time spacing intervals feasibility checks. (see comment C44)
- Add depictions of the dynamic flight test constraints (e.g., traffic) encountered in ATD-1: other traffic performing tests at the airport (i.e., Mitsubishi flight tests), extra no-fly margins on the edges of the MOA, crew awareness of their proximity to ATC center boundaries, etc. (see comment C47)
- Include a flight testing cycle with actual hardware/software systems (see comments C13-C14).

4.3.2 Enhance ATD-1 FIM-S Procedures Design and Operations

With ATD-1 flight test complete and many of the MOPS testing criteria reviewed, it is necessary to also discuss opportunities to enhance FIM-S procedures design to improve IM operations. To this end we recommend the following:

- Apply FIM-S logic (i.e., algorithm speed management criteria, etc.) to design STARS and transitions to approaches with optimized IM airspeed and altitude windows (see comments C1, C5, C6 and C43).
- Develop and modify existing arrival procedures to allow for additional speed authority on the flight deck (see comments C7 – C9, C12) such as using ~2.6 degrees vertical path descents rather than the 3 degrees of traditional arrivals (see comment C1).
- Include ATC in the execution and training of experiments rather than use the Test Director's 'scripted' experiment set up information (see comment C1).
- Require baseline FMS performance for RNP AR procedures (see section 2.2).

4.3.3 Future Prototypes Development Processes

The report discussed the CPFF nature of the flight test contract, in particular the compressed schedule that limited software loads and the number of test cycles to two. From the observations discussed throughout the report, the following general recommendations for future prototypes development are made:

- Include additional software development test cycles linked to specific test objectives (e.g., add one or several flight days for initial software checkout test – see sections 2.5, 4.1.1 Display/Human Interface and comment C22).

- Enhance the FIM-S algorithm (see comments C5 – C9, C15, Table A-5 item #273, #274, #276, #278).
- Explore alternative hardware and platform architectures to enhanced PoFV displays and augmented data sources integration (see comments C3, C10, C11, C18, C19, and C20).
- Include MOPS test vectors for all clearance types in support of hardware-in-the-loop system testing. (see sections 2.5 and 4.1.1 Algorithms)
- Include a software usability testing cycle on hardware-in-the-loop test benches to enable crew HMI focus group discussions and CDTI layout reviews. (See section 4.1.1 Display/Human Machine Interface and Table A-5 #275).

4.3.4 Future End-to-End Flight Test Planning

The report's introduction section describes the FAA and NASA efforts at deploying both ground automation and airborne capabilities to perform integrated air and ground IM operations. The goal is for continued improvement in the level of spacing precision on final approach. The full integration with ground ATC systems was not part of this testing and should be the primary goal of any follow-on activities. The SE lessons learned illustrate important processes to successfully plan a future testing campaign. From the programmatic observations discussed throughout the report, the following recommendations are made:

- Include integrated ATC (air and ground) technologies including GIM, FIM-S, TBFM and RTA (see section 1 and comments C16, C36).
- Test in a mixed datalink and voice environment (see section 1, Table A-5 #277).
- Develop and test a broader set of MOPS test vectors with enhanced procedure designs leading to enhanced operations (e.g., see section 2.5 and apply recommendation 4.3.3 enhanced with data link test vectors).
- Use accelerated, yet risk and cost rational, processes (i.e., from a funding perspective) to integrate air & ground capabilities (e.g., jointly integrate and certify air and ground capabilities using ATD-1 accelerated processes – see section 1.1 and comment C2).

It should be mentioned that to ensure successful end-to-end flight testing as recommended in section 4.3.4, the recommendations in sections 4.3.1 – 4.3.3 should be taken into account in the planning of end-to-end testing.

Acronyms

ABP	Achieve-By Point
ADS-B	Automatic Dependent Surveillance – Broadcast
AID	Aircraft Interface Device
AIRB	Airborne Basic Situation Awareness
ANSP	Air Navigation Services Provider
ARINC	Aeronautical Radio, Incorporated
ASG	Assigned Spacing Goal
ASTAR	Airborne Spacing for Terminal Arrivals Routes
AR	Authorization Required
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATD-1	Air Traffic Management Technology Demonstration 1
ATM	Air Traffic Management
CAS	Calibrated Air Speed
CDR	Critical Design Review
CDRL	Contracted Deliverable Requirements List
CDTI	Cockpit Display of Traffic Information
CGD	Configurable Graphic Display
CMS	Controller Managed Spacing
CONOPS	Concept of Operations
CPFF	Cost Plus Fixed Fee
DO	Designation for RTCA DOcument Number
EFB	Electronic Flight Bag
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration

FIM	Flight Interval Management
FIM-S	Flight Interval Management - Spacing
FMS	Flight Management System
FRAC	Final Review and Comment (RTCA)
FSI	Fast/Slow Indicator
GFI	Government Furnished Information
GIM	Ground-based Interval Management
GIM-S	Ground-based Interval Management - Spacing
GNSS	Global Navigation Satellite System
HMI	Human Machine Interface
ICD	Interface Control Document
IFPI	Intended Flight Path Information
IFR	Instrument Flight Rule
IM	Interval Management
I/O	Input Output
IP	Internet Protocol
ITP	In Trail Spacing
LNAV	Lateral Navigation
MCP	Mode Control Panel
MOA	Military Operations Area
MOPS	Minimum Operational Performance Standards
MSI	Measured Spacing Interval
MWH	Moses Lake Airport
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAV DB	Navigation Database

PDR	Preliminary Design Review
PFoV	Primary Field of View
PI	Progress Indicator
PSI	Predicted Spacing Interval
PTP	Planned Termination Point
RCAG	Remote Communications Air Ground
RNAV	Area Navigation
RNP	Required Navigation Performance
RTA	Required Time of Arrival
RTCA	RTCA Inc., formerly Radio Technical Commission for Aeronautics
SA	Situational Awareness
SAR	System Acceptance Review
SATCOM	Satellite Communications
SDD	Software Design Description
SE	System Engineering
SOW	Statement of Work
SRD	System Requirements Document (NASA)
SRDD	System Requirements Definition Document (Boeing)
SRS	Software Requirements Specification
STAR	Standard Terminal Arrival Route
STP	System Test Plan
SW	Software
TBFM	Time-based Flow Management
TCAS	Traffic Alert and Collision Avoidance System
TG	Trajectory Generator

TM	Terminal Metering
TMA	Traffic Management Advisor
TPU	Traffic Processor Unit
TTF	Traffic To Follow
UTC	Universal Time Coordinated or UTC Aerospace Inc.
VHF	Very High Frequency
VNAV	Vertical Navigation
WG	Working Group

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Appendix A FIM Software Test Issues

This appendix summarizes the software test issues that were discovered during development and testing and that were either deferred before the flight test began or were discovered during the flight test itself. Some of these issues were corrected with builds released during the flight test program, and some are still open.

Table A-1 gives a timeline of the flight test and the software build versions that were used. For software issues that were corrected, the build number containing the correction is listed and can be cross-referenced to this table to determine the impact on flight test.

The remaining tables list items deferred before SAR, issues found during the January SAR re-run, issues found in the flight test proper and post-flight test suggestions for future work respectively. In these tables, test issues listed in GREEN text are still open. Issues **listed in BLACK text** were corrected in a build sometime before the completion of the flight test program.

A complete listing of all software test issues found during the development phases before SAR was delivered as a separate database to NASA in conjunction with the SAR. That database included detailed descriptions of the issues found up until that time, including the deferred items in Table A-2. An updated summary of test issues was included as an attachment to the Software Version Description document [15] (deliverable 4.4f) including items found after SAR.

Table A-1. Flight Test Build Timeline

Build	Usage
2.0.2	January SAR rerun, 1/18 Ferry flight/check flight, Flight test days 1-3 (1/20 – 1/25)
2.0.5	Flight test days 4-5 (1/26 – 1/27)
2.0.8	Flight test days 6-16 (2/1 – 2/16)
2.1.0 + Modified NavDB	Flight test days 17-19 (2/20 – 2/22)

Note: Build are cumulative, i.e. fixes listed for build 2.0.3 and 2.0.4 were not flown until 2.0.5 installed on 1/26, etc.

Table A-2. Issues Deferred Before Flight Test

Issue #	Title
#2	TPU calculated track angle should match heading when velocity is zero
#43	Non IM Eligible Targets can be manually selected
#81	Traffic not removed upon TCAS failure
#89	Naming of PTP ABP before after waypoint not per HMI wireframe

Issue #	Title
#104	ABP and PTP entry selection shows waypoints that are not common to TGT and Ownship routes
#150	Traffic IM Eligibility - Traffic Velocity Age
#151	Traffic IM Eligibility - ADS-B Source
#152	Traffic IM Eligibility - Same Flight Id
#192	Extrapolation of Target Data
#203	Incorrect Control Law running when switching clearances
#209	Default Planned Termination Point insertion
#219	Speed Commands sometimes shown in non-rounded values
#232	Procedural Speed Limits not always enforced in the absence of speed change commands
#236	Erratic display of Target Absolute Altitude
#237	IM DB NOT CURRENT does not force UNABLE
#244	FAST/SLOW Indicator changes are required
#246	When selected PTP does not have a speed constraint, the wrong default is sometime applied
#249	Sudden Change in Nominal profile limit during Transition to After PTP (probably caused by ground speed matching)
#250	PTP ABP selection At/Before/After Runway not working correctly (closed - not reproducible in current build)
#252	Default PTP selection when no runway is entered in IFPI

Table A-3. Issues found during SAR rerun

Issue #	Title/Status
#253	Changing the Waypoint from Slave corrupted Waypoint Entry list Fixed in build 2.0.3
#254	HMI can show inconsistent Runway and Flight Path elements Fixed in build 2.0.3
#255	Navigation database cycle dates annunciation Found after SAR (with new Nav DB) Fixed in build 2.1.0
#256	Not able to see all STARs associated with an Airport once a runway has been selected Fixed in build 2.0.4

Table A-4. Issues Found During Flight Test

Issue #	Title/Status
#257	Waypoints not shown in ABP and PTP menus • Found on ferry flight/check flight • Work-around used during flight test • Problem may have been fixed by subsequent builds, but is still listed as Active
#258	Descent winds lost when clearance information is re-entered (or even just looked at?) Work-around used for some flights Fixed in build 2.0.6
#259	OWNSHIP ENTRY page sometimes shows TARGET ENTRY as title No work-around (never reported as a problem by the flight crew) Fixed in build 2.0.6
#260	CTD Algorithm Maintain Time-History (THDB lookup problem) Partial work-around was to fly the Falcon like an air transport jet Several fixes tried, final fix in build 2.0.9
#261	BAD ROUTE – Upstream Speed Constraint Ultimately caused by a complicated interaction between low altitude “cruise” segments and inappropriate deceleration parameters Fixed in build 2.0.5
#262	Target Bearing and Range missing from CTDI • Work around was to use RTA, Planet and other ADS-B data for test director situational awareness • Root cause found, but not fixed yet, listed as Active
#263	Re-entering runway clears all data except Destination airport • Actual problem is slightly more complicated than title implies – the data is cleared but the new data isn’t used if a previous clearance was active at the time of the change • Fixed in build 2.0.3
#264	SUSPENDED or UNABLE with no fault message & system must be reset to recover Traced to buffer overrun in Trajectory Generator Fixed in build 2.0.8
#265	Trajectory "loops" back to start of IFPI Work around was to wait after arming until route stabilized before executing Software fix was to add comparison of distance to destination for candidate active legs as well as cross track error and heading Fixed in build 2.0.8
#266	(duplicate of #258)
#267	Dropped upstream speed constraints cause incorrect speed profile Problem affected Target TG regens. Previously sequenced speed constraints wouldn’t be applied and the calculated speed profile would be incorrect Fixed in build 2.0.7_Interim

#268	Cruise/Descent Profile entry page CLEAR button sets bad default cruise altitude Work around was to avoid using the clear function when updating the profile Fixed in build 2.0.8
#269	TG Regen reason appears to be incorrect in the logs • Did not affect flight testing but may affect data analysis – needs to be kept in mind when interpreting log data • Still listed as Active
#270	(deleted)
#271	TG regens when target is past PTP cause bad route and IM UNABLE • Can also occur when target passes ABP but before CTD algorithm applies • Would require requirements analysis to determine best solution • Still listed as Active
#272	Transient faults causing IM AVAILABILITY fail not handled properly • Temporary drop in GPS integrity caused system to not be eligible for IM • Fault was not logged correctly or cleared properly when GPS returned • Still listed as Active

Table A-5. Post Flight Test Issues/Suggestions for Future Work

Issue #	**Title/Status**
#273	Add hysteresis to CTD gain schedule • Small variations in spacing error could cause different gain values to be used and could cause extra speed commands to be issued • Listed as Deferred

#274	Develop complete Mach Control Law • Current speed control implementation uses ad hoc methods to control the speed in the Mach regime • Worst case behavior could theoretically cause speed commands in the wrong direction • Listed as Deferred with detailed description provided here: The Mach handling existing in the current baseline was developed to satisfy the need to quickly define a basic set of rules designed to provide acceptable performance under common conditions. It should be evaluated whether development of a more complete Mach Control Law is warranted. Topics to be considered would include: (1) performance when selector is not left at its 'default' setting (ex. outputting Mach commands below the Crossover Altitude), (2) limiting (including nominal profile limiting as well as IM Speed Upper Limit and Mmo - conversion of Mach limit values to CAS can result in "rounding" which further restricts the limits), (3) CAS/Mach conversions when ownship is not flying its nominal altitude profile (ex. ownship begins to descend early relative to the nominal TOD. For TBO, in the case of needing to incorporate a speed correction, the sum of the nominal profile CAS and the speed correction are converted to Mach based on the reported altitude, not the nominal altitude at which the nominal CAS was derived. If the altitude differences between reported and nominal are very large (very close to the TG re-generation limit), this could possibly lead to Commanded IM Speed values in the opposite trend of the correction.
#275	Proposed enhancements from HMI dev team • Improvements to dialogs, text boxes, symbology and HMI controls are suggested • (Details listed in Test Issue DB) • Listed as Deferred
#276	MACH/CAS speed limits should be separate and independent • NASA suggested improvement • The Mach/CAS page should have a separate minimum and maximum limits entered, and the software should apply those limits only when the airplane is within that regime • Listed as Feature Request
#277	Wind data entry should come from datalink • NASA suggested improvement • The data entry of wind data was time consuming and prone to error. Hopefully some form of datacomm or ACARS will be available in the future • Listed as Feature Request
#278	Speed Control enhancements suggested by NASA • Recommendations are provided to improve pilot acceptability of the speed commands • (Complete details listed in Test Issue Database, partial list under #274) • Listed as Feature Request

#279	"Shadows" in reported spacing interval • When TTF passes the ABP, the reported spacing interval often shows a distinct noise pattern that looks like a second, shadowing, curve offset slightly from the primary curve. • Listed as Active
#280	For distance-based clearances, the gain schedule in the requirements does not reflect the gain schedule implemented in the software • Based on observed speed control performance at SAR, NASA requested changes to the distance-based gain schedule. These changes were incorporated into the flight software, but the software requirements and code tags have not been updated with the new values yet. • Listed as Deferred

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14. ABSTRACT

This document provides a summary of the avionics design, implementation, and evaluation activities conducted for the ATD-1 Avionics Phase 2. The flight test data collection and a subset of the analysis results are described. This report also documents lessons learned, conclusions, and recommendations to guide further development efforts.

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