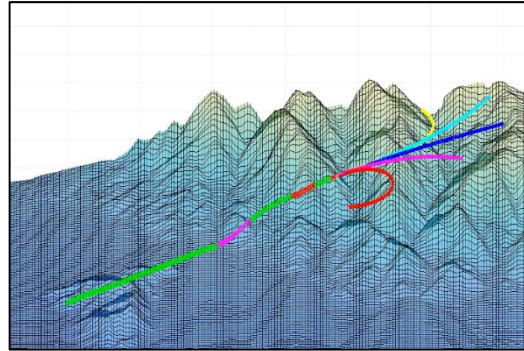




A LIMITED EVALUATION OF AN AUTOMATIC GROUND COLLISION AVOIDANCE SYSTEM FOR PERFORMANCE LIMITED AIRCRAFT

(Project Have MEDUSA)



KENNETH C. GAHAN, Capt, USAF
Project Manager, Project Test Combat Systems Officer

CARL A. GOTWALD, Capt, USAF
Scheduling Chief, Project Test RPA Pilot

MICHAEL A. BAKUN, Capt, USAF
Safety Chief, Project Test Pilot

MARK A. HAMMOND, Capt, USAF
Security/Budget/Logistics Chief, Project Test Pilot

SHANNON MAK JIAN MING, Capt, RSAF
Test Plans Chief, Project Flight Test Engineer

RYAN S. KOLESAR, Capt, USAF
Data Management Chief, Project Flight Test Engineer

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FINAL TECHNICAL INFORMATION MEMORANDUM

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Prepared by:

GAHAN.KENNETH.
CHRISTOPHE.1297
727954

Digitally signed by
GAHAN.KENNETH.CHRISTOPH
E.1297727954
Date: 2018.12.04 07:24:00 -08'00'

KENNETH C. GAHAN
Capt, USAF
Project Manager/Test Combat Systems Officer

GOTWALD.CARL.A
NDREW.128342075
9

Digitally signed by
GOTWALD.CARL.ANDREW.128
3420759
Date: 2018.12.04 07:29:18 -08'00'

CARL A. GOTWALD
Captain, USAF
Project Test RPA Pilot

BAKUN.MICHAEL.A
NTHONY.13983118
13

Digitally signed by
BAKUN.MICHAEL.ANTHONY.13
98311813
Date: 2018.12.04 07:31:14 -08'00'

MICHAEL A. BAKUN
Captain, USAF
Project Test Pilot

HAMMOND.MAR
K.A.1291054893

Digitally signed by
HAMMOND.MARK.A.129105489
3
Date: 2018.12.04 07:32:18 -08'00'

MARK A. HAMMOND
Captain, USAF
Project Test Pilot

MAK.JIAN MING
SHANNON.154199
7632

Digitally signed by MAK.JIAN
MING SHANNON.1541997632
Date: 2018.12.04 08:26:31
-08'00'

SHANNON MAK JIAN MING
Captain, RSAF
Project Flight Test Engineer

KOLESAR.RYAN.S
COTT.1368168781

Digitally signed by
KOLESAR.RYAN.SCOTT.136816
8781
Date: 2018.12.04 08:33:17 -08'00'

RYAN S. KOLESAR
Captain, USAF
Project Flight Test Engineer

**This technical information
memorandum has been reviewed and is
approved for publication by:**

FREEBORN.ANDR
EW.B.1174435606

Digitally signed by
FREEBORN.ANDREW.B.117443
5606
Date: 2018.12.04 08:58:45 -08'00'

ANDREW B. FREEBORN
NH-IV, USAF
Staff Advisor, USAF Test Pilot School

COOKSON.JERE
MY.L.1274642188

Digitally signed by
COOKSON.JEREMY.L.12746421
88
Date: 2018.12.04 17:34:30 -08'00'

JEREMY L. COOKSON
NH-IV, USAF
Technical Expert, USAF Test Pilot School

VANHOY.DAVI
D.L.1229799688

Digitally signed by
VANHOY.DAVID.L.1229799688
Date: 2018.12.07 09:10:04 -08'00'

DAVID L. VANHOY
NH-IV, USAF
Technical Director, USAF Test Pilot School

BLAKE.RYAN.
D.1129274553

Digitally signed by
BLAKE.RYAN.D.1129274553
Date: 2018.12.17 16:52:46
-08'00'

RYAN D. BLAKE
Colonel, USAF
Commandant, USAF Test Pilot School

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a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19B. TELEPHONE NUMBER (937) 798-4601

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EXECUTIVE SUMMARY

This report presents the results for the Have Multi-path Escape Decisions Using Sophisticated Algorithms (Have MEDUSA) test management project (TMP). The lead developmental test organization (LDTO) was the Air Force Test Center, Edwards AFB, California. The executing test organization (ETO) was Class 18A of the United States Air Force Test Pilot School (USAF TPS) working in partnership with Calspan Corporation, Buffalo, New York and the Air Force Institute of Technology (AFIT), Wright-Patterson AFB, Ohio. Testing was requested by the Air Force Research Laboratory, Wright-Patterson AFB, Ohio. Testing was performed in the Calspan Learjet 25D (LJ-25D) Variable Stability System (VSS), tail number N203VS, from 5 to 18 September 2018. Testing included 11 sorties and 19.9 flight hours in the R-2508 complex and 2 ground test hours under the job order number (JON) MT18A200.

A successfully implemented automatic ground collision avoidance system (Auto-GCAS) for performance limited aircraft, such as transports and bombers, will help mitigate future Air Force mishaps. Have MEDUSA used the Rapidly Selectable Escape Trajectory (RSET) system to predict terrain collision potential and automatically command appropriate ground avoidance maneuvers. The RSET algorithms used aircraft state and navigation information to predict escape maneuvers using five trajectory prediction algorithms (TPAs) which projected the aircraft path forward 30 seconds. The TPA maneuvers consisted of left and right 60° bank turns, left and right 30° bank climbing turns, and a wings-level climb. All five TPAs used a speed-scaled, g-limited, flight path angle control law designed for performance limited (Class III) aircraft as defined in *MIL-STD-1797B* (reference 1). These five maneuvers were simultaneously compared to the surrounding Digital Terrain Elevation Database (DTED) terrain data, which was vertically biased to create a terrain safety buffer. When the RSET system predicted that all the TPA maneuvers would intersect the terrain safety buffer, the flight control system was commanded to execute the last previously open path. During this test the VSS, which could simulate various aircraft, was configured as a baseline LJ-25D.

The RSET system was flight tested at 15,000 ft PA, 8,000 ft PA, and 500 ft AGL, each at 220 and 270 KIAS. Entry conditions consisted of straight-and-level, climbing, descending, and turning attitudes. The system was manually activated by the test team via the center console system between the pilots and a laptop at the test conductor station. The system was automatically activated by DTED from a mountain in R-2508 which was virtually relocated to the aircraft position with a position and heading slewing tool. For safety, the Learjet was hand-flown in the vicinity of actual terrain to evaluate nuisance in the system with the RSET command link severed.

The overall test objective was to demonstrate the utility of the RSET system as a multipath Auto-GCAS for performance limited aircraft. All objectives were met.

Overall, the RSET system was assessed to be MARGINAL. The RSET system performance demonstrated the utility of using a multi-path collision avoidance system for performance limited aircraft. Path prediction error (PPE) did not meet the specified criteria and was larger than expected for the 30-second path predictions; however, at the maximum refresh rate of 12.5 Hz, the RSET system ensured terrain clearance in all cases tested. Incorrect accounting for wind drift effects, the Learjet VSS auto-trim feature, and the low fidelity engine model were possible sources of PPE. The test team recommended the main sources of PPE be determined prior to further testing. Despite the simple design of the control logic, the RSET system was able to achieve and maintain target load factor and flight path angle with momentary overshoots. The RSET system response was in line with the timely and aggressive characteristics desirable for Auto-GCASs. The system showed no tendency for nuisance activations for all cases tested. The RSET hand-back implementation utilized was immature and the Learjet VSS safety trips were repeatedly triggered. Despite the unrefined hand-back, the response was deemed favorable in most cases and could be utilized as a baseline for future Auto-GCAS implementations.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY	ii
TABLE OF CONTENTS	iv
LIST OF FIGURES	vi
LIST OF TABLES	vii
INTRODUCTION	1
BACKGROUND	1
AGGRESSIVE AND TIMELY	2
F-16 AUTO-GCAS	2
PERFORMANCE LIMITED AIRCRAFT GCAS	3
TEST ITEM DESCRIPTION	5
RSET SYSTEM	5
TRAJECTORY PREDICTION ALGORITHMS	7
COLLISION DETECTOR	7
MANEUVER AUTOPILOTS	8
HAND-BACK	9
HAVE ESCAPE DIFFERENCES SUMMARY	10
RESEARCH VEHICLE	10
RESEARCH LAPTOP COMPUTER	13
OVERALL TEST OBJECTIVE	13
CONSTRAINTS	14
ASSUMPTIONS	14
TEST AND EVALUATION	15
RSET SYSTEM PREDICTION ACCURACY	15
REFRESH RATE IMPACT ON ESCAPE PATH CALCULATION	27
NUISANCE ACTIVATION TENDENCY	35
MANEUVER TERMINATION CONTROL HAND-BACK	46
TEST RESULTS SUMMARY AND RECOMMENDATIONS	48
REFERENCES	50
APPENDIX A – DETAILED TEST ITEM DESCRIPTION	A-1
MODEL DEVELOPMENT	A-1
ENGINE MODEL	A-7
CONTROL LAW DESIGN	A-8

MODEL DEGREES OF FREEDOM	A-9
APPENDIX B – RATING CRITERIA.....	B-1
APPENDIX C – DATA ANALYSIS PROCEDURES	C-1
APPENDIX D – TEST POINTS	D-1
APPENDIX E – PATH PREDICTION ERROR RESULTS.....	E-1
APPENDIX F – VIRTUAL TERRAIN ACTIVATION RESULTS	F-1
APPENDIX G – MEDUSA CONFIGURATION TRACKER.....	G-1
APPENDIX H – DAILY FLIGHT TEST REPORTS	H-1
APPENDIX I – LESSONS LEARNED.....	I-1
APPENDIX J – LIST OF ACRONYMS	J-1
APPENDIX K – DIGITAL APPENDIX.....	K-1
APPENDIX L – TEST LAPTOP SPECIFICATIONS	L-1
APPENDIX M – HAND-BACK SURVEY	M-1
APPENDIX N – AIRCREW COMMENTS.....	N-1
APPENDIX O – DISTRIBUTION LIST.....	O-1

LIST OF FIGURES

Figure 1 – Top Commercial Aviation Fatal Accident Categories 2008 – 2017 (reference 2)	1
Figure 2 – Aggressive and Timely Recovery Depiction (reference 4)	2
Figure 3 - F-16 Auto-GCAS Functional Block Diagram (reference 8)	3
Figure 4 - Have ESCAPE Time Delay and Bubble Safety Margins (reference 10)	4
Figure 5 – RSET System Logic Flow Diagram	6
Figure 6 – RSET System Block Diagram	6
Figure 7 - RSET Path Prediction Example with 12.5 Hz Refresh Rate (from simulation).....	7
Figure 8 - RSET Active Path History (from simulation)	9
Figure 9 – Calspan Variable Stability System Learjet LJ-25D.....	11
Figure 10 – Learjet Center Console System RSET Path Status Page	12
Figure 11 - Test Conductor Station Path Status Indication.....	12
Figure 12 - View from Test Conductor's Workstation.....	13
Figure 13 – Maximum Path Prediction Error - SLUF Entry.....	16
Figure 14 – Maximum Path Prediction Error - Level Turn Entry.....	17
Figure 15 – Maximum Path Prediction Error - Climbing Entry	17
Figure 16 – Maximum Path Prediction Error - Diving Entry	18
Figure 17 – Side View of Forward Climb.....	20
Figure 18 - Bird's Eye View of 60 deg Right Turn (Path 5)	21
Figure 19 - VSS Control Surface Positions	23
Figure 20 - VSS vs TPA Path: Flight 5 Record 14	23
Figure 21 - VSS vs TPA Path: Flight 7 Record 14 with Wind: 227@12	24
Figure 22 - Time History of RSS Error (PPE) during a manual activation.	25
Figure 23 - Location of "Heavy GCAS Mountain"	27
Figure 24 - Forward Look-Ahead Time.....	28
Figure 25 - Terrain Miss Distance with Initial Condition Variation.....	29
Figure 26 - Learjet VSS Flight Path versus DTED: Flight 7, Record 24, 220 KIAS, 500 ft AGL, IC 1....	30
Figure 27 - Distance to Terrain: Flight 7, Record 24, 220 KIAS, 500 ft AGL, IC 1	30
Figure 28 - Terrain Miss Distance with Altitude Variation	31
Figure 29 - Terrain Miss Distance with Airspeed Variation.....	32
Figure 30 - Forward Look-Ahead Time with Initial Condition Variation	33
Figure 31 - Forward Look-Ahead Time with Altitude Variation.....	34
Figure 32 - Forward Look Ahead Time with Airspeed Variation	35
Figure 33 – Path 3 Performance, 220 KIAS, 500 ft AGL, SLUF Entry	37
Figure 34 – Path 3 Performance, 270 KIAS, 500 ft AGL, 45° Left Turning Entry	38
Figure 35 – Path 4 Performance, 220 KIAS, 500 ft AGL, 45° Left Turning Entry	39
Figure 36 – Path 4 Performance, 270 KIAS, 500 ft AGL, 45° Left Turning Entry	40
Figure 37 – Path 5 Performance, 220 KIAS, 500 ft AGL.....	41
Figure 38 – Path 5 Performance, 270 KIAS, 500 ft AGL.....	42
Figure 39 – Nuisance Terrain Route.....	43
Figure 40 – Lateral Offset from Terrain	44
Figure 41 - Path of Aircraft during Lateral Offset Test Points	45
Figure 42 - Path of Aircraft with 60° Right RSET Predictions during Lateral Offset Test Points	45

Figure 43 - Model Stitching Block Diagram Schematic (reference 12)	A-1
Figure 44 - State Space Equations of Motion (reference 12).....	A-2
Figure 45 - Longitudinal Axis Stability and Control Derivatives as a Function of Airspeed (15,000 ft) (reference 12).....	A-3
Figure 46 - Lateral/Directional Axis Stability and Control Derivatives as a Function of Airspeed (15,000 ft) (reference 12)	A-3
Figure 47 - Stitched Model SIMULINK® Overview (reference 12).....	A-4
Figure 48 - Pitch Doublet Response (250 kts, 15,000 ft) (reference 12)	A-4
Figure 49 - Roll Doublet Response (250 kts, 15,000 ft) (reference 12).....	A-5
Figure 50 - Longitudinal Response Comparison of Stitched and RSET (Converted) Models (250 KIAS, 15000 ft MSL).....	A-5
Figure 51 - Longitudinal Response Comparison of Stitched and RSET (Converted) Models (250 KIAS, 15000 ft MSL).....	A-6
Figure 52 – Lateral-Directional Response Comparison of Stitched and RSET (Converted) Models (250 KIAS, 15000 ft MSL)	A-6
Figure 53 - Lateral-Directional Response Comparison of Stitched and RSET (Converted) Models (250 KIAS, 15000 ft MSL)	A-6
Figure 54 - Coordinated Turn Control Law	A-8
Figure 55 - Speed Scaled Gamma (γ) Command with Load Factor (Nz) Limiter Control Law	A-9
Figure 56 - Effect of Terrain Slope on Vertical Offset Terrain Safety Buffer.....	I-2

LIST OF TABLES

Table 1 – Auto-GCAS Requirements in Order of Importance (reference 8).....	5
Table 2 - Differences Between Have ESCAPE and RSET	10
Table 3 – LJ-25D VSS Safety Parameters (reference 14).....	11
Table 4 – Maximum Path Prediction Error - Varied Entry	18
Table 5 - Maximum Path Prediction Error - Varied Airspeed	19
Table 6 - Summary of PPE Directionality	22
Table 7 - Theil's Inequality Coefficient for RSET Model Compared to Stitched Model	A-7
Table 8 - RSET Path Bank Angle Command and Maneuver Restrictions.....	A-8
Table 9 - 412th Test Wing Rating Criteria	B-1
Table 10 - Test Points	D-1
Table 11 - Test Laptop Specifications	L-1

INTRODUCTION

This report presents the results for the Have Multi-path Escape Decisions Using Sophisticated Algorithms (Have MEDUSA) test management project (TMP). The lead developmental test organization (LDTO) was the Air Force Test Center, Edwards AFB, California. The executing test organization (ETO) was Class 18A of the United States Air Force Test Pilot School (USAF TPS) working in partnership with Calspan Corporation, Buffalo, New York and the Air Force Institute of Technology (AFIT), Wright-Patterson AFB, Ohio. Testing was requested by the Air Force Research Laboratory, Wright-Patterson AFB, Ohio. Testing was performed in the Calspan Learjet 25D (LJ-25D) Variable Stability System (VSS), tail number N203VS, from 5 to 18 September 2018. Testing included 11 sorties and 19.9 flight hours in the R 2508 complex and 2 ground test hours under the job order number (JON) MT18A200.

BACKGROUND

As of 2018, controlled flight into terrain (CFIT) was a primary reason for aircraft total losses and fatalities. In fact, it was only shortly before the time of the test program discussed herein that loss of control in-flight (LOC-I) overtook CFIT as the leading cause of fatal accidents in air transportation as discussed in *Controlled Flight Into Terrain Accident Analysis Report: 2008-2017 Data* (reference 2). According to the Federal Aviation Administration (FAA), "CFIT occurs when an airworthy aircraft is flown, under the control of a qualified pilot, into terrain, water, or obstacles with inadequate awareness on the part of the pilot of the impending collision" as seen in *Airworthiness Criteria for the Installation Approval of a Terrain Awareness and Warning System* (reference 3). The issues that arose which led to CFIT were directly related to the pilot and crew. These issues were both external (weather/visibility, air traffic control (ATC) error, aid to navigation (ATON) malfunction, etc.) and internal (poor crew resource management (CRM), failure to adhere to standard operating procedures (SOPs), poor cross-check, etc.). Figure 1 presents a ten year look at CFIT accident rates in commercial aviation according to the International Air Transport Association (IATA). While the IATA statistics did not include general, military, agricultural, test, or training aviation statistics they provided the most comprehensive analysis of CFIT available at the time. Although CFIT only accounted for 6% of all accidents (ranked 7th for number of accidents) it represented 28% of fatal accidents (ranked 2nd behind LOC-I) in the IATA Report (reference 2).

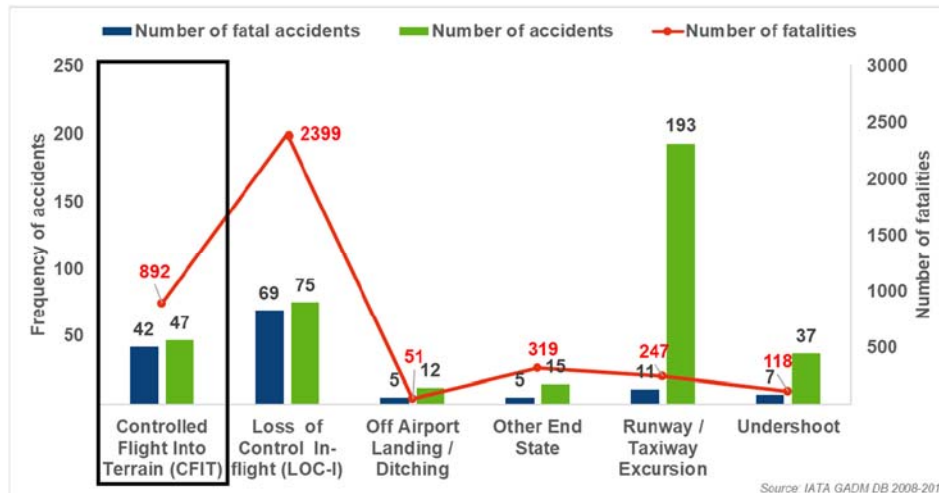


Figure 1 – Top Commercial Aviation Fatal Accident Categories 2008 – 2017 (reference 2)

AGGRESSIVE AND TIMELY

According to the works of Suplisson's *PhD Dissertation: An Optimal Control Approach to Aircraft Automatic Ground Collision Avoidance*, Skoog's *Automatic Collision Avoidance Technologies: Auto-GCAS Flight Test and Development & Evaluation*, and Swihart's *Automatic Collision Avoidance Technology*, "in order to reduce nuisances and not interfere with the military mission, an Auto-GCAS recovery maneuver must be both aggressive and timely" (references 4, 5 and 6). In Figure 2 below from Suplisson's PhD Dissertation (reference 4), the red dotted line shows a buffer that is added to the digital terrain which is used to account for path prediction and execution errors. The blue dashed line represents an aggressive but not timely ground avoidance maneuver, which is indicated by the fact that the aircraft performs an aggressive zoom climb, but does so unnecessarily early. The green dashed line represents a timely but not aggressive ground avoidance maneuver since the aircraft just misses the terrain, but could have waited longer and maneuvered more aggressively. The solid orange line represents a recovery that is both aggressive and timely and hence meets both Auto-GCAS maneuver criteria.

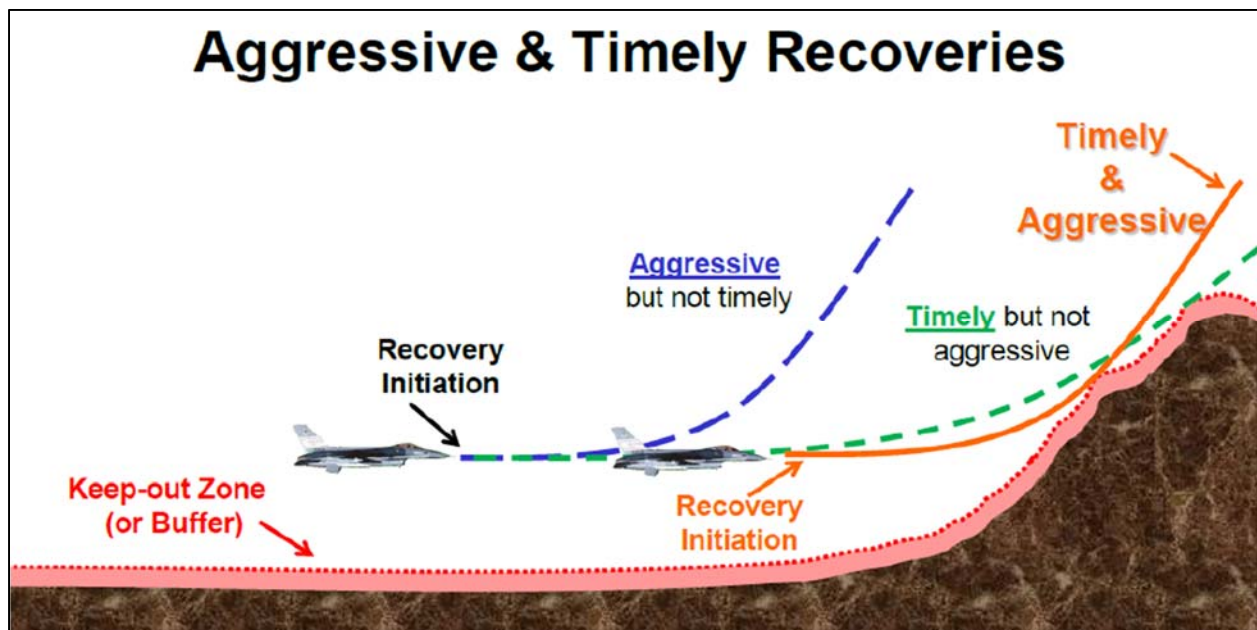


Figure 2 – Aggressive and Timely Recovery Depiction (reference 4)

F-16 AUTO-GCAS

The successful F-16 Fighting Falcon Auto-GCAS program can be traced back to the 1980s. A 2006 Secretary of Defense directed business case analysis (BCA), *Fighter/Attack Automatic Collision Avoidance Systems Business Case Analysis*, AFRL-HE-WP-TR-2006-0023, identified that in fact CFIT was the #1 cause of fighter pilot fatalities (reference 7). This BCA prompted renewed support for the fielding of an automatic system. The F-16 Auto-GCAS system was fielded in 2014 and saved seven aircraft and eight aircrew from imminent CFIT by mid-2018. The F-16 Auto-GCAS predicted the future path of the aircraft, compared that path to digital terrain elevation data (DTED), and if a collision was predicted used an automatic roll to wings-level followed by a 5-g pull to safely avoid terrain. A functional block diagram for the F-16 Auto-GCAS is shown in Figure 3 from *Automatic Ground Collision Avoidance System Design, Integration, & Flight Test* (reference 8).

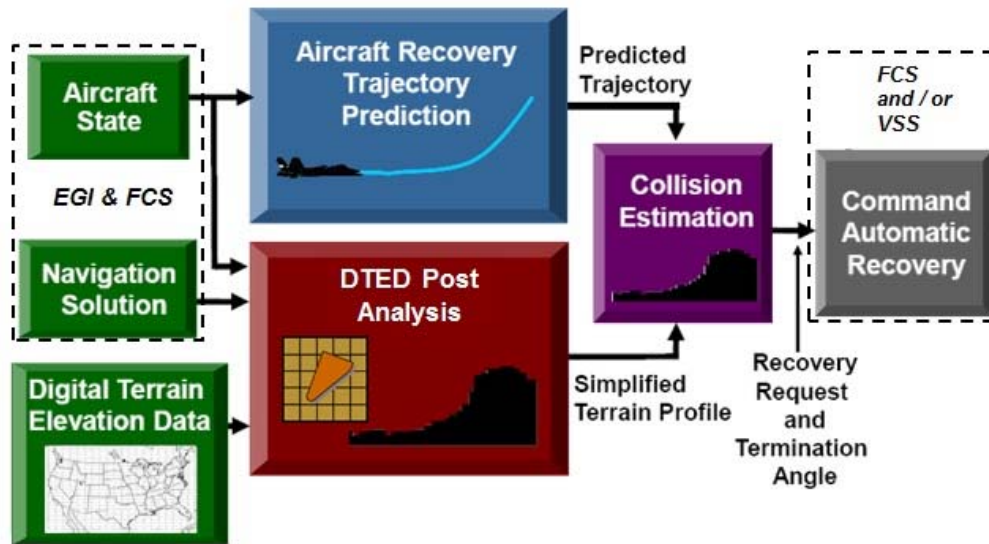


Figure 3 - F-16 Auto-GCAS Functional Block Diagram (reference 8)

PERFORMANCE LIMITED AIRCRAFT GCAS

In addition to CRM training, over the years the USAF adopted a number of systems to reduce the risk of CFIT in performance limited aircraft, such as the C-130 or C-17. These systems included the passive Terrain Awareness and Warning System (TAWS) and the Ground Proximity Warning System (GPWS). TAWS and GPWS, however, relied on aircrew action to execute the ground avoidance maneuver. Aircrew were susceptible to distraction, task saturation, fixation, and incapacitation, all of which could lead to CFIT. These manual systems, however, were not sufficient for preventing CFIT. At the time of this writing, there were no automatic systems, such as that in the F-16, which provided pilot-free automatic CFIT protection. Additionally a formal BCA had not been accomplished for Class III aircraft (transports, tankers, bombers, etc. as defined in MIL-STD-1797B), but research showed that CFIT was still a concern for these military aircraft (reference 1). For example, according to Lockheed Martin the C-130 Hercules across all customers experienced 30 CFIT accidents resulting in 433 deaths from 1954-2011 listed in *C-130 Retrofit Kit Offerings* (reference 9). The Lockheed-Martin data did not account for a 2012 Norwegian C-130J CFIT which claimed five lives, bringing the total to 31 CFITs and 438 deaths. From a system design perspective, Class III aircraft were less maneuverable and typically had much less climb performance than an F-16. For this reason a single-path climb-only Auto-GCAS would have required early activation to “out climb” threatening terrain when a turning maneuver or a climbing turn would have been more appropriate. In that case, a single-path Auto-GCAS would be prone to nuisance since an aware pilot would choose to maneuver laterally to avoid terrain instead of just starting an early climb. In other words, a single-path Auto-GCAS would be aggressive, but not timely. It should be noted that the Auto-GCAS discussed herein was not intended to prevent ground collision in the event of a catastrophic system failure. Rather, based on the definition of “controlled” flight into terrain, Auto-GCAS preventable accidents included spatial disorientation, physiological effects such as hypoxia, or flight into instrument meteorological conditions (IMC). For the reasons listed here, a multi-path Auto-GCAS solution was investigated for performance limited aircraft.

HAVE ESCAPE TMP

A 2015 USAF TPS TMP titled Have Emergency Safe Calculated Autonomous Predetermined Exit (ESCAPE) tested basic algorithms for autonomous ground avoidance on the Learjet VSS detailed in *Limited Evaluation of Automatic Ground Collision Avoidance Algorithm for Climb Limited Aircraft (Project Have ESCAPE)* (reference 10). The Have ESCAPE was inspired by the work of Sorokowski's *Small UAV Automatic Ground Collision Avoidance System Design Considerations and Flight Test Results* et al who successfully used a three degree of freedom (3-DOF) model connected to a commercial off-the-shelf (COTS) autopilot as an Auto-GCAS solution for a small unmanned aerial vehicle (UAV) (reference 11). Have ESCAPE investigated the use of a 3-path and a 5-path system for ground collision avoidance. The Have ESCAPE system modeled the motion of the aircraft using simplified 3-DOF equations of motion. Have ESCAPE used those equations of motion to create trajectory prediction algorithms (TPAs) which predict the path of the aircraft based on five collision avoidance profiles: a 2-g 60° bank turn to the left and right, a 2-g pull at 30° bank angle to a 15° flight path angle, and a forward 2-g climb to a 15° flight path angle to the left and right. Each TPA calculated the location of the aircraft at 0.5 second intervals and used a variable radius "bubble" around the aircraft to predict intersection with DTED. The bubble diameter was nominally set at 300 ft and was required due to the spacing of discrete DTED posts (approximately 295 ft). Once the bubble was found to intersect a DTED post then the associated path was flagged as unavailable. When all paths were unavailable, the Have ESCAPE algorithms chose the last available TPA as the escape path. A 0.5 second safety margin was included to allow for the last path to predict an "impact", yet still allow time for the path to be flown and avoid terrain. Figure 4, from the Have ESCAPE test report, depicts the projected paths as well as the time delay and bubble safety margins (reference 10). Once this "Last Man Standing" path was identified, a series of pre-planned normal acceleration (N_z or g) and bank angle (ϕ) commands were sent to the Learjet VSS to perform the selected maneuver.

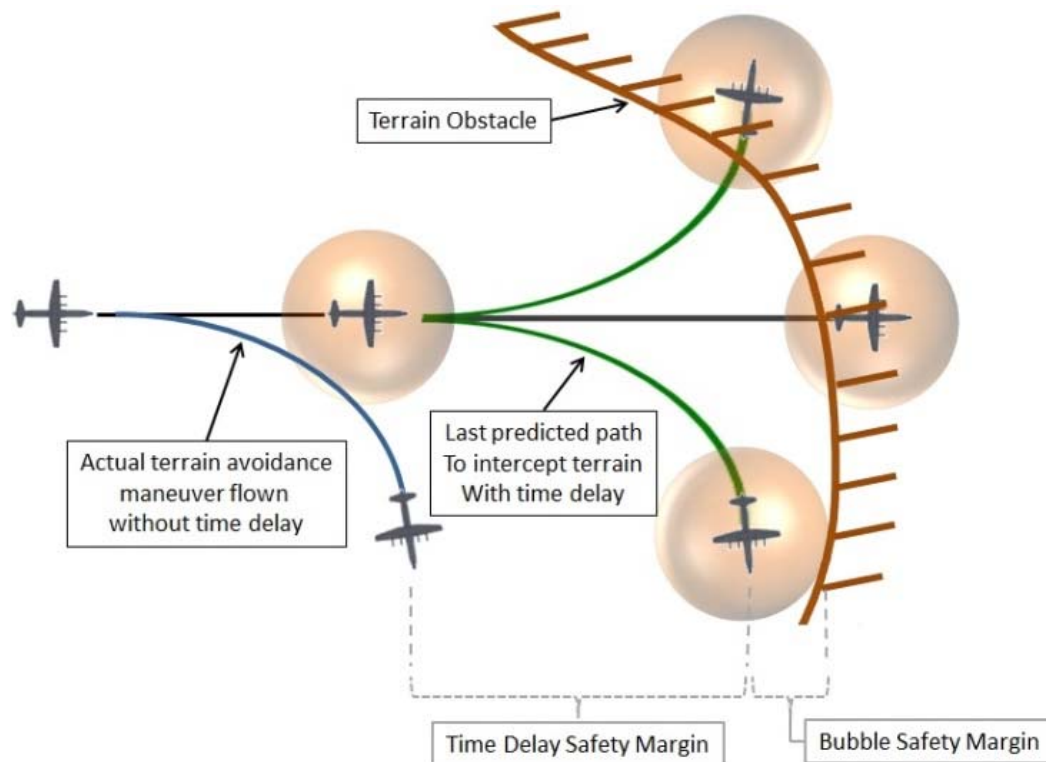


Figure 4 - Have ESCAPE Time Delay and Bubble Safety Margins (reference 10)

The Have ESCAPE algorithms showed promise for multi-path GCAS as a solution to preventing CFIT in performance limited aircraft, but there were a number of constraints imposed by the design of the system found in the Have ESCAPE test report (reference 10). The Have ESCAPE algorithms required that the maneuvers be initiated from straight-and-level flight at 15,000 ft PA and 310 knots groundspeed. The Have ESCAPE algorithms also did not continue to analyze the aircraft collision avoidance paths once a path was chosen. Lastly, the implementation of the simplified 3-DOF model and time-sequenced commands did not produce consistent flight profiles or maneuver performance.

Have MEDUSA built upon the work of Have ESCAPE and tested advanced algorithms coded in MATLAB® and SIMULINK®. It was designed to command terrain avoidance flight paths for performance limited aircraft. The system tested was known as the Rapidly Selectable Escape Trajectory (RSET) system. The Have ESCAPE TPAs did not conduct continual path analysis and used open loop command logic. The RSET system used an 18-DOF model and used identical architecture for TPA and maneuver autopilots. It simultaneously calculated five different terrain avoidance maneuvers which included 60° left and right turns, 30° left and right climbing turns and a straight ahead climb. The algorithms were designed to choose the best flight path to keep the aircraft and aircrew safe with minimal negative impact on mission operations or nuisance activations.

TEST ITEM DESCRIPTION

RSET SYSTEM

The test item was the RSET system, which was designed to predict terrain collision potential and to automatically command an appropriate ground avoidance maneuver. As with F-16 Auto-GCAS and Have ESCAPE, the RSET system was designed with three overarching design requirements, shown in Table 1, in mind: Do No Harm, Do Not Impede Mission Operations, and Avoid Ground Collisions. These algorithms, written in MATLAB® and SIMULINK®, were adapted to be integrated with the Learjet VSS flight control system, which was able to be controlled externally via a laptop which sent commands through a SIMULINK® interface.

Table 1 – Auto-GCAS Requirements in Order of Importance (reference 8)

Priority	Auto-GCAS Requirement
1	Do No Harm
2	Do Not Impede Mission Operations
3	Avoid Ground Collisions

The RSET system consisted of three major components: the trajectory prediction algorithms (TPAs), the collision detector, and the maneuver autopilots. The RSET system logic flow diagram is depicted in Figure 5 and the system block diagram is shown in Figure 6.

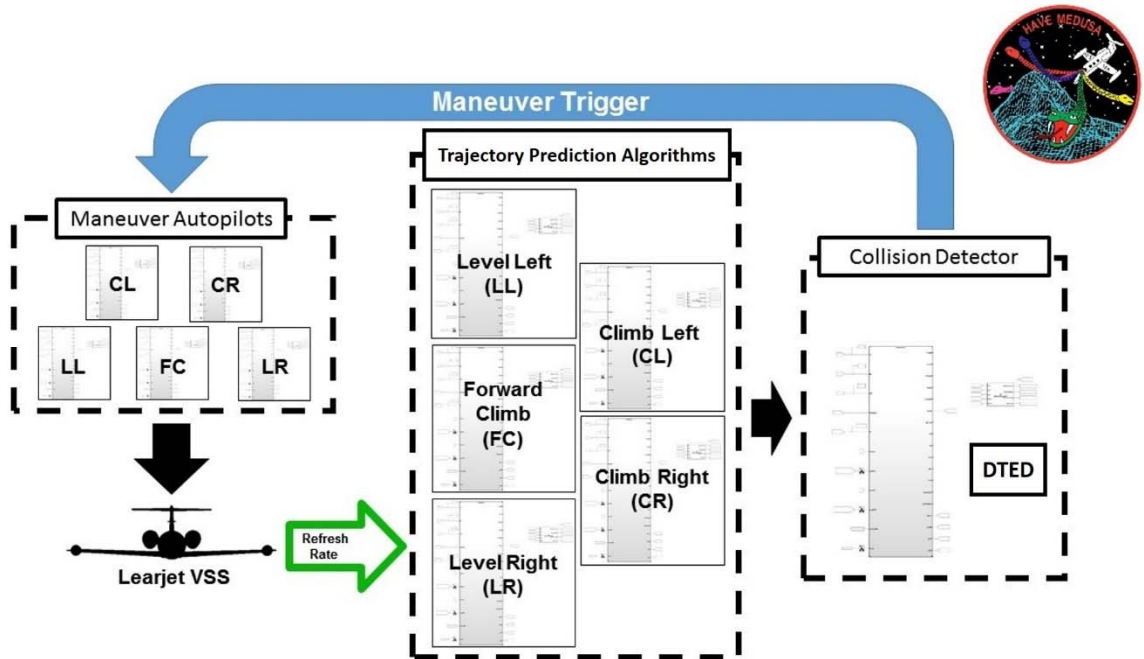


Figure 5 – RSET System Logic Flow Diagram

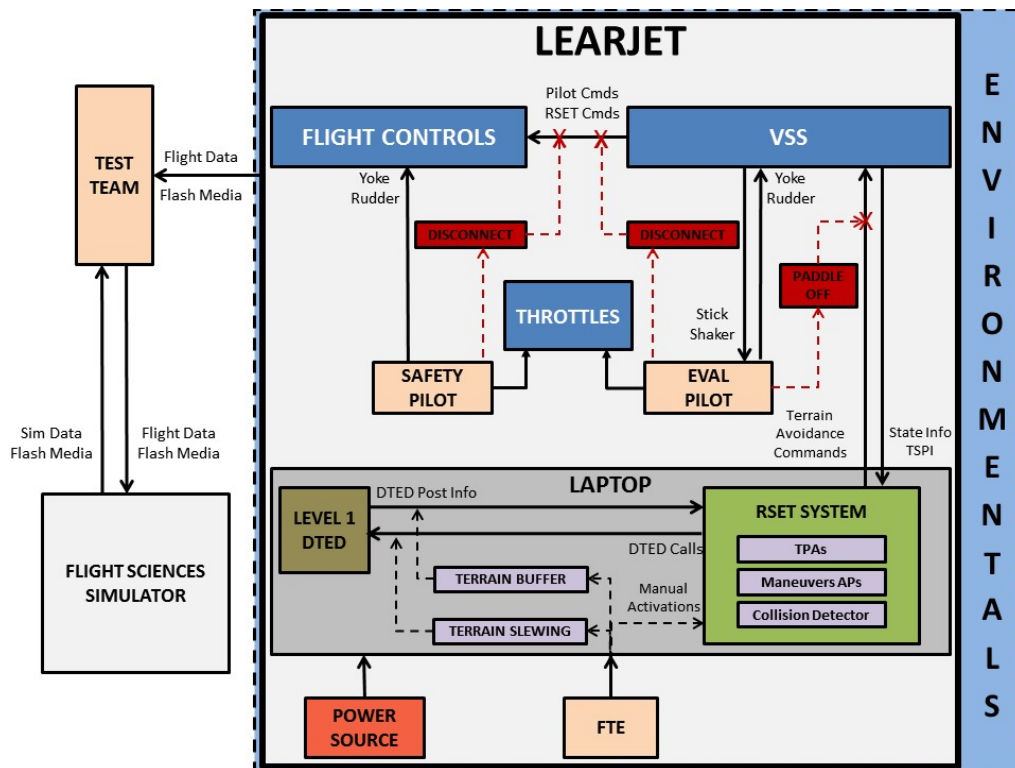


Figure 6 – RSET System Block Diagram

TRAJECTORY PREDICTION ALGORITHMS

The system received time, space, position information (TSPI) and the aircraft states from the VSS and, using this information as a starting point, used trajectory prediction algorithms (TPAs) to predict the paths of the terrain avoidance maneuvers. At the core of the path predictions was an 18-degree of freedom (18-DOF) aircraft model developed for the TPS Learjet VSS simulator detailed in *Development and Validation of a Flight-Identified Full-Envelope Business Jet Simulation Model Using a Stitching Architecture* (reference 12). The high fidelity model is discussed further in APPENDIX A – DETAILED TEST ITEM DESCRIPTION.

This high fidelity model was coupled with five TPAs which predicted the path of the aircraft based on performing five different maneuvers. The TPA maneuvers included left and right 60° bank turns, left and right 30° bank angle climbing turns limited to 2-g, and a wings-level climb. All five TPAs used a speed-scaled flight path angle (γ) control law with an N_z -limiter. These paths were each calculated for 30 seconds into the future. The control laws used to generate the TPAs are discussed further in APPENDIX A. All five 30-second “look-aheads”, known as the path prediction time, were computed at a planned rate of 12.5 Hz, 6.25 Hz, or 1.5625 Hz, known as the “refresh rate”. The TPAs were calculated based on the throttle being advanced to maximum continuous power, which for testing was manually activated by the test pilots as discussed in CONSTRAINTS. Figure 7 shows a visual representation of the 5 paths generated by the RSET system TPA logic.

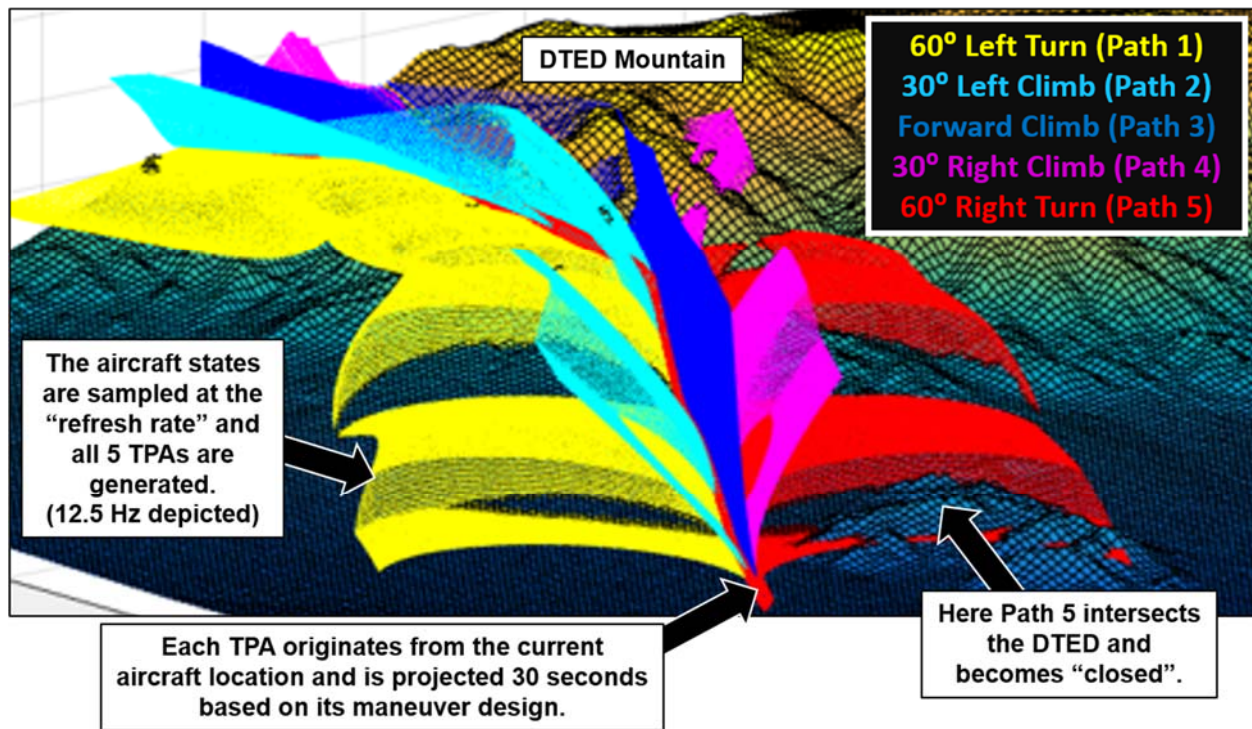


Figure 7 - RSET Path Prediction Example with 12.5 Hz Refresh Rate (from simulation)

COLLISION DETECTOR

The generated paths were compared to Level 1 DTED, available from the National Geospatial-Intelligence Agency website, to find the distance between the flight path and the terrain for each possible maneuver. DTED were comprised of a matrix of “posts” which each had a latitude, longitude, and MSL height. The aircraft path was compared against the interpolated DTED posts to determine the distance

between the aircraft altitude and the height of the terrain. Since Level 1 DTED had a spacing of approximately 295 ft between posts, interpolation was used to ensure that the aircraft did not simply “fly between” posts and fail to identify a collision. The interpolation method used was called “nearest”, and referenced the closest DTED post to the TPA. This interpolation method was chosen since it significantly reduced computational time versus other interpolation methods, such as “cubic” or “spline”. Please refer to APPENDIX I – LESSONS LEARNED for more information. If one or more maneuvers was predicted to maintain safe separation from the terrain, the system did not take any action because it assumed an aware pilot would be able to avoid the collision in a timely manner. This was an important feature to avoid nuisance activations. When the system predicted that every path intersected the terrain safety buffer (evaluated at 200 feet¹), the system immediately took control of the aircraft and commanded the maneuver which was last predicted to violate the terrain safety buffer. In this way, the algorithm waited for the last path to intersect terrain allowing for pilot intervention up to the point where a collision would become imminent. Safety buffers added to the terrain elevation accounted for TSPI and path prediction errors as well as the time needed for the last available path to be selected and executed. The terrain safety buffer was simply a fixed height value added to each DTED post. Level 1 DTED was required to have a vertical error of less than 30 meters (98.4 ft) from *Performance Specification: Digital Terrain Elevation Data (DTED) [MIL-PRF-89020B]* (reference 13). Level 1 DTED error was accounted for in the terrain safety buffer.

MANEUVER AUTOPILOTS

When the collision detector identified the need to perform an avoidance maneuver, a flag was sent to autopilot control laws which were capable of commanding the Learjet VSS. The maneuver autopilots were identical in architecture and control law design to the TPAs. This was important for ensuring the path flown by the aircraft matched the path calculated by the RSET system as closely as possible. Once the system identified that the aircraft was no longer on a collision course with terrain, control was relinquished back to the pilot. Identical to the TPAs, the maneuver autopilots included left and right 60° bank turns, left and right 30° bank angle climbing turns limited to 2-g, and a wings-level climb. All five maneuver autopilots also used a speed-scaled flight path angle control law with a load factor (Nz) limiter. Simulator results indicated that forward climbing escape maneuvers resulted in a steady-state flight path angle of approximately 8°. The evaluation pilot (EP) had the ability to “paddle off”, or manually disconnect, the maneuver autopilots and regain control of the Learjet VSS for safety or test efficiency. Once the collision detector determined that one path was again available, a handover autopilot was engaged. The handover autopilot rolled the aircraft to wings-level and targeted zero flight path angle in preparation of handing the controls back to the EP. Any time after the hand-back autopilot was engaged, the collision detector could reengage if another collision event was detected. Figure 8 shows the results of a simulation with the path color-coded to depict which autopilot was controlling the aircraft (green means the pilot was in control).

¹ For Flights 1 – 9, the terrain safety buffer was erroneously set to 100 ft. The buffer was corrected to 200 ft. for Flights 10 and 11. All of the data was post-processed to correct the errors for a 200 ft. buffer.

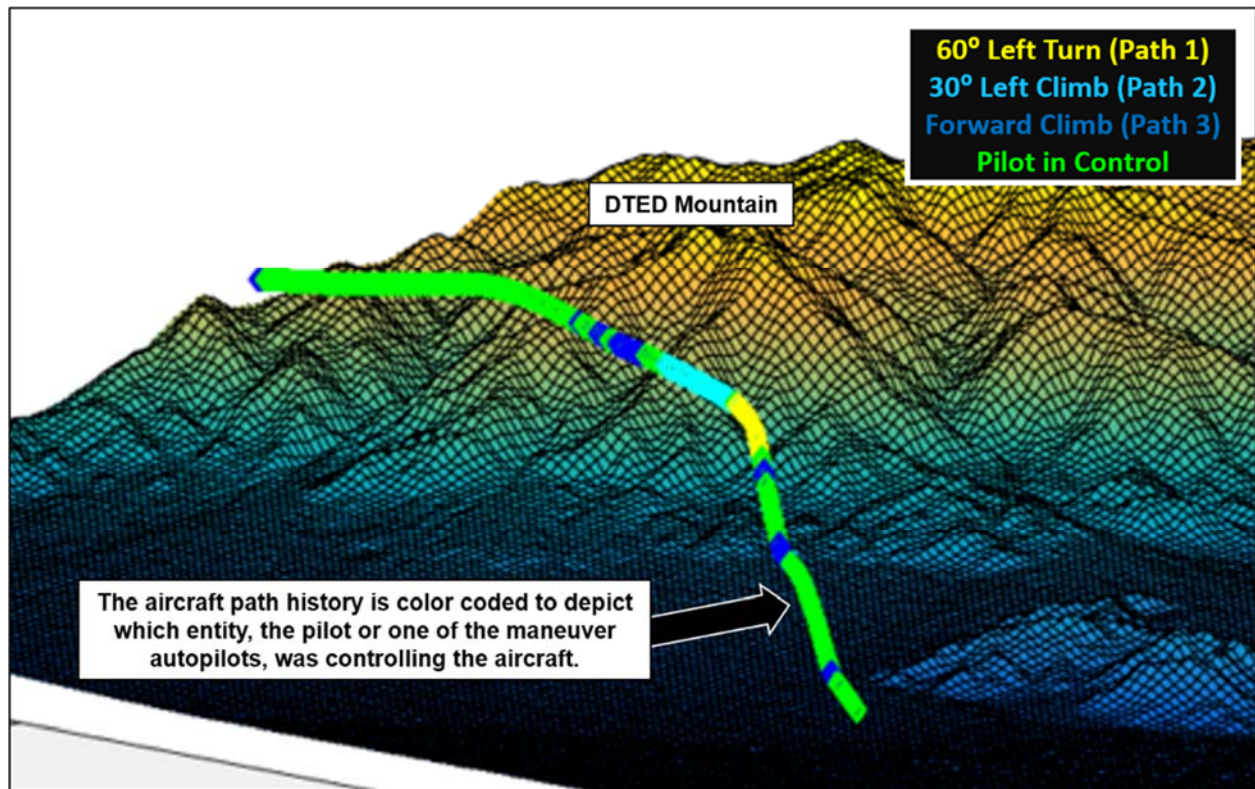


Figure 8 - RSET Active Path History (from simulation)

HAND-BACK

As discussed in the Collision Detector section, the RSET system took control of the aircraft when all paths became unavailable, or closed, and executed the last available path to avoid the terrain. During an RSET activation, if another path became available, or open, then the system would hand back control to the pilot. The hand-back sequence consisted off a roll to wings-level and targeting zero flight path angle. The hand-back algorithm was fairly simple and immature, as is discussed later in the test results.

HAVE ESCAPE DIFFERENCES SUMMARY

Table 2 below summarizes the primary differences between the RSET system and the Have ESCAPE algorithm from the Have ESCAPE test report (reference 10).

Table 2 - Differences Between Have ESCAPE and RSET

Parameter	Have ESCAPE	RSET	Comments
Model fidelity	3-DOF	18-DOF	The aircraft model used by RSET includes numerous aircraft equations of motion and atmospherics.
Path prediction	Five pre-calculated 3-DOF paths	Five autopilot calculated paths	
Can operate anywhere within Learjet VSS flight envelope?	No – only compatible with 1 airspeed and altitude	Yes – able to adapt to changing airspeed, altitude, and attitude.	
DTED used	Level 1	Level 1	
Collision detection method	“bubble” around aircraft touches DTED post	Aircraft position was interpolated against DTED	
Maneuver execution	Time series of g and bank angle commands	Used same autopilots as path prediction	

RESEARCH VEHICLE

The Calspan VSS-equipped Learjet LJ-25D (LJ-25D), displayed in Figure 9, was employed as a platform to test the RSET system. The VSS was capable of inflight simulation of different aircraft control laws and aircraft responses in four degrees of freedom (pitch, roll, yaw, and thrust) using control surface and feel actuators. Since the aircraft model at the core of the RSET system was developed using the baseline LJ-25D, the VSS was used in the baseline configuration for this test. The cockpit accommodated a pilot and copilot crew. There was seating in the cabin for a Test Conductor (TC) and one more occupant to include technical representatives or incentive flyers. Minimum test aircrew included the two pilots and a TC. A TPS student evaluation pilot flew from the right seat control stick with VSS components. A Calspan instructor pilot served as the pilot-in-command as well as the safety pilot (SP) from the left seat. The left seat pilot controls were mechanically linked to the flight control surfaces, and provide un-augmented flight control when the VSS was disengaged. Under normal operation, the right seat evaluator pilot (EP) controlled the VSS via an interface that sent electrical signals from his controls to the hydraulic actuators connected to the control surfaces.



Figure 9 – Calspan Variable Stability System Learjet LJ-25D

In the VSS mode, engagement and safety trip logic existed which detected failure conditions including aircraft states and loads, feel system, control surface parameters, and hydraulic fluid level. If a failure condition or safety trip logic was satisfied, as shown in Table 3, hydraulic pressure was removed from the control surface and feel actuators, failures were annunciated in the cockpit, and the VSS was disengaged as discussed in *Learjet Flight Syllabus and Background Material for the US Air Force/US Naval Test Pilot School Variable Stability Programs, TM-FRG-LJ1-0061-R05* (reference 14). The VSS could also be manually disengaged by either pilot. Any VSS disengagement automatically returned aircraft control to the SP. The Learjet-25D was instrumented to collect aircraft performance and state data required to evaluate test objectives at a rate of 200 Hz.

Table 3 – LJ-25D VSS Safety Parameters (reference 14)

<u>Parameter</u>	<u>Limits</u>	<u>Automatic VSS Trip?</u>
Airspeed (At or below 14K Ft)	306 KCAS	No*
Airspeed (Above 14K Ft)	325 KCAS / 0.79 M	No*
Load Factor	+0.25 to +2.8	Yes
Angle of Attack	12°	Yes
Angle of Sideslip	10°	Yes
*Airspeed was not monitored by VSS Trip logic. The aircrew ensured limits were not exceeded.		
The safety trip logic for the above parameters was within the normal LJ-25D flight envelope.		
This table presents just a small sample of the VSS safety trips. Several additional sensors (such as load factor onset rate, control surface actuator pressure, etc.) are not discussed here.		

The RSET system interfaced with the VSS, which directly implemented the escape maneuvers. During flight tests, the VSS operated using autopilots of the same design as those used to generate the RSETs. The LJ-25D had a radar altimeter but did not incorporate TAWS, GPWS, or any other altitude-dependent systems that would interfere with the RSET system. When the RSET system commanded a maneuver to the aircraft, it sent a flag to the control autopilots to perform the ground avoidance maneuver. These maneuvers were commanded until a clear of terrain flag was sent at which time the system rolled the aircraft to wings-level and targeted zero flight path angle in preparation of handing the controls back to the EP. Then, the RSET system disengaged and control of the aircraft was returned to the EP. The EP also

had the option to manually terminate the automatic maneuver by pressing a “paddle-off” button on the yoke. The TC had the ability to monitor the activation and termination of the RSETs on the test laptop. Additionally, the center console displayed the status of the five RSET paths during flight. Figure 10 shows the status of the Center Console System (CCS) during an RSET activation with all five paths unavailable (highlighted white). The CCS did not give an indication of which path, if any, was currently being flown. Rather, other than the motion of the aircraft, the only way from the CCS to know which path was active was to see which path was the last to remain open. The test laptop at the TC station, however, gave a visual depiction of path closures as well as the current active path, as shown in Figure 11. When the RSET system was controlling the aircraft, a stick shaker on the right yoke (EP) activated to notify the pilots. The left seat yoke stick shaker still only activated to indicate a stall.

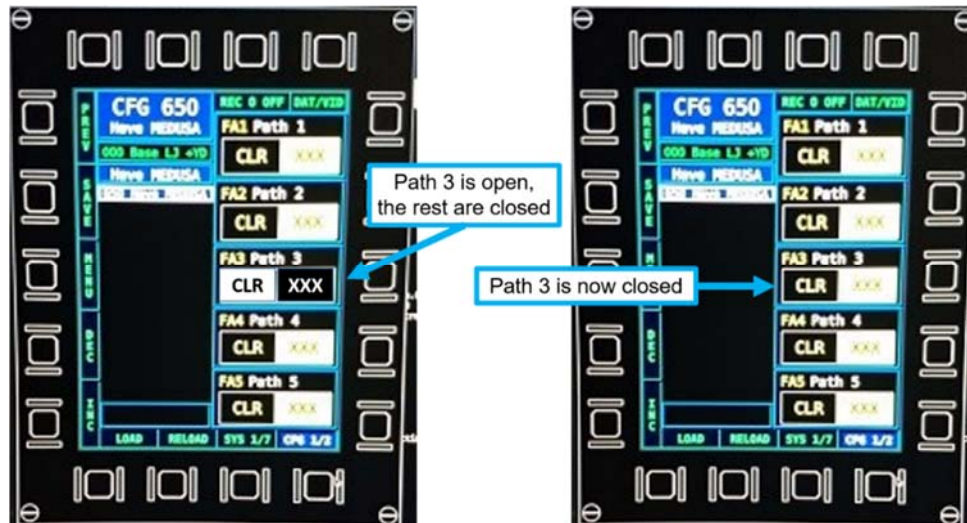


Figure 10 – Learjet Center Console System RSET Path Status Page

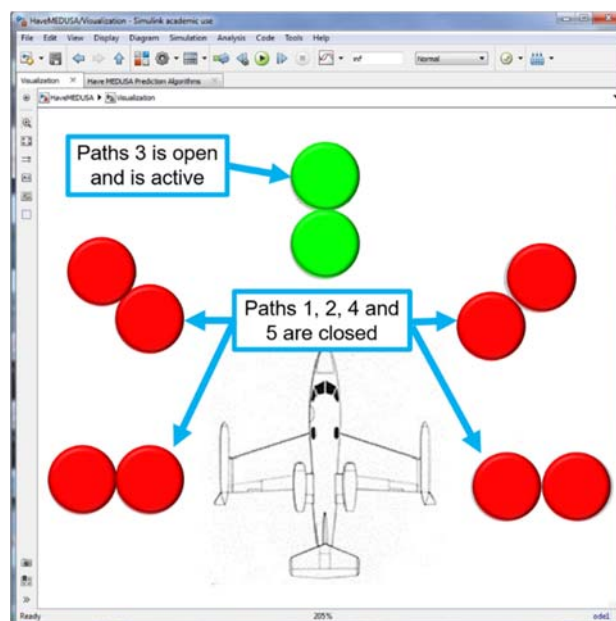


Figure 11 - Test Conductor Station Path Status Indication

RESEARCH LAPTOP COMPUTER

The RSET system was run via MATLAB® and SIMULINK® on a research laptop computer which interfaced with the VSS on the Learjet. It was the physical hardware which both received the aircraft state information as input to the RSET system and communicated the maneuver commands to maneuver the aircraft. The research laptop computer specifications can be found in APPENDIX L – TEST LAPTOP SPECIFICATIONS.

The laptop was equipped with a solid-state hard drive to minimize the probability of malfunctions caused by aircraft motion. During flight, the research laptop was securely fastened to the TC workstation in the aircraft cabin. The view from the TC's workstation is shown in Figure 12.



Figure 12 - View from Test Conductor's Workstation

OVERALL TEST OBJECTIVE

The overall test objective was to demonstrate the utility of the RSET system as a multi-path automatic ground collision avoidance system for performance limited aircraft. The specific test objectives were to:

1. Demonstrate the prediction accuracy of the RSET system.
2. Demonstrate the impact of changing refresh rate on the RSET system's ability to calculate an achievable escape path.
3. Observe RSET system tendency to nuisance activation.
4. Observe the control hand-back of the RSET algorithm after maneuver termination.

All test objectives were met.

CONSTRAINTS

- The auto throttle in the Learjet VSS was not capable to setting consistent throttle settings and, as such, was not used. Because of this, when an escape maneuver was commanded, the EP had to manually advance the throttles to the required setting. This added some variability to the model path prediction and actual path performance, although based on the already low-fidelity of the engine model. The engine model is discussed further in APPENDIX A – DETAILED TEST ITEM DESCRIPTION.

ASSUMPTIONS

- Navigation errors and DTED accuracy were not evaluated in this project. As such, any reference to the distance between the aircraft and terrain refers to the distance between the aircraft's navigation solution and the artificially elevated DTED data loaded in the research laptop. This was different than the actual distance between the aircraft and real terrain features since DTED elevations and navigation solutions are known to have error.

TEST AND EVALUATION

Overall, the RSET system performance demonstrated the utility of using a multi-path collision avoidance system for performance limited aircraft. Path prediction error (PPE) did not meet the specified criteria and was larger than expected for the 30-second path predictions; however, at the maximum refresh rate of 12.5 Hz, the RSET system ensured terrain clearance in all cases tested. Incorrect accounting for wind drift effects, the Learjet VSS auto-trim feature, and the low fidelity engine model were possible sources of PPE. The test team recommended the main sources of PPE be determined prior to further testing. Despite the simple design of the control logic, the RSET system was able to achieve and maintain target load factor and flight path angle with momentary overshoots. The system showed no tendency for nuisance activations for all cases tested. The RSET hand-back implementation utilized was immature and the Learjet VSS safety trips were repeatedly triggered. Despite the unrefined hand-back, the response was deemed favorable in most cases and could be utilized as a baseline for future Auto-GCAS implementations.

Overall, the RSET system was assessed to be MARGINAL. System assessments were made according to the 412th Test Wing Rating Criteria shown in APPENDIX B – RATING CRITERIA.

RSET SYSTEM PREDICTION ACCURACY

The prediction accuracy of the RSET system was demonstrated by comparing the difference of the predicted flight path of the aircraft for a given collision avoidance maneuver and the actual path of the aircraft while executing that maneuver. Path Prediction Error (PPE) was defined as the distance between the two flights paths, and was computed at each sampled time from maneuver activation until handback of the aircraft. Refer to APPENDIX C – DATA ANALYSIS PROCEDURES for the details on how PPE was calculated. The evaluation criteria for RSET prediction accuracy was expressed in terms of the maximum value of PPE encountered during a 30 second maneuver. A maximum PPE of less than 100 ft was classified as satisfactory, between 100 ft to 300 ft as acceptable and above 300 ft as marginal. The test objective was met and the prediction accuracy of the RSET system was MARGINAL.

Overall Test Methods and Conditions

The RSET system was flight tested at 15,000 ft PA, 8,000 ft PA, and 500 ft AGL, each at 220 and 270 KIAS. Entry conditions consisted of straight and level, unaccelerated flight (SLUF), 45° left banked turns, 5° climbs, and 5° dives. All 500 ft AGL SLUF entry test points were repeated on separate flights. No diving entries were performed at 500 ft AGL. All five RSET system escape paths were tested at each of the stipulated pressure altitude, airspeed and entry conditions.

Prior to flight, the TC entered the number of passengers into the RSET system via a laptop at the engineer's station. This increased the accuracy of the weight and balance measurement. At the established test point conditions, the TC entered the current wind speed and direction derived from the onboard embedded GPS/INS (EGI) and air data systems, and manually activated the RSET system escape path via the laptop. Immediately upon indications of an RSET path activation, the pilot set the throttle for maximum continuous power (MCP) (95±2% RPM) in approximately 3 seconds. The maneuver was completed after 30 seconds had passed since the autopilot commanded the aircraft to fly the chosen RSET system escape path, which allowed for comparison to the 30 sec path prediction.

Flights 1-3 were used to debug the RSET system, and only data from Flight 4-11 were used for data analysis. For the 30 test points collected during Flight 4 (SLUF at 15,000 ft PA, 8,000 ft PA, and 500 ft AGL (only for the first set of data) at 220 and 270 KIAS), the RSET system did not consider any inputs on the number of passengers, wind conditions, and had an allowable maximum flight path angle of up to

20 degrees instead of 12 degrees for the chosen RSET system escape path. Flights 5-11 accounted for wind through TC entered parameters. Wind drift was identified as a potential source of error as discussed later.

Overall Test Results

Overall, the prediction accuracy of the RSET system was BORDERLINE. None of the conditions tested had a maximum PPE of less than 100 ft, which was the threshold for the satisfactory region. Only three of the conditions tested had a maximum PPE of less than 300 ft, which was the threshold for the acceptable region. The remaining 117 test points had a maximum PPE above 300 ft, which was the threshold for the marginal region. The summarized maximum PPE results across all altitudes are presented in Figure 13 through Figure 16, and in Table 4. The results for each test point are detailed in APPENDIX E – PATH PREDICTION ERROR RESULTS.

Additionally, figures for every manual activation can be found in APPENDIX K – DIGITAL APPENDIX. The smallest maximum PPE of 172 ft was encountered during the following test condition: 500 ft AGL, 220 KIAS, SLUF entry, Path 3 activation. The largest maximum PPE of 6568 ft was encountered during the following test condition: 15,000 ft PA, 270 KIAS, diving entry, Path 1 activation.

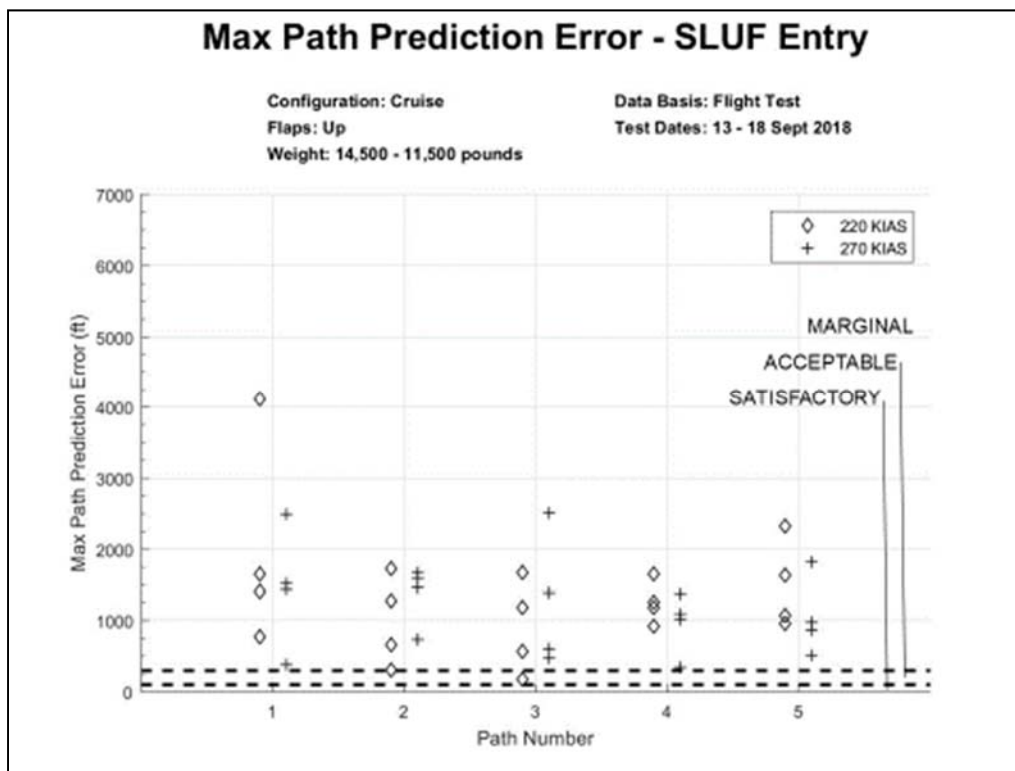


Figure 13 – Maximum Path Prediction Error - SLUF Entry

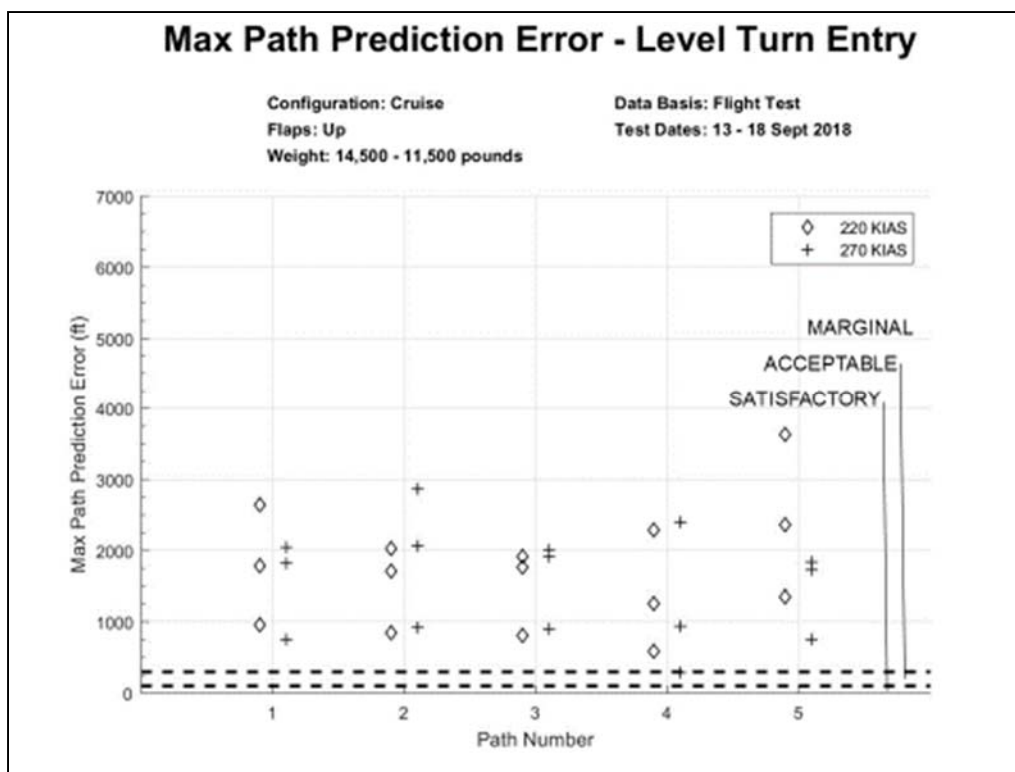


Figure 14 – Maximum Path Prediction Error - Level Turn Entry

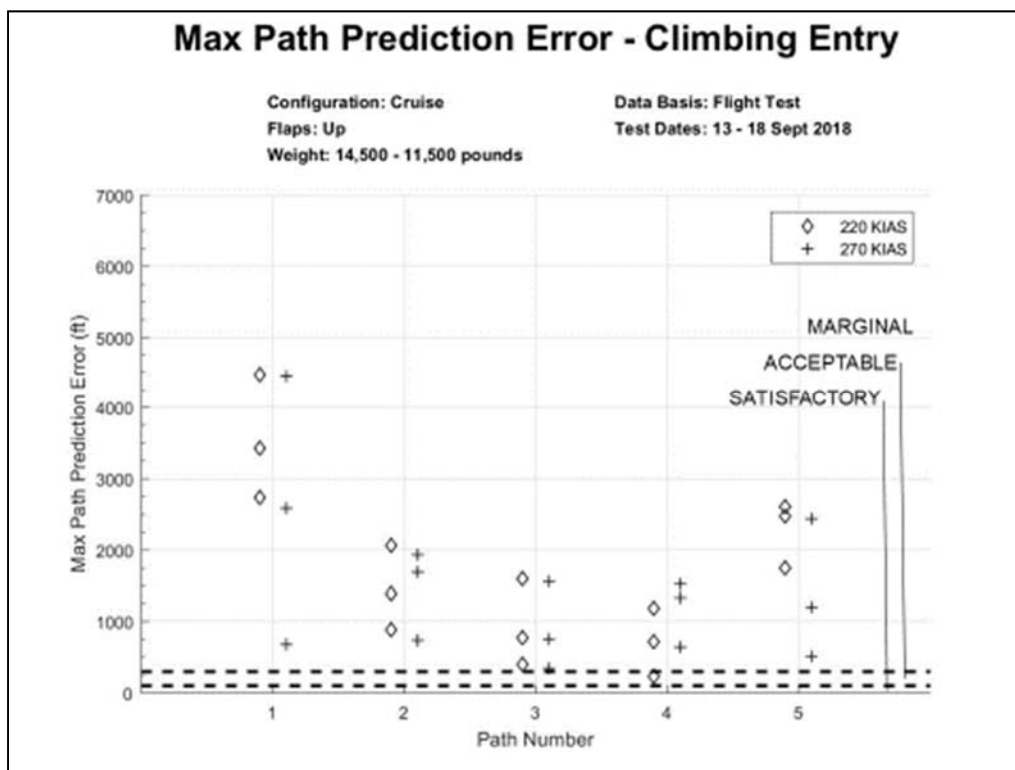


Figure 15 – Maximum Path Prediction Error - Climbing Entry

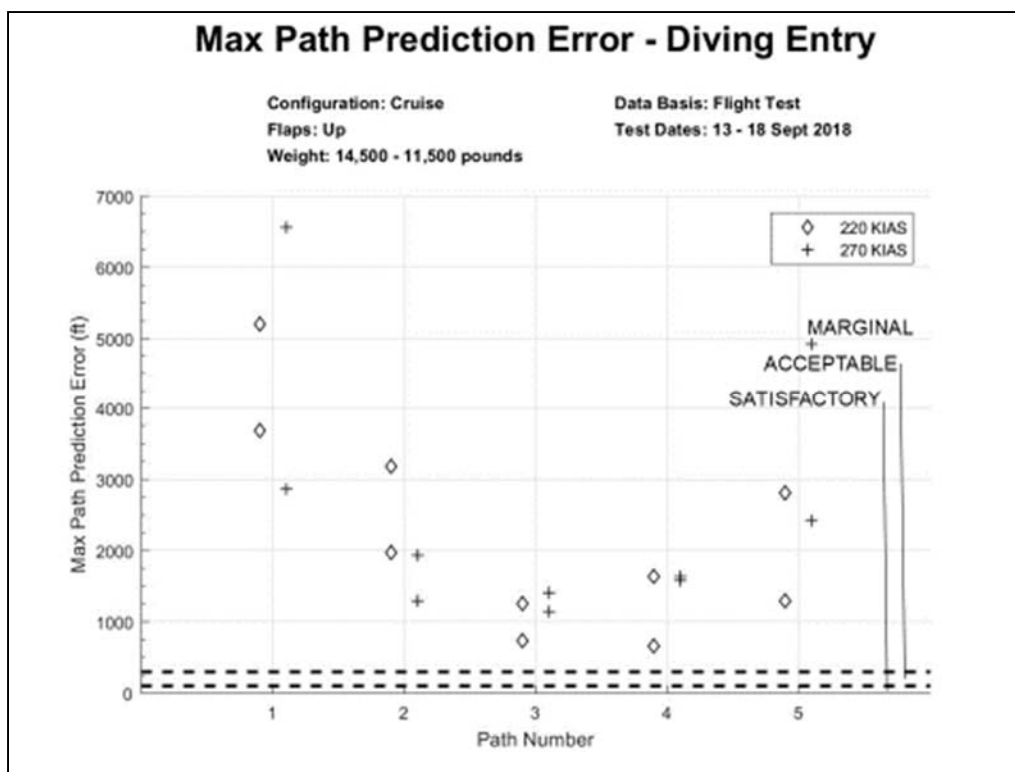


Figure 16 – Maximum Path Prediction Error - Diving Entry

Table 4 – Maximum Path Prediction Error - Varied Entry

		Average of Maximum PPE (ft) by Path Type					Average of Maximum PPE (ft) regardless of Path Type
		Path 1	Path 2	Path 3	Path 4	Path 5	
Entry Conditions	SLUF	1723	1178	1073	1106	1270	1270
	45° Level Left Turn	1665	1735	1555	1294	1948	1640
	5° Climb	3056	1447	906	940	1831	1636
	5° Dive	4577	2093	1133	1376	2856	2407
Average of Maximum PPE (ft) regardless of Entry Conditions		2517	1537	1162	1157	1844	--

Since the majority of test points represent a unique test condition that was only tested once, there was no statistical significance in the error data. However, a few trends were observed. In general, error tended to be higher for Path 1 and 5 activations, followed by Path 2 and 4 activations and lowest for Path 3 activations. In addition, error tended to be higher for the diving entries, followed by level turn and climbing entries, then SLUF entries. Notice that these figures and tables mask dynamic pressure effects, as the effect of altitude and airspeed on error is not apparent. Table 5 shows a summary table of PPE results categorized by airspeed and altitude. In general, there was no observed effect of airspeed on error, and error tended to increase with increasing altitude.

Table 5 - Maximum Path Prediction Error - Varied Airspeed

		Average of Maximum PPE (ft) by Altitude			Average of Maximum PPE (ft) regardless of Altitude
		500 ft AGL	8k ft MSL	15k ft MSL	
Entry Airspeed	220 KIAS	1365	1781	1930	1692
	270 KIAS	864	1810	2109	1594
Average of Maximum PPE (ft) regardless of Entry Airspeed		1115	1796	2020	--

The RSET system did not meet the evaluation criteria for the magnitude of the PPE over a 30 second path activation, indicating that the TPAs are not adequately modeling the aircraft's motion during the collision avoidance maneuvers. However, one must look at the directionality of the error in addition to the magnitude in order to fully assess whether RSET had utility as a ground collision avoidance system. For instance, if the aircraft position was 1000 ft off from the predicted position, but it resulted in the aircraft being farther away from terrain than predicted, then the system was still successful in preventing a collision. It may have caused the aircraft to command a collision avoidance maneuver sooner than necessary, which may be considered a nuisance by the pilots, but that is a more desirable outcome than CFIT.

In order to characterize the directionality of the PPE for a given manual activation, the actual path of the aircraft was compared with the predicted path in two aspects: climb performance and turn performance. To compare the climb performance, the actual and predicted paths were plotted and viewed from the side to determine if the aircraft out-climbed the prediction. Figure 17 shows an example of a side view of a Path 3 manual activation. The actual aircraft path, shown in blue, stayed below the predicted path for the entire maneuver, which indicates that the aircraft had worse climb performance than was predicted by the TPA and that the path error was towards the terrain.

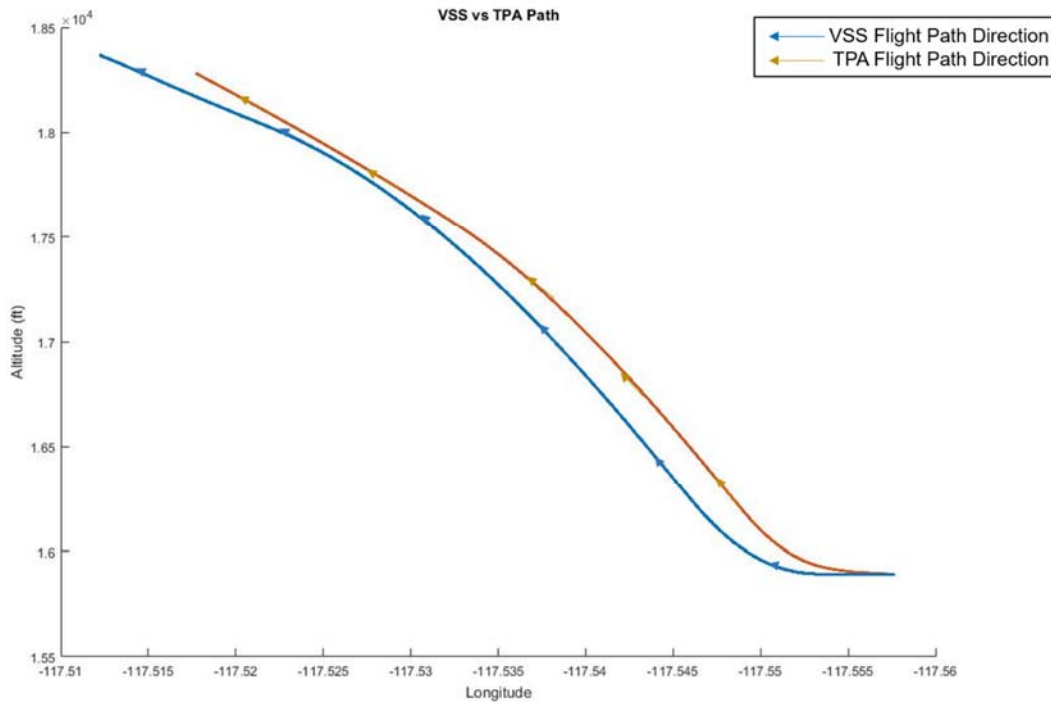


Figure 17 – Side View of Forward Climb

To compare the turn performance of the actual aircraft to the TPA, the paths were plotted and viewed from above to determine if the aircraft had a smaller or larger turn radius than what was predicted by the algorithm. Figure 18 shows an example top view of a Path 5 manual activation. The actual aircraft path had a larger turn radius than the predicted path, which indicates that the aircraft had worse turn performance than was predicted and that the path error was towards the terrain.

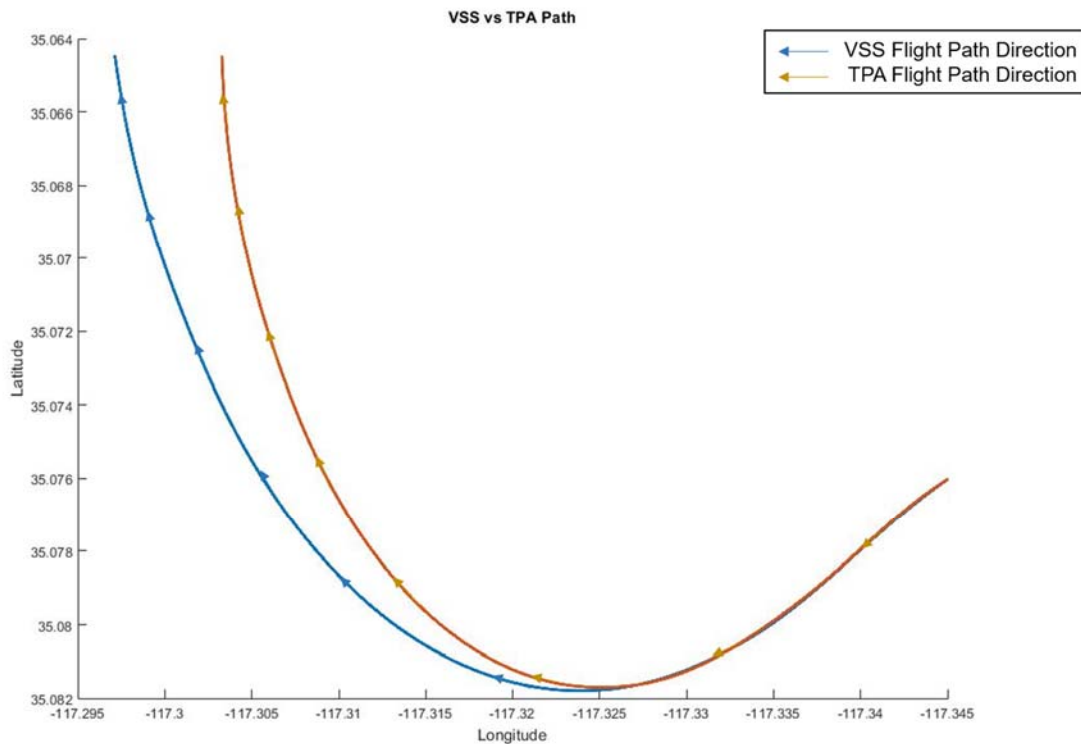


Figure 18 - Bird's Eye View of 60 deg Right Turn (Path 5)

If both the climb and turn performance of the actual aircraft exceeded (i.e. out-performed) the prediction, then it was concluded that the error was in a direction “away from terrain”. Alternatively, if both the climb rate and turn radius of the actual aircraft under-performed the prediction, then it was concluded that the error was in a direction “toward terrain”, indicating a more dangerous situation. If the actual aircraft out-performed the prediction in one aspect but under-performed in the other aspect, then the direction of the error was deemed to be “inconclusive”, because the safety of the maneuver would be dependent on the terrain feature. A summary of the results for the directionality of the PPE is presented in Table 6. Results for each test point are provided in APPENDIX E – PATH PREDICTION ERROR RESULTS.

Table 6 - Summary of PPE Directionality

	# Test Points	Total Test Points	Percentage
Actual Climb Performance Exceeded Prediction (Applicable for all Paths)	61	120	50.8%
Actual Turn Performance Exceeded Prediction (N/A for Path 3 activations)	41	96	42.7%
Error Away from Terrain	44	120	36.7%
Error Towards Terrain	54	120	45.0%
Inconclusive	22	120	18.3%

Two general trends were observed in the PPE direction data. First, the direction of the PPE was correlated to the airspeed flown. At the slower airspeed, 220 KIAS, the actual path generally had a smaller turn radius than predicted, but worse climb performance than predicted. This resulted in Paths 1 and 5 generally erring away from terrain and Path 3 erring toward terrain. At the higher airspeed, 270 KIAS, the actual path generally had a larger turn radius than predicted, but better climb performance than predicted. This resulted in Paths 1 and 5 generally erring toward terrain and Path 3 erring away from terrain. The second trend observed from the PPE direction data was a correlation with the entry condition. For SLUF and climbing entries, the aircraft generally out-performed the prediction and erred away from terrain. For level turn and descending entries, the aircraft generally under-performed the prediction and erred toward terrain. This suggests that the current implementation of RSET performs best when the aircraft starts from straight-and-level flight or from a slight climb.

Thus far, the discussion has focused on trends in the PPE magnitude and direction data with respect to the control variables (airspeed, altitude, entry condition, and RSET path). However, there are several confounding variables that could have had a significant effect on the PPE results. Possible sources of error include (1) the auto-trim feature of the VSS, (2) incorrect accounting of wind speed and direction in the TPAs, and (3) the low fidelity of the Learjet engine model used in the TPAs. The first two error sources were investigated in post-flight analysis, but the error due to engine model inaccuracies was not investigated. The engine model used by the TPAs was a simplistic model, but its limitations are not fully understood. A separate study would need to be performed to understand the accuracy of the model for various flight conditions.

One potential source of error was the auto-trim feature of the VSS. This function was in place to reduce hinge loads on the horizontal stabilizer, and was a normal part of the LJ-25D flight control system. Therefore, this feature could not be disabled for flight safety, and was not accounted for due to the discovery of this feature during flight test. The RSET system used the initial value for the horizontal stabilizer deflection at activation, and did not account for auto-trim changes during the maneuver. This error can be seen in Figure 19 and Figure 20. At the time the auto-trim functions activates, the RSS error begins to grow at a faster pace. While this was not the only source of error, it did appear to be a contributing factor.

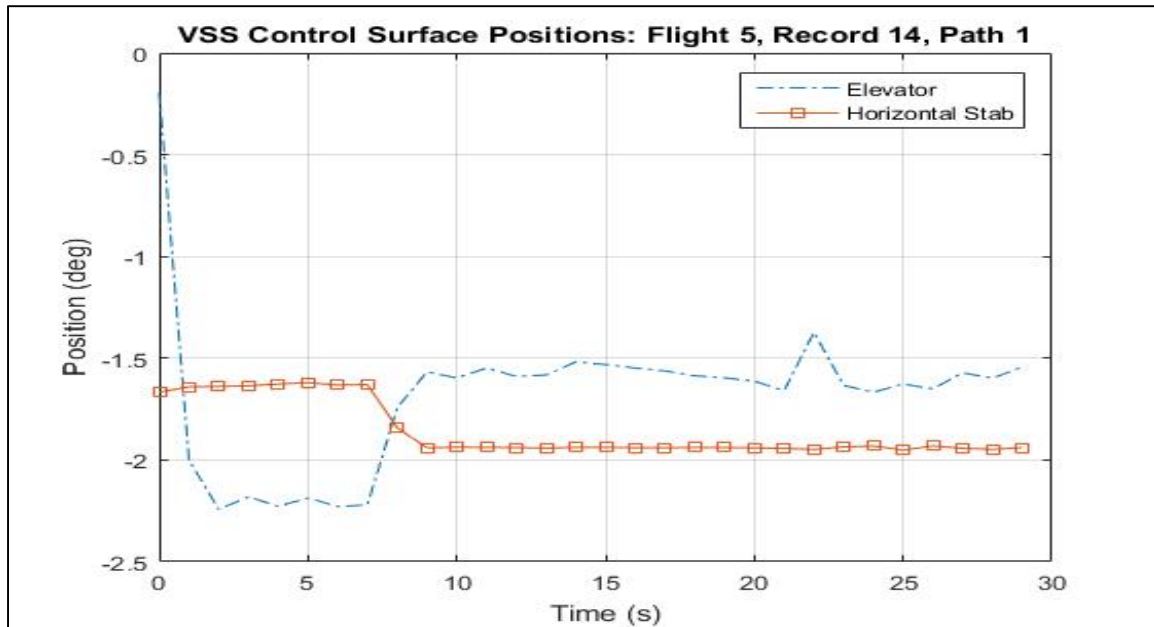


Figure 19 - VSS Control Surface Positions

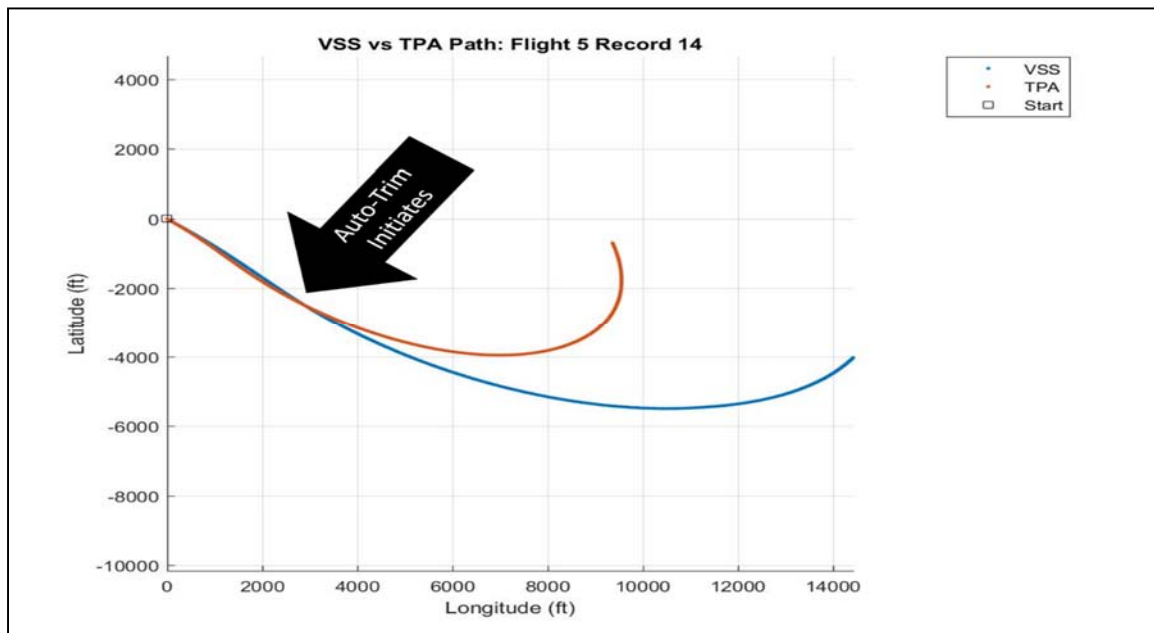


Figure 20 - VSS vs TPA Path: Flight 5 Record 14

Another confounding variable that was investigated as a source of error was wind. The wind data entered by the TC was derived from the onboard EGI and air data systems. The TPAs compensated for the wind in its path predictions. The wind speed and direction were assumed to be constant throughout the RSET maneuver. However, post-flight data analysis showed that the aircraft was consistently drifting away from the predicted path in the direction of the wind during manually activated RSET maneuvers. Figure 21 shows a bird's eye view of the actual aircraft path and the predicted path with the wind vectors overlaid for the following test point: 500 ft AGL, 270 KIAS, level turn entry, Path 1 activation. The actual aircraft path appears to be drifting away from the predicted path in roughly the same direction that the wind is blowing. The same plot was generated for all 120 manual activation test points, and APPENDIX E – PATH PREDICTION ERROR RESULTS presents the wind speed for each point and whether or not the wind direction appears to be contributing to the PPE. For 88% of the test points, the actual aircraft path appears to be drifting away from the predicted path in the same direction as the wind. These results suggest that the TPAs are not accurately accounting for winds in their path predictions. Furthermore, this error due to wind could explain some of the previous trends. For instance, since wind speed generally increased with increasing altitude, the inability to fully account for winds could explain why PPE increased with increasing altitude.

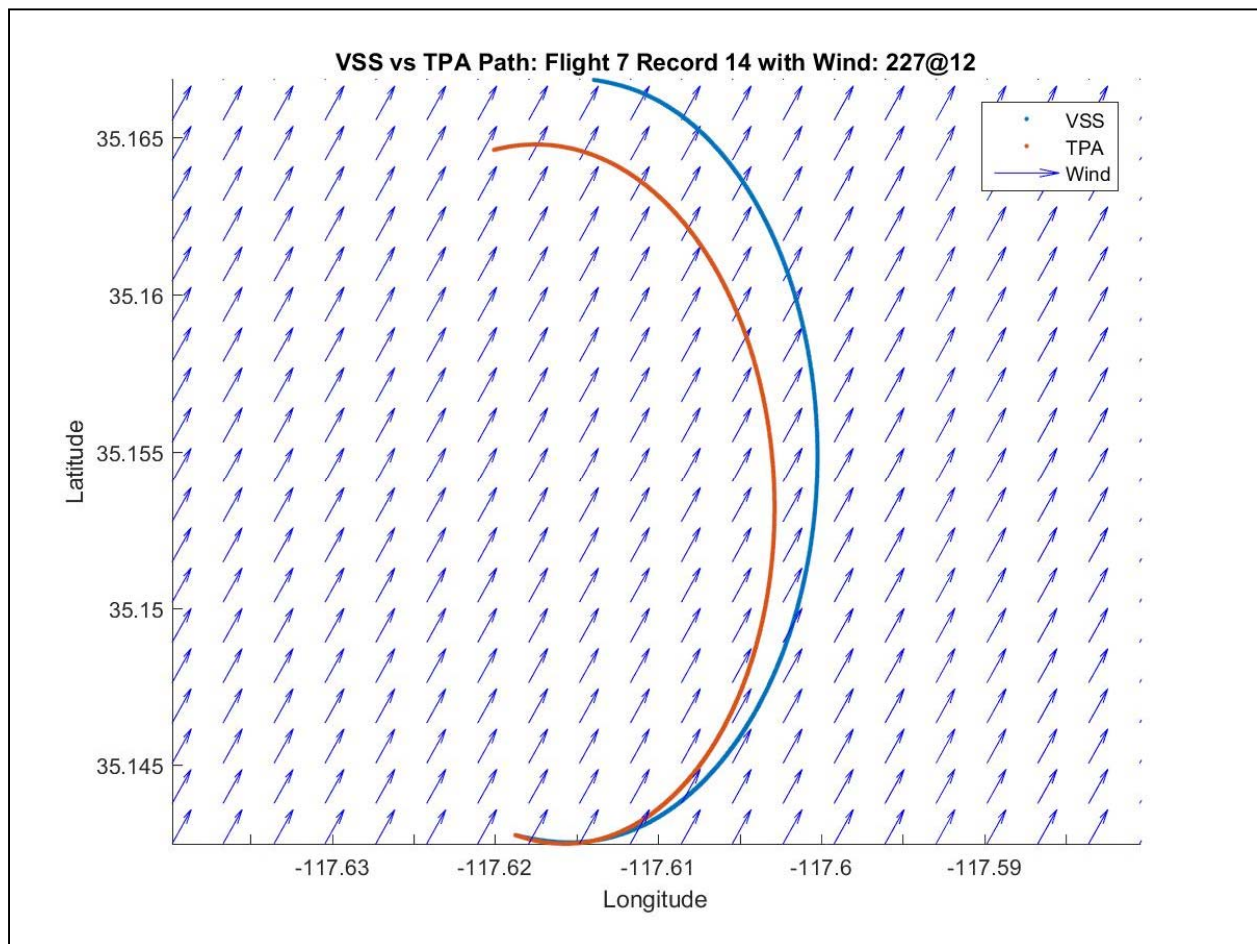


Figure 21 - VSS vs TPA Path: Flight 7 Record 14 with Wind: 227@12

While the maximum PPE calculated during each 30 second maneuver was found to be, on average, much higher than the amount deemed to be acceptable (300 ft), it is believed that this metric is not a fair indicator of the overall utility of the RSET system. Since the actual aircraft position drifted from the predicted path as time progresses during an RSET maneuver, the calculated PPE is usually at a maximum at the very end of the 30 second maneuver. As will be seen in the results for forward look-ahead time, it typically takes significantly less than 30 seconds to clear a terrain feature when a refresh rate of 12.5 Hz is used. Hypothetically, if it takes the aircraft 10 seconds to clear a terrain feature from the start of a commanded RSET maneuver, then there is a chance that the PPE at the 10 second point is within the acceptable amount; whereas the PPE at the 30 second point would have grown enough to be outside the acceptable amount. Since the evaluation criteria for RSET prediction accuracy did not take into account intermediate time steps within a manual activation and the direction of the error (toward vs. away from terrain), little can be concluded on the utility of RSET as a ground collision avoidance system with this metric alone. Figure 22 shows a time history of the PPE during a manual maneuver of RSET Path 3 at the following conditions: 15,000 ft PA, 270 KIAS, climbing entry. It can be seen that while the maximum PPE, which occurs at 30 seconds after activation, is 754 ft, the PPE stays under the acceptable value of 300 ft for the first 13 seconds during the maneuver. If the terrain had been cleared within 13 seconds, then the unacceptable PPE error for the remainder of the maneuver is irrelevant to the utility of the RSET system.

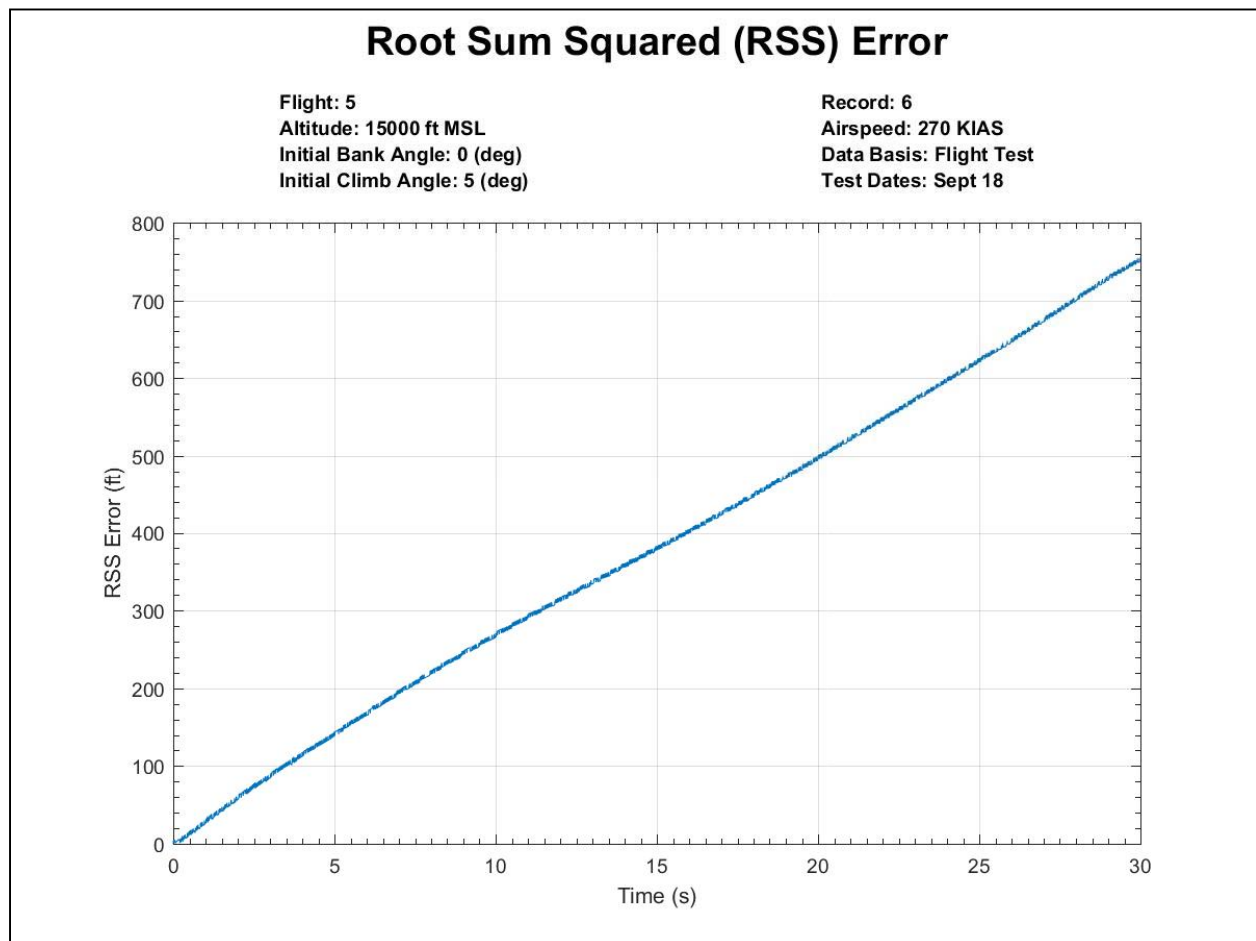


Figure 22 - Time History of RSS Error (PPE) during a manual activation.

Overall, the RSET system received a MARGINAL rating. Three test points were acceptable with a maximum PPE between 100 ft to 300 ft, and the remaining 117 test points were marginal with maximum

PPE above 300 ft. The smallest maximum PPE was 172 ft and the largest maximum PPE was 6568 ft. It was observed that maximum PPE tended to be higher for Path 1 and 5 activations, followed by Path 2 and 4 activations and lowest for Path 3 activations. Next, maximum PPE was higher for diving entries compared to the other three entries. Lastly, it was concluded that out of the 120 test points analyzed, 44 had PPE erring away from terrain, 54 had PPE erring towards terrain and the remaining 22 test points were inconclusive. The possible sources of error that could account for the marginal rating of the prediction accuracy of the RSET system could be the auto-trim feature of the VSS, incorrect accounting of wind speed and direction in the TPAs, and the low fidelity of the Learjet engine model used in the TPAs. In particular, post-flight analysis suggested that the TPAs were not properly accounting for winds. **R1: Conduct further data analysis to determine the sources of error and their impact to PPE.** Furthermore, the majority of test points were only tested once and had no statistical significance in PPE. **R2: Conduct repeat runs of specific test conditions to increase statistical significance of PPE results.**

REFRESH RATE IMPACT ON ESCAPE PATH CALCULATION

The specific test objective was to gather terrain miss distance and forward look-ahead time data to characterize a baseline performance model for the RSET solution. An initial baseline was demonstrated for the RSET system. Slower refresh rates appeared to have a negative impact on the ability of the system to safely avoid virtual terrain. No significant correlation between, airspeed, altitude or initial condition and terrain miss distance was found. Additionally, the necessary forward look-ahead time increased as refresh rate decreased. At the lowest refresh rates, the 30 sec path prediction time used did not appear to be adequate to ensure sufficient terrain miss distance. The test objective was met.

Overall Test Methods and Conditions

The baseline performance of the RSET system was tested using one terrain feature which included large mountain peaks located within the R-2508 complex as shown in Figure 23. The terrain feature was located at 35° 31' 42.0" N, 116° 18' 31.2" W. The base of the mountain was approximately at 0 ft MSL, and the peak was approximately 6,200 ft MSL. The test included three altitudes (15k ft PA, 8k ft PA, and 500 ft AGL), two airspeeds (220 and 270 KIAS), and three initial conditions. The three initial conditions were selected to present different headings which provided varying terrain features to ensure all five paths were exercised. While the real aircraft was flown at varying altitudes, the virtual altitude induced by the terrain slewing tool was always set to 2,000 ft MSL. Three refresh rates were tested at each of these conditions (12.5 Hz, 6.25 Hz, and 1.5625 Hz).

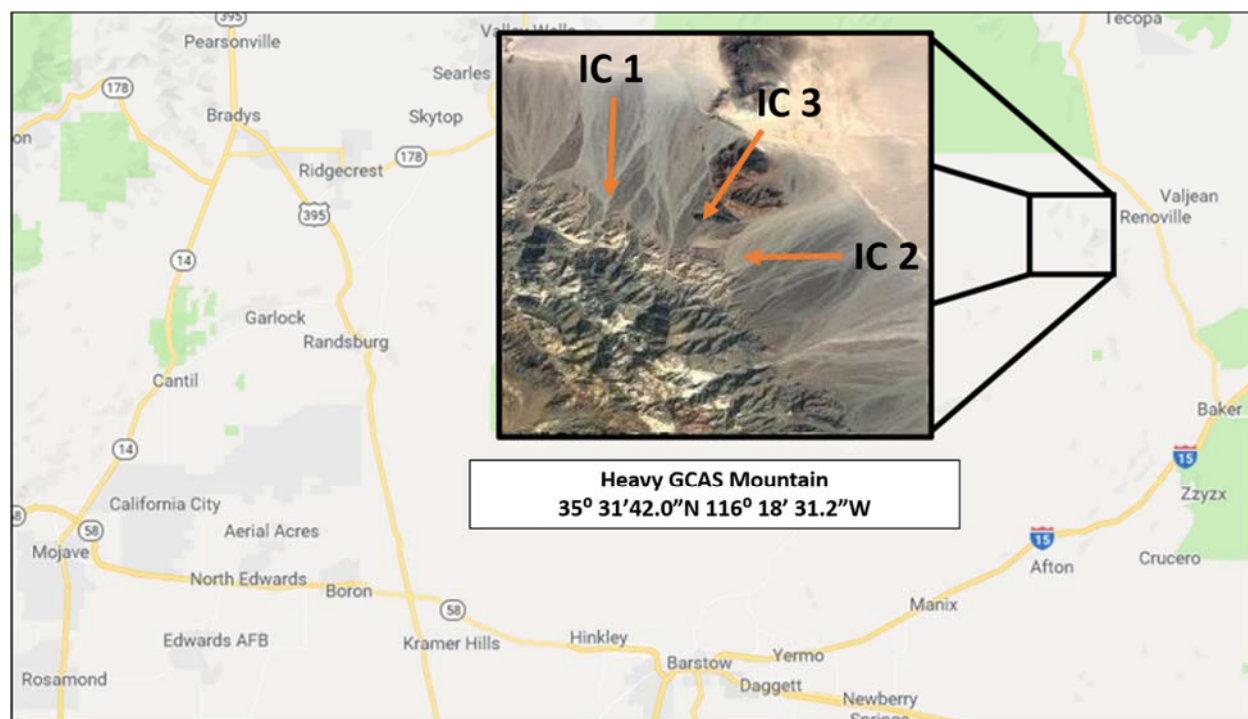


Figure 23 - Location of "Heavy GCAS Mountain"

The terrain miss distance data were analyzed by calculating the difference of the aircraft altitude to the height of the interpolated DTED surface directly below the aircraft. The sign of this value was used to determine whether the aircraft was above or below the virtual terrain. The actual distance to the virtual terrain was calculated as the smallest distance from the aircraft's location to a plane defined by the three closest DTED posts. This calculation was repeated at every time step throughout the path activation. The

details of this calculation can be seen in APPENDIX C – DATA ANALYSIS PROCEDURES. The minimum value for each test run was then recorded as the terrain miss distance, with a negative value indicating terrain impact. Those miss distances were plotted against refresh rate with markers identifying either the initial condition (starting point and heading), test altitude, or test airspeed. This method was not the originally planned analysis method. An alternate method for calculating terrain miss distance using a root sum squared distance from the aircraft location to the nearest DTED posts of the surrounding terrain was planned. However, this presented scenarios that displayed a terrain impact when the aircraft was clear of the interpreted DTED terrain, since only the DTED posts were used in this method.

The forward look ahead time was analyzed by determining the first point along the prediction path that impacted terrain, at the moment the last remaining path was determined to be closed by the collision detector. This point was reported as a time along the path, with the point closest to the aircraft at zero seconds, and the end of the path being 30 seconds (30 seconds was the length of each path prediction, known as the path prediction time). All five paths were analyzed, and the highest of the five times was used as the required forward look-ahead time. Figure 24 shows a graphical representation of this analysis. These look-ahead times were plotted to compare the impact of refresh rate on forward look-ahead time. The plots also included indications of whether each activation impacted terrain or not. A terrain impact implied that the current path prediction time was not adequate.

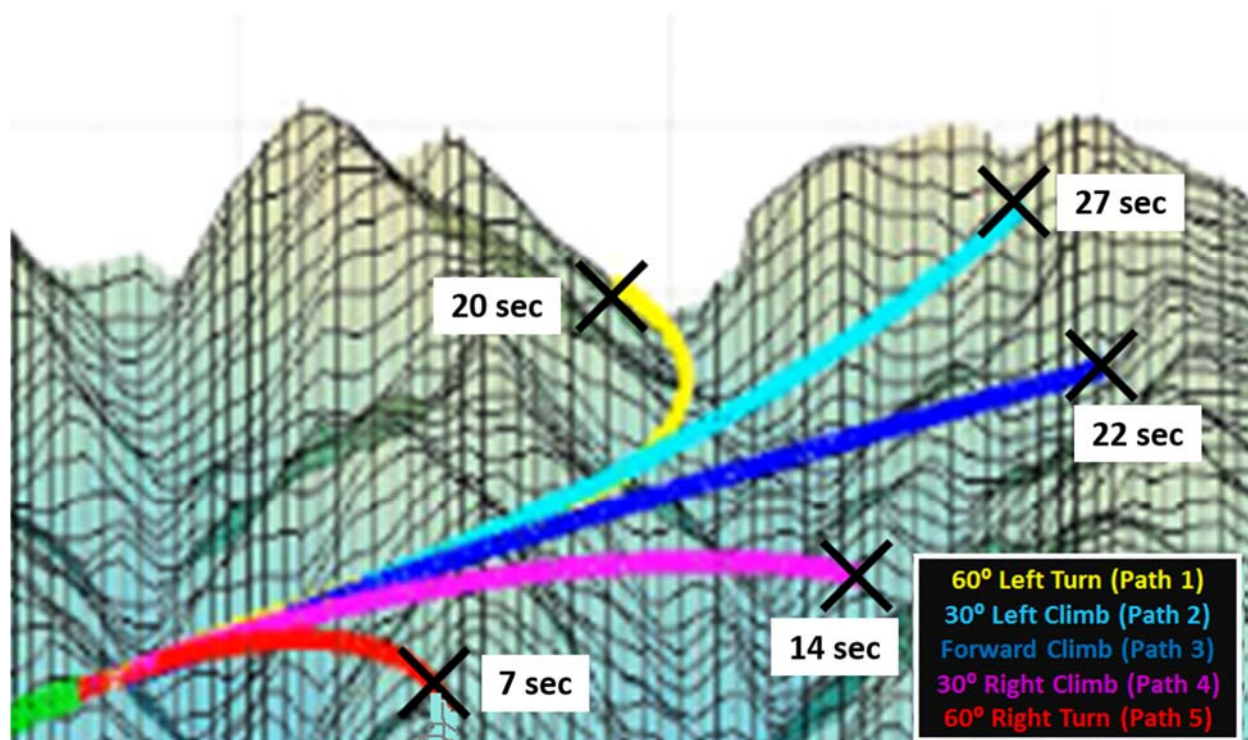


Figure 24 - Forward Look-Ahead Time

Terrain Miss Distance Test Results

The results showed that the highest refresh rate was required to ensure a successful terrain avoidance maneuver. A 12.5 Hz refresh rate showed no virtual terrain impacts, while at lower refresh rates terrain impacts did occur for the same test conditions. Figure 25 shows the effect of the starting location and heading on miss distance. Although it was beyond the scope of this test to exercise the RSET system against numerous terrain types, the obstacle chosen, “Heavy GCAS Mountain”, presented different terrain

profiles from each starting point. These profiles included slowly rising terrain, steeply rising terrain, and valleys.

The initial conditions did not appear to have a significant impact on terrain miss distance at the highest refresh rate. At the lower refresh rates there appeared to be slightly more variation in initial condition 3 which flew directly towards the mountain. Initial conditions 1 and 2 placed the aircraft on more of a “glancing” angle with the terrain, which meant that, in general, once the avoidance maneuver away from the terrain was executed then the aircraft was clear of any other local co-altitude terrain.

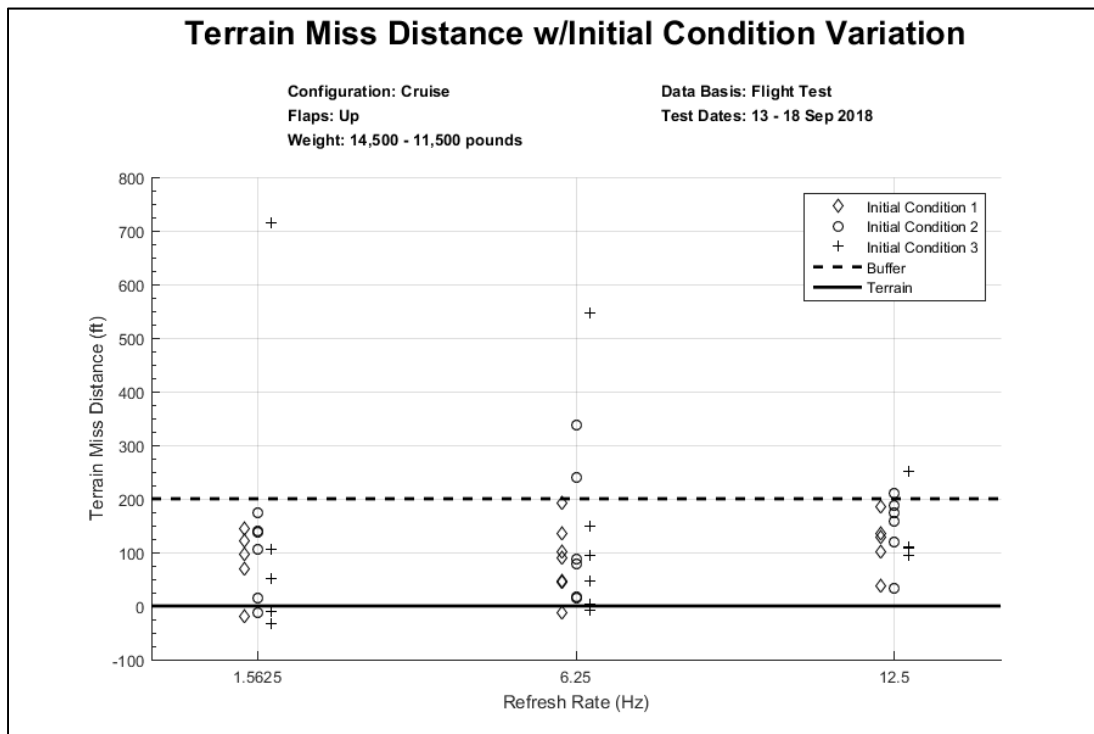


Figure 25 - Terrain Miss Distance with Initial Condition Variation

Figure 26 and Figure 27 shows a typical terrain miss distance profile. The low speed is the primary cause of the flight path closely following the terrain. However, at no time did the aircraft's flight path intersect the digital terrain. This was also the case for all the other runs at a 12.5 Hz refresh rate. The rest of the data results can be found in APPENDIX K – DIGITAL APPENDIX.

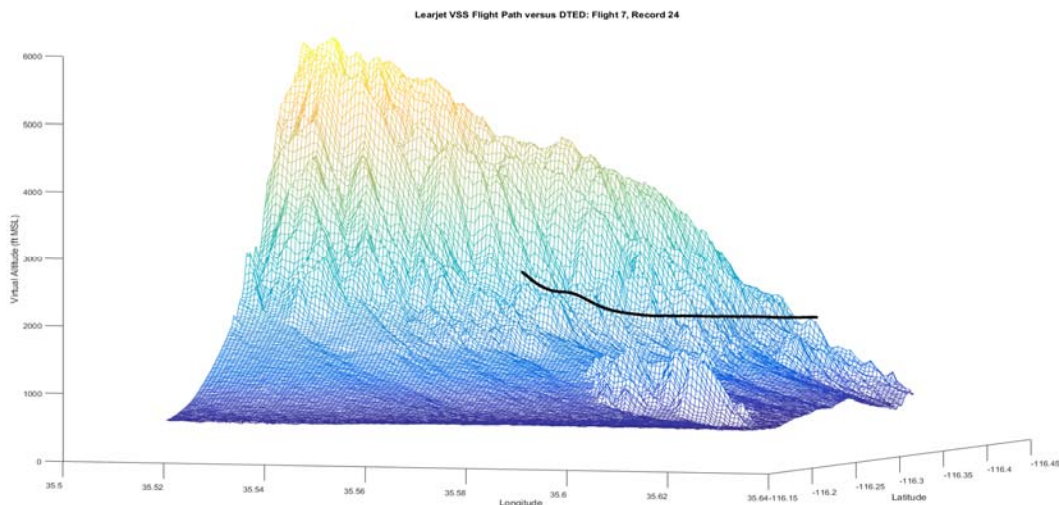


Figure 26 - Learjet VSS Flight Path versus DTED: Flight 7, Record 24, 220 KIAS, 500 ft AGL, IC 1

Root Sum Squared (RSS) Distance to Closest Terrain

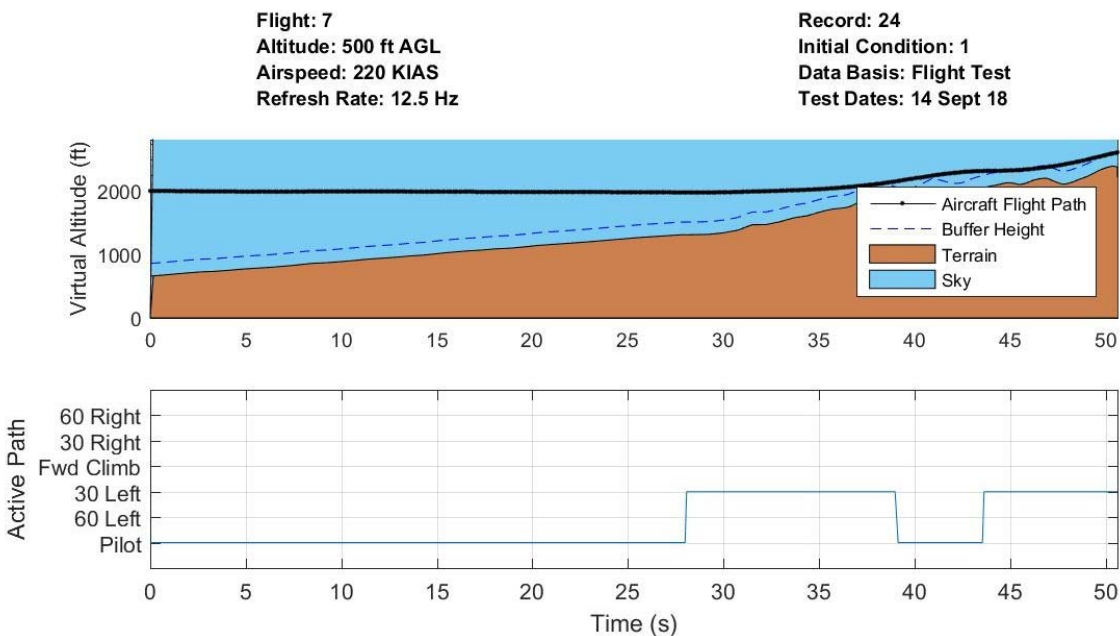


Figure 27 - Distance to Terrain: Flight 7, Record 24, 220 KIAS, 500 ft AGL, IC 1

As can be seen from Figure 28, at the highest refresh rate there appeared to be no significant change in performance with altitude variation. At the 6.25 Hz refresh rate there was slightly more variation with higher altitude, but this was not significantly observed at the other refresh rates.

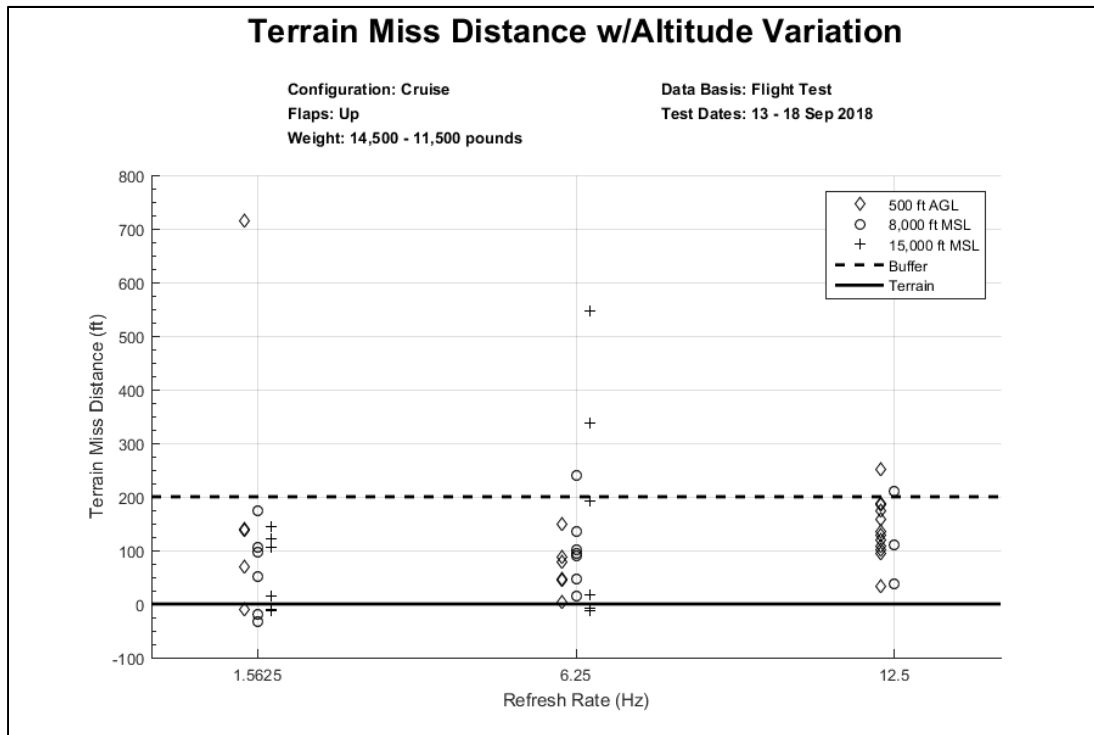


Figure 28 - Terrain Miss Distance with Altitude Variation

As seen in Figure 29, airspeed also had no well-defined trend. The terrain miss distance appeared to vary randomly across both airspeeds.

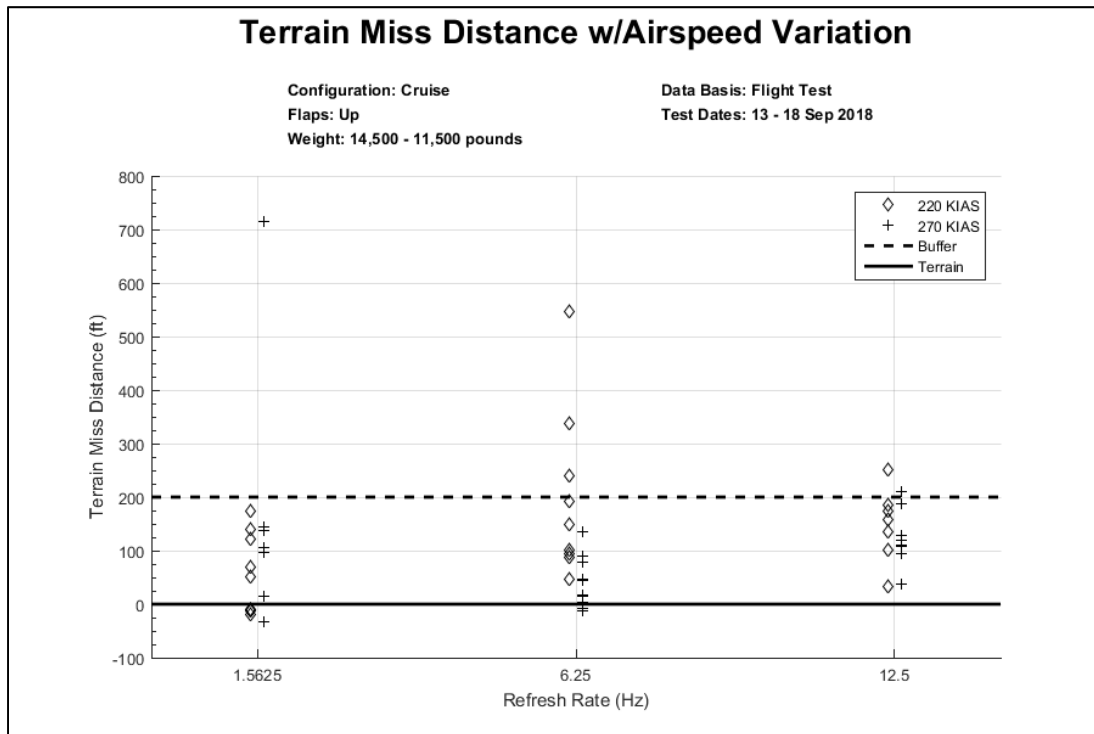


Figure 29 - Terrain Miss Distance with Airspeed Variation

Based on these results, it appeared that a higher refresh rate near 12.5 Hz was required to ensure terrain clearance with this implementation of the RSET system. The other factors appeared to have no significant impact on terrain clearance. The selection of an appropriate terrain buffer was also a critical parameter for system performance. The 200 ft terrain buffer used in this implementation provided an initial reference for the size of terrain buffers for future system implementations. Future systems must also evaluate the mission set and aircraft performance ability when determining a terrain buffer. Overall, these findings should provide a reference for future multi-path systems on required system performance. **R3: Using a refresh rate of 12.5 Hz or faster, investigate the effect of varied operationally representative terrain types and terrain buffers on miss distance.**

Forward Look-Ahead Time Test Results

Figure 30 shows a trend of decreasing forward look-ahead time required with increasing refresh rate. At the lowest refresh rate all 30 seconds or more were required indicated by the number of virtual impacts seen, but at the highest refresh rate 16 seconds was the highest required forward look-ahead time with no virtual impacts observed. No significant trend was seen based on initial condition, although it was predicted that more look-ahead time would be required for more aggressive terrain. This trend may not have been clearly seen during this test since all initial conditions contained fairly aggressive terrain features.

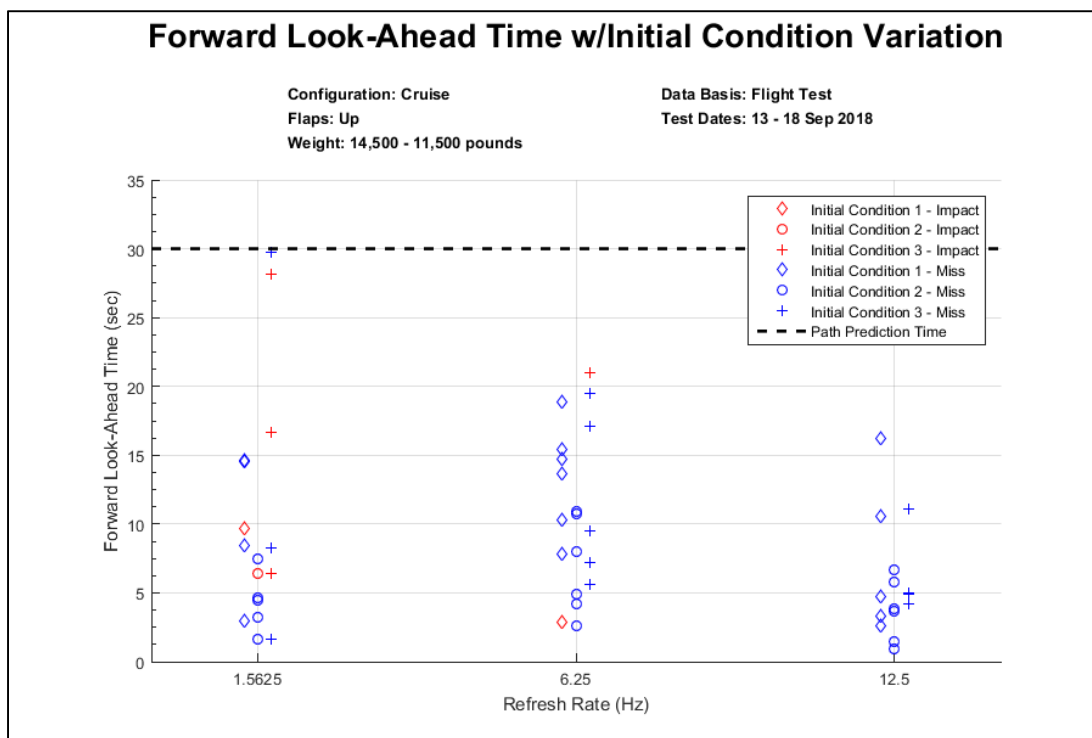


Figure 30 - Forward Look-Ahead Time with Initial Condition Variation

As seen in Figure 31, no clear trend was seen across refresh rates for the effect of altitude on forward look-ahead time. Model accuracy was expected to decrease with deviation from 15,000 ft, the model's validation altitude. However, this trend was not seen consistently across refresh rates.

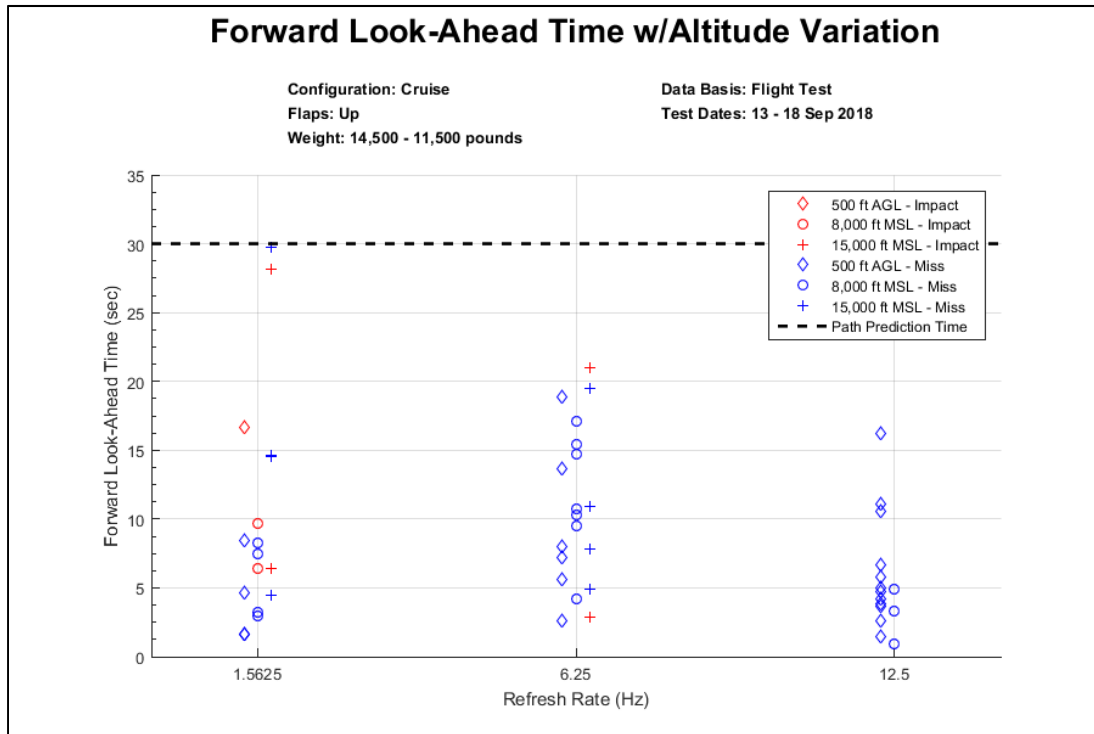


Figure 31 - Forward Look-Ahead Time with Altitude Variation

Figure 32 shows the variation of airspeed across each refresh rate. No significant trend was observed from flight test. This behavior was expected since the paths were a fixed time, e.g. a 30 sec prediction path at 270 KIAS was a longer distance than a 220 KIAS prediction path.

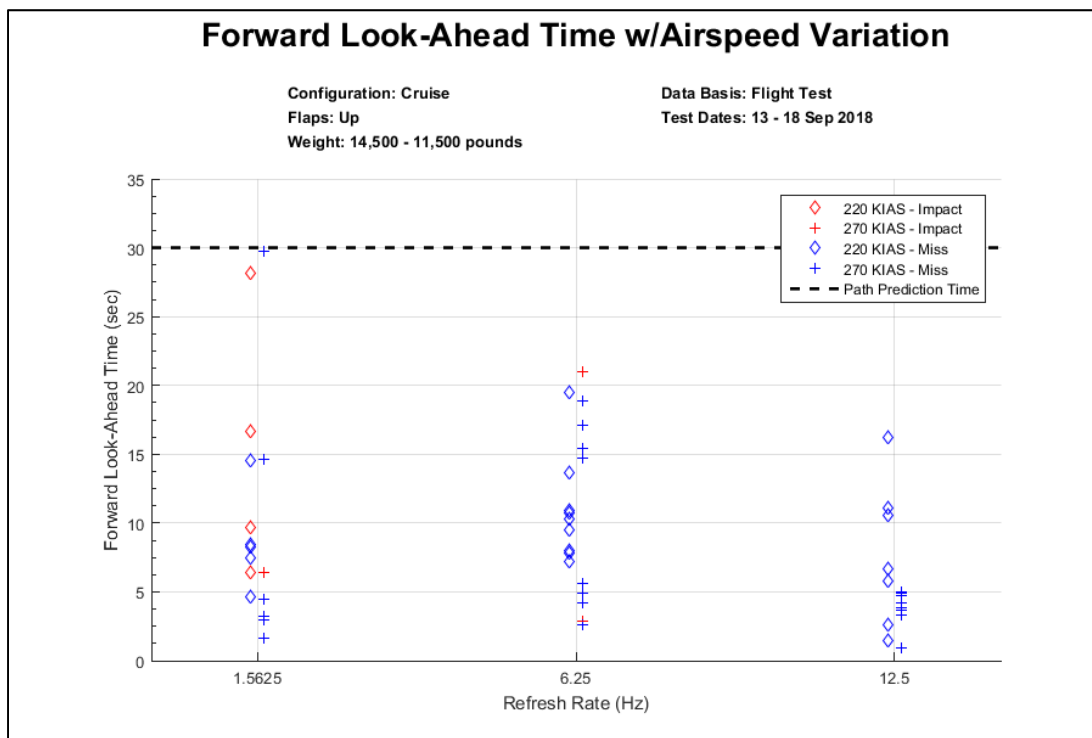


Figure 32 - Forward Look Ahead Time with Airspeed Variation

The data showed that an increased refresh rate yielded a shorter required forward look-ahead time. Forward look-ahead time did not appear to be significantly affected by other factors such as initial condition, airspeed, or altitude. The system refresh rate will drive the forward look ahead time, and the presented data should provide a rough starting point for future multi-path collision avoidance systems.

R4: Evaluate the need for forward look-ahead times beyond 30 seconds.

NUISANCE ACTIVATION TENDENCY

The specific test objective was to observe the system's tendency for nuisance activations. The European Aviation Safety Agency (EASA) defined nuisance alerts as inappropriate alerts, occurring during normal safe procedures, which are the result of design performance limitations. The FAA defined nuisance alerts as alerts generated by a system that is functioning as designed but which is inappropriate or unnecessary for the particular condition. For this evaluation, nuisance activations were defined as RSET path closures that were perceived as unnecessary for terrain avoidance.

The pilots' perception of nuisance relied heavily on the system's ability to operate both timely and aggressively. Since the system already demonstrated its timeliness, the test team looked to characterize its aggressiveness. That is, ability of the RSET to command escape maneuvers at or near the VSS limits, as well as the aircraft's ability to perform at or near the RSET-commanded conditions. The system's

aggressiveness was important to characterize since the pilots would have considered a system that maneuvered less aggressively than they would have as nuisance prone. The test objective was met.

Path Performance Test Methods and Conditions

Data were collected during manually activated escape paths to compare predicted escape paths and actual aircraft flight paths. The TC manually activated escape paths via a laptop at the engineer's station. The laptop communicated a value from 1-5 to the VSS, which then activated the corresponding RSET autopilot (1: 60° Left Turn, 2: 30° Climbing Left, 3: Forward Climb, 4: 30° Climbing Right, 5: 60° Right Turn). That autopilot then commanded the aircraft to fly the chosen maneuver and data were collected to compare the predicted and actual aircraft paths. The pilot set MCP for each maneuver within three seconds of path activation. Maneuvers were considered complete once the RSET system returned control of the aircraft to the pilot following the escape maneuver.

Path Performance Test Results

The RSET system was designed to command escape maneuvers near the Learjet VSS safety trip limits, specifically +0.25g to +2.8g and 12° flight path angle. Flight test data were gathered to identify how well the RSET system commanded maneuvers at or near its performance design targets.

The RSET system commanded maneuvers commensurate with available aircraft performance. For all activations, MCP was set within three seconds of the escape maneuver beginning. By design, the VSS commanded more aggressive escape maneuvers during the 270 KIAS test points than it did during the 220 KIAS test points. That is, the RSET commanded higher load factors and FPAs when more aircraft performance was available. As a result, airspeed and RSET-commanded load factor and FPA gradually decreased throughout the escape maneuver until reaching a steady energy state. The aircraft generally achieved steady state, RSET-commanded AOB within five seconds of escape maneuver activation. With less performance available during the 220 KIAS escape maneuvers, the aircraft initially performed at reduced load factors and FPAs but gained energy as the throttles were advanced. As a result, airspeed and RSET-commanded load factor and FPA gradually increased throughout the escape maneuvers until reaching a steady energy state. These behaviors can be seen in Figure 33 through Figure 38. Path performance of paths 4 and 5 (right turning escape maneuvers) was representative of paths 1 and 2 (left turning escape maneuvers).

Figure 33 shows a path 3 escape maneuver initiated from straight and level flight, at 220 KIAS and 500 ft AGL. Initially, performance available was low so the RSET commanded a gradual increase in load factor and FPA. The available performance increased as power reached MCP and the aircraft stabilized on the RSET-commanded limit of approximately 8° FPA. Once on the RSET limit of FPA, the system no longer commanded an increase in load factor.

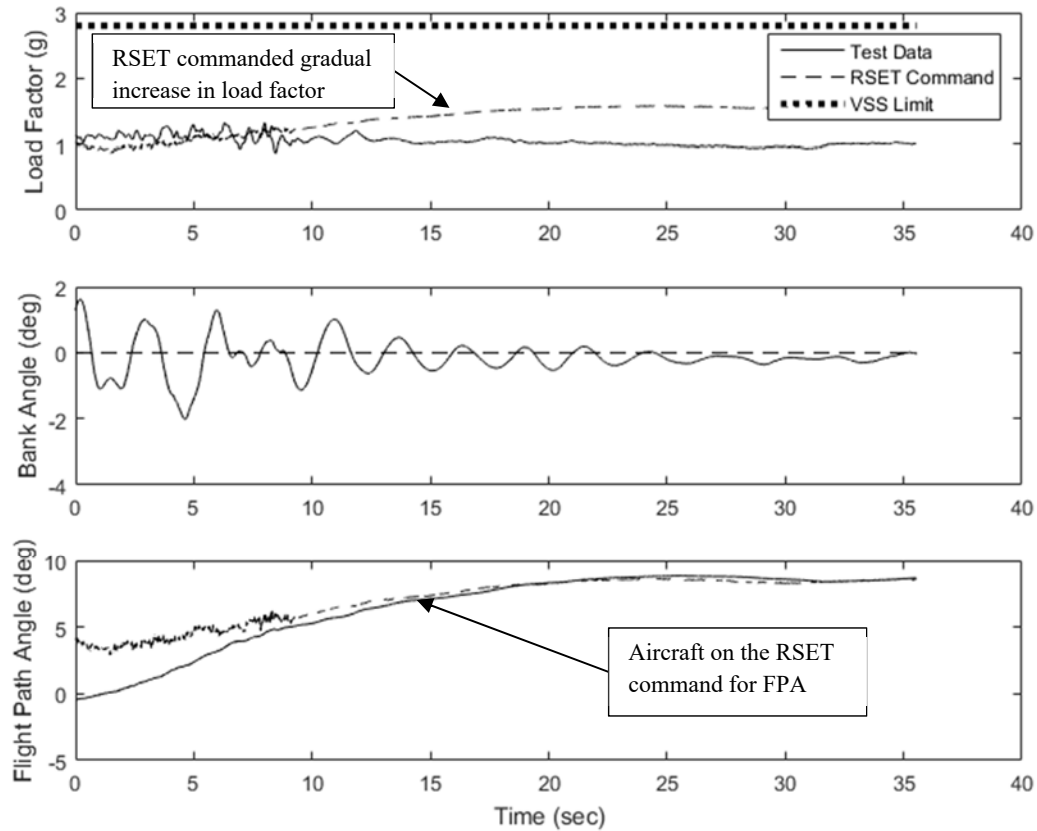


Figure 33 – Path 3 Performance, 220 KIAS, 500 ft AGL, SLUF Entry

Figure 34 shows a path 3 escape maneuver initiated from a left 45° bank, at 270 KIAS and 500 ft AGL. Initially, performance available was high so the RSET commanded the aircraft to simultaneously roll wings level and increase load factor to keep FPA greater than or equal to zero. The aircraft reached the RSET-commanded load factor limit when wings level and the FPA began to rapidly increase to the RSET limit. The RSET commanded the aircraft to maintain the load factor limit until reaching the FPA limit. As a result of this binary-style logic, the aircraft overshoot the FPA limit by approximately 5° (50%). The FPA gradually decreased until the RSET-commanded limit and the aircraft's actual FPA were in agreement. The airspeed never decreased below the test limit of 200 KIAS during the FPA overshoot; however, the system should account for potential FPA overshoots to preclude unsafe airspeeds during escape maneuvers.

R5: Account for FPA overshoots in the escape maneuver control laws for high aircraft performance conditions.

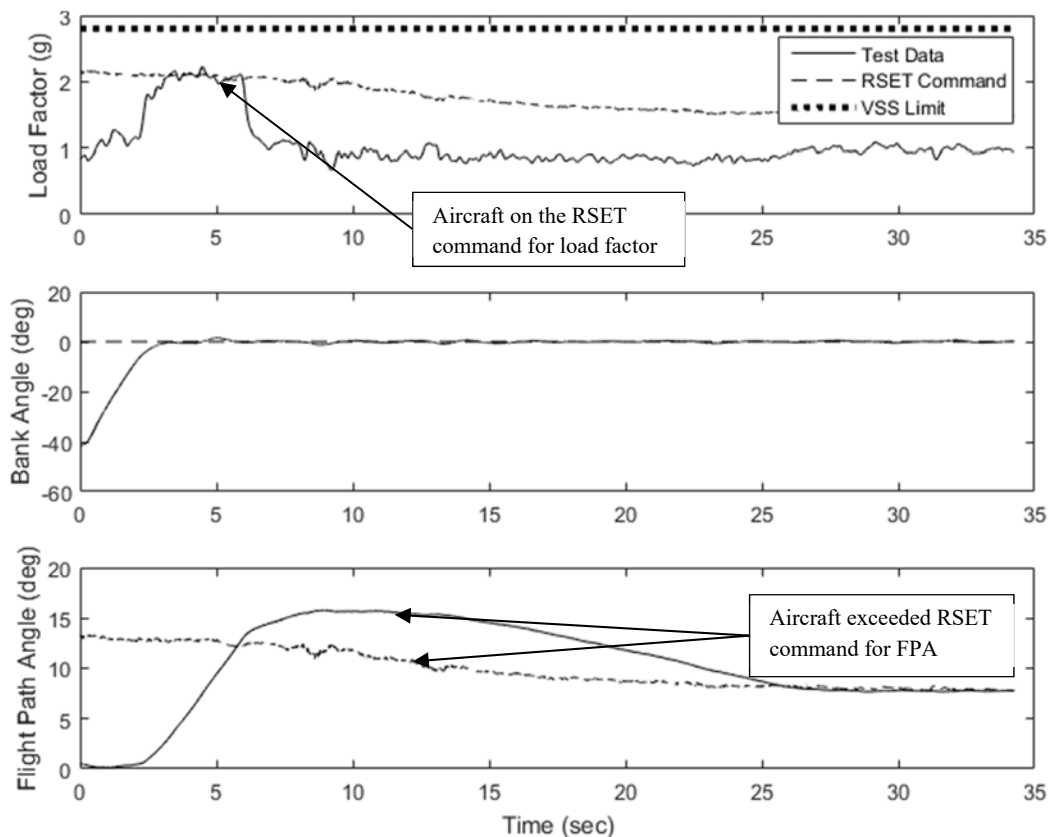


Figure 34 – Path 3 Performance, 270 KIAS, 500 ft AGL, 45° Left Turning Entry

Figure 35 shows a path 4 escape maneuver initiated from a left 45° bank, at 220 KIAS and 500 ft AGL. Initially, performance available was low so the RSET commanded a gradual increase in load factor and FPA. The available performance increased as power reached MCP and the aircraft stabilized on the RSET-commanded limit of approximately 8° FPA. Once on the RSET limit of FPA, the system no longer commanded an increase in load factor.

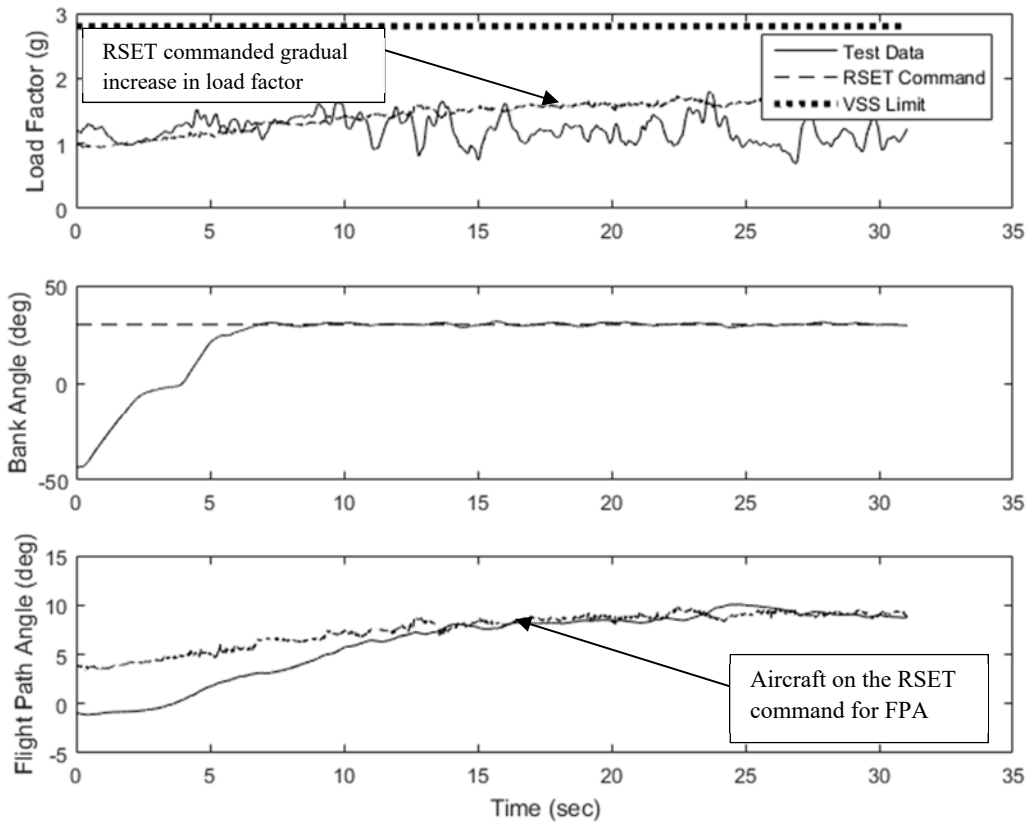


Figure 35 – Path 4 Performance, 220 KIAS, 500 ft AGL, 45° Left Turning Entry

Figure 36 shows a path 4 escape maneuver initiated from a left 45° bank, at 270 KIAS and 500 ft AGL. Initially, performance available was high so the RSET commanded the aircraft to roll wings level and, passing through 0° of bank, increase load factor to keep FPA greater than or equal to zero. The aircraft reached the RSET-commanded load factor limit and the FPA began to rapidly increase to the RSET limit. The RSET commanded the aircraft to maintain the load factor limit until reaching the FPA limit. As a result of the excess performance available, the aircraft overshoot the FPA limit by approximately 2° (17%). The FPA gradually decreased until the RSET-commanded limit and the aircraft's actual FPA were in agreement.

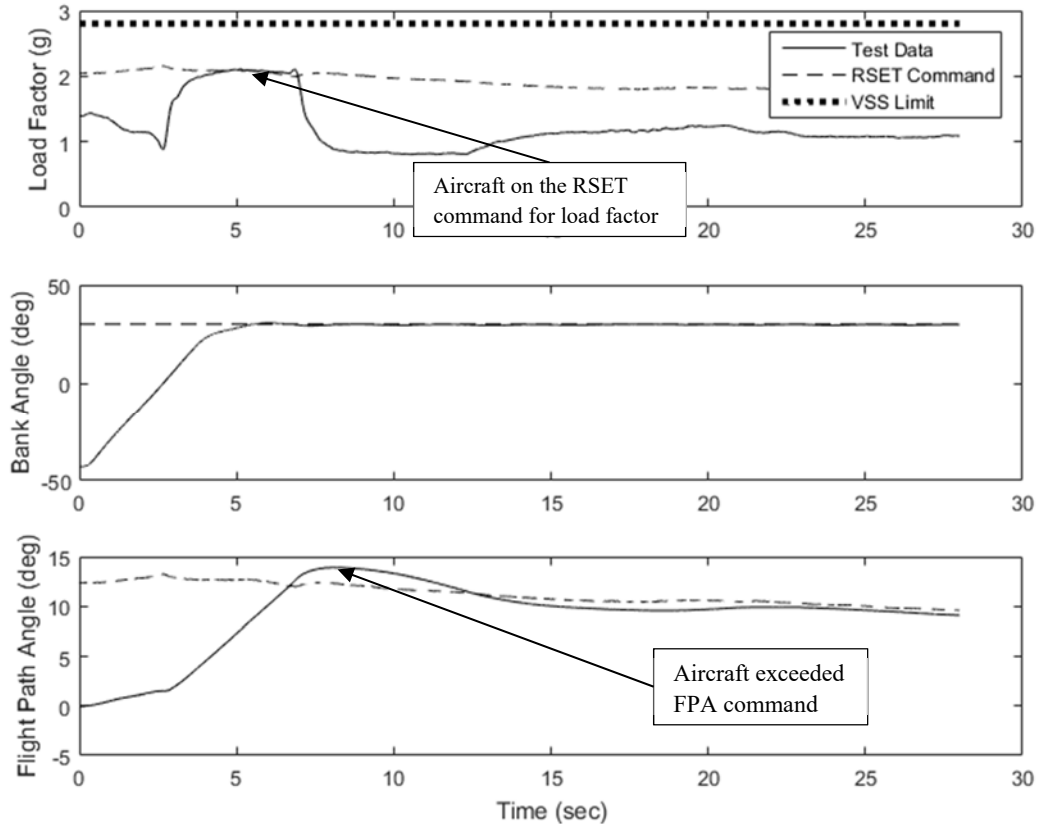


Figure 36 – Path 4 Performance, 270 KIAS, 500 ft AGL, 45° Left Turning Entry

Figure 37 shows a path 5 escape maneuver initiated from straight and level flight, at 220 KIAS and 500 ft AGL. Initially, performance available was too low to maintain the RSET-commanded 60° AOB without descending. The RSET control logic prioritized maintaining greater than or equal to zero FPA over the escape maneuver's 60° AOB. As a result, the aircraft decreased AOB, raised the nose until greater than or equal to zero FPA could be reestablished, and then continued its 60° AOB. This ratcheting was undesirable, and could lead to confusion and incorrect pilot actions. This behavior was not common during the 270 KIAS test points as enough aircraft performance was available to keep greater than or equal to zero FPA throughout the entire escape maneuver. Additional consideration of low aircraft performance conditions in the control laws could alleviate this behavior. **R6: Tailor escape maneuver control laws for low aircraft performance conditions.**

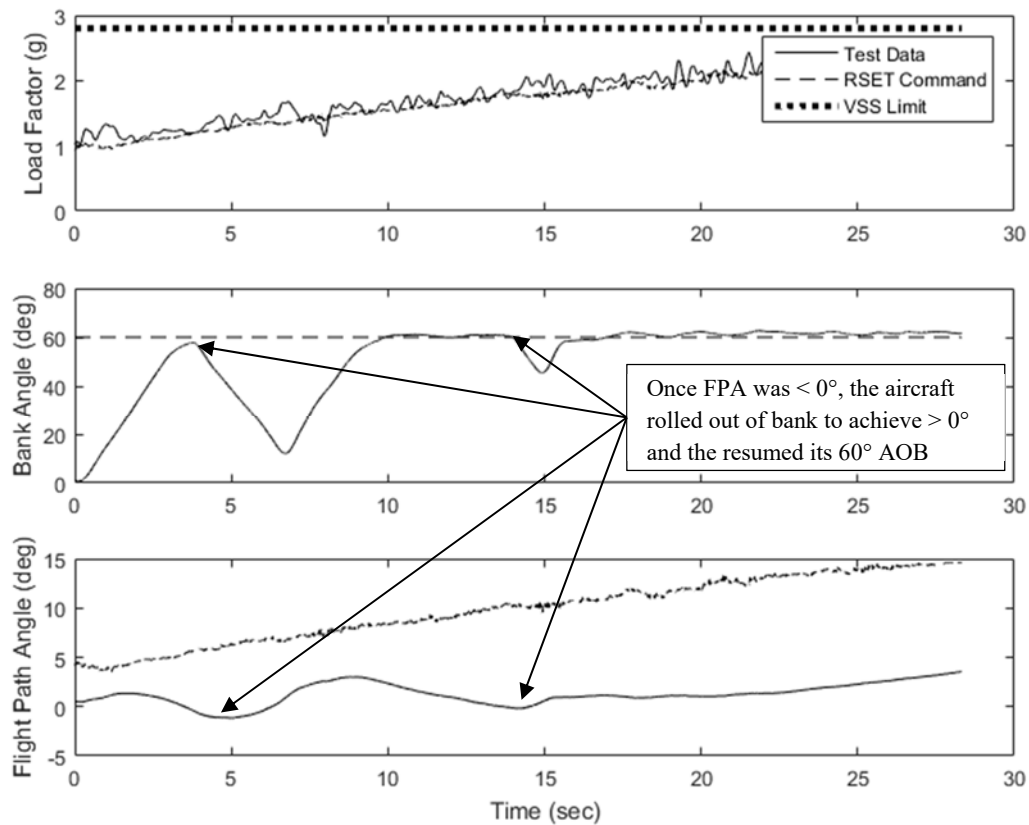


Figure 37 – Path 5 Performance, 220 KIAS, 500 ft AGL

Figure 38 shows a path 5 escape maneuver initiated from a left 45° bank, at 270 KIAS and 500 ft AGL. Initially, performance available was high so the RSET commanded the aircraft to simultaneously roll into a right 60° bank and increase load factor to increase FPA. The aircraft reached the RSET-commanded load factor limit and the FPA began to rapidly increase to the RSET limit. The RSET commanded the aircraft to maintain the load factor limit until reaching the FPA limit. As a result of the excess performance available, the aircraft overshoot the FPA limit by approximately 2° (17%). After the FPA overshoot was rectified, the aircraft remained on the RSET limit for load factor.

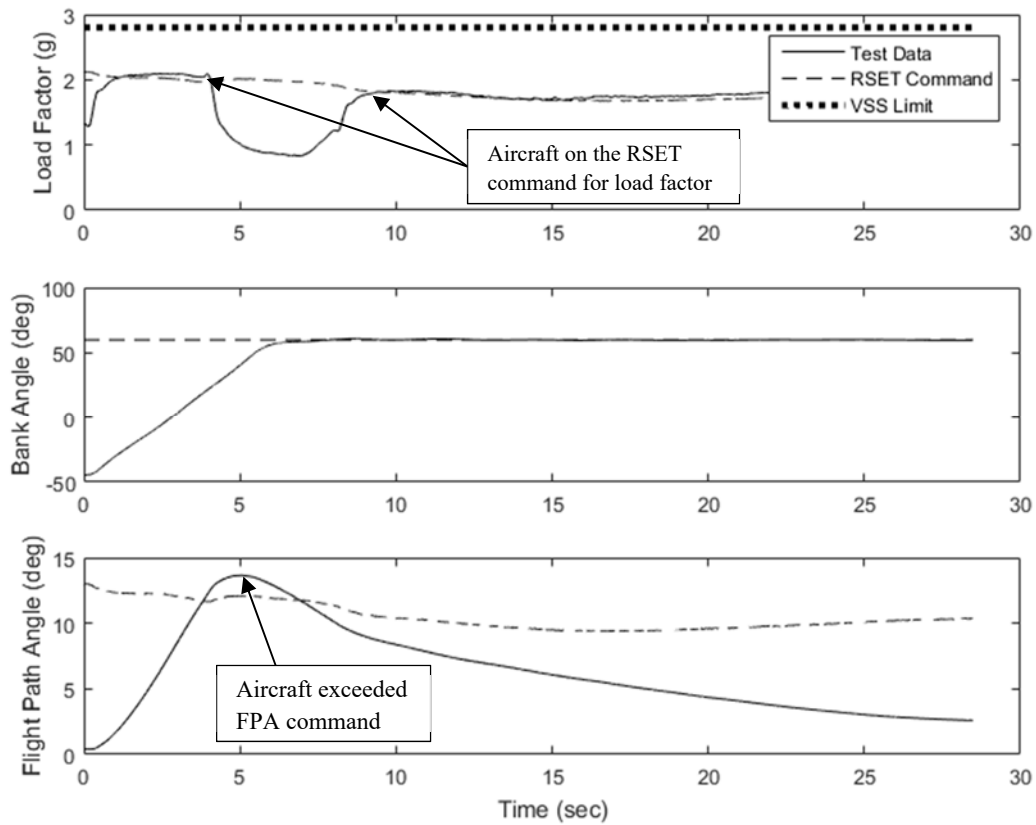


Figure 38 – Path 5 Performance, 270 KIAS, 500 ft AGL

Nuisance Activations Test Methods and Conditions

Each safety pilot performed multiple lateral passes on the North portion of terrain identified in Figure 39. A 60° level banked turn was first conducted at 2,000 ft above ground level to estimate turning radius and verify RSET system disconnect. The EP then descended to 500 ft AGL and made three passes abeam the terrain while the RSET ran in the background evaluating the terrain. During each pass, the EP moved closer to the terrain until subjectively inside his comfort level needed to execute a 60° escape maneuver. Figure 40 shows the view from the right side of the aircraft during these test points.

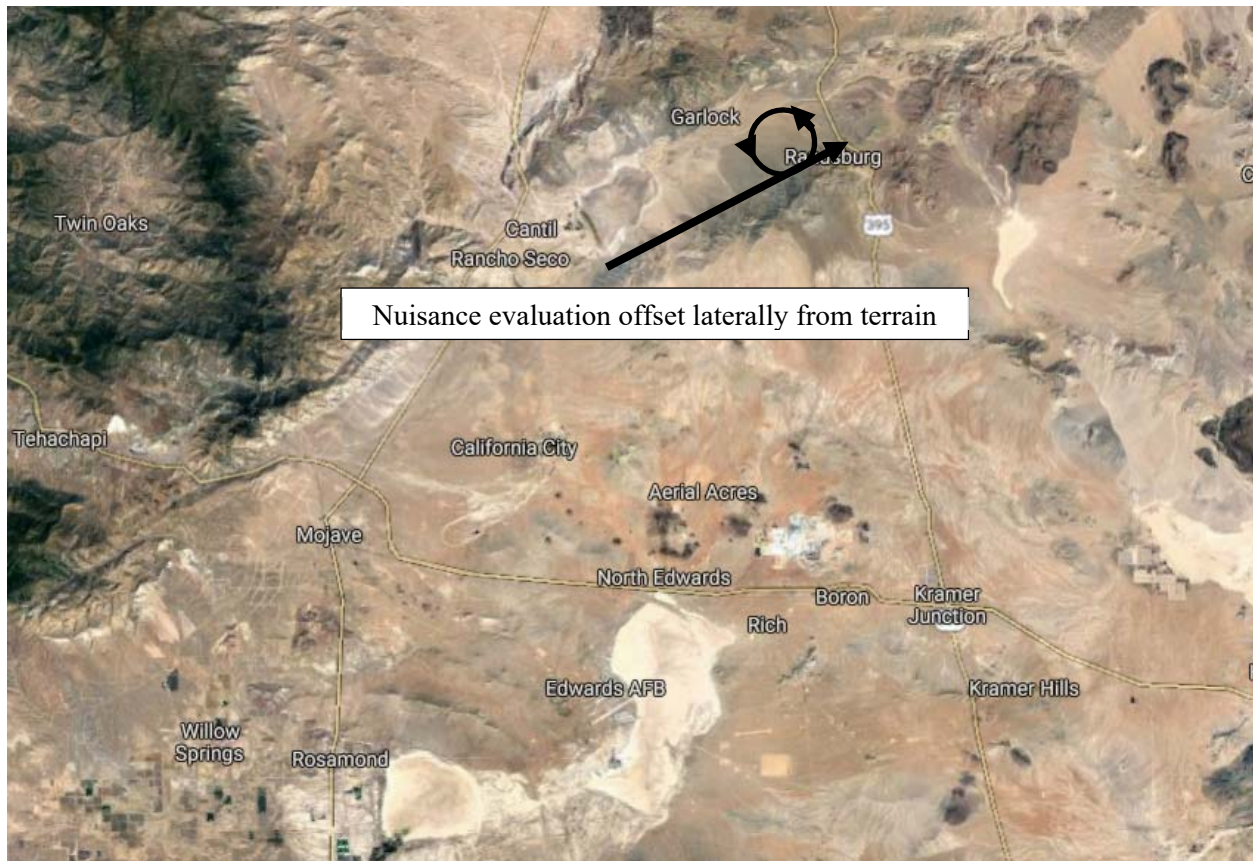


Figure 39 – Nuisance Terrain Route

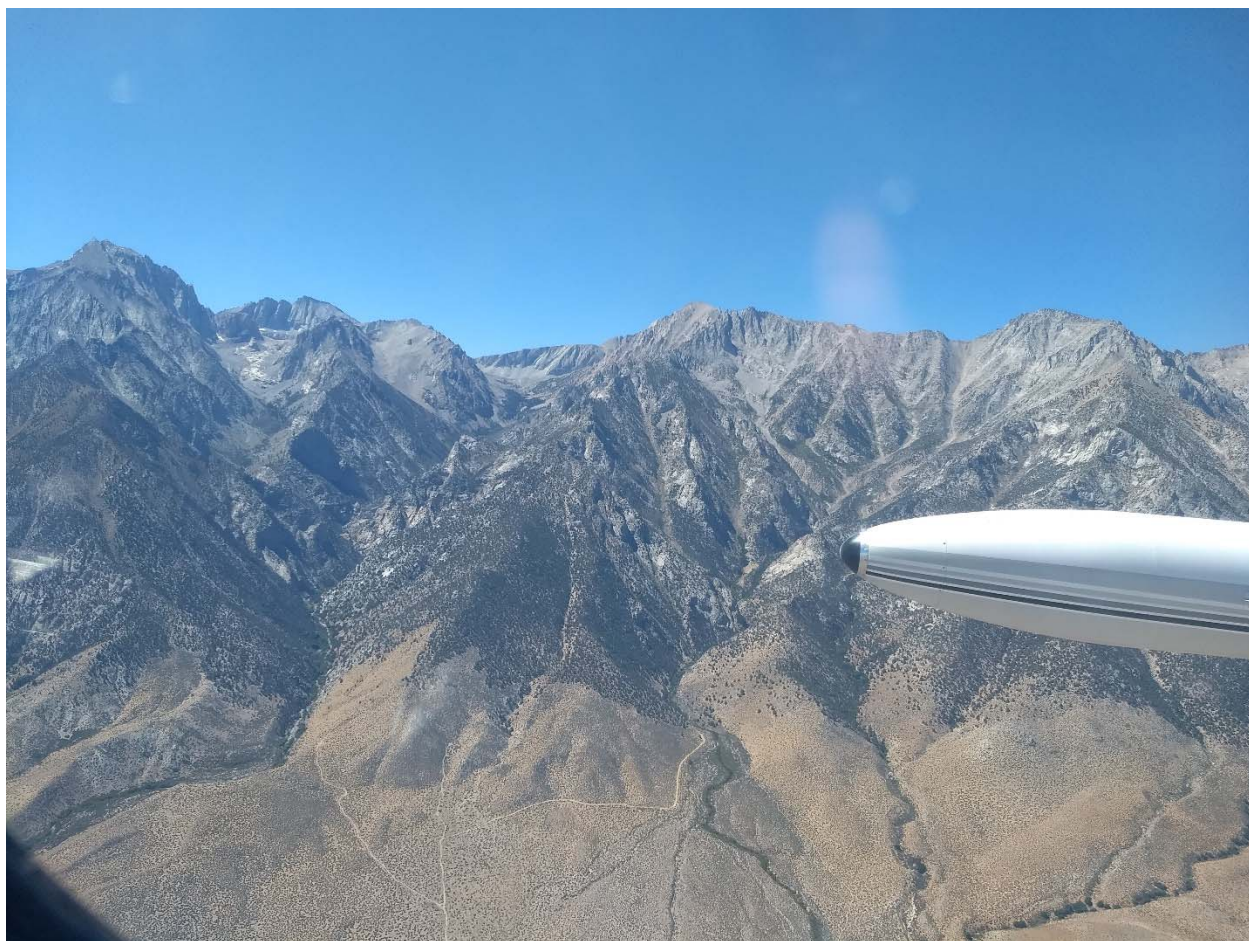


Figure 40 – Lateral Offset from Terrain

Nuisance Activations Test Results

The aircraft did not exhibit nuisance activations during testing against lateral terrain. For each pass flown, the RSET showed the level escape maneuver was available and would avoid terrain, but the EP commented that he would not consider turning in the direction of terrain if he were to manually fly a 60° level turn escape maneuver. Figure 41 and Figure 42 depict the path of the aircraft and the RSET 60° right turn predictions of path 5 in red. At no point did the RSET path nuisance activate near lateral terrain.

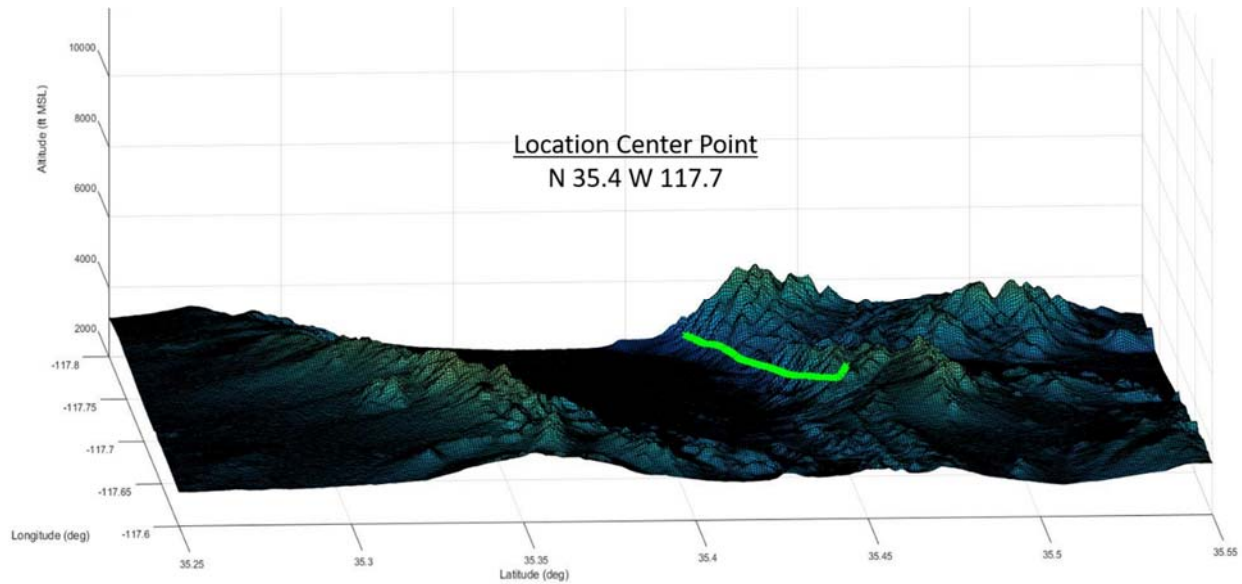


Figure 41 - Path of Aircraft during Lateral Offset Test Points

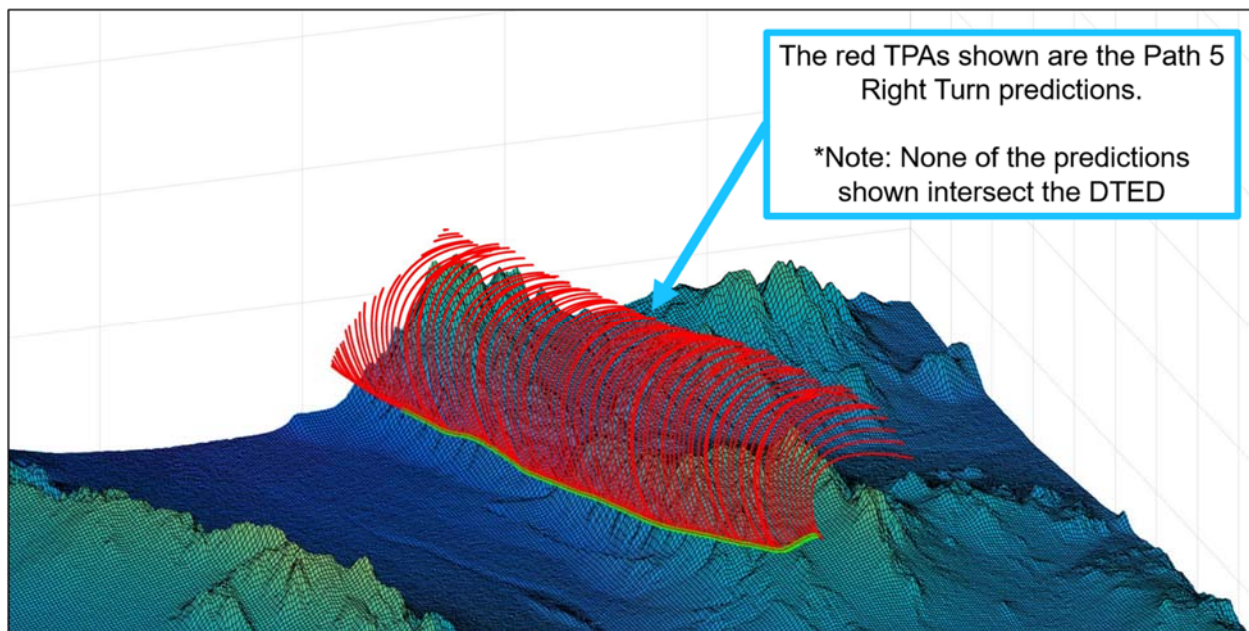


Figure 42 - Path of Aircraft with 60° Right RSET Predictions during Lateral Offset Test Points

Operational Nuisance Activations Test Methods and Conditions

The EP flew multiple 60° level banked turns at 2,000 ft AGL and clear of terrain to gain familiarity with the aircraft's turn radius at both 220 and 270 KIAS. The EP then descended to 500 ft AGL and flew a low-level profile at what the EP determined to be an operationally representative lateral offset from terrain to gather nuisance activation data at each respective airspeed. The RSET's ability to control the aircraft was severed to protect against inadvertent activations, but it still accepted state parameters from the VSS to determine if an escape maneuver was necessary. The TC informed the pilots anytime a path closed and collected comments on whether the pilots thought the path closure was necessary or not. Aircraft state parameters were recorded for all RSET activations.

Operational Nuisance Activations Test Results

The RSET did not exhibit nuisance activations during operationally representative profiles against lateral terrain. Typically, the RSET showed the 60° bank escape maneuver was available and would avoid terrain, but the EP commented that they would not consider turning in the direction of terrain if they were to manually fly a level turn escape maneuver. On each flight against operational terrain, the team observed at least one to two instances when the turning escape path towards terrain would momentarily close. In all cases, the crew agreed that the closure was appropriate. This data was also objectively confirmed via numerous team comments during the operational terrain evaluation which stated surprise that the path towards terrain was not closed off. In spite of the large path prediction error, the system still demonstrated no tendency to nuisance for the operational profile flown.

MANEUVER TERMINATION CONTROL HAND-BACK

Upon completion of any RSET path maneuvering, the aircraft autopilots commanded a roll to wings level and pitch reduction to zero gamma as described in HAND-BACK. The test objective was met.

Overall Test Methods and Conditions

Following any maneuver where the RSET system was activated, the EP qualitatively evaluated the control hand-back immediately following maneuver termination. The test team produced an aircrew survey to guide EP commentary following control hand-back. Before flight, the team familiarized themselves with the survey flow and comments were given in accordance with survey criteria. A copy of the hand-back survey can be found in APPENDIX M – HAND-BACK SURVEY.

Overall Test Results

For low-speed test points, aircrew comments indicated a smooth, logical, and safe hand-back. However, the test team found that at higher airspeeds, the hand-back would trip the Learjet VSS safety logic, as was seen in Table 3, due to an under-g condition (less than 0.25g). Because of this, the team was unable to fully characterize and evaluate every single hand-back scenario. During these maneuvers where the VSS tripped, the aggressive unload from 2g to 0.25g repeatedly caused aircrew motion sickness. This maneuver would likely have caused an aircraft limit exceedance without the VSS safety logic. This behavior would need to be addressed prior to any hand-back implementation in order to avoid airframe limit exceedance and aircrew discomfort. Additionally, based on aircrew comments, airframe mission also needs to be considered in future versions of the hand-back. This consideration would need to account for tactics such as terrain masking where unnecessary maneuvering would be detrimental to platform survivability.

The addition of the stick shaker during escape maneuver activation was well received by the pilots. It provided tactile feedback that the RSET was handing back control of the aircraft after the initial escape maneuver was complete. The stick shaker ceased concurrent with the completion of RSET hand-back. The stick shaker was the only usable indication to the aircrew that the RSET was still in control of the aircraft as the location of the CSS made it unusable to the pilots during “heads up” flying. Aircrew comments were in favor of a display that could be incorporated into a normal crosscheck for the low-level phase of flight. **R7: Mature system hand-back to be less aggressive for aircrew comfort and relocate PVI to pilot’s line-of-sight.**

Aircrew were in favor of the ability to “paddle off” the system and take control any time the RSET was controlling the aircraft. Paddling off the system during the hand-back was common when the pilots felt like the aircraft was in a safe condition and they did not want to wait for the RSET to complete the entire hand-back process. The aircrew strongly agreed the ability to paddle off the system was a requirement rather than a desired feature. **R8: Future implementation of the RSET should also include a means for aircrew to override the system and take control of the aircraft.**

Throughout the test period, all EP’s provided their qualitative opinion of the hand-back following RSET maneuver completion. An extensive listing of EP comments can be found in APPENDIX N – AIRCREW COMMENTS. A sampling of EP comments are displayed below:

“Felt smooth and safe. Adequate for system maturity.”

“Hand-back took a little too long in order to stay smooth. I would probably pickle off and take command earlier to recover faster.”

“Higher airspeed hand-back was more aggressive vs lower energy state hand-backs.”

“During low speed points, it’s hard to tell if the aircraft is in a hand-back state or attempting a different path. Visual indication of system state would be useful.”

“In a non-combat environment this would be totally fine. It gets the aircraft back to a place I feel comfortable taking control.”

TEST RESULTS SUMMARY AND RECOMMENDATIONS

For path prediction accuracy, the RSET system was evaluated as MARGINAL with 117 out of 120 test points having a maximum path prediction error (PPE) above 300 ft. It was observed that maximum PPE tended to be highest for Path 1 activation and lowest for Path 3 activation. Maximum PPE was higher for diving entries compared to the other three entries. Out of 120 test points analyzed, 44 had PPE erring away from terrain, 54 had PPE erring towards terrain, and the remaining 22 test points were inconclusive. Possible sources of error could be the auto-trim feature of the VSS, incorrect accounting of wind speed and direction in the TPAs, and the low fidelity of the Learjet engine model used in the TPAs. **R1: Conduct further data analysis to determine the sources of error and their impact to PPE.** Furthermore, the majority of test points were only tested once and had no statistical significance in PPE. **R2: Conduct repeat runs of specific test conditions to increase statistical significance of PPE results.**

With respect to terrain miss distance, it appeared that a refresh rate near 12.5 Hz was required to ensure terrain clearance with this implementation of the RSET system. The selection of an appropriate terrain buffer was a critical parameter. Future systems should evaluate the mission and aircraft performance ability when determining a terrain buffer. **R3: Using a refresh rate of 12.5 Hz or faster, investigate the effect of varied operationally representative terrain types and terrain buffers on miss distance.**

Data showed that increasing refresh rate required a shorter forward look-ahead time. Forward look-ahead time was evaluated at 30 seconds only and did not appear to be significantly affected by other factors. System refresh rate drove forward look-ahead time, and the presented data would provide a rough starting point for future multi-path collision avoidance systems. **R4: Evaluate the need for forward look-ahead times beyond 30 seconds.**

For path performance, the aircraft generally achieved steady state, RSET-commanded AOB within five seconds of escape maneuver activation. With less performance available during the 220 KIAS escape maneuvers, the aircraft initially performed at reduced load factors and FPAs but gained energy as the throttles were advanced. With more performance available during the 270 KIAS escape maneuvers, the aircraft exhibited the tendency to overshoot the RSET-commanded FPA by up to 5° (50%). The FPA gradually decreased until the RSET-commanded limit and the aircraft's actual FPA agreed. The airspeed never decreased below the test limit of 200 KIAS during FPA overshoots; however, the system should account for FPA overshoots to preclude unsafe airspeeds during escape maneuvers. **R5: Account for FPA overshoots in the escape maneuver control laws for high aircraft performance conditions.**

During 60° AOB escape maneuvers at low performance states, the aircraft was unable to maintain the RSET-commanded 60° AOB without descending. The RSET control logic prioritized maintaining greater than or equal to zero FPA over the escape maneuver's 60° AOB. As a result, the aircraft decreased AOB, raised the nose until greater than or equal to zero FPA, and then continued its 60° AOB. This ratcheting was undesirable and could lead to confusion or incorrect pilot actions. This behavior was not common during the 270 KIAS test points as enough aircraft performance was available to keep greater than or equal to zero FPA throughout the entire escape maneuver. Additional consideration of low aircraft performance conditions in the control laws could alleviate this behavior. **R6: Tailor escape maneuver control laws for low aircraft performance conditions.**

The aircraft did not exhibit nuisance activations during testing against lateral terrain as well as for operationally representative profiles against lateral terrain. Typically, the RSET showed the 60° AOB escape maneuver was available, but the aircrew commented they would not consider turning in the direction of terrain if they were to manually fly a 60° AOB escape maneuver. As a result of these findings and the aggressive path performance results, this RSET implementation was not nuisance prone.

For low-speed test points, aircrew comments indicated a smooth, logical, and safe hand-back. However, the test team found that at higher airspeeds, the hand-back would trip the Learjet VSS safety logic due to an under-g condition ($\leq 0.25g$). During maneuvers where the VSS tripped, the aggressive unload from 2g to 0.25g caused aircrew motion sickness. Based on aircrew comments, airframe mission also needs to be considered in future versions of the hand-back. Consideration should be given to tactics such as terrain masking where unnecessary maneuvering would be detrimental to platform survivability.

The addition of the stick shaker during escape maneuver activation was well received by the pilots. It provided tactile feedback that the RSET was handing back control of the aircraft after the initial escape maneuver was complete. The stick shaker ceased with the completion of RSET hand-back. The stick shaker was the only usable indication to the aircrew that the RSET was still in control of the aircraft as the location of the CSS made it unusable to the pilots during “heads up” flying. Aircrew comments were in favor of a display that could be incorporated into a normal crosscheck for the low-level phase of flight. **R7: Mature system hand-back to be less aggressive for aircrew comfort and relocate PVI to pilot’s line-of-sight.**

Aircrew were in favor of the ability to “paddle off” the system and take control any time the RSET was controlling the aircraft. Paddling off the system during the hand-back was common when the pilots felt like the aircraft was in a safe condition and they did not want to wait for the RSET to complete the entire hand-back process. The aircrew strongly agreed the ability to paddle off the system was a requirement rather than a desired feature. **R8: Future implementation of the RSET should also include a means for aircrew to override the system and take control of the aircraft.**

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APPENDIX A – DETAILED TEST ITEM DESCRIPTION

MODEL DEVELOPMENT

As part of Master's thesis research conducted at the Air Force Institute of Technology (AFIT), the RSET system was executed in MATLAB® /SIMULINK® to verify its basic functionality and to streamline integration with the Learjet VSS detailed in *Quasi-Optimal Multi-Path Automatic Ground Collision Avoidance System for Performance Limited Aircraft – DRAFT* (reference 15). The Learjet performance model used a high fidelity flight tested model developed in collaboration between the U.S. Army Aviation Development Directorate, Textron Aviation, and USAF TPS detailed in the model stitching conference paper (reference 12). This model was created in SIMULINK® and used a combination of numerous equations and flight test data to create what was called a “stitched model”. A block diagram of this process is presented in Figure 43.

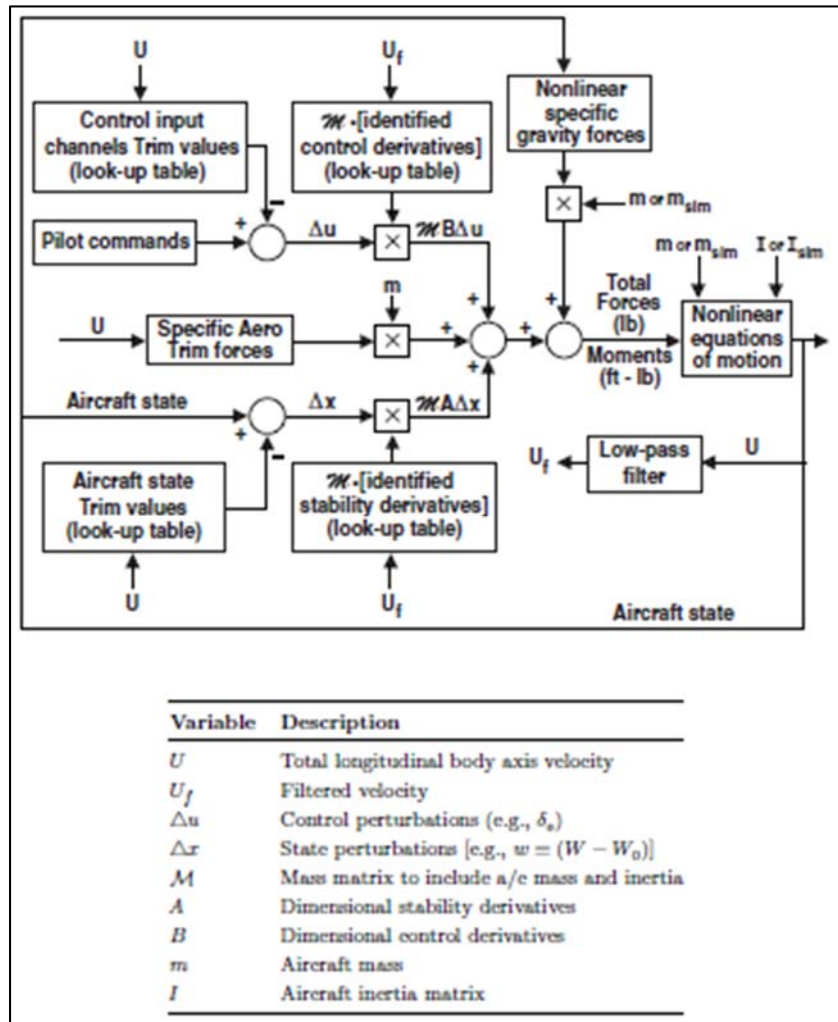


Figure 43 - Model Stitching Block Diagram Schematic (reference 12)

Using the stitched model process, the aircraft model was identified for the longitudinal and lateral/directional axes. The state space form of these equations is presented in Figure 44. The associated stability derivatives are shown in Figure 45 and Figure 46.

$$\begin{aligned}
 \begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} &= \begin{bmatrix} X_u & X_w & X_q - W_0 & -g \cos \Theta_0 \\ Z_u & Z_w & Z_q + U_0 & -g \sin \Theta_0 \\ M_u & M_w & M_q & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} X_{\delta_e} & X_{\delta_T} \\ Z_{\delta_e} & Z_{\delta_T} \\ M_{\delta_e} & M_{\delta_T} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_T \end{bmatrix} \\
 \begin{bmatrix} q \\ \alpha \\ a_x \\ a_z \\ \dot{u} \\ \dot{w} \end{bmatrix} &= \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1/U_0 & 0 & 0 \\ X_u & X_w & X_q & 0 \\ Z_u & Z_w & Z_q & 0 \\ X_u & X_w & X_q - W_0 & -g \cos \Theta_0 \\ Z_u & Z_w & Z_q + U_0 & -g \sin \Theta_0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ X_{\delta_e} & X_{\delta_T} \\ Z_{\delta_e} & Z_{\delta_T} \\ X_{\delta_e} & X_{\delta_T} \\ Z_{\delta_e} & Z_{\delta_T} \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_T \end{bmatrix} \\
 \begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \end{bmatrix} &= \begin{bmatrix} Y_v & Y_p + W_0 & Y_r - U_0 & g \cos \Theta_0 \\ L_v & L_p & L_r & 0 \\ N_v & N_p & N_r & 0 \\ 0 & 1 & \tan \Theta_0 & 0 \end{bmatrix} \begin{bmatrix} v \\ p \\ r \\ \phi \end{bmatrix} + \begin{bmatrix} Y_{\delta_a} & Y_{\delta_r} \\ L_{\delta_a} & L_{\delta_r} \\ N_{\delta_a} & N_{\delta_r} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} \\
 \begin{bmatrix} p \\ r \\ a_y \\ \beta \\ \dot{v} \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ Y_v & Y_p & Y_r & 0 \\ 1/V_{\text{tot}} & 0 & 0 & 0 \\ Y_v & Y_p + W_0 & Y_r - U_0 & g \cos \Theta_0 \end{bmatrix} \begin{bmatrix} v \\ p \\ r \\ \phi \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ Y_{\delta_a} & Y_{\delta_r} \\ 0 & 0 \\ Y_{\delta_a} & Y_{\delta_r} \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix}
 \end{aligned}$$

Figure 44 - State Space Equations of Motion (reference 12)

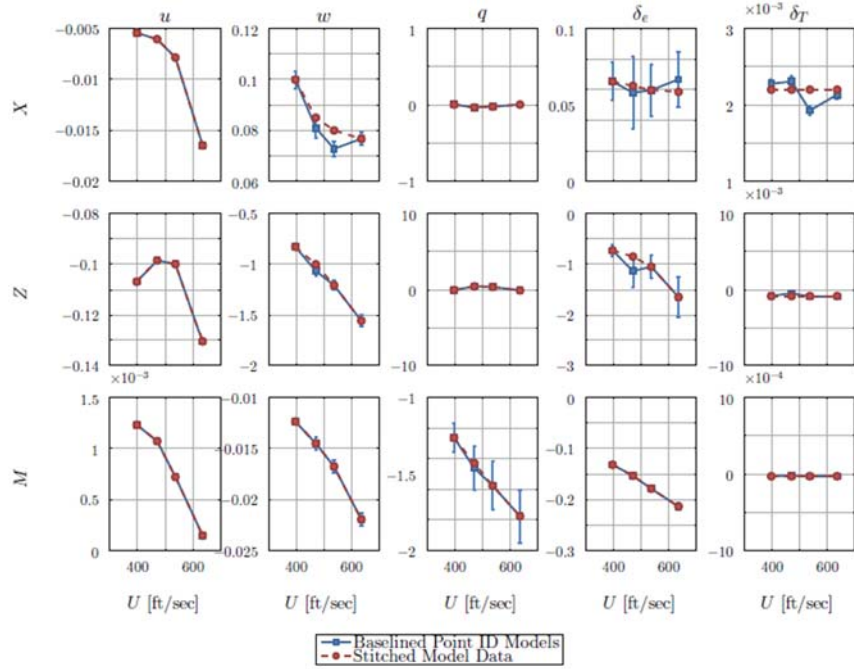


Figure 45 - Longitudinal Axis Stability and Control Derivatives as a Function of Airspeed (15,000 ft) (reference 12)

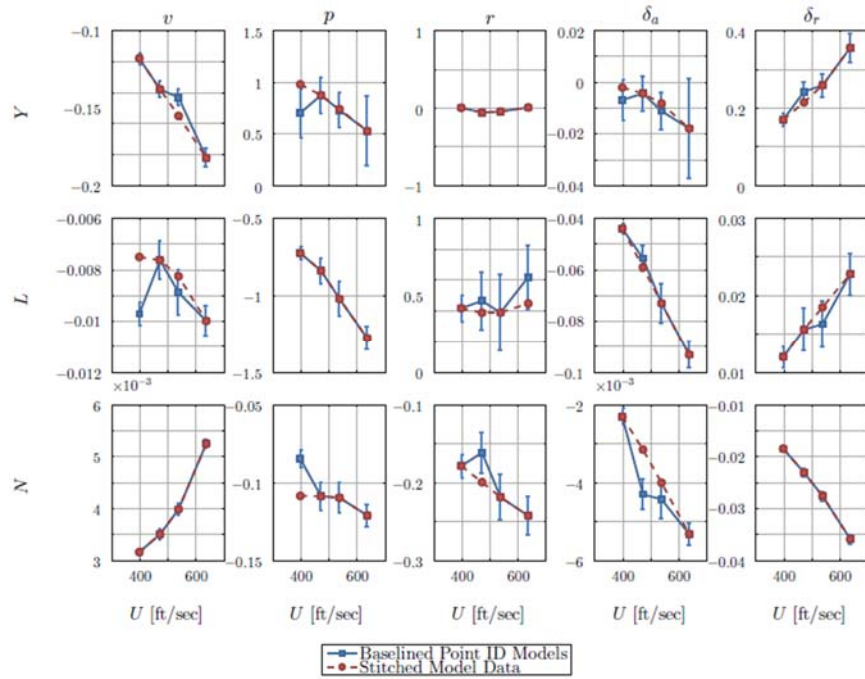


Figure 46 - Lateral/Directional Axis Stability and Control Derivatives as a Function of Airspeed (15,000 ft) (reference 12)

Once the aerodynamic model was developed it was implemented in SIMULINK® as shown in Figure 47. The SIMULINK® model was then used to compare simulated and actual aircraft response from a series of model validation flights. The results of those model validation flights showed excellent agreement, and are presented in Figure 48 and Figure 49.

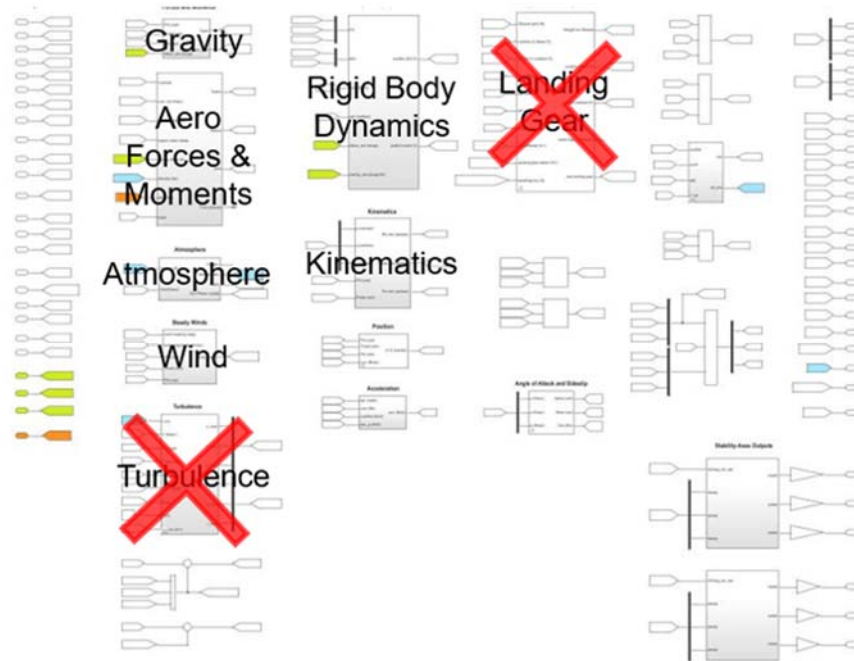


Figure 47 - Stitched Model SIMULINK® Overview (reference 12)

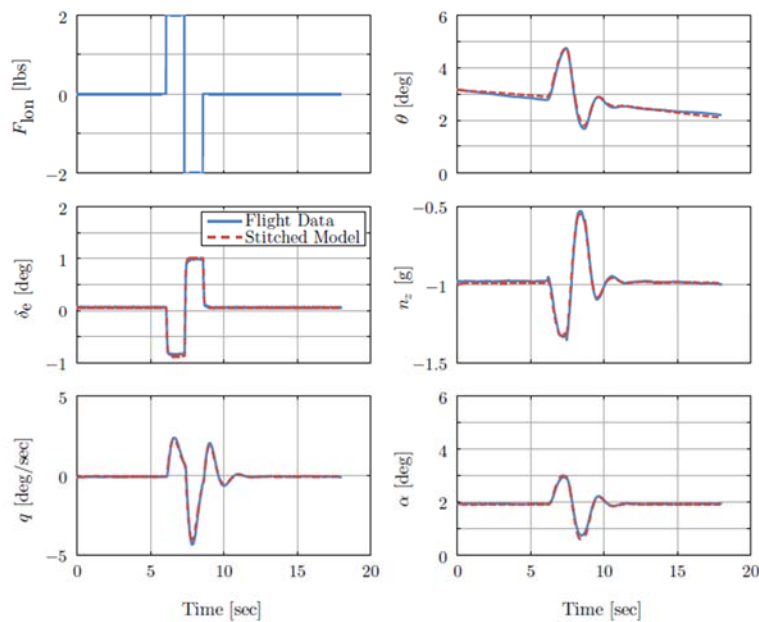


Figure 48 - Pitch Doublet Response (250 kts, 15,000 ft) (reference 12)

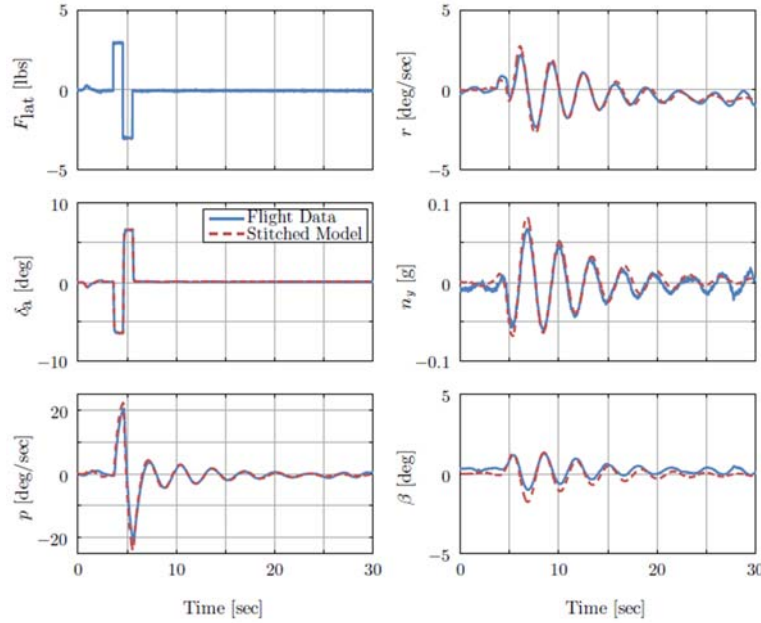


Figure 49 - Roll Doublet Response (250 kts, 15,000 ft) (reference 12)

For the purpose of developing the RSET system it was necessary to rewrite the stitched model in MATLAB[®] so that faster-than-real-time path predictions could be performed. A concern prior to these conversion efforts was that the fidelity of the model would be lost during the conversion process, especially considering the complexity of the stitched model. Preliminary results showed that the RSET MATLAB[®] model and the stitched model matched very closely. The turbulence and gear models were not included in the RSET MATLAB[®] model conversion. Figure 50 thru Figure 53 show the responses of both systems to step inputs in their respective axes. These inputs were purposefully chosen to match the inputs used to compare the stitched model to the aircraft. In other words, if the stitched model matched the aircraft, and the RSET MATLAB[®] model matched the stitched model, then the RSET model should match the aircraft.

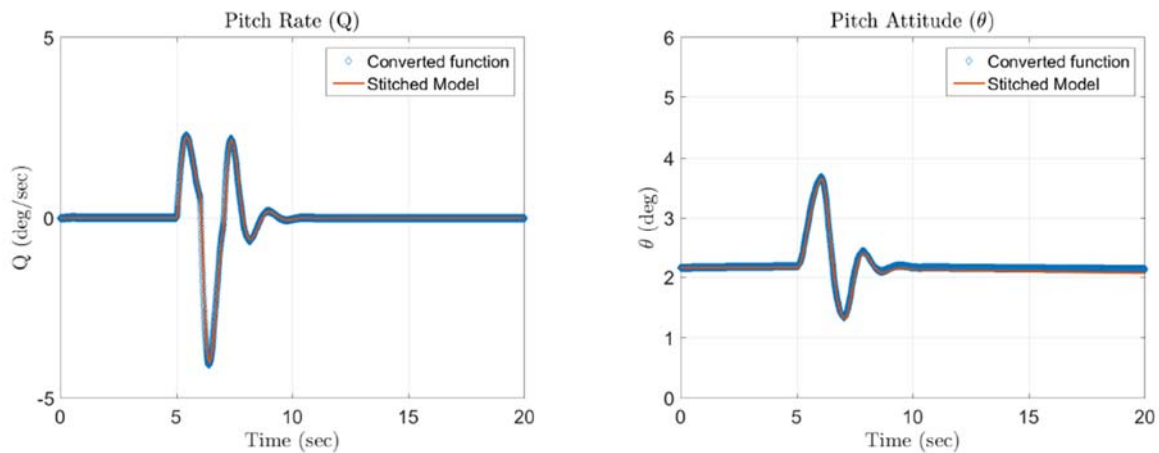


Figure 50 - Longitudinal Response Comparison of Stitched and RSET (Converted) Models (250 KIAS, 15000 ft MSL)

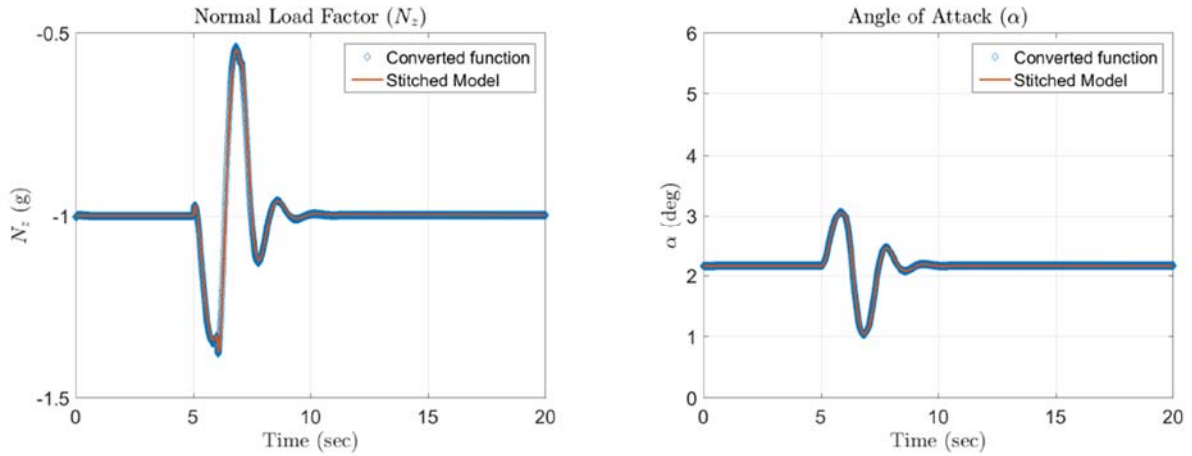


Figure 51 - Longitudinal Response Comparison of Stitched and RSET (Converted) Models (250 KIAS, 15000 ft MSL)

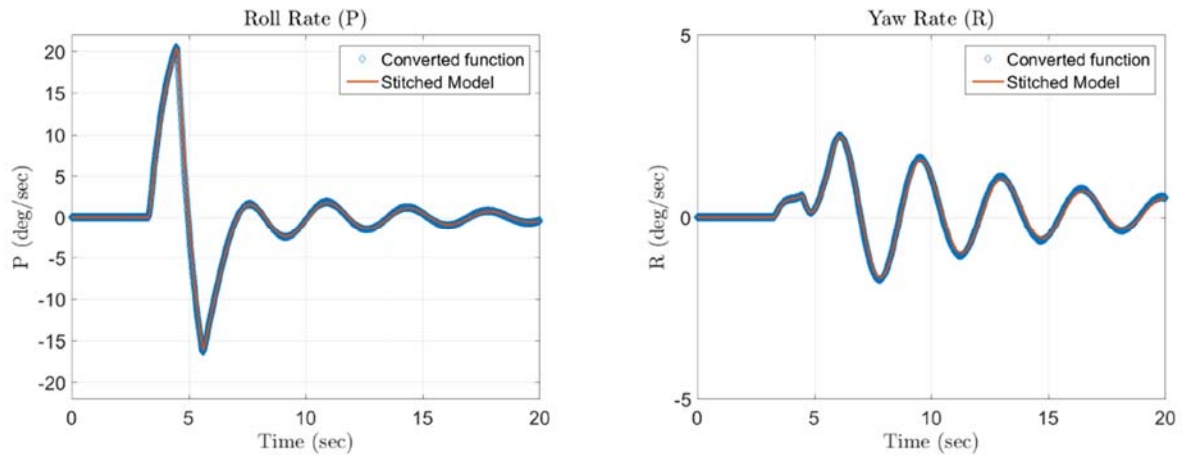


Figure 52 – Lateral-Directional Response Comparison of Stitched and RSET (Converted) Models (250 KIAS, 15000 ft MSL)

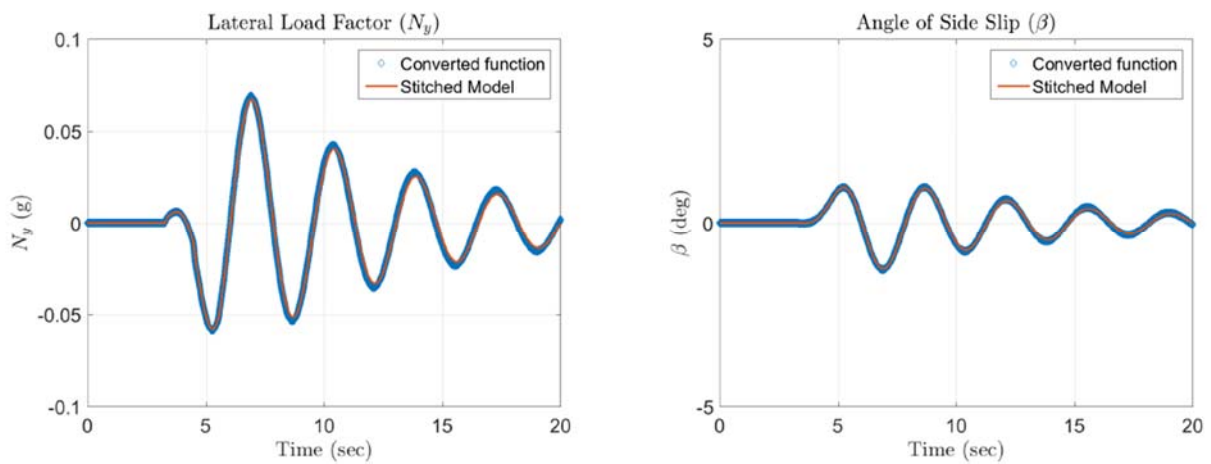


Figure 53 - Lateral-Directional Response Comparison of Stitched and RSET (Converted) Models (250 KIAS, 15000 ft MSL)

Additionally, Table 7 shows the numerical agreement between aircraft states for both models in response to pitch and roll doublets using Theil's Inequality Coefficient (TIC). Models with a TIC value less than 0.3 are accepted as accurate and all aircraft states fall below this value, with most TIC values near zero as discussed in *Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples* (reference 16).

Table 7 - Theil's Inequality Coefficient for RSET Model Compared to Stitched Model

--Pitch Doublet--	
State	TIC Value
Pitch Rate (Q)	0.269
Pitch Attitude (θ)	0.008
Normal Acceleration (Nz)	4.27e-04
Angle of Attack (α)	8.84e-04
--Roll Doublet--	
State	TIC Value
Roll Rate (P)	0.025
Yaw Rate (R)	0.002
Lateral Acceleration (Ny)	0.009
Angle of Side Slip (β)	0.005
$TIC = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N [x(i) - \hat{x}(i)]^2}}{\sqrt{\frac{1}{N} \sum_{i=1}^N [x(i)]^2} + \sqrt{\frac{1}{N} \sum_{i=1}^N [\hat{x}(i)]^2}}$ x = trusted model state $\hat{x}$ = un-trusted model state N = number of data points	

The RSET system relied upon the idea that if the stitched model matched flight data closely, and the RSET model matched the stitched model closely, then the RSET model should match flight data closely. This test program identified how well this assumption held true.

ENGINE MODEL

A known weakness of the overall Learjet aerodynamics model was the engine model. Since the model was developed using primarily flying qualities flight test techniques with limited engine performance data the engine model consisted of lookup tables. The lookup tables provided maximum and idle thrust values at 0 and 40,000 ft., both at 0, 0.25, and 0.8 Mach. For intermediate airspeeds and altitudes, the thrust values were simply interpolated and scaled linearly based on the percent of throttle commanded.

CONTROL LAW DESIGN

Once the model was converted to MATLAB® code and verified that it match the original stitched model, the next step was to develop the control laws which were used to complete the trajectory prediction algorithms and the maneuver execution autopilots. Two control loops were used to perform all five paths. The bank angle command was changed dependent on the maneuver to be performed. To prevent altitude loss during the maneuver as well as asymmetric loading, additional restrictions were place on the control laws as described in Table 8. The restrictions were used to allow for safe and effective path execution regardless of aircraft maneuvering (e.g. calculating a 60° left turn when in a right turn).

Table 8 - RSET Path Bank Angle Command and Maneuver Restrictions

Path	Bank Angle Command	Maneuver Restrictions
1	-60°	If flight path angle (γ) drops below 0, the bank angle command goes to 0.
2	-30°	- If flight path angle (γ) drops below 0, the bank angle command goes to 0. - Delay gamma command loop until bank angle is less than +5°
3	0°	Delay gamma command loop until bank angle is between -10° and +10°
4	+30°	- If flight path angle (γ) drops below 0, the bank angle command goes to 0. - Delay gamma command loop until bank angle is greater than -5°
5	+60°	If flight path angle (γ) drops below 0, the bank angle command goes to 0.

The coordinated turn control law loop is shown in Figure 54. This simple control law design was effective at producing the desired bank angle with minimal sideslip. As discussed above, the bank angle command was changed depending on the path to be performed.

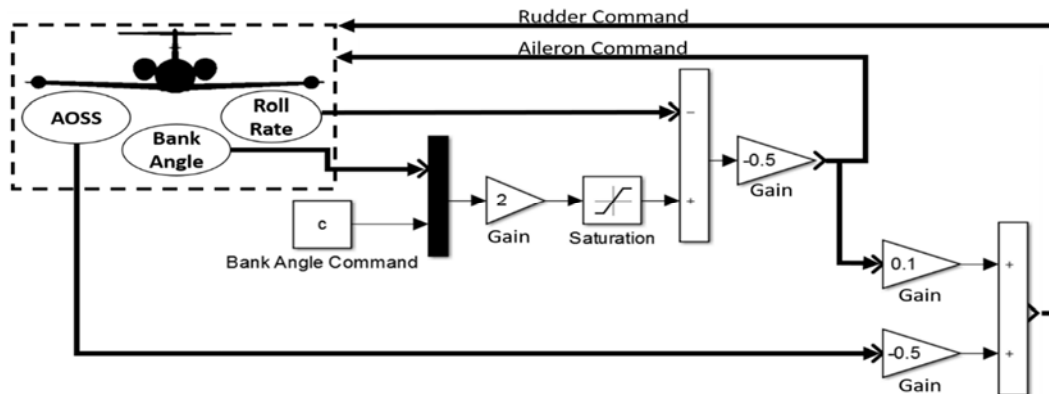


Figure 54 - Coordinated Turn Control Law

Figure 55 depicts the control law used to execute the “pull” portions of the maneuvers, which was a speed-scale flight path angle (γ) command with a load factor (N_z) limiter. The control law was designed to primarily achieve the maximum aircraft flight path angle at maximum continuous power (MCP). From simulator testing and early checkout flights this was found to be 12° at 270 KCAS. For safety purposes the lower airspeed limit was set at 200 KCAS, so the speed scaler was used to adjust the target γ down as speed decreased during a climb. Due to the simple nature of this design, at high speed from level flight the initial pull command was aggressive enough to overshoot the target of approximately

2-g. For this reason, the Nz limiter was added. Additionally there were instances during a maneuver where the aircraft would “unload” to a low g condition, so a lower Nz limiter of 0.6-g was added.

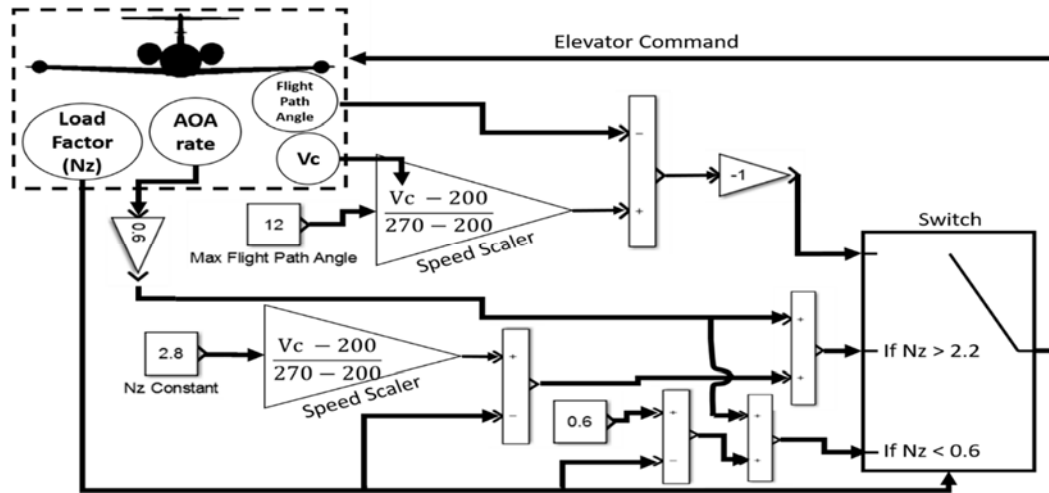


Figure 55 - Speed Scaled Gamma (γ) Command with Load Factor (Nz) Limiter Control Law

MODEL DEGREES OF FREEDOM

The final model which included the bare airframe, actuator dynamic, control surfaces, and control laws contained 18 degrees of freedom (18-DOF). This 18-DOF model included the traditional aircraft 6-DOF aircraft states (body velocities (U, V, W) and body rotational rates (P, Q, R)) as well as additional integrators which were associated with the control surface (elevator, ailerons, rudder, and horizontal stabilizer) actuators and rate limiters.

APPENDIX B – RATING CRITERIA

Table 9 - 412th Test Wing Rating Criteria

How Well Does the System Meet Mission and/or Task Requirements?	Changes Recommended for Improvement	Mission/Task Impact	Descriptor	Rating
Exceeds requirements.	None	None	Excellent	Satisfactory
Meets all or a majority of the requirements.	Negligible changes needed to enhance or improve operational test or field use	Negligible	Good	Satisfactory
Some requirements met; can do the job, but not as well as it could or should.	Minor changes needed to improve operational test or field use	Minor	Adequate	Satisfactory
Minimum level of acceptable capability and/or some noncritical requirements not met.	Moderate changes needed to reduce risk in operational test or field use	Moderate	Borderline	Marginal
One or some of the critical functional requirements were not met.	Substantial changes needed to achieve satisfactory functionality	Substantial	Deficient	Unsatisfactory
A majority or all of the functional requirements were not met.	Major changes required to achieve system functionality	Major	Unacceptable	Unsatisfactory
Mission not safe.	Critical changes mandatory	Critical	Unsafe	Failed

APPENDIX C – DATA ANALYSIS PROCEDURES

The following sections describe the data analysis procedures used in the Have MEDUSA test project in order to produce the required final data products. The primary data source for analysis was the Learjet VSS Data Acquisition System. This system sampled parameters at 200 Hz, and saved these parameters to a Microsoft Excel compatible file, which was imported into MATLAB®.

Objective	1 – Demonstrate the Prediction Accuracy of the RSET System		
MOP	1.1 – Path Prediction Error		
<u>Required Data Parameters</u>			
<u>Description</u>	<u>Name</u>	<u>Units</u>	<u>Source</u>
Time	gps_time	Seconds	DAS
True Latitude	gps_lat	Degrees North	DAS
True Longitude	gps_lon	Degrees East	DAS
True Altitude	gps_alt	Feet	DAS
Indicated Airspeed	Vc	Knots	DAS
Flight Path Angle	gamma_cf	Degrees	DAS
Bank Angle	phi	Degrees	DAS
Heading		Degrees	DAS
Wind Speed		Knots	DAS
Wind Direction		Degrees	DAS
Predicted Latitude		Degrees North	RSET Algorithm
Predicted Longitude		Degrees East	RSET Algorithm
Predicted Altitude		Feet	RSET Algorithm
<u>Qualitative Data Required</u>			
<u>Description</u>		<u>Source</u>	
Pilot Comments		Handheld Data, noted by FTE on flight cards	

Data Quality	Maneuver Quality Determination	Pilot & FTE (real time) FTE (post-flight)
	Data gathering effectiveness and procedure if data are unusable	Determine if effective real-time. If unusable or unsure, repeat test point.
	Repeats	None planned, but approved, fuel allowing.
Analysis Procedure	1. For the entire duration of the RSET commanded autopilot maneuver, latitude (ϕ), longitude (λ), and altitude (h) was obtained from the aircraft TSPI data (considered the truth source). Also, at the time of RSET activation, the lat, long, and altitude for each time step along the 30 second RSET predicted path was obtained. 2. Both sets of coordinates were converted into Cartesian earth-centered, earth-fixed (ECEF) coordinates (u, v, w) using the equations below. $\begin{aligned}u &= (N + h) \cos \phi \cos \lambda \\v &= (N + h) \cos \phi \sin \lambda \\w &= (N(1 - e^2) + h) \sin \phi\end{aligned}$ where $\left. \begin{aligned}a &= 20925646.32546 \text{ ft} \\e^2 &= 0.0066943799 \\N &= \frac{a}{\sqrt{1 - e^2 \sin^2 \phi}}\end{aligned} \right\} \text{Ellipsoid Earth model parameters}$ 3. The distance vector ($\Delta u, \Delta v, \Delta w$) between the two paths was then calculated at each sampled time throughout the maneuver. The aircraft's data acquisition had a different sampling rate (200 Hz) than the RSET path prediction (100 Hz), so the two data sets needed to be matched up in time. $\begin{aligned}\Delta u &= u_2 - u_1 \\ \Delta v &= v_2 - v_1 \\ \Delta w &= w_2 - w_1\end{aligned}$ 4. The Path Prediction Error (PPE) was calculated at each sampled time $PPE = \sqrt{\Delta u^2 + \Delta v^2 + \Delta w^2}$ 5. The maximum PPE during the RSET commanded maneuver was identified. 6. The actual aircraft path and the RSET predicted path were plotted on the same axes in order to determine whether the direction of the error was towards terrain or away from terrain in both the vertical (climb) and horizontal (turn) directions.	

Data Products

The maximum PPE data was summarized in a table as shown below in Table A1.

Table A1 – Summary Table of Max PPE Results

Flight #	Record #	Alt	A/S	Entry	Path	Wind Speed (kts)	Wind in Direction of Error?	Prediction Error (ft)	Out-climb prediction?	Tighter turn radius than prediction?	Error Away from Terrain?
#	#	ft	KIAS	#	#	kts	Yes/No	ft	Yes/No	Yes/No	Yes/No/ Inconclusive

For each manually activated RSET maneuver, the PPE was plotted as a function of time. Also, the aircraft’s actual position and the RSET predicted path was plotted in three dimensions on the same axes in order to show a visualization of the paths. Later, wind vectors were also plotted on the same chart in order to show the effect of wind.

Objective	2 – Demonstrate the impact of changing refresh rate on the RSET system’s ability to calculate an achievable escape path.		
MOP	2.1 – Terrain Miss Distance		
<u>Required Data Parameters</u>			
<u>Description</u>	<u>Name</u>	<u>Units</u>	<u>Source</u>
Time	gps_time	Seconds	DAS
True Latitude	gps_lat	Degrees North	DAS
True Longitude	gps_lon	Degrees East	DAS
True Altitude	gps_alt	Feet	DAS
Indicated Airspeed	Vc	Knots	DAS
DTED Point Latitude		Degrees North	DTED Matrix
DTED Point Longitude		Degrees East	DTED Matrix
DTED Point Altitude		Feet	DTED Matrix
Refresh Rate		Hertz	RSET Algorithm
<u>Qualitative Data Required</u>			
<u>Description</u>		<u>Source</u>	
Pilot Comments		Handheld Data, noted by FTE on flight cards	
Data Quality	Maneuver Quality Determination	Pilot & FTE (real time) FTE (post-flight)	
	Data gathering effectiveness and procedure if data are unusable	Determine if effective real-time. If unusable or unsure, repeat test point.	
	Repeats	None planned, but approved, fuel allowing.	
Analysis Procedure	1.For the entire run against virtual terrain, the aircraft’s TSPI data (latitude, longitude, and altitude) were obtained. 2.At each time sample, the distance from the aircraft’s position to the interpolated DTED elevation at the point directly below the aircraft (same latitude and longitude)		

	was calculated. This value was used to determine if the aircraft impacted the virtual terrain or not (negative or positive value). The RSS distance to the terrain was calculated by defining a plane with the three DTED posts that were closest to the aircraft. These DTED posts formed the base of a tetrahedron with the aircraft position at the apex of the tetrahedron. The smallest difference from the aircraft to terrain was calculated by calculating the height of the tetrahedron (see equations below). This was repeated for every time step during the system activation. The distances from the aircraft to each of the three closest DTED posts were defined as (a, b, c) using the same Cartesian earth-centered, earth-fixed (ECEF) coordinates (u, v, w) from MOP 1.1. The distances between each of the DTED posts were defined as (x, y, z). Then, the closest distance, h, was calculated using the following equations and defined the magnitude of the terrain miss distance. $X = b^2 + c^2 - z^2$ $Y = a^2 + c^2 - y^2$ $Z = a^2 + b^2 - x^2$ $V = \frac{\sqrt{4abc - a^2X^2 - b^2Y^2 - c^2Z^2 + XYZ}}{12}$ $h = \frac{3V}{\frac{1}{2}(xy)}$ 3. The minimum terrain miss distance for each run was identified.
Data Products	Summary charts of the minimum terrain miss distance for each test condition were generated. In addition, for each run against virtual terrain, the following plots were generated: 1. The aircraft's actual path and the DTED matrix plotted together in a three-dimensional chart. 2. Terrain miss distance as a function of time throughout the entire run. 3. Active RSET path, aircraft virtual altitude and virtual terrain elevation as a function of time throughout the entire run.

Objective	2 – Demonstrate the impact of changing refresh rate on RSET system ability to calculate an achievable escape path		
MOP	2.2 – Forward look ahead time		
<u>Required Data Parameters</u>			
<u>Description</u>	<u>Name</u>	<u>Units</u>	<u>Source</u>
Time	gps_time	Seconds	DAS
True Latitude	gps_lat	Degrees North	DAS
True Longitude	gps_lon	Degrees East	DAS
True Altitude	gps_alt	Feet	DAS
Ground Speed	gps_Vg	Feet per Second	DAS
Indicated Airspeed	Vc	Knots	DAS
Pitch Attitude	theta	Degrees	DAS
Bank Angle	phi	Degrees	DAS
Heading		Degrees	DAS
Wind Speed		Knots	DAS
Wind Direction		Degrees	DAS
Predicted Latitude		Degrees North	RSET Algorithm
Predicted Longitude		Degrees East	RSET Algorithm
Predicted Altitude		Feet	RSET Algorithm
DTED Point Latitude		Degrees North	DTED Matrix
DTED Point Longitude		Degrees East	DTED Matrix
DTED Point Altitude		Feet	DTED Matrix
Terrain Safety Buffer		Feet	RSET Algorithm
<u>Qualitative Data Required</u>			

<u>Description</u>		<u>Source</u>
Pilot Comments		Handheld Data, noted by FTE on flight cards
Data Quality	Maneuver Quality Determination	Pilot & FTE (real time) FTE (post-flight)
	Data gathering effectiveness and procedure if data are unusable	Determine if effective real-time. If unusable or unsure, repeat test point.
	Repeats	None planned, but approved, fuel allowing.
Analysis Procedure	1. For the entire run against virtual terrain, the aircraft's TSPI data (latitude, longitude, and altitude) was obtained. 2. The moments at which RSET triggered an escape maneuver were identified. 3. At each of these moments, the forward look-ahead time was determined by finding the time along each of the 5 path predictions at which the algorithm predicted a collision and taking the highest of the five times.	
Data Products	The forward look-ahead times were plotted in a summary chart to compare the impact of refresh rate on forward look-ahead time. The plots also included indications of whether each activation impacted terrain or not.	

Objective	3 – Observe RSET system tendency to nuisance activation.		
MOP	3.1 – Path Performance		
<u>Required Data Parameters</u>			
<u>Description</u>	<u>Name</u>	<u>Units</u>	<u>Source</u>
Time	gps_time	Seconds	DAS
Indicated Airspeed	Vc	Knots	DAS
Flight Path Angle	gamma	Degrees	DAS
Bank Angle	phi	Degrees	DAS
Normal Load Factor	nz	g	DAS
<u>Qualitative Data Required</u>			
<u>Description</u>		<u>Source</u>	
Pilot Comments		Handheld Data, noted by FTE on flight cards	
Data Quality	Maneuver Quality Determination	Pilot & FTE (real time) FTE (post-flight)	
	Data gathering effectiveness and procedure if data are unusable	Determine if effective real-time. If unusable or unsure, repeat test point.	
	Repeats	None planned, but approved, fuel allowing.	
Analysis Procedure	1. For each manually activated RSET maneuver, the normal acceleration, airspeed, flight path angle, and bank angle from the aircraft VSS data were collected for the entire 30 second maneuver. 2. For each time step along the RSET maneuver, the algorithm’s g limit was calculated using the equation below. $n_{Zlimit} = -\frac{1}{2}\left(-3\frac{V_c - 200}{270 - 200} - 1\right)$ 3. For each time step along the RSET maneuver, the algorithm’s target flight path angle was calculated using the equation below.		

	$\gamma_{command} = 12 \left(\frac{V_c - 200}{270 - 200} \right)$
Data Products	Three plots were generated for each manually activated RSET maneuver: 1. Aircraft normal acceleration (n_z), RSET g limit (n_{zlimit}), and the VSS g limit (2.8) as a function of time. 2. Aircraft bank angle (ϕ) and RSET target bank angle (ϕ_{target}) as a function of time. 3. Aircraft flight path angle (γ) and RSET target flight path angle (γ_{target}) as a function of time.

Objective	3 – Observe RSET system tendency to nuisance activation		
MOP	3.2 – Nuisance Activations		
<u>Required Data Parameters</u>			
<u>Description</u>	<u>Name</u>	<u>Units</u>	<u>Source</u>
Time	gps_time	Seconds	DAS
True Latitude	gps_lat	Degrees North	DAS
True Longitude	gps_lon	Degrees East	DAS
True Altitude	gps_alt	Feet	DAS
Indicated Airspeed	Vc	Knots	DAS
Flight Path Angle	gamma_cf	Degrees	DAS
Bank Angle	phi	Degrees	DAS
Heading		Degrees	
Wind Speed		Knots	
Wind Direction		Degrees	
Predicted Latitude		Degrees North	RSET Algorithm
Predicted Longitude		Degrees East	RSET Algorithm
Predicted Altitude		Feet	RSET Algorithm
DTED Point Latitude		Degrees North	DTED Matrix
DTED Point Longitude		Degrees East	DTED Matrix
DTED Point Altitude		Feet	DTED Matrix
Terrain Safety Buffer		Feet	RSET Algorithm
<u>Qualitative Data Required</u>			
<u>Description</u>		<u>Source</u>	

Pilot Comments		Handheld Data, noted by FTE on flight cards
Data Quality	Maneuver Quality Determination	Pilot & FTE (real time) FTE (post-flight)
	Data gathering effectiveness and procedure if data are unusable	Determine if effective real-time. If unusable or unsure, repeat test point.
	Repeats	None planned, but approved, fuel allowing.
Analysis Procedure	1. The aircraft's states and TSPI data (latitude, longitude, and altitude) and the surrounding DTED data were obtained for each run against terrain. 2. The RSET data was examined to see if the 60° banked turn TPA towards terrain was closed off (collision detected) at any point along the run. 3. The RSET data was combined with pilot comments to determine nuisance.	
Data Products	Each test run was re-constructed by plotting the position of the aircraft in three dimensions relative to the DTED matrix. The RSET predicted path of the 60° turn towards the terrain was overlaid on the plot at regular intervals along the aircraft path to show whether or not RSET predicted a path closure. Also, the pilot's comments for each run were presented to show whether or not the pilot felt that such a turn into terrain was possible.	

Objective	3 – Observe RSET system tendency to nuisance activation		
MOP	3.3 – Aircrew Comments		
<u>Required Data Parameters</u>			
Time	gps_time	Seconds	DAS
True Latitude	gps_lat	Degrees North	DAS
True Longitude	gps_lon	Degrees East	DAS
True Altitude	gps_alt	Feet	DAS
Indicated Airspeed	Vc	Knots	DAS
Flight Path Angle	gamma_cf	Degrees	DAS
Bank Angle	phi	Degrees	DAS
Heading		Degrees	
Wind Speed		Knots	
Wind Direction		Degrees	
Predicted Latitude		Degrees North	RSET Algorithm
Predicted Longitude		Degrees East	RSET Algorithm
Predicted Altitude		Feet	RSET Algorithm
DTED Point Latitude		Degrees North	DTED Matrix
DTED Point Longitude		Degrees East	DTED Matrix
DTED Point Altitude		Feet	DTED Matrix
Terrain Safety Buffer		Feet	RSET Algorithm
<u>Qualitative Data Required</u>			
<u>Description</u>		<u>Source</u>	
Pilot Comments		Handheld Data, noted by FTE on flight cards	

Data Quality	Maneuver Quality Determination	Pilot & FTE (real time) FTE (post-flight)
	Data gathering effectiveness and procedure if data are unusable	Determine if effective real-time. If unusable or unsure, repeat test point.
	Repeats	None planned, but approved, fuel allowing.
Analysis Procedure	1. The aircraft's states and TSPI data (latitude, longitude, and altitude) and the surrounding DTED data were obtained for each operationally representative low-level profile. 2. At any point during the profile when RSET predicted that an escape path activation was necessary, pilot comments were gathered along with the TSPI data to determine whether nuisance occurred.	
Data Products	Aircrew comments were summarized and presented.	

APPENDIX D – TEST POINTS

Table 10 - Test Points

Learjet Flight #	Flight #	Record #	Point Description
2111	1	1	Manual, 15k ft, 220 KIAS, SLUF entry, Path #3
2111	1	2	Manual, 15k ft, 220 KIAS, SLUF entry, Path #2
2111	1	3	Manual, 15k ft, 220 KIAS, SLUF entry, Path #1
2111	1	4	Manual, 15k ft, 220 KIAS, SLUF entry, Path #4
2111	1	5	Manual, 15k ft, 220 KIAS, SLUF entry, Path #5
2111	1	6	Manual, 15k ft, 270 KIAS, SLUF entry, Path #3
2111	1	7	Manual, 15k ft, 270 KIAS, SLUF entry, Path #2
2111	1	8	Manual, 15k ft, 270 KIAS, SLUF entry, Path #5
2111	1	9	Manual, 15k ft, 270 KIAS, SLUF entry, Path #1
2111	1	10	Manual, 15k ft, 220 KIAS, SLUF entry, Path #3
2111	1	11	Manual, 15k ft, 220 KIAS, SLUF entry, Path #1
2111	1	12	Manual, 15k ft, 270 KIAS, SLUF entry, Path #4
2111	1	13	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #1
2111	1	14	Virtual, 15k ft, 270 KIAS, 1.5625 Hz, IC #1
2111	1	15	Virtual, 15k ft, 270 KIAS, 1.5625 Hz, IC #1
2111	1	16	Manual, 8k ft, 270 KIAS, SLUF entry, Path #3
2111	1	17	Manual, 8k ft, 270 KIAS, SLUF entry, Path #1
2111	1	18	Manual, 8k ft, 220 KIAS, SLUF entry, Path #5
2111	1	19	Manual, 8k ft, 220 KIAS, SLUF entry, Path #4
2111	1	20	Manual, 8k ft, 220 KIAS, SLUF entry, Path #2
2111	1	21	Virtual, 8k ft, 270 KIAS, 12.5 Hz, IC #1
2111	1	22	Virtual, 8k ft, 270 KIAS, 12.5 Hz, IC #1
2111	1	23	Virtual, 8k ft, 270 KIAS, 12.5 Hz, IC #1
2111	1	24	Virtual, 8k ft, 270 KIAS, 12.5 Hz, IC #1
2111	1	25	Virtual, 8k ft, 270 KIAS, 12.5 Hz, IC #1
2113	2	1	Manual, 15k ft, 220 KIAS, SLUF entry, Path #3
2113	2	2	Manual, 15k ft, 220 KIAS, SLUF entry, Path #2
2113	2	3	Manual, 15k ft, 220 KIAS, SLUF entry, Path #1
2113	2	4	Manual, 15k ft, 270 KIAS, SLUF entry, Path #3
2113	2	5	Manual, 15k ft, 270 KIAS, SLUF entry, Path #2
2113	2	6	Manual, 15k ft, 270 KIAS, SLUF entry, Path #5
2113	2	7	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #1
2113	2	8	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #2
2113	2	9	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #3
2113	2	10	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #3
2113	2	11	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #3
2113	2	12	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #3
2113	2	13	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #3

Learjet Flight #	Flight #	Record #	Point Description
2113	2	14	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #3
2113	2	15	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #3
2113	2	16	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #3
2113	2	17	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #3
2113	2	18	Virtual, 15k ft, 270 KIAS, 12.5 Hz, IC #1
2113	2	19	N/A
2113	2	20	Virtual, 15k ft, 270 KIAS, 12.5 Hz, IC #1
2113	2	21	Virtual, 15k ft, 270 KIAS, 12.5 Hz, IC #2
2113	2	22	Virtual, 15k ft, 270 KIAS, 12.5 Hz, IC #3
2113	2	23	Manual, 8k ft, 220 KIAS, SLUF entry, Path #3
2113	2	24	Manual, 8k ft, 220 KIAS, SLUF entry, Path #5
2113	2	25	Manual, 8k ft, 220 KIAS, SLUF entry, Path #4
2113	2	26	Manual, 8k ft, 270 KIAS, SLUF entry, Path #3
2113	2	27	Manual, 8k ft, 270 KIAS, SLUF entry, Path #3
2113	2	28	Manual, 8k ft, 270 KIAS, SLUF entry, Path #4
2113	2	29	Low Level Fam
2113	2	30	Low Level Fam
2113	2	31	Low Level Fam
2114	3	1	Manual, 15k ft, 270 KIAS, $\phi = 45^\circ$ entry, Path #3
2114	3	2	Manual, 15k ft, 270 KIAS, $\phi = 45^\circ$ entry, Path #2
2114	3	3,4,6,7	Manual, 15k ft, 270 KIAS, $\phi = 45^\circ$ entry, Path #4
2114	3	8	Manual, 15k ft, 270 KIAS, $\phi = 45^\circ$ entry, Path #1
2114	3	9	Manual, 15k ft, 270 KIAS, $\phi = 45^\circ$ entry, Path #5
2114	3	10	Manual, 15k ft, 270 KIAS, $\gamma = 5^\circ$ entry, Path #3
2115	4	1	N/A
2115	4	2	Manual, 15k ft, 220 KIAS, SLUF entry, Path #3
2115	4	3	Manual, 15k ft, 220 KIAS, SLUF entry, Path #2
2115	4	4	Manual, 15k ft, 220 KIAS, SLUF entry, Path #4
2115	4	5	Manual, 15k ft, 220 KIAS, SLUF entry, Path #1
2115	4	6	Manual, 15k ft, 220 KIAS, SLUF entry, Path #5
2115	4	7	Manual, 15k ft, 270 KIAS, SLUF entry, Path #3
2115	4	8	Manual, 15k ft, 270 KIAS, SLUF entry, Path #3
2115	4	9	Manual, 15k ft, 270 KIAS, SLUF entry, Path #3
2115	4	10	Manual, 15k ft, 270 KIAS, SLUF entry, Path #4
2115	4	11	Manual, 15k ft, 270 KIAS, SLUF entry, Path #2
2115	4	12	Manual, 15k ft, 270 KIAS, SLUF entry, Path #5
2115	4	13	Manual, 15k ft, 270 KIAS, SLUF entry, Path #1
2115	4	14	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #1
2115	4	15	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #2
2115	4	16	Virtual, 15k ft, 220 KIAS, 12.5 Hz, IC #3

Learjet Flight #	Flight #	Record #	Point Description
2115	4	17	Virtual, 15k ft, 270 KIAS, 12.5 Hz, IC #1
2115	4	18	Virtual, 15k ft, 270 KIAS, 12.5 Hz, IC #2
2115	4	19	Virtual, 15k ft, 270 KIAS, 12.5 Hz, IC #3
2115	4	20	Manual, 8k ft, 220 KIAS, SLUF entry, Path #3
2115	4	21	Manual, 8k ft, 220 KIAS, SLUF entry, Path #4
2115	4	22	Manual, 8k ft, 220 KIAS, SLUF entry, Path #2
2115	4	23	Manual, 8k ft, 220 KIAS, SLUF entry, Path #5
2115	4	24	Manual, 8k ft, 220 KIAS, SLUF entry, Path #1
2115	4	25	Manual, 8k ft, 270 KIAS, SLUF entry, Path #3
2115	4	26	N/A
2115	4	27	Manual, 8k ft, 270 KIAS, SLUF entry, Path #2
2115	4	28	Manual, 8k ft, 270 KIAS, SLUF entry, Path #4
2115	4	29	Manual, 8k ft, 270 KIAS, SLUF entry, Path #1
2115	4	30	Manual, 8k ft, 270 KIAS, SLUF entry, Path #5
2115	4	31	Virtual, 8k ft, 220 KIAS, 12.5 Hz, IC #1
2115	4	32	Virtual, 8k ft, 220 KIAS, 12.5 Hz, IC #2
2115	4	33	Virtual, 8k ft, 220 KIAS, 12.5 Hz, IC #3
2115	4	34	Manual, 500 ft, 220 KIAS, SLUF entry, Path #3
2115	4	35	Manual, 500 ft, 220 KIAS, SLUF entry, Path #2
2115	4	36	Manual, 500 ft, 220 KIAS, SLUF entry, Path #4
2115	4	37	Manual, 500 ft, 220 KIAS, SLUF entry, Path #1
2115	4	38	Manual, 500 ft, 220 KIAS, SLUF entry, Path #5
2115	4	39	Manual, 500 ft, 270 KIAS, SLUF entry, Path #3
2115	4	40	Manual, 500 ft, 270 KIAS, SLUF entry, Path #2
2115	4	41	Manual, 500 ft, 270 KIAS, SLUF entry, Path #4
2115	4	42	Manual, 500 ft, 270 KIAS, SLUF entry, Path #5
2116	5	1	Manual, 15K ft, 270 KIAS, 45° entry, Path #3
2116	5	2	Manual, 15K ft, 270 KIAS, 45° entry, Path #2
2116	5	3	Manual, 15K ft, 270 KIAS, 45° entry, Path #4
2116	5	4	Manual, 15K ft, 270 KIAS, 45° entry, Path #1
2116	5	5	Manual, 15K ft, 270 KIAS, 45° entry, Path #5
2116	5	6	Manual, 15K ft, 270 KIAS, 5° entry, Path #3
2116	5	7	Manual, 15K ft, 270 KIAS, 5° entry, Path #2
2116	5	8	Manual, 15K ft, 270 KIAS, 5° entry, Path #4
2116	5	9	Manual, 15K ft, 270 KIAS, 5° entry, Path #1
2116	5	10	Manual, 15K ft, 270 KIAS, 5° entry, Path #5
2116	5	11	Manual, 15K ft, 270 KIAS, -5° entry, Path #3
2116	5	12	Manual, 15K ft, 270 KIAS, -5° entry, Path #2
2116	5	13	Manual, 15K ft, 270 KIAS, -5° entry, Path #4
2116	5	14	Manual, 15K ft, 270 KIAS, -5° entry, Path #1
2116	5	15	Manual, 15K ft, 270 KIAS, -5° entry, Path #5

Learjet Flight #	Flight #	Record #	Point Description
2116	5	16	Virtual, 15k ft, 270 KIAS, 6.25 Hz, IC #1
2116	5	17	Virtual, 15k ft, 270 KIAS, 6.25 Hz, IC #2
2116	5	18	Virtual, 15k ft, 270 KIAS, 6.25 Hz, IC #3
2116	5	19	Virtual, 15k ft, 220 KIAS, 6.25 Hz, IC #1
2116	5	20	Virtual, 15k ft, 220 KIAS, 6.25 Hz, IC #2
2116	5	21	Virtual, 15k ft, 220 KIAS, 6.25 Hz, IC #3
2116	5	22&23	Manual, 8K ft, 270 KIAS, 45° entry, Path #3
2116	5	24	Manual, 8K ft, 270 KIAS, 45° entry, Path #2
2116	5	25	Manual, 8K ft, 270 KIAS, 45° entry, Path #4
2116	5	26	Manual, 8K ft, 270 KIAS, 45° entry, Path #1
2116	5	27	Manual, 8K ft, 270 KIAS, 45° entry, Path #5
2116	5	28	Manual, 8K ft, 270 KIAS, 5° entry, Path #3
2116	5	29	Manual, 8K ft, 270 KIAS, 5° entry, Path #2
2116	5	30	Manual, 8K ft, 270 KIAS, 5° entry, Path #4
2116	5	31	Manual, 8K ft, 270 KIAS, 5° entry, Path #1
2116	5	32	Manual, 8K ft, 270 KIAS, 5° entry, Path #5
2116	5	33	Manual, 8K ft, 270 KIAS, -5° entry, Path #3
2116	5	34	Manual, 8K ft, 270 KIAS, -5° entry, Path #2
2116	5	35	Manual, 8K ft, 270 KIAS, -5° entry, Path #4
2116	5	36	Manual, 8K ft, 270 KIAS, -5° entry, Path #1
2116	5	37	Manual, 8K ft, 270 KIAS, -5° entry, Path #5
2116	5	38	Virtual, 8k ft, 270 KIAS, 12.5 Hz, IC #1
2116	5	39	Virtual, 8k ft, 270 KIAS, 12.5 Hz, IC #2
2116	5	40	Virtual, 8k ft, 270 KIAS, 12.5 Hz, IC #3
2116	5	41	Virtual, 8k ft, 270 KIAS, 6.25 Hz, IC #1
2117	6	1	Manual, 15k ft, 220 KIAS, 45° entry, Path #3
2117	6	2	Manual, 15k ft, 220 KIAS, 45° entry, Path #2
2117	6	3	Manual, 15k ft, 220 KIAS, 45° entry, Path #4
2117	6	4	Manual, 15k ft, 220 KIAS, 45° entry, Path #1
2117	6	5	Manual, 15k ft, 220 KIAS, 45° entry, Path #5
2117	6	6	Manual, 15K ft, 220 KIAS, 5° entry, Path #3
2117	6	7	Manual, 15K ft, 220 KIAS, 5° entry, Path #2
2117	6	8	Manual, 15K ft, 220 KIAS, 5° entry, Path #4
2117	6	9	Manual, 15K ft, 220 KIAS, 5° entry, Path #1
2117	6	10	Manual, 15K ft, 220 KIAS, 5° entry, Path #5
2117	6	11	Manual, 15K ft, 220 KIAS, -5° entry, Path #3
2117	6	12	Manual, 15K ft, 220 KIAS, -5° entry, Path #2
2117	6	13	Manual, 15K ft, 220 KIAS, -5° entry, Path #4
2117	6	14	Manual, 15K ft, 220 KIAS, -5° entry, Path #1
2117	6	15	Manual, 15K ft, 220 KIAS, -5° entry, Path #5

Learjet Flight #	Flight #	Record #	Point Description
2117	6	16	Virtual, 15k ft, 220 KIAS, 1.5625 Hz, IC #1
2117	6	17	Virtual, 15k ft, 220 KIAS, 1.5625 Hz, IC #2
2117	6	18	Virtual, 15k ft, 220 KIAS, 1.5625 Hz, IC #3
2117	6	19	Virtual, 15k ft, 270 KIAS, 1.5625 Hz, IC #1
2117	6	20	Virtual, 15k ft, 270 KIAS, 1.5625 Hz, IC #2
2117	6	21	Virtual, 15k ft, 270 KIAS, 1.5625 Hz, IC #3
2117	6	22	Manual, 8k ft, 220 KIAS, 45° entry, Path #3
2117	6	23	Manual, 8k ft, 220 KIAS, 45° entry, Path #2
2117	6	24	Manual, 8k ft, 220 KIAS, 45° entry, Path #4
2117	6	25	Manual, 8k ft, 220 KIAS, 45° entry, Path #1
2117	6	26	Manual, 8k ft, 220 KIAS, 45° entry, Path #5
2117	6	27	Manual, 8k ft, 220 KIAS, 5° entry, Path #3
2117	6	28	Manual, 8k ft, 220 KIAS, 5° entry, Path #2
2117	6	29	N/A
2117	6	30	Manual, 8k ft, 220 KIAS, 5° entry, Path #4
2117	6	31	Manual, 8k ft, 220 KIAS, -5° entry, Path #3
2117	6	32	Manual, 8k ft, 220 KIAS, -5° entry, Path #2
2117	6	33	Manual, 8k ft, 220 KIAS, -5° entry, Path #4
2117	6	34	Manual, 8k ft, 220 KIAS, -5° entry, Path #1
2117	6	35	Manual, 8k ft, 220 KIAS, 5° entry, Path #1
2117	6	36	Manual, 8k ft, 220 KIAS, 5° entry, Path #5
2117	6	37	Manual, 8k ft, 220 KIAS, -5° entry, Path #5
2117	6	38	Virtual, 8k ft, 220 KIAS, 1.5625 Hz, IC #1
2117	6	39	Virtual, 8k ft, 220 KIAS, 1.5625 Hz, IC #2
2117	6	40	Virtual, 8k ft, 220 KIAS, 1.5625 Hz, IC #3
2117	6	41	Virtual, 8k ft, 270 KIAS, 1.5625 Hz, IC #1
2117	6	42	Virtual, 8k ft, 270 KIAS, 1.5625 Hz, IC #2
2117	6	43	Virtual, 8k ft, 270 KIAS, 1.5625 Hz, IC #3
2118	7	5	Virtual, 8k ft, 270 KIAS, 6.25 Hz, IC #3
2118	7	6	Virtual, 8k ft, 270 KIAS, 6.25 Hz, IC #2
2118	7	7	Virtual, 8k ft, 220 KIAS, 6.25 Hz, IC #1
2118	7	8	Virtual, 8k ft, 220 KIAS, 6.25 Hz, IC #2
2118	7	9	Virtual, 8k ft, 220 KIAS, 6.25 Hz, IC #2
2118	7	10	Manual, 500 ft AGL, 270 KIAS, SLUF entry, Path #1
2118	7	11	Manual, 500 ft AGL, 270 KIAS, 45° entry, Path #3
2118	7	12	Manual, 500 ft AGL, 270 KIAS, 45° entry, Path #2
2118	7	13	Manual, 500 ft AGL, 270 KIAS, 45° entry, Path #4
2118	7	14	Manual, 500 ft AGL, 270 KIAS, 45° entry, Path #1
2118	7	15	Manual, 500 ft AGL, 270 KIAS, 45° entry, Path #5
2118	7	16	Manual, 500 ft AGL, 270 KIAS, 5° entry, Path #3
2118	7	17	Manual, 500 ft AGL, 270 KIAS, 5° entry, Path #2

Learjet Flight #	Flight #	Record #	Point Description
2118	7	18	Manual, 500 ft AGL, 270 KIAS, 5° entry, Path #4
2118	7	19	Manual, 500 ft AGL, 270 KIAS, 5° entry, Path #1
2118	7	20	Manual, 500 ft AGL, 270 KIAS, 5° entry, Path #5
2118	7	21	Virtual, 500 ft AGL, 270 KIAS, 12.5 Hz, IC #1
2118	7	22	Virtual, 500 ft AGL, 270 KIAS, 12.5 Hz, IC #2
2118	7	23	Virtual, 500 ft AGL, 270 KIAS, 12.5 Hz, IC #3
2118	7	24	Virtual, 500 ft AGL, 220 KIAS, 12.5 Hz, IC #1
2118	7	25	Virtual, 500 ft AGL, 220 KIAS, 12.5 Hz, IC #2
2118	7	26	Virtual, 500 ft AGL, 220 KIAS, 12.5 Hz, IC #3
2118	7	27	Lateral Offset to Actual Terrain
2118	7	28	Lateral Offset to Actual Terrain
2118	7	29	Lateral Offset to Actual Terrain
2119	8	1	N/A
2119	8	2	Manual, 500 ft, 220 KIAS, 45° entry, Path #3
2119	8	3	Manual, 500 ft, 220 KIAS, 45° entry, Path #2
2119	8	4	Manual, 500 ft, 220 KIAS, 45° entry, Path #1
2119	8	5	Manual, 500 ft, 220 KIAS, 45° entry, Path #5
2119	8	6	Manual, 500 ft, 220 KIAS, 45° entry, Path #4
2119	8	7	Manual, 500 ft, 220 KIAS, 5° entry, Path #3
2119	8	8	Manual, 500 ft, 220 KIAS, 5° entry, Path #2
2119	8	9	Manual, 500 ft, 220 KIAS, 5° entry, Path #1
2119	8	10	Manual, 500 ft, 220 KIAS, 5° entry, Path #5
2119	8	11	Manual, 500 ft, 220 KIAS, 5° entry, Path #4
2119	8	12	Virtual, 500 ft, 220 KIAS, 6.25 Hz, IC #1
2119	8	13	Virtual, 500 ft, 220 KIAS, 6.25 Hz, IC #2
2119	8	14	Virtual, 500 ft, 220 KIAS, 6.25 Hz, IC #3
2119	8	15	Virtual, 500 ft, 270 KIAS, 6.25 Hz, IC #1
2119	8	16	Virtual, 500 ft, 270 KIAS, 6.25 Hz, IC #2
2119	8	17	Virtual, 500 ft, 270 KIAS, 6.25 Hz, IC #3
2119	8	18	Virtual, 500 ft, 220 KIAS, 1.5625 Hz, IC #1
2119	8	19	N/A
2119	8	20	Virtual, 500 ft, 220 KIAS, 1.5625 Hz, IC #2
2119	8	21	Virtual, 500 ft, 220 KIAS, 1.5625 Hz, IC #3
2119	8	22	Virtual, 500 ft, 270 KIAS, 1.5625 Hz, IC #1
2119	8	23	Virtual, 500 ft, 270 KIAS, 1.5625 Hz, IC #1
2119	8	24	Virtual, 500 ft, 270 KIAS, 1.5625 Hz, IC #2
2119	8	25	Virtual, 500 ft, 270 KIAS, 1.5625 Hz, IC #3
2119	8	26	Virtual, 500 ft, 270 KIAS, 1.5625 Hz, IC #3
2119	8	27	N/A
2119	8	28	RSET disconnect check

Learjet Flight #	Flight #	Record #	Point Description
2119	8	29	Practicing level turn above 2,000 ft AGL
2119	8	30	Descending to 500 ft AGL
2119	8	31	Lateral Offset to Actual Terrain
2119	8	32	Lateral Offset to Actual Terrain
2119	8	33	Lateral Offset to Actual Terrain
2120	9	1	Lateral Offset to Actual Terrain
2120	9	2	Lateral Offset to Actual Terrain
2120	9	3	Low Level Flight
2120	9	4	Low Level Flight
2120	9	5	Low Level Flight
2120	9	6	Low Level Flight
2120	9	7	Manual, 500 ft, 220 KIAS, SLUF entry, Path #3
2120	9	7 to 8	Manual, 500 ft, 220 KIAS, SLUF entry, Path #2
2120	9	9	Manual, 500 ft, 220 KIAS, SLUF entry, Path #4
2120	9	10	Manual, 500 ft, 220 KIAS, SLUF entry, Path #1
2120	9	11	Manual, 500 ft, 220 KIAS, SLUF entry, Path #5
2120	9	12	Manual, 500 ft, 270 KIAS, SLUF entry, Path #3
2121	10	1	Lateral Offset to Actual Terrain
2121	10	2	Lateral Offset to Actual Terrain
2121	10	3	Low Level Flight
2121	10	4	Low Level Flight
2121	10	5	Low Level Flight
2121	10	6	Low Level Flight
2121	10	7	Manual, 500 ft, 270 KIAS, SLUF entry, Path #2
2121	10	8	Manual, 500 ft, 270 KIAS, SLUF entry, Path #4
2121	10	9	Manual, 500 ft, 270 KIAS, SLUF entry, Path #1
2121	10	10	Manual, 500 ft, 270 KIAS, SLUF entry, Path #5
2121	10	11	Virtual, 500 ft, 220 KIAS, 12.5 Hz, IC #1
2121	10	12	Virtual, 500 ft, 220 KIAS, 12.5 Hz, IC #2
2122	11	1	Low Level Flight
2122	11	2	Low Level Flight
2122	11	3	Low Level Flight
2122	11	4	Low Level Flight
2122	11	5	Low Level Flight
2122	11	6	Low Level Flight
2122	11	7	Low Level Flight
2122	11	8	Virtual, 500 ft AGL, 220 KIAS, 12.5 Hz, IC #1
2122	11	9	Virtual, 500 ft AGL, 220 KIAS, 12.5 Hz, IC #2
2122	11	10	Virtual, 500 ft AGL, 220 KIAS, 12.5 Hz, IC #3
2122	11	11	Virtual, 500 ft AGL, 270 KIAS, 12.5 Hz, IC #1

Learjet Flight #	Flight #	Record #	Point Description
2122	11	12	Virtual, 500 ft AGL, 270 KIAS, 12.5 Hz, IC #2
2122	11	13	Virtual, 500 ft AGL, 270 KIAS, 12.5 Hz, IC #3
2122	11	14	Manual, 500 ft, 270 KIAS, 45° entry, Path #3
2122	11	15	Manual, 500 ft, 270 KIAS, 45° entry, Path #4
2122	11	16	Manual, 500 ft, 270 KIAS, 45° entry, Path #2
2122	11	17	Manual, 500 ft, 270 KIAS, 45° entry, Path #1
2122	11	18	Manual, 500 ft, 270 KIAS, 45° entry, Path #1
2122	11	19	Manual, 500 ft, 270 KIAS, 45° entry, Path #5
2122	11	20	Manual, 500 ft, 220 KIAS, 45° entry, Path #3
2122	11	21	Manual, 500 ft, 220 KIAS, 45° entry, Path #2
2122	11	22	Manual, 500 ft, 220 KIAS, 45° entry, Path #4

APPENDIX E – PATH PREDICTION ERROR RESULTS

Flt #	Rec #	Alt	A/S	Entry	Path	Wind (kts)	Wind (deg)	Prediction Error (ft)	Out-climb prediction?	Tighter than prediction?	Error Away from Terrain?
4	2	15000	220	1	3	31	Yes	1672	No	N/A	No
4	3	15000	220	1	2	34	Yes	1719	No	No	No
4	4	15000	220	1	4	33	Yes	1654	Yes	Yes	Yes
4	5	15000	220	1	1	32	Yes	1651	Yes	Yes	Yes
4	6	15000	220	1	5	37	Yes	1636	Yes	No	Inconclusive
4	9	15000	270	1	3	33	No	1399	Yes	N/A	Yes
4	10	15000	270	1	4	37	Yes	1024	Yes	No	Inconclusive
4	11	15000	270	1	2	30	Yes	1671	Yes	Yes	Yes
4	12	15000	270	1	5	31	Yes	1816	Yes	Yes	Yes
4	13	15000	270	1	1	37	Yes	1524	No	No	No
4	20	8000	220	1	3	24	Yes	1191	Yes	N/A	Yes
4	21	8000	220	1	4	28	No	1256	No	Yes	Inconclusive
4	22	8000	220	1	2	28	Yes	1272	Yes	No	Inconclusive
4	23	8000	220	1	5	25	Yes	962	Yes	No	Inconclusive
4	24	8000	220	1	1	27	Yes	773	Yes	No	Inconclusive
4	25	8000	270	1	3	25	Yes	2505	Yes	N/A	Yes
4	27	8000	270	1	2	26	Yes	1602	No	No	No
4	28	8000	270	1	4	28	Yes	1365	No	No	No
4	29	8000	270	1	1	26	Yes	1445	No	No	No
4	30	8000	270	1	5	28	Yes	514	Yes	Yes	Yes
4	34	500	220	1	3	17	No	172	No	N/A	No
4	35	500	220	1	2	12	Yes	659	Yes	Yes	Yes
4	36	500	220	1	4	14	Yes	918	No	No	No
4	37	500	220	1	1	13	No	1408	Yes	No	Inconclusive
4	38	500	220	1	5	13	No	2332	Yes	No	Inconclusive
4	39	500	270	1	3	13	Yes	481	Yes	N/A	Yes
4	40	500	270	1	2	16	Yes	728	No	No	No
4	41	500	270	1	4	17	Yes	350	Yes	Yes	Yes
4	42	500	270	1	5	18	Yes	864	No	Yes	Inconclusive
5	1	15000	270	2	3	34	Yes	1922	No	N/A	No
5	2	15000	270	2	2	37	Yes	2862	No	No	No
5	3	15000	270	2	4	31	Yes	947	Yes	No	Inconclusive
5	4	15000	270	2	1	32	Yes	1821	Yes	Yes	Yes
5	5	15000	270	2	5	35	Yes	1843	No	No	No
5	6	15000	270	3	3	28	Yes	754	Yes	N/A	Yes
5	7	15000	270	3	2	30	Yes	1687	Yes	Yes	Yes
5	8	15000	270	3	4	32	Yes	1524	Yes	Yes	Yes
5	9	15000	270	3	1	43	Yes	4447	No	No	No
5	10	15000	270	3	5	43	Yes	1201	No	Yes	Inconclusive
5	11	15000	270	4	3	34	No	1404	No	N/A	No
5	12	15000	270	4	2	37	Yes	1290	Yes	No	Inconclusive
5	13	15000	270	4	4	36	Yes	1571	No	No	No
5	14	15000	270	4	1	42	Yes	6568	No	No	No
5	15	15000	270	4	5	41	Yes	4914	No	No	No
5	24	8000	270	2	2	45	Yes	2061	No	No	No
5	25	8000	270	2	4	45	No	2392	No	Yes	No
5	26	8000	270	2	1	30	Yes	748	No	No	No
5	27	8000	270	2	5	25	Yes	1733	No	Yes	No
5	28	8000	270	3	3	33	Yes	1553	Yes	N/A	Yes
5	29	8000	270	3	2	28	Yes	1936	Yes	Yes	Yes
5	30	8000	270	3	4	21	Yes	1337	Yes	Yes	Yes
5	31	8000	270	3	1	29	Yes	2588	No	No	No
5	32	8000	270	3	5	26	Yes	2430	Yes	Yes	Yes
5	33	8000	270	4	3	27	Yes	1140	No	N/A	No
5	34	8000	270	4	2	33	No	1935	No	No	No
5	35	8000	270	4	4	35	Yes	1632	No	No	No
5	36	8000	270	4	1	38	Yes	2864	No	No	No
5	37	8000	270	4	5	30	Yes	2411	Yes	Yes	Yes

Flt #	Rec #	Alt	A/S	Entry	Path	Wind (kts)	Wind (deg)	Prediction Error (ft)	Out-climb prediction?	Out-turn?	Error Away from Terrain?
5	23	8000	270	2	3	28	Yes	2007	No	N/A	No
6	1	15000	220	2	3	36	Yes	1914	No	N/A	No
6	2	15000	220	2	2	33	Yes	1702	No	No	No
6	3	15000	220	2	4	34	Yes	2285	No	No	No
6	4	15000	220	2	1	32	Yes	1786	No	No	No
6	5	15000	220	2	5	23	Yes	1353	Yes	No	No
6	6	15000	220	3	3	30	Yes	1601	Yes	N/A	Yes
6	7	15000	220	3	2	27	Yes	2057	Yes	Yes	Yes
6	8	15000	220	3	4	25	Yes	1176	Yes	Yes	Yes
6	9	15000	220	3	1	31	Yes	3422	Yes	Yes	Yes
6	10	15000	220	3	5	34	Yes	2612	Yes	No	Inconclusive
6	11	15000	220	4	3	31	Yes	1256	Yes	N/A	Yes
6	12	15000	220	4	2	35	Yes	1964	Yes	Yes	Yes
6	13	15000	220	4	4	29	Yes	660	Yes	Yes	Yes
6	14	15000	220	4	1	36	Yes	3685	No	No	No
6	15	15000	220	4	5	38	Yes	2803	No	No	No
6	22	8000	220	2	3	30	No	1768	No	N/A	No
6	23	8000	220	2	2	24	Yes	2019	Yes	Yes	Yes
6	24	8000	220	2	4	27	Yes	1258	Yes	No	Inconclusive
6	25	8000	220	2	1	25	Yes	2632	Yes	Yes	Yes
6	26	8000	220	2	5	32	Yes	2369	No	No	No
6	27	8000	220	3	3	27	Yes	771	Yes	N/A	Yes
6	28	8000	220	3	2	19	Yes	1383	Yes	Yes	Yes
6	30	8000	220	3	4	11	Yes	721	Yes	Yes	Yes
6	31	8000	220	4	3	28	Yes	732	No	N/A	No
6	32	8000	220	4	2	33	Yes	3184	No	No	No
6	33	8000	220	4	4	32	Yes	1641	No	No	No
6	34	8000	220	4	1	34	Yes	5192	No	No	No
6	35	8000	220	3	1	28	Yes	2727	Yes	Yes	Yes
6	36	8000	220	3	5	28	Yes	2482	Yes	No	Inconclusive
6	37	8000	220	4	5	30	Yes	1294	Yes	Yes	Yes
7	10	500	270	1	1	5	Yes	383	Yes	Yes	Yes
7	11	500	270	2	3	16	Yes	913	No	N/A	No
7	12	500	270	2	2	6	Yes	915	Yes	Yes	Yes
7	13	500	270	2	4	7	Yes	291	Yes	No	Inconclusive
7	14	500	270	2	1	12	Yes	2036	No	No	No
7	15	500	270	2	5	10	Yes	751	No	No	No
7	16	500	270	3	3	6	Yes	346	Yes	N/A	Yes
7	17	500	270	3	2	8	Yes	739	No	No	No
7	18	500	270	3	4	8	Yes	652	Yes	Yes	Yes
7	19	500	270	3	1	10	Yes	687	No	No	No
7	20	500	270	3	5	14	Yes	516	No	Yes	Inconclusive
8	2	500	220	2	3	2	No	806	No	N/A	No
8	3	500	220	2	2	9	Yes	853	Yes	Yes	Yes
8	4	500	220	2	1	8	No	967	Yes	Yes	Yes
8	5	500	220	2	5	8	Yes	3640	Yes	No	Inconclusive
8	6	500	220	2	4	11	Yes	592	No	Yes	Inconclusive
8	7	500	220	3	3	5	Yes	409	No	N/A	No
8	8	500	220	3	2	10	No	880	No	No	No
8	9	500	220	3	1	12	Yes	4464	No	No	No
8	10	500	220	3	5	10	No	1742	Yes	No	Inconclusive
8	11	500	220	3	4	11	No	232	No	Yes	Inconclusive
9	7	500	220	1	3	19	No	565	No	N/A	No
9	8	500	220	1	2	9	Yes	301	No	No	No
9	9	500	220	1	4	1	Yes	1191	Yes	Yes	Yes
9	10	500	220	1	1	14	Yes	4114	Yes	Yes	Yes
9	11	500	220	1	5	12	Yes	1064	Yes	No	Inconclusive
9	12	500	270	1	3	16	Yes	603	Yes	N/A	Yes
10	7	500	270	1	2	13	Yes	1471	No	No	No
10	8	500	270	1	4	14	Yes	1090	Yes	Yes	Yes
10	9	500	270	1	1	20	Yes	2486	No	No	No
10	10	500	270	1	5	17	Yes	973	No	No	No

APPENDIX F – VIRTUAL TERRAIN ACTIVATION RESULTS

Test Flight	Rec #	Alt (ft)	MSL AGL	Airspeed (KIAS)	IC	Refresh Rate (Hz)	Set Buffer	Forward Look-Ahead Time (sec)	RSS Dist. (ft)	HaT (ft)
5	16	15000	MSL	270	1	6.25	100	3	-13	-220
5	17	15000	MSL	270	2	6.25	100	5	16	23
5	18	15000	MSL	270	3	6.25	100	21	-9	-422
5	19	15000	MSL	220	1	6.25	100	8	191	226
5	20	15000	MSL	220	2	6.25	100	11	337	342
5	21	15000	MSL	220	3	6.25	100	20	547	576
5	38	8000	MSL	270	1	12.5	100	3	37	109
5	39	8000	MSL	270	2	12.5	100	1	211	212
5	40	8000	MSL	270	3	12.5	100	5	110	133
5	41	8000	MSL	270	1	6.25	100	15	135	151
6	16	15000	MSL	220	1	1.5625	100	15	121	154
6	17	15000	MSL	220	2	1.5625	100	6	-11	-45
6	18	15000	MSL	220	3	1.5625	100	28	-9	-294
6	19	15000	MSL	270	1	1.5625	100	15	145	153
6	20	15000	MSL	270	2	1.5625	100	5	15	44
6	21	15000	MSL	270	3	1.5625	100	30	105	106
6	38	8000	MSL	220	1	1.5625	100	10	-20	-33
6	39	8000	MSL	220	2	1.5625	100	7	173	184
6	40	8000	MSL	220	3	1.5625	100	8	50	75
6	41	8000	MSL	270	1	1.5625	100	3	95	101
6	42	8000	MSL	270	2	1.5625	100	3	105	137
6	43	8000	MSL	270	3	1.5625	100	6	-32	-24
7	5	8000	MSL	270	3	6.25	100	17	47	74
7	6	8000	MSL	270	2	6.25	100	4	15	71
7	7	8000	MSL	220	1	6.25	100	10	100	132
7	8	8000	MSL	220	2	6.25	100	11	239	242
7	9	8000	MSL	220	3	6.25	100	10	94	102
7	21	8000	MSL	270	1	6.25	100	15	90	190
7	22	500	AGL	270	2	12.5	100	4	119	123
7	23	500	AGL	270	3	12.5	100	5	108	125
7	24	500	AGL	220	1	12.5	100	11	136	169
7	25	500	AGL	220	2	12.5	100	7	157	179
8	12	500	AGL	220	1	6.25	100	14	46	48
8	13	500	AGL	220	2	6.25	100	8	87	141
8	14	500	AGL	220	3	6.25	100	7	149	157
8	15	500	AGL	270	1	6.25	100	19	45	137
8	16	500	AGL	270	2	6.25	100	3	79	82
8	17	500	AGL	270	3	6.25	100	6	4	141
8	18	500	AGL	220	1	1.5625	100	8	70	86
8	20	500	AGL	220	2	1.5625	100	5	139	172
8	21	500	AGL	220	3	1.5625	100	17	-11	-124
8	24	500	AGL	270	2	1.5625	100	2	138	143
8	26	500	AGL	270	3	1.5625	100	2	715	720
10	11	500	AGL	220	1	12.5	200	3	102	174
10	12	500	AGL	220	2	12.5	200	6	34	99
11	8	500	AGL	220	1	12.5	200	16	184	221
11	9	500	AGL	220	2	12.5	200	1	175	203
11	10	500	AGL	220	3	12.5	200	11	251	270
11	11	500	AGL	270	1	12.5	200	5	128	151
11	12	500	AGL	270	2	12.5	200	4	187	214
11	13	500	AGL	270	3	12.5	200	4	95	151

APPENDIX G – MEDUSA CONFIGURATION TRACKER

Flight #	EP(s)	TC(s)	Changes Made Before Flight	Issues Discovered During or After Flight
1	Gotwald	Gahan Mak Jian Ming	*Baseline configuration resulting from simulator and ground tests.	*Actual control surface rate limits significantly different than the requested rate limits (persistent variables issue), causing numerous VSS trips. *Wind data from Learjet was not being passed to RSET - variable names too long (discovered post flight 2). *Initial horizontal stab position was incorrectly being passed to RSET as the aileron position (discovered flight 3). *Learjet sending unreliable heading value (Psi) to RSET instead of INS ground track value (discovered post flight 3). *C.G. offset set to a fixed value instead of changing based on current fuel balance (discovered post flight 3).
2	Hammond	Kolesar Gahan	*Issue with rate limit variables resolved.	*Wind data from Learjet was not being passed to RSET - variable names too long. *Initial horizontal stab position was incorrectly being passed to RSET as the aileron position (discovered flight 3). *Learjet sending unreliable heading value (Psi) to RSET instead of INS ground track value (discovered post flight 3). *C.G. offset set to a fixed value instead of changing based on current fuel balance (discovered post flight 3). *MATLAB froze mid-flight and required a lot of troubleshooting to get all settings set up.
3	Bakun	Mak Jian Ming Gahan	*Wind variable names changed so they are properly passed to RSET *Extensive list of VSS parameters added to recording list	*Initial horizontal stab position was incorrectly being passed to RSET as the aileron position. *Learjet sending unreliable heading value (Psi) to RSET instead of INS ground track value. *C.G. offset set to a fixed value instead of changing based on current fuel balance. *Learjet sending unreliable wind speed data to RSET (~80 kts) *Learjet reported incorrect causes for valid VSS trips

Flight #	EP(s)	TC(s)	Changes Made Before Flight	Issues Discovered During or After Flight
4	Hammond	Gahan	*Initial aileron position issue fixed. *Aircraft heading parameter changed from "psi" to "ins_track_true" *Updated Lear 3 mass property calculation in order to pass correct c.g. offset to RSET *Wind set to zero *Autopilot updated to improve smoothness (removed Nz feedback; added lower Nz bound)	*Max gamma changed to 12 deg during flight to prevent excessive airspeed loss. *Under-g VSS trips during hand-back after multiple automatic activations.
5	Bakun	Mak Jian Ming	*Drop-down menu for number of back seat passengers added to GUI in order to increase accuracy of weight & balance measurement *Fields added to GUI for entering wind speed and direction before each test point. Wind speed/direction will be considered constant throughout each test point.	
6	Gotwald	Kolesar	None	
7	Hammond	Mak Jian Ming	*Drop-down field for DTED region added to GUI	
8	Gotwald	Gahan	None	
9	Bakun Gotwald	Mak Jian Ming	None	
10	Hammond Lt Col Abel	Kolesar	None	
11	Bakun	Gahan	None	

APPENDIX H – DAILY FLIGHT TEST REPORTS

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE LJ-25	2. SERIAL NUMBER N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO HAVE MEDUSA	B. FLIGHT NO / DATA POINT 1	C. DATE 5 Sep 18	
D. FRONT COCKPIT Crunch/Solo	E. FUEL LOAD 5,600	F. JON	
G. REAR COCKPIT Caddy/Hula	H. No Fuel Weight 9916	I. WEATHER SKC clm 24 deg	
J. TO TIME / SORTIE TIME 1225/1.1	K. CONFIGURATION / LOADING 001	L. SURFACE CONDITIONS 2237' PA Alt: 30.00	
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A	
4. PURPOSE OF FLIGHT / TEST POINTS RSET Check out			
5. RESULTS OF TESTS <i>(Continue on reverse if needed)</i> Able to check RADAR altimeter on ground, showed approximately 5 ft. Should work up to 2500 ft. Recommend adding systems check to ground block card. Rest of taxi/takeoff was uneventful Crunch recommended having more rigid checklist steps... Worked Kohn to Cuddeback which was not bad, did require some extra turning. Should be fine working cords/ black mtn. Some issues getting the FTE console and laptop set up, but after discussion with control (Jay/George) we were able to execute as planned. Conducted manual activations of each path at 15k, with no issues. Conducted flight against virtual terrain also with no major issues. Then went to 8k and was able to fly all manual activation points with no issue. Started experiancing aileron pressure differential VSS trips during handback. Adjusting ailerons gains which helped some, but then led to elevator pressure differential trips. Those trips occurred at path activation. Gains seemed to work everywhere else, troubleshooting required to understand what these trips are. Records 21-25 All trips were seen at 8k, IC#1, also the airplance was experiancing moderate turbulence. GUI had no major issues once laptop IP issue was fixed.			
6. RECOMMENDATIONS Lockdown RSET rate limting and press to data collection. Also recommend to complete low level fam on next sortie.			
COMPLETED BY Capt Carl Gotwald		SIGNATURE e-signed //cag//	DATE 5 Sep 18

TPS Form 5314 NOV 86 NOT REALLY AN OFFICIAL FORM, BUT THIS IS WHAT WILL BE USED AT TPS.

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE LJ-25	2. SERIAL NUMBER N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO HAVE MEDUSA	B. FLIGHT NO / DATA POINT 2	C. DATE 7 Sep 18	
D. FRONT COCKPIT Crunch/COBE	E. FUEL LOAD 5,600	F. JON 998TMP0004	
G. REAR COCKPIT HEX/Hula	H. No Fuel Weight 9916	I. WEATHER SKC clm 18°C	
J. TO TIME / SORTIE TIME 0733/1.9	K. CONFIGURATION / LOADING 002	L. SURFACE CONDITIONS 2200' PA Alt: 30.04	
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A	
4. PURPOSE OF FLIGHT / TEST POINTS RSET Validation flight and low level fam to satisfy safety package for 500' AGL data points.			
5. RESULTS OF TESTS (Continue on reverse if needed) Implemented new RSET ground checkout using mode 802 on CSS (ground sim w/o hydro). Initially failed the test until surface servos were turned off. Recommend adding this step (and reactivation of switches) to next ground block checklist. NSTR through climbout/system checks. Left seat instruments showed 3kts slower and 100ft higher than right seat instruments. Worked Cords road which was satisfactory. This area did require some planning regarding which maneuver to fly next especially for virtual terrain activations. Planned mission frequency did not work for Sport which required some radio dancing when we needed to call back to CALSPAN DE. Conducted manual activations of each path at 15k, with no issues. Conducted virtual activations at 15k. IC 1&2 performed as expected. Following IC #2, MATLAB froze which required calling back to control for reset instructions. Following this reset, RSET would not activate against virtual terrain. It was determined that initial parameters in MATLAB (latitude, longitude, altitude) were populating incorrectly. Following these corrections, virtual activations occurred as expected, but RSET would not "handback" control following the handback maneuver for the remainder of the flight. Manual activations at 8k' were then performed. Initial path 3 at 270kts had VSS trip due to elevator pressure differential. Rate limit adjusted from 50 to 35 with no further issues. Paths ¾ at 8k' and 270kts showed approximately 5-10° of gamma hunting in the climb. Due to time constraints, paths 1/5 were not tested and we dropped down to perform low level fam near Harpers lake area to include 60° banked turns.			
6. RECOMMENDATIONS Lockdown RSET to learjet wind model and press to data collection. Also recommend to complete low level manual activations on next sortie.			
COMPLETED BY Capt Mark Hammond		SIGNATURE e-signed ///mah//	DATE 10 Sep 18

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DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE LJ-25	2. SERIAL NUMBER N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO HAVE MEDUSA	B. FLIGHT NO / DATA POINT 3	C. DATE 10 Sep 18	
D. FRONT COCKPIT Crunch/Smoked	E. FUEL LOAD 5,600	F. JON 998TMP0004	
G. REAR COCKPIT Caddy/Hula	H. No Fuel Weight 9916	I. WEATHER Winds 220/11, SKC, >5500ft	
J. TO TIME / SORTIE TIME 1104L/1.0	K. CONFIGURATION / LOADING 002	L. SURFACE CONDITIONS 2339' PA Alt: 29.89	
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A	
4. PURPOSE OF FLIGHT / TEST POINTS Highest priority points were the manual activations with varied entry conditions starting at 15k ft and working down to 500 ft AGL. Lowest priority points were the different refresh rates for virtual terrain activations.			
5. RESULTS OF TESTS (Continue on reverse if needed) NSTR through climbout/system checks. Left seat instruments showed 6kts faster and 40ft higher than right seat instruments. Worked Cords road in the block 7-20k ft. Manual activations of all five paths were accomplished from the starting conditions of 270 KIAS, level flight, and 45° left bank. Power was routinely set between 94-96% rpm within 3 seconds of manual activations. The majority of the escape maneuvers appeared to be flown as the team expected. The first time we activated path 4, the aircraft rolled right and buried the nose below the horizon. EP and SP intervention was required to disconnect the system and recover to level flight. This appeared to be an anomaly as subsequent activations of path 4 performed in the correct sense (climbing right turns). One VSS trip (aileron pressure differential) occurred during these activations. In general, the nose of the aircraft "hunted" longitudinally between ~13-15° flight path angle (FPA) during the escape maneuvers. The RSET would not "handback" control following the handback maneuver for the majority of the flight and the EP had to paddle the system off to take control. Manual activation of path 3 was accomplished from the starting condition of 270 KIAS, wings level, 5° FPA and resulted in a VSS trip (aileron pressure differential). The TC paused testing and investigated the output parameter list to troubleshoot the recurring issue. The TC discovered that the elevator (h_stab) deflection was being fed in to the ailerons within the OFP. We called back to control and discussed with the Calspan DE a way forward. It was determined the OFP was incorrect and the mix-up was due to a copy/paste error in the code. The TC stopped test and the pilots proceeded to spiral down to 500 ft AGL over Harper's Lake to accomplish low-level fam for the EP. The EP built his site picture and cross check down at 500 ft AGL and then accomplished left and right 60 ° AOB turns for familiarity. RTB was routine.			
6. RECOMMENDATIONS Analyze flight data for the path 4 activation that descended. Troubleshoot gamma hunting during activations. Fix OFP issues, perform ground check-out, and lock down the code for the remainder of the flight test window.			
COMPLETED BY Capt Mike Bakun		SIGNATURE e-signed //mab//	DATE 11 Sep 18

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DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE LJ-25	2. SERIAL NUMBER N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO HAVE MEDUSA	B. FLIGHT NO / DATA POINT 4	C. DATE 12 Sep 18	
D. FRONT COCKPIT Hineline/Hammond	E. FUEL LOAD 5,600	F. JON 998TMP0004	
G. REAR COCKPIT Gahan	H. No Fuel Weight 9916	I. WEATHER SKC 210/8 17°C	
J. TO TIME / SORTIE TIME 0749/2.0	K. CONFIGURATION / LOADING 003	L. SURFACE CONDITIONS 2200' PA Alt: 30.04	
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A	
4. PURPOSE OF FLIGHT / TEST POINTS RSET Validation flight with updated configuration. MANUAL ACTIVATIONS – 15K' PA VIRTUAL TERRAIN ACTIVATIONS – 15K' PA MANUAL ACTIVATIONS – 8K' PA VIRTUAL TERRAIN ACTIVATIONS – 8K' PA (priority 2) MANUAL ACTIVATIONS 500 AGL			
5. RESULTS OF TESTS (Continue on reverse if needed) NSTR for ground Ops through climbout. Left seat instruments showed 3kts slower and 100ft higher than right seat instruments. Manual Activations (15k' PA)-Initial climbing activations had a Gamma command for 20° nose high. This resulted in airspeed dropping below 200kts (point termination) before wings level. Gamma command was reduced to 15° resulting in min speed of 203kts. Final command was set at 12° with new min airspeed of 210kts. Test proceeded with new Gamma command set. Virtual Activations (15k' PA)-Aircraft maneuvered as predicted in the sim with no Gamma hunting as experienced in prior RSET config. Did experience VSS trips due to under G on handback theorized to be a result of multiple paths rapidly changing to handback conditions. These trips shouldn't affect testing as it stands. Also noted that winds displayed by the aircraft during dynamic maneuvering were higher than when flying straight and level. Manual Activations (8k' PA)-All paths were flown with NSTR. Virtual Activations (8k' PA)-Accomplished 220 kts all 3 IC's at max refresh rate. NSTR. Manual Activations (500' AGL)-Points were flown towards top of databand to increase safety margin. All paths showed at least a 2000' climb with high engine performance capability. For path #5 activation at 220kts, the aircraft accelerated out to 270kts and tripped VSS for elevator pressure differential at handback. Only point not accomplished was path 1 at 270kts due to fuel limitations. NSTR for RTB			
6. RECOMMENDATIONS Press with test. No further RSET config changes needed.			
COMPLETED BY Capt Mark Hammond		SIGNATURE e-signed //mah//	DATE 12 Sep 18

TPS Form 5314 NOV 86 NOT REALLY AN OFFICIAL FORM, BUT THIS IS WHAT WILL BE USED AT TPS.

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE	2. SERIAL NUMBER
		LJ-25	N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO	B. FLIGHT NO / DATA POINT	C. DATE	
HAVE MEDUSA	5	13 Sep 18	
D. FRONT COCKPIT	E. FUEL LOAD	F. JON	
Hineline/Bakun	5,600	998TMP0004	
G. REAR COCKPIT	H. No Fuel Weight	I. WEATHER	
Mak/Carpenter	9916	SKC 190/4 17°C	
J. TO TIME / SORTIE TIME	K. CONFIGURATION / LOADING	L. SURFACE CONDITIONS	
0758/1.9	003	2320' PA Alt: 29.93	
M. CHASE ACFT / SERIAL NO	N. CHASE CREW	O. CHASE TO TIME / SORTIE TIME	
N/A	N/A	N/A	
4. PURPOSE OF FLIGHT / TEST POINTS			
Manual Activations – 15K' PA, 270 KIAS, varied entry conditions (15 pts) Virtual Activations – 15K' PA, 220/270 KIAS, 6.25Hz (6 pts) Manual Activations – 8K' PA, 270 KIAS, varied entry conditions (15 pts) Virtual Activations – 8K' PA, 220/270 KIAS, 12.5Hz (3 pts) Virtual Activations – 8K' PA, 220/270 KIAS, 6.25Hz (6 pts) Manual Activations – 500' AGL, 270 KIAS, SLUG (1 pt) Manual Activations – 500' AGL, 270 KIAS, varied entry conditions (10 pts)			
5. RESULTS OF TESTS (Continue on reverse if needed)			
NSTR for ground Ops through climbout. Left seat instruments showed 4kts faster and 100ft higher than right seat instruments. We read winds from straight and level flight in the databand before each test point so the TC could manual enter the values into the laptop. The system activated escape maneuvers in the correct sense the crew was expecting for the most part. A few of the virtual activations resulted in different escape paths than we expected from the sim results. Manual Activations (15k' PA) – VSS trip (under g) on path 1 activation from left 45° turn entry condition. Virtual Activations (15k' PA) – VSS trip (under g) on test point 5 during the handback. Manual Activations (8k' PA) – Immediate VSS trip (elevator pressure delta) on path 3 activation from left 45° turn entry condition. VSS trip (under g) on path 1 activation from left 45° turn entry condition. VSS trip (under g) on path 5 activation from -5° FPA entry condition. Virtual Activations (8k' PA) – 12.5Hz refresh rate VSS trip (under g) on test points 1, 2, and 3 during the handback. 6.25Hz refresh rate at 220 KIAS VSS trip (under g) on test point 1 during the handback. Did not complete test points 2-6 with 6.25Hz refresh rate due to fuel limitations. Manual Activations (500' AGL) – Not accomplished due to fuel limitations. NSTR for RTB			
6. RECOMMENDATIONS			
Acquire data.			
COMPLETED BY	SIGNATURE	DATE	
Capt Mike Bakun	e-signed //mab//	13 Sep 18	

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DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE LJ-25	2. SERIAL NUMBER N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO HAVE MEDUSA	B. FLIGHT NO / DATA POINT 6	C. DATE 13 Sep 18	
D. FRONT COCKPIT Crunch/Solo	E. FUEL LOAD 5,600	F. JON	
G. REAR COCKPIT Suplisson/Hex	H. No Fuel Weight 9916	I. WEATHER SKC clm 27 deg	
J. TO TIME / SORTIE TIME 1202/2.1	K. CONFIGURATION / LOADING 001	L. SURFACE CONDITIONS 2283' PA Alt: 29.95	
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A	
4. PURPOSE OF FLIGHT / TEST POINTS Manual/Virtual activations at 15k and 8k. Manual activations at 220 KIAS, virtual activations at 1.5625 Hz.			
5. RESULTS OF TESTS <i>(Continue on reverse if needed)</i> Taxi/takeoff was uneventful All points were completed successfully. This sortie included entering in winds before each test point. 5 VSS trips, all during handback on virtual activations at 270 KIAS, for low g as seen previously. Some turbulence seen near the end of the sortie on the 8k points. A number of very slow handbacks which required the EP to terminate for airspace. One point still showed some gamma hunting, but it was pretty benign.			
6. RECOMMENDATIONS Continue testing, finish manual/virtual activations and start nuisance testing.			
COMPLETED BY Capt Carl Gotwald		SIGNATURE e-signed //cag//	DATE 13 Sep 18

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DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE LJ-25	2. SERIAL NUMBER N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO HAVE MEDUSA	B. FLIGHT NO / DATA POINT 7	C. DATE 14 Sep 18	
D. FRONT COCKPIT Hineline/Hammond	E. FUEL LOAD 5,600	F. JON	
G. REAR COCKPIT Mak	H. No Fuel Weight 9916	I. WEATHER SKC clm 16 deg	
J. TO TIME / SORTIE TIME 0946/1.7	K. CONFIGURATION / LOADING 003	L. SURFACE CONDITIONS 2292' PA Alt: 29.94	
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A	
4. PURPOSE OF FLIGHT / TEST POINTS Virtual activations at 8k for 6.25 Hz. Manual/virtual (12.5Hz) activations at 500' AGL, all airspeeds and attitudes. Lateral offset to actual terrain 500' AGL.			
5. RESULTS OF TESTS (Continue on reverse if needed) Taxi/takeoff was uneventful All points were completed successfully. This sortie included entering in winds before each test point. Wind interface inputs were changed after the previous sortie and went unnoticed for the first 3 virtual activations. This led to unexpected path activation for each IC. After the change was found, all points were reflighted successfully. 5 VSS trips, all during handback on virtual activations at 270 KIAS, for low g as seen previously. A number of very slow handbacks which required the EP to terminate for airspace. The terrain chosen for the lateral offset was the southern ridgeline between Koen and Cuddeback lakes. This terrain was moderately sloping which limited the ability to "walk in" lateral distance for evaluation. Recommend flying the northern portion of the ridge which is steeper and should give more opportunity to decrease offset proportionally. For all points flown near the ridgeline, EP would not have felt comfortable executing a level 60° banked turn. In all cases the RSET never determined path closure which shows promise regarding lack of nuisance alerts.			
6. RECOMMENDATIONS Refly lateral offset on north side of ridgeline.			
COMPLETED BY Capt Mark Hammond		SIGNATURE e-signed //mah//	DATE 17 Sep 18

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DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE LJ-25	2. SERIAL NUMBER N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO HAVE MEDUSA	B. FLIGHT NO / DATA POINT 8	C. DATE 14 Sep 18	
D. FRONT COCKPIT Hineline/Gotwald	E. FUEL LOAD 5,600	F. JON 998TMP00	
G. REAR COCKPIT Kolesar/Gahan	H. No Fuel Weight 9916	I. WEATHER >5500 Winds 070/04 Temp 28	
J. TO TIME / SORTIE TIME 1231/1.8	K. CONFIGURATION / LOADING 001	L. SURFACE CONDITIONS 2320' PA Alt: 29.91	
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A	
4. PURPOSE OF FLIGHT / TEST POINTS Flew manual activations and virtual activations at 500' AGL. Also flew lateral offset to actual terrain at 500' AGL north of Koehn Lake.			
5. RESULTS OF TESTS <i>(Continue on reverse if needed)</i> Taxi/takeoff was uneventful. Manual activation were flown at 500' AGL and 200 KIAS. One g trip was seen during a path 1 handback. Virtual activations were flown at 500' AGL and both 6.25 Hz and 1.5625 Hz. G trips were seen during every handback at 6.25 Hz. One g trip was seen at 270 KIAS. Lateral offsets were flown, and no nuisance was noted. A path 1 closure was seen by flying very close to terrain, well inside both pilots comfort level. Pilots also commented that there were times that they did not think a path 1/5 could be executed but the system did.			
6. RECOMMENDATIONS Finish low level nuisance testing.			
COMPLETED BY Capt Carl Gotwald		SIGNATURE e-signed //cag//	DATE 14 Sep 18

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DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE LJ-25	2. SERIAL NUMBER N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO HAVE MEDUSA	B. FLIGHT NO / DATA POINT 9	C. DATE 17 Sep 18	
D. FRONT COCKPIT Hineline/Bakun	E. FUEL LOAD 5,600	F. JON 998TMP00	
G. REAR COCKPIT Mak/Gotwald	H. No Fuel Weight 9916	I. WEATHER >5500 Winds 210/8 Temp 17C	
J. TO TIME / SORTIE TIME 0946/1.7	K. CONFIGURATION / LOADING 003	L. SURFACE CONDITIONS 2283' PA Alt: 29.95	
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A	
4. PURPOSE OF FLIGHT / TEST POINTS Lateral offset to actual terrain 500' AGL south of Koehn to Cudde airspace. Operational low-level nuisance eval on Sidewinder from points C-E for both pilots. Manual activations at 220/270 KIAS and 500' AGL.			
5. RESULTS OF TESTS (Continue on reverse if needed) Taxi/takeoff was uneventful. Lateral offset to terrain 500' AGL: The terrain chosen for the lateral offset was the southern ridgeline between Koehn and Cuddeback lakes. We completed several 360 degree turns at 60 degrees AOB well above the terrain using ground references for lateral offset estimation. Once comfortable with the turn radius, we stepped down to 500' AGL at the offset where I felt comfortable performing a level 60 degree turn. Path 1 remained open in agreement with our expectations. I decreased lateral spacing to the terrain until I felt I could no longer perform a 60 degree turn without striking terrain. Path 1 again remained open. I was able to get close enough to terrain to see Path 1 close for an extended period of time and Path 2 close intermittently. Operational low-level nuisance eval: Both pilots flew the Sidewinder from points C-E at 500' AGL. Winds were light and no turbulence was noted. There were a few test points between points D-E where the system indicated we could perform a level right turn and avoid terrain; however, the entire crew unanimously disagreed. Recommend thorough analysis of these test points to determine the truth. Manual activations at 220/270 KIAS and 500' AGL: I hopped back in the seat for these test points. We accomplished all five manual activations from straight and level at 220 KIAS and a path 3 activation from 270 KIAS. The paths activated in the sense that we expected. Engine performance was strong down low with slightly cooler temps. Path 5 activation accelerated to 292 KIAS and achieved 2.4g in the pull. NSTR for the remaining test points and RTB.			
6. RECOMMENDATIONS Press			
COMPLETED BY Capt Mike Bakun		SIGNATURE e-signed //mab//	DATE 17 Sep 18

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DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE LJ-25	2. SERIAL NUMBER N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO HAVE MEDUSA	B. FLIGHT NO / DATA POINT 10	C. DATE 18 Sep 18	
D. FRONT COCKPIT Hineline/Hammond/Abel	E. FUEL LOAD 5,600	F. JON 998TMP00	
G. REAR COCKPIT Kolesar	H. No Fuel Weight 9916	I. WEATHER >5500 cfm Temp 12C	
J. TO TIME / SORTIE TIME 0804/1.9	K. CONFIGURATION / LOADING 003	L. SURFACE CONDITIONS 2329' PA Alt: 29.90	
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A	
4. PURPOSE OF FLIGHT / TEST POINTS Lateral offset to actual terrain 500' AGL south of Koehn to Cudde airspace. Operational low-level nuisance eval on Sidewinder from points C-E for both pilots. Manual activations at 270 KIAS and 500' AGL and virtual at 270KIAS.			
5. RESULTS OF TESTS (Continue on reverse if needed) Taxi/takeoff was uneventful. Lateral offset to terrain 500' AGL: The terrain chosen for the lateral offset was the southern ridgeline between Koehn and Cuddeback lakes to mimic previous sorties with other project pilots. We completed several 360 degree turns at 60 degrees AOB well above the terrain using ground references for lateral offset estimation. Once comfortable with the turn radius, we stepped down to 500' AGL at the offset where I felt comfortable performing a level 60 degree turn. Path 1 remained open in agreement with our expectations. I decreased lateral spacing to the terrain until I felt I could no longer perform a 60 degree turn without striking terrain. At my comfort level, the RSET never indicated path closure for an extended period of time Operational low-level nuisance eval: Both pilots flew the Sidewinder from points C-E at 500' AGL. Winds were light and no turbulence was noted. There were a few test points between points D-E where the system indicated we could perform a level right turn and avoid terrain; however, the entire crew unanimously disagreed. During manual/virtual activations at 500' AGL, SPORT called traffic in our vicinity that did not have approval to be there. We took some time getting eyes on them which resulted in some repeat test points lost. LtCol Abel flew all these points with no significant differences noted from previous flights. VSS tripped on both path 1 and 5 handbacks per usual. RTB NSTR			
6. RECOMMENDATIONS Press			
COMPLETED BY Capt Mark Hammond		SIGNATURE e-signed //mah//	DATE 18 Sep 18

TPS Form 5314 NOV 86 NOT REALLY AN OFFICIAL FORM, BUT THIS IS WHAT WILL BE USED AT TPS.

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE LJ-25	2. SERIAL NUMBER N203VS
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO HAVE MEDUSA	B. FLIGHT NO / DATA POINT 11	C. DATE 18 Sep 18	
D. FRONT COCKPIT Hineline/Bakun	E. FUEL LOAD 5,600	F. JON 998TMP0004	
G. REAR COCKPIT Gahan/Suplisson	H. No Fuel Weight 9916	I. WEATHER SKC 200/6 17°C	
J. TO TIME / SORTIE TIME 1207/1.9	K. CONFIGURATION / LOADING	L. SURFACE CONDITIONS 2320' PA Alt: 29.95	
M. CHASE ACFT / SERIAL NO N/A	N. CHASE CREW N/A	O. CHASE TO TIME / SORTIE TIME N/A	
4. PURPOSE OF FLIGHT / TEST POINTS Operational low-level nuisance eval on Sidewinder from points C-E for both pilots. Manual activations at both airspeeds, 5°FPA, 45° bank at 500' AGL and virtual activations at 12.5 Hz for both airspeeds.			
5. RESULTS OF TESTS <i>(Continue on reverse if needed)</i> Taxi/takeoff was uneventful. Operational low-level nuisance eval: I flew the Sidewinder from points C-E at 500' AGL. Winds were light and no turbulence was noted. There were a few test points between points D-E where the system indicated we could perform a level right turn and avoid terrain; however, the entire crew unanimously disagreed. Only during one point along the route did path 2 momentarily close when in proximity to a small mound rising ahead of the mountain terrain. Crew agreed that this closure was appropriate. VSS tripped on both path 1 and 5 handbacks per usual during slow speed activations. RTB NSTR			
6. RECOMMENDATIONS Complete Report			
COMPLETED BY Capt Mike Bakun		SIGNATURE e-signed //mab//	DATE 18 Sep 18

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APPENDIX I – LESSONS LEARNED

While there were many technical and programmatic challenges, the overall perception of how the program went was positive. Still, there were many lessons learned that should be incorporated, or at least addressed, in follow-on and similar programs.

Configuration Management was Essential for Test Effectiveness and Efficiency

There were instances throughout the test program where the improper RSET build was loaded onto the Learjet following code changes. This either resulted in early termination of the sortie (when realized in flight) or data gathered in the incorrect configuration. A list of configuration details and changes is shown in APPENDIX G – MEDUSA CONFIGURATION TRACKER.

The opportunities to load the incorrect build were greater earlier in the fly window when new RSET builds were commonplace. As the fly window progressed, the configuration was finalized and locked down, which resulted in fewer opportunities to load the incorrect build. Follow-on programs should ensure tight configuration management, especially when reliant on contractors or third parties.

Test Conductor Communication Increased Pilot Situational Awareness

The pilots had minimal indications in the cockpit regarding the current state of the RSET. The one display that did show RSET status was located on the center console (between the pilots) and was not viewable during heads-up flying. As such, the pilots relied heavily on the TCs to paint them a picture of what the RSET was currently doing and what was going to be doing in the near future. This awareness allowed pilots to anticipate what was next and keep an efficient airspace plan for subsequent test points. This was primarily achieved with effective TC communication over the aircraft intercom system. Follow-on programs should emphasize additional means (that are readily available while flying) to provide pilots awareness of RSET behavior.

Effect of interpolation on DTED

The interpolation method chosen has a direct impact on the Auto-GCAS terrain miss distance. Using a “nearest” method, such as the one used for the RSET system, is computationally efficient, but does not smoothly transition from one DTED post to another “linear” or “cubic” methods would. Conversely, the nearest method is the only method that always uses truth data, whereas the other method attempt to calculate intermediate terrain heights between posts. Auto-GCAS developers should consider the pros and cons of each approach.

Terrain Safety Buffer Considerations

The terrain safety buffer method used during this test was a simple vertical offset added to the DTED. As can be seen in Figure 56, this method provides a consistent vertical buffer, but does not provide a consistent orthogonal or shortest distance, offset from sloped terrain. In fact, in the case of sheer terrain such as a canyon wall, a vertical offset terrain safety buffer provides no protection laterally. Consideration should be given to other methods of adding a terrain safety buffer to prevent these variations.

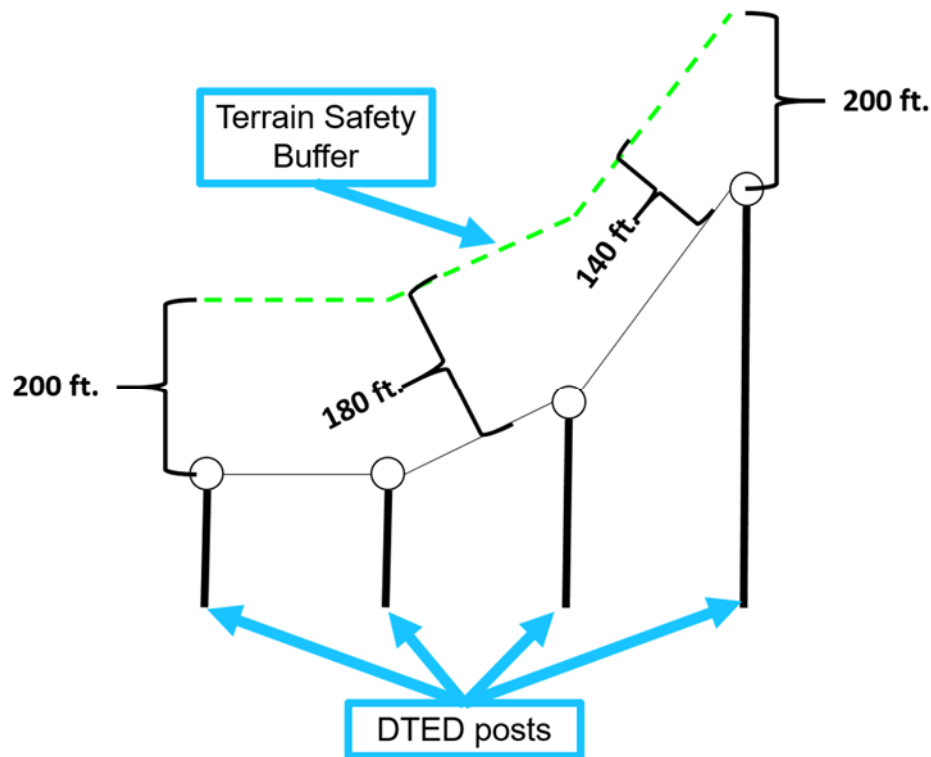


Figure 56 - Effect of Terrain Slope on Vertical Offset Terrain Safety Buffer

Integration issues

As a follow-on program to HAVE ESCAPE, there were no show-stopping integration issues throughout the program. There were myriad instances, though, where the test team expected data to flow from the VSS to the RSET in a certain manner only to find out otherwise later on. APPENDIX G – MEDUSA CONFIGURATION TRACKER contains many of these instances. This occurred well into the test window and resulted in lots of time sunk investigating the issues. This also occurred with specific data parameters. For example, the test team expected to receive certain parameters from the VSS only to find out during integration they were not available or they were in a different format. Having the equivalent of an Interface Control Document (ICD) would have been instrumental in ensuring seamless integration and more effective flight testing. Follow-on programs should ensure sufficient understanding of the system(s) their system under test will interface with.

APPENDIX J – LIST OF ACRONYMS

AFB	Air Force Base
AFIT	Air Force Institute of Technology
AFRL	Air Force Research Laboratory
AGL	Above Ground Level
AOA	Angle of Attack
AOB	Angle of Bank
ATC	Air Traffic Control
ATON	Aid to Navigation
Auto-GCAS	Automatic Ground Collision Avoidance System
BCA	Business Case Analysis
CCS	Center Console System
CFIT	Controlled Flight Into Terrain
COTS	Commercial-Off-The-Shelf
DAP	Data Analysis Plan
DAS	Data Acquisition System
DOF	Degree Of Freedom
DTED	Digital Terrain Elevation Data
EASA	European Aviation Safety Agency
EGI	Embedded GPS/INS
EP	Evaluator Pilot
ESCAPE	Emergency Safe Calculated Autonomous Predetermined Exit
ETO	Executing Test Organization
FAA	Federal Aviation Administration
FPA	Flight Path Angle
FSS	Flight Sciences Simulator
GPWS	Ground Proximity Warning System
Hz	Hertz (Cycle per Second)
IATA	International Air Transportation Association
IMC	Instrument Meteorological Conditions
JON	Job Order Number
KIAS	Knots Indicated Airspeed
LDTO	Lead Developmental Test Organization
LJ-25D	Learjet 25D
LOC-I	Loss of Control-Inflight
MATLAB®	Matrix Laboratory
MCP	Maximum Continuous Power
MEDUSA	Multi-Path Escape Decisions Using Sophisticated Algorithms

MOP	Measure of Performance
MSL	Mean Sea Level
PPE	Path Prediction Error
RSET	Rapidly Selectable Escape Trajectory
RSS	Root Sum Squared
SLUF	Straight and Level Unaccelerated Flight
SP	Safety Pilot
TAWS	Terrain Avoidance Warning System
TC	Test Conductor
TIC	Theil's Inequality Coefficient
TIM	Technical Information Memorandum
TPA	Trajectory Performance Algorithm
TMP	Test Management Project
TPS	Test Pilot School
TSPI	Time, Space, Position Information
UAV	Unmanned Aerial Vehicle
USAF	United States Air Force
VSS	Variable Stability System

APPENDIX K – DIGITAL APPENDIX

Raw flight test data, additional figures, and MATLAB® code used to reduce the flight test data are available by contacting the USAF Test Pilot School. Please see APPENDIX L – TEST LAPTOP SPECIFICATIONS for recommended minimum system specifications for running the RSET system.

The files are held in four folders. Their structure is listed below.

0. RSET System MATLAB Code
 - a. All files needed to run the RSET System
 - b. Primary files is “HaveMEDUSA.slx”
1. Raw Data
 - a. All flight test data gathered from flights 4 - 11
 - b. Data is separated as data gathered from the RSET algorithm and that gathered from the Learjet sensors.
 - c. RSET data: “Flight XX MEDUSA data”
 - d. Learjet data: “Flight XXX VSS data”
2. Data Reduction Scripts
 - a. For calculating PPE: “Manual_path_prediction_error_v6.m”
 - b. For calculating RSS distance from terrain: “closest_point_approach_v9.m”
3. Figures and Plots
 - a. Contains manual and virtual terrain activation figures
 - b. Manual figures: “Flight XX_Man_Act”
 - c. Virtual figures: “Flight XX Virtual Figures”

APPENDIX L – TEST LAPTOP SPECIFICATIONS

Table 11 - Test Laptop Specifications

Model	ASUS ROG G701VI
Operating System	64-Bit Windows 10 Pro
MATLAB Version	R2015B
RAM	32 GB
Processor	Intel Core I7-7820HK, 2.9 GHZ
Graphics	NVIDIA GTX 1080
Microarchitecture	Kaby Lake
Data width	64 bit
Number of cores	4
Number of threads	8
Level 1 cache size	256 KB
Level 2 cache size	1 MB
Level 3 cache size	8 MB

APPENDIX M – HAND-BACK SURVEY

Pt #	Date	Pilot	Alt/Airspeed
Initial Aircraft Control Input: Smooth Abrupt VSS trip? ____ Pulsing Comments:			
Pilot Comments: _____ _____ _____			
Aircraft Control Through Maneuver : Smooth Abrupt VSS trip? ____ Pulsing Comments:			
Pilot Comments: _____ _____ _____			

Did maneuver feel aggressive? Not Aggressive Nominal Slightly Aggressive Aggressive Very Aggressive Pilot Comments: _____ _____	Did pilot think maneuver was necessary to avoid terrain? Yes No Pilot Comments: _____ _____
Was the hand-back logical, safe, smooth, and desirable? Yes No Pilot Comments: _____ _____ _____	

APPENDIX N – AIRCREW COMMENTS

"Felt smooth and safe. Adequate for system maturity."
"Hand-back took a little too long in order to stay smooth. I would probably pickle off and take command earlier to recover faster."
"Higher airspeed hand-back was more aggressive vs lower energy state hand-backs, but not undesirable."
"During low speed points, it's hard to tell if the aircraft is in a hand-back state or attempting a different path. Visual indication of system state would be useful."
"In a non-combat environment this would be totally fine. It gets the aircraft back to a place I feel comfortable taking control."
"The handback may be problematic for spec ops terrain masking missions as the RSET doesn't account for these mission-specific requirements."
"Mission must be accounted for in the hand-back design"
"The stick shaker was a nice way to identify the RSET was controlling the aircraft. Termination of stick shaker made it unambiguous that the handback was complete."
"While slightly too aggressive at times, a hand-back sequence needs to be incorporated."
"Low speed was very smooth."
"Same comments as before"

APPENDIX O – DISTRIBUTION LIST

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