



HAVE DOUBLE VISION

Flight Test Evaluation of Stereo Vision System for Relative Position and Navigation for Automated Aerial Refueling

DAVID T. BAXTER, Maj, USAF
Project Manager

JOSEPH S. HAGGBERG, Capt, USAF
Project Flight Test Engineer

ERIK M. HILLARD, Maj, USAF
Project Test Pilot

AHMET F. KARAKAYA, Maj, TURAF
Project Test Pilot

FRANK J. PANEBIANCO, Maj, USAF
Project Test Pilot

ANDREW K. PETRY, Capt, USAF
Project Flight Test Engineer



JUNE 2019

FINAL TECHNICAL INFORMATION MEMORANDUM

DISTRIBUTION A. Approved for public release; distribution is unlimited.

DISCLAIMER: This report has been prepared in partial fulfillment of the graduation requirements of the Test Pilot School and the award of a Master's Degree in Flight Test Engineering by Air University. While thoroughly reviewed for technical veracity, the analysis, conclusions, and recommendations herein are not endorsed by the 412th Test Wing or the Air Force Test Center. It is intended for the sole use of the sponsoring agency of the report and the Test Pilot School Staff. It is not to be distributed beyond those agencies without the express permission of the Commandant of the Test Pilot School and the appropriate representative of the sponsoring agency.

**USAF TEST PILOT SCHOOL
AIR FORCE TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE**

U
S
A
F

T
P
S

This technical information memorandum (USAF TPS-TIM-18B-03, Have Double Vision) was prepared and submitted under Job Order Number MT18B600 by the Commandant, USAF Test Pilot School, Edwards AFB, California 93523-5000

Prepared by:

BAXTER.DAVID
.T.1270118255
Digitally signed by
BAXTER.DAVID.T.1270118255
Date: 2019.05.28 16:21:09 -07'00'

DAVID T. BAXTER, Maj, USAF
Project Manager
USAF Test Pilot School

HAGGBERG.JOSE
PH.S.1388069020
Digitally signed by
HAGGBERG.JOSEPH.S.138806
9020
Date: 2019.05.28 16:23:05 -07'00'

JOSEPH S. HAGGBERG, Capt, USAF
Project Engineer
USAF Test Pilot School

HILLARD.ERIK
.M.1146760194
Digitally signed by
HILLARD.ERIK.M.1146760194
Date: 2019.05.28 16:24:41 -07'00'

ERIK M. HILLARD, Maj, USAF
Project Pilot
USAF Test Pilot School

KARAKAYA.AHMET
FARUK.1385386024
Digitally signed by
KARAKAYA.AHMET
FARUK.1385386024
Date: 2019.05.29 07:18 :08 -07'00'

AHMET F. KARAKAYA, Maj, TURAF
Project Pilot
USAF Test Pilot School

PANEBIANCO.FRA
NK.JOSEPH.12834
25513
Digitally signed by
PANEBIANCO.FRANK.JOSEPH.
1283425513
Date: 2019.05.28 16:19:43 -07'00'

FRANK J. PANEBIANCO, Maj, USAF
Project Pilot
USAF Test Pilot School

PETRY.ANDREW.
KYLE.1368168960
Digitally signed by
PETRY.ANDREW.KYLE.1368168960
Date: 2019.05.28 16:26:34 -07'00'

ANDREW K. PETRY, Capt, USAF
Project Engineer
USAF Test Pilot School

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

FREEBORN.ANDR
EW.B.1174435606
Digitally signed by
FREEBORN.ANDREW.B.117443
5606
Date: 2019.06.03 12:19:29 -07'00'

ANDREW B. FREEBORN, NH-04, DAF
Staff Advisor
USAF Test Pilot School

COOKSON.JEREMY
.L.1274642188
Digitally signed by
COOKSON.JEREMY.L.1274642188
Date: 2019.06.04 14:25:05 -07'00'

JEREMY L. COOKSON, NH-04, DAF
Flight Test Foundations Technical Expert
USAF Test Pilot School

VANHOY.DAVID.L.
1229799688
Digitally signed by
VANHOY.DAVID.L.1229799688
Date: 2019.06.06 13:54:49 -07'00'

DAVID L. VANHOY, NH-04, DAF
Technical Director
USAF Test Pilot School

BLAKE.RYAN.D.1
129274553
Digitally signed by
BLAKE.RYAN.D.1129274553
Date: 2019.06.07 13:06:27
-07'00'

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

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.					
1. REPORT DATE (DD-MM-YYYY) 03-06-2019		2. REPORT TYPE Final Technical Information Memorandum		3. DATES COVERED (From - Through) 07 March – 18 March 2019	
4. TITLE AND SUBTITLE HAVE DOUBLE VISION Flight Test Evaluation of Stereo Vision System for Relative Position and Navigation for Automated Aerial Refueling				5A. CONTRACT NUMBER	
				5B. GRANT NUMBER	
				5C. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) DAVID T. BAXTER, Maj, USAF JOSEPH S. HAGGBERG, Capt, USAF ERIK M HILLARD, Maj, USAF AHMET F. KARAKAYA, Maj, TURAF FRANK J. PANEBIANCO, Maj, USAF ANDREW K. PETRY, Capt, USAF				5D. PROJECT NUMBER MT18B600	
				5E. TASK NUMBER	
				5F. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Test Center 412 th Test Wing USAF Test Pilot School Edwards AFB CA 93524-6485				8. PERFORMING ORGANIZATION REPORT NUMBER USAF TPS-TIM-18B-03	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Control Systems Branch AFRL/RQQC 2210 Eighth Street, Wright Patterson AFB, OH 45324				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release: distribution unlimited. Other requests for this document shall be referred to: Air Force Institute of Technology, 2950 Hobson Way, Wright-Patterson AFB, OH 45324.					
13. SUPPLEMENTARY NOTES SC: 012100 CA: 412th Test Wing Edwards AFB CA Print this document in COLOR .					
14. ABSTRACT This report documents the results of the Have Double Vision Test Management Project. Testing was requested by the USAF Test Pilot School, Edwards AFB, California. The lead developmental test organization was the Air Force Test Center, Edwards AFB, California. The executing test organization was the 412th Test Wing/USAF TPS, Edwards AFB. Testing was conducted from 7 to 18 March 2019 and comprised 9 test missions totaling 19 sorties and 35.4 flying hours. The overall test objective was to assess the performance of a stereo vision relative position and attitude estimating system for automated aerial refueling and collect an inflight dataset for further research and development. All test objectives were met.					
15. SUBJECT TERMS Stereo Vision, Vision Algorithm, Relative Position Algorithm, Automated Aerial Refueling, Pixel Matching, Relative Pose Estimation with Computer Vision and Iterative Closest Point, Point Cloud. Double Vision System.					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report	18. NUMBER OF PAGES 191	19A. NAME OF RESPONSIBLE PERSON USAF Test Pilot School
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19B. TELEPHONE NUMBER (INCLUDE AREA CODE) (661) 277-3000

This page was intentionally left blank.

EXECUTIVE SUMMARY

This report presents the results of the Have Double Vision Test Management Project (TMP). This was a continuation of the Have Vision TMP completed in 2017. The overall test objective was to assess the performance of a stereo vision relative position and attitude estimating system for automated aerial refueling and collect an inflight dataset for further research and development. This objective was accomplished by modifying a C-12 with a stereo vision system to fly as a simulated (pseudo) tanker in an aerial refueling formation with another C-12 or T-38 which acted as a pseudo receiver. Testing included obtaining time-stamped electro-optical (EO) and infrared (IR) stereo camera images and relative position truth data sets. These data sets were processed using an algorithm developed at the Air Force Institute of Technology (AFIT). This algorithm, called Iterative Closest Point (ICP), used stereo imaging to create a 3-dimensional point cloud of a trailing aircraft. This point cloud was filtered and compared to a model of the aircraft to determine relative position and attitude. The stereo vision system was the primary system under test. The intended future application of this technology includes automated aerial refueling of unmanned receivers. In addition, this research can be applied to currently fielded aircraft with stereo vision systems.

Testing was conducted at Edwards AFB, California, by USAF Test Pilot School (TPS) Class 18B working in partnership with AFIT and Air Force Research Laboratory (AFRL). The Air Force Test Center (AFTC) was the Lead Developmental Test Organization. Flight tests were conducted from 7 to 18 March in the R-2508 complex and surrounding airspace. Testing consisted of 9 test missions totaling 19 sorties and 35.4 flying hours in two C-12Cs, tail numbers 76-00158 (pseudo-tanker with stereo vision system) and 76-00161 (pseudo-receiver), and one T-38, tail number 64-13189 (pseudo-receiver).

For the data collection objective, the Double Vision Team collected 436,608 EO image pairs and 206,735 IR image pairs, totaling 3.85 terabytes of data to support further research. The EO and IR images feature both C-12C and T-38C pseudo-receivers over desert, mountainous, urban, water and cloud covered backgrounds with altitudes varying from 5,000 to 25,000 feet. This image dataset paired with the high quality GPS generated truth data could be utilized to develop and refine future stereo imaging algorithms.

The Have Double Vision team analyzed 369 independent image pairs of a C-12C in the contact position to statistically assess the precision and accuracy of the stereo vision system. The ICP algorithm generated a relative position and attitude estimate of the pseudo-receiver. Comparing the ICP output with Geodetics RelNav truth data revealed a significant translational accuracy error bias of 4.3 meters on average in radial magnitude. This bias was consistent for specific data sets (different flights with same background & altitude) but varied when the background, altitude, or sun angle changed. Translational precision was consistently within 0.164 meters or less of the RelNav solution. Rotational accuracy with EO was found to be on average 1.26 degrees off in pitch and roll, but up to 8.14 degrees off in yaw. The ICP algorithm showed promise, but the test team had three recommendations for future development. First, the bias needs to be corrected. Second, noise in the ICP relative position and orientation needs to be reduced or eliminated to stop the aircraft from “jumping” for multiple frames. Finally, the C-12C model utilized by the ICP algorithm needs refinement.

In its current stage of development, the vision system did not demonstrate satisfactory operational military utility without further development. This was expected given that the ICP algorithm was designed for research and development and not military utilization. Calibration error was significant with a standard deviation of 1.7 meters when a calibration was not accomplished on the same day. Error was even observed to be sensitive to calibrations conducted on the same day just four hours apart, with an average measured error magnitude of 8.7 cm. The test team believed that calibrating prior to every sortie would be unrealistic in an operational environment. The test team also determined that ICP estimated RMS error was not currently a suitable tool for intrinsic performance determination. For airborne system operation, the EO and IR camera streams and ICP point cloud had no discernable latency. However, the ICP point cloud refresh rate varied between 0.5-1.5 seconds. This low refresh rate would be inadequate for automated aerial refueling applications. Improving the processing speed of the Have Vision system would be required for satisfactory operational utility.

This page was intentionally left blank.

TABLE OF CONTENTS

Executive Summary	iv
Introduction.....	1
Background	1
Test Item Description.....	2
Test and Evaluation.....	6
Overall Test Objective	6
Limitations and Constraints	6
Calibrated Time Stamped Imagery	7
ICP Accuracy and Precision	10
Translational Accuracy:	10
Rotational Accuracy:.....	14
Translational Precision.....	15
Rotational Precision:	17
Military Utility for Aerial Refueling.....	18
Calibration Sensitivity	18
Airborne System Operation	22
System Processing Time	23
ICP Reported RMS Accuracy	24
Test Results Summary	28
References.....	29
Appendix A – Detailed Test Item Description.....	A1
Appendix B – Abbreviations, Acronyms, and Symbols	B1
Appendix C – Rating Criteria	C1
Appendix D - Test Execution	D1
Appendix E: Formation Position Reference Slides.....	E1
Appendix F – ICP Performance Statistical Analysis	F1
Appendix G – Data Analysis Plan	G1
Appendix H – Coordinate Frames	H1
Appendix I – Supplemental Data	I1
Appendix J - Geodetics RelNav and GLite TSPI Comparison	J1
Appendix K – Lessons learned	K1

Appendix L – Double Vision Questionnaire.....	L1
Appendix M – Equipment Specification Sheets	M1
Appendix N – TSPI Parameter List	N1
Appendix O– Daily Flight Reports	O1
Appendix P– Recommendations for Future Research	P1
Appendix Q– Customer Error Correction	Q1
Appendix R– Distribution List.....	R1

LIST OF FIGURES

Figure 1: Hypothetical Automated Aerial Refueling System Block Diagram.....	2
Figure 2: Stereo Camera Location and Field of View on Pseudo-Tanker Aircraft.....	3
Figure 3: EO and IR Cameras, Mounted on C-12C Pseudo-Tanker Aircraft	3
Figure 4: Block Diagram of Have Vision System Hardware and Software.....	4
Figure 5: Strobe Light Flash Guard Visual Reference.....	7
Figure 6: Background Terrain Features and Altitude Blocks	8
Figure 7: Simplified Center of Mass Shift due to Visible Mass, Side View.....	13
Figure 8: Screenshot of In-flight ICP program (Recreated Post Flight)	13
Figure 9: Camera Exposure Setting Differences from 15,000 μ s to 5,000 μ s	13
Figure 10: EO Camera Calibration Board (Left) and IR Camera Calibration Board (Right)	19
Figure 11: Screenshot of In-flight ICP program with descriptions (Recreated Post Flight).....	23
Figure 12: EO Slant Range Error and RMS, Flight 7	26
Figure 13: Image Pair with High and Low RMS error showing similar L/R Asymmetry	27

LIST OF TABLES

.....	Table 1: Aerial Refueling Maneuver Blocks	8
Table 2: Calibrated Time Stamped Imagery Results		9
Table 3: Independent Samples Collected.....		10
Table 4: EO Translational Accuracy Statistical Results		11
Table 5: IR Translational Accuracy Initial Results.....		12
Table 6: EO Rotational Accuracy Results		14
Table 7: IR Rotational Accuracy Results.....		15
Table 8: EO Translational Precision Results		16
Table 9: IR Translational Precision Results.....		16
Table 10: EO Rotational Precision Results.....		17
Table 11: IR Rotational Precision Results		18
Table 12: Calibration Average Pixel Error		20
Table 13: EO Calibration Error from Flight 6		21
Table 14: IR Calibration Error from Flight 6.....		21
Table 15: Flight 7 Pre and Post flight Calibration Change		21
Table 16: Post Processing Time for ICP and NRT ICP Variant		24
Table 17: RMS Sample Runs.....		25
Table 18: Overall Have Double Vision Test Results		28

This page was intentionally left blank.

INTRODUCTION

This report presents the results of the Have Double Vision test management project (TMP). The lead developmental test organization was the Air Force Test Center (AFTC), Edwards AFB, California. The executing test organization was Class 18B of the USAF Test Pilot School (TPS) working in partnership with the Air Force Institute of Technology (AFIT) and Air Force Research Laboratory, Aerospace Systems Directorate, Control Systems Branch (AFRL/RQQC), Wright-Patterson AFB, Ohio. Testing was conducted by the Have Double Vision Test Team IAW the Have Double Vision test plan (USAFTPS-TP-18B-03) under Job Order Number (JON) MT18B600. Testing was conducted at Edwards AFB from 07 March 2019 to 18 March 2019 and comprised of 9 missions comprised of and 19 sorties totaling 35.4 flight test hours.

BACKGROUND

The Have Double Vision TMP and the associated research ongoing at AFIT and AFRL sought to demonstrate the feasibility of using computer vision algorithms to provide and/or augment a robust relative navigation capability. This is a continuation of the Have Vision TMP completed in 2017. The key features of a vision-based relative navigation system include (1) the system is passive, (2) the system is not reliant on the GPS constellation, and (3) the system could be deliberately designed to leverage existing DoD sensor system.

More specifically, the Have Double Vision TMP assessed the performance of a vision-based relative navigation system that was developed for applications in automated aerial refueling (AAR). The ability to refuel unmanned aerial vehicles (UAVs) would enable the fielding of more capable UAV systems and would provide valuable support during contested, degraded operations (CDO). Research has been conducted into automated aerial refueling and relative navigation algorithms, however most of these systems rely on emitting sensors and/or the GPS constellation. By contrast, vision-based relative navigation systems are passive and have no reliance upon the GPS constellation. As such, it is potentially well-suited for use in GPS denied and CDO environments. This TMP assessed the performance of one promising solution developed by AFIT and AFRL.

The key functions of a hypothetical vision-based automated aerial refueling system are depicted in Figure 1 below. The Have Double Vision TMP assessed a subset of the overall system depicted. Image pairs were captured with EO and IR cameras and processed to obtain a relative navigation state estimate with an associated uncertainty. This state would be fused with measurements from other systems, such as inertial measurement units (IMUs), in a Kalman filter to obtain an updated relative navigation state estimate. This estimate could then be fed into the formation control laws for either or both aircraft, which ultimately results in a new relative state between the tanker and UAV. These relevant components are boxed in red in Figure 1 for emphasis.

The EO/IR stereo vision camera system was similar to other fielded EO/IR stereo vision systems currently in use (i.e. KC-30, KC-46). With this configuration installed, the modified C-12C flew maneuvers typical of a tanker while the cameras captured images of a second aircraft flying maneuvers typical of an AR receiver. Obtaining a data set suitable for research and development of vision-based algorithms was a sought after tool to evaluate algorithms without laboratory for flight testing.

Have Vision's 2017 TMP (reference 12) conducted previous testing of two algorithms, the Relative Pose Estimation with Computer Vision and Iterative Closest Point (R7) and Vision and Bayesian Inference Based Integrity Monitor (V5). These had both provided promise in laboratory development. They reported the R7 algorithm was a good candidate for further development due to higher precision in measurements. The found a 3.19 meter translational bias from GLite TSPI truth source with a 0.99 meter standard deviation. The angular accuracy also needed improvement. Have Vision reported a high degree

of pitch bias up to 15° with a high level of variance. The other advantage to the R7 algorithm was a faster processing time than the V5. This made the R7 a better candidate for real time processing in an airborne system. The R7 algorithm continued development at AFIT and became the Iterative Closest Point (ICP) algorithm used in Have Double Vision. The new system included more robust hardware safeguards and data collection and management practices.

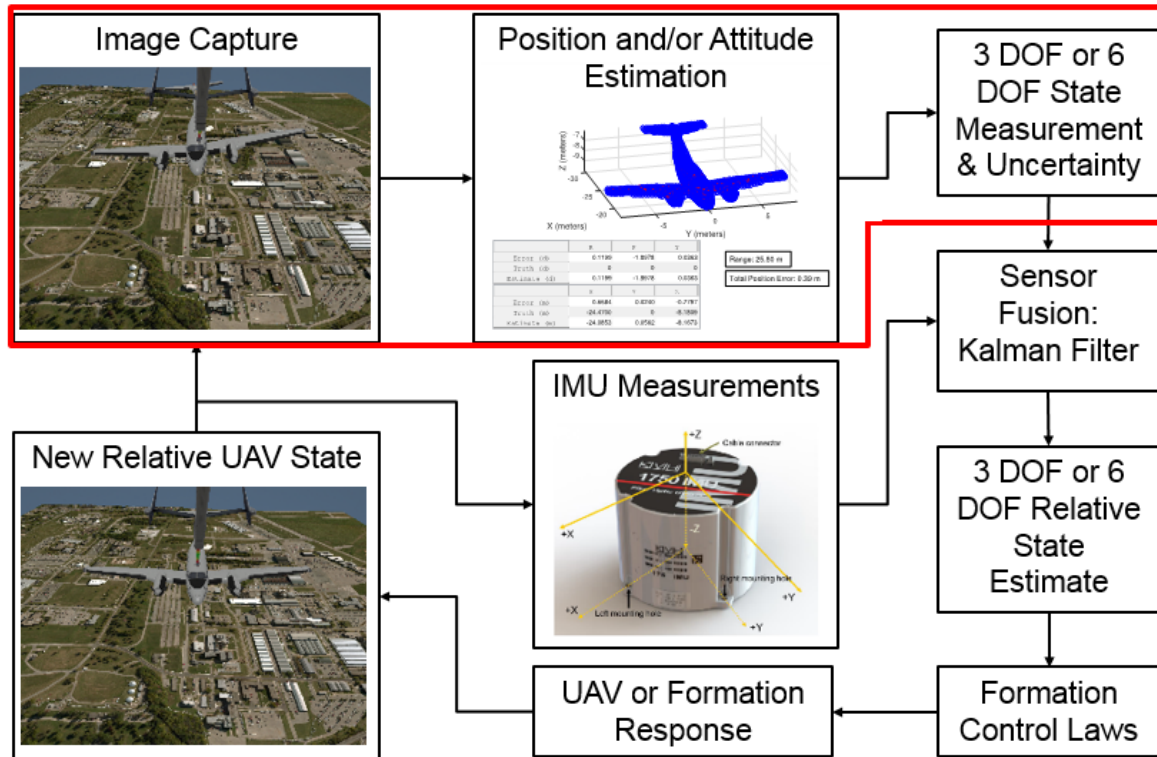


Figure 1: Hypothetical Automated Aerial Refueling System Block Diagram

TEST ITEM DESCRIPTION

The system under test was the Have Double Vision stereo vision system. This included two stereo camera pairs—a long-wave infrared (LWIR) stereo camera pair and an electro-optical (EO) stereo camera pair, each mounted on a lateral support on the belly of the aircraft (Figure 2). Additionally the stereo vision system included a data collection and processing computer which recorded images captured from the cameras and ran the ICP algorithm. The cameras within a stereo pair were separated by 0.5 m and were oriented such that they looked aft of the aircraft at a 25° down look angle. This configuration approximated the configuration used on other platforms using stereo vision systems, with the cameras mounted approximately two feet forward of the simulated boom attachment point, as illustrated in Figure 2. The cameras and the associated mount are shown in Figure 3.

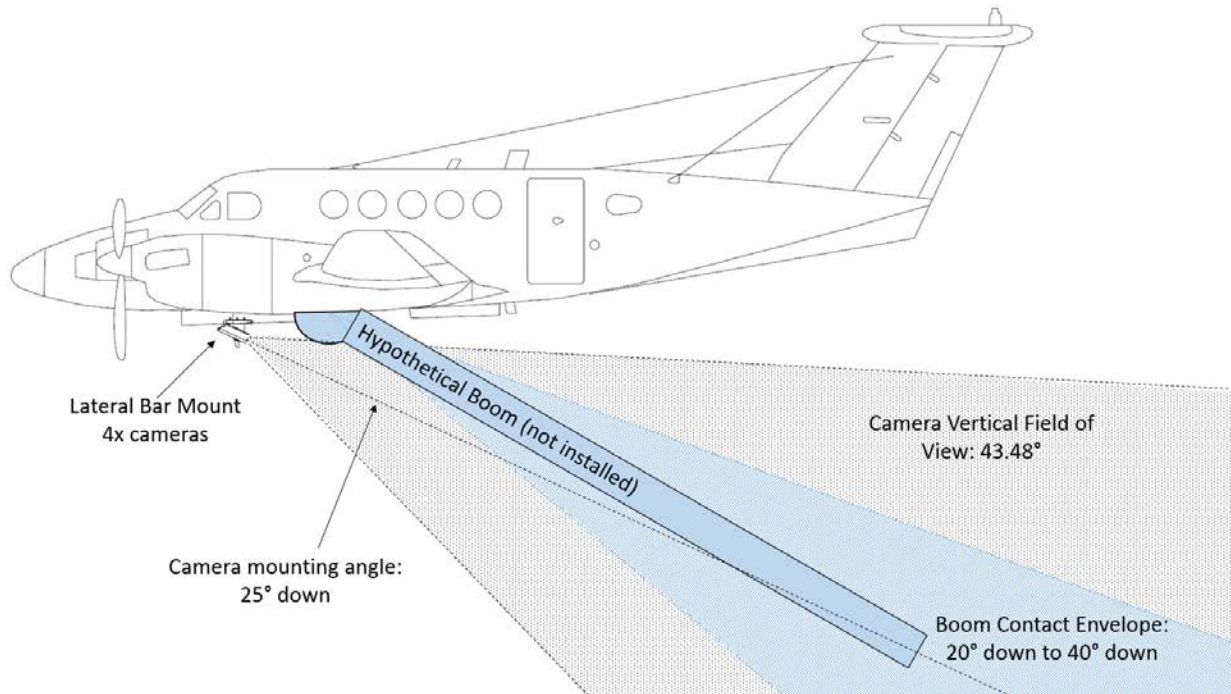


Figure 2: Stereo Camera Location and Field of View on Pseudo-Tanker Aircraft

IR Cameras

The IR cameras were Atom™ 1024G models with a 16.4 millimeter fixed focus lens and a Gigabit Ethernet (GigE) interface produced by Sofradir. These cameras operated in the 8 to 14 micron spectral range and produced images at 30 Hz, 1294 x 768 pixels, with a 56.0° horizontal Field of View (FOV) and 43.5° vertical FOV. Consult Appendix M for more information.

EO Cameras

The EO cameras were Prosilica GT1290Cs models with a Kowa 4.4 millimeter fixed focus lens and a GigE interface produced by Allied Vision. These cameras operated in the 400 to 700 nanometer spectral range and produced images at 30 Hz which were 1280 x 960 pixels in size with a 55.5° horizontal FOV and a 43.0° vertical FOV. Consult Appendix M for more information.

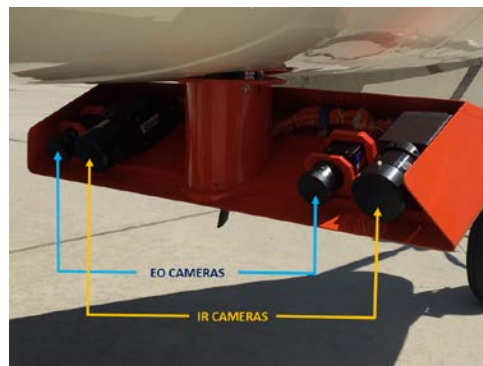


Figure 3: EO and IR Cameras, Mounted on C-12C Pseudo-Tanker Aircraft

Data Acquisition Computer

The shutters on the EO and IR cameras were triggered at a rate of 30 Hz by the data acquisition computer. The data acquisition computer, including applicable software, was built by Dr. Scott Nykl of AFIT. The computer had the capability to store about 2 hours of flight test data. After the data acquisition computer triggered the cameras, the cameras captured images and sent these images back to the computer for storage. An operator on board the aircraft accessed the data acquisition computer and chose between recording and non-recording modes. Additionally, the operator had real time access to images from all four cameras. After images reached the computer, the computer applied a time stamp to each image. The time stamp was referenced to the computer clock that was synced to the GPS constellation. These images were fed to the ICP algorithm in flight and analyzed with truth data post-flight. During flight the relative position estimation was displayed to the operator at real time. The hardware and software components of the Have Double Vision system are depicted in block diagram form in Figure 4. Computer specifications can be found in Appendix M.

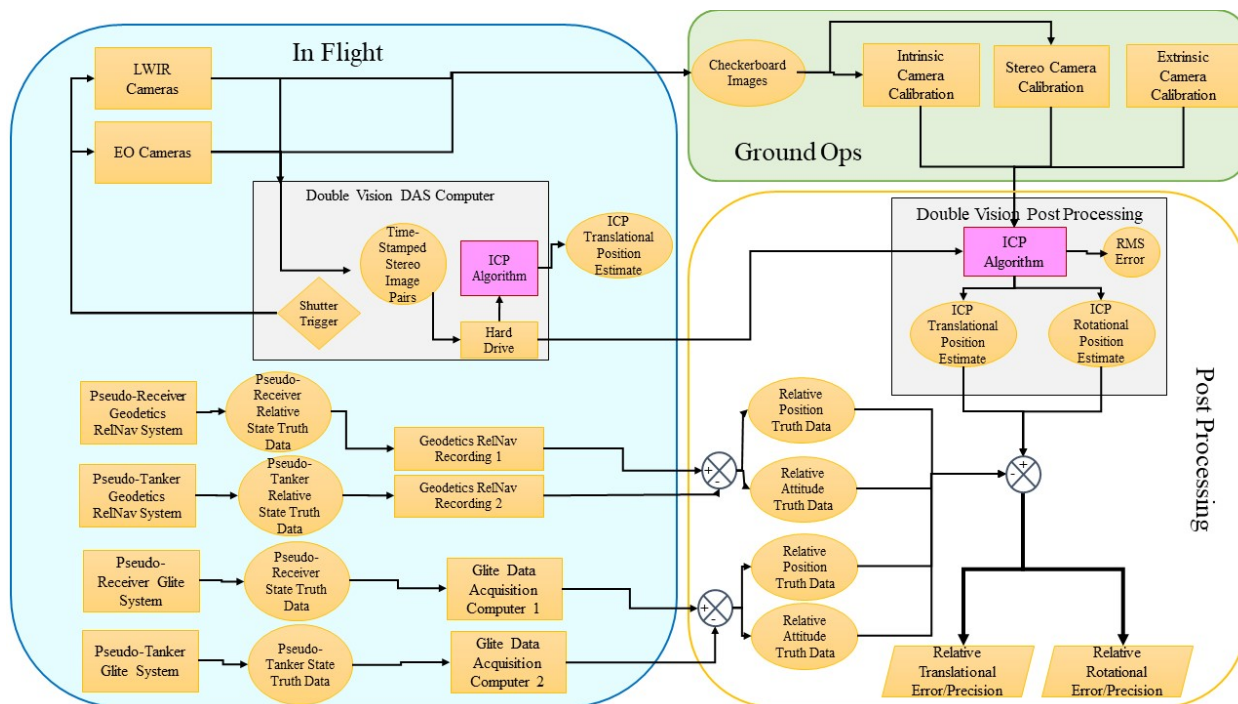


Figure 4: Block Diagram of Have Vision System Hardware and Software

Test Aircraft

The test required flying two aircraft in relative positions similar to those used during AR. The pseudo-tanker aircraft was a uniquely-modified C-12C (tail number 76-00158) that contained the Have Double Vision stereo vision system and both position truth data systems. The pseudo-tanker served as the lead aircraft in the simulated aerial refueling formation. The pseudo-receiver aircraft was either a C-12C (tail number 76-00161) or T-38C (tail number 64-10403) that contained either one or both of the position truth data systems. The pseudo-receivers served as the trail aircraft in the simulated aerial refueling formation.

Have Vision's 2017 TMP (reference 12) also identified degraded flight characteristics with the camera mount and therefore recommended safety margins at high and low speeds in the flight envelope, which were adhered to during this test. For the pseudo-tanker with the stereo vision system mount, indicated airspeed was limited to 230 KIAS below 10K feet PA. Standard aircraft limits applied (259

KIAS) above 10K feet PA. Additionally the pseudo-tanker takeoff and landing speeds were increased by 3 knots when gross weights exceeded 11,500 lb.

ICP Algorithm

From the perspective of the Have Double Vision test team, the ICP algorithm functioned as a software-fixed system under test. Algorithm development and modification was accomplished at AFIT. A full description of the ICP algorithm can be found in Appendix A. A brief description of the ICP follows.

The time-stamped stereo images, intrinsic camera calibration results, stereo camera calibration results, and extrinsic camera calibration results serve as the inputs to the ICP algorithm. Using the camera calibration and each pair of images (EO and IR work independently) the algorithm transformed the stereo images into a set of three-dimensional points called a point cloud. By comparing the observed point cloud to a model point cloud, the ICP algorithm generated a relative position and attitude estimate of the pseudo-receiver in the pseudo-tanker body frame. The algorithm could also be configured to return these estimates in a user-specified camera frame. In addition, the ICP algorithm aggregated raw RelNav truth data, applied GPS time stamp matching, and output relative truth position in a user-specified reference frame. For this test, the left camera frame was used as the primary frame of reference for all position estimation. See Appendix H for the coordinate frames used in Have Double Vision.

Calibrations

Multiple calibrations were performed to correct various camera errors. Intrinsic camera calibrations were performed individually on each camera to determine camera distortion parameters and correction matrices. This was accomplished by capturing still images of a checkerboard of precisely known dimensions and processing them through the Stereo Camera Calibration Toolbox for MATLAB® (Reference 5). Stereo camera calibrations were performed on each camera pair (EO and IR) to determine relative position and orientation of the two cameras in each pair. This was also accomplished using the Stereo Camera Calibration Toolbox for MATLAB® using image pairs collected at the same instant. Extrinsic calibrations were performed by boresight measurements on all critical components to determine precise relative position and orientation. This was accomplished by the USAF TPS instrumentation team using a 7-axis FaroArm articulating measuring arm. These measurements enabled the relative positions and/or attitudes estimated by the ICP algorithm to be compared to the returns from the truth data systems.

Truth Data Systems

The relative position and attitude estimates returned by the ICP algorithm were compared against truth data to characterize its performance. Two sources of truth data were used to ensure redundancy. First, a Geodetics RelNav system was installed on both C-12C aircraft. The RelNav system provided a GPS time-stamped measurement of the relative position and attitude of the pseudo-receiver in the pseudo-tanker body frame. This system was advertised to produce relative position and attitude measurement uncertainties of up to 2 cm and 0.02°, respectively. Second, a GLite TSPI system was installed on the pseudo-tanker and pseudo-receiver aircraft (C-12C and T-38C). This system was capable of returning GPS time-stamped absolute position and attitude measurements of the pseudo-tanker and pseudo-receivers. This system was rated by the 412 Range Squadron (RANS) to produce position and attitude measurement uncertainties of up to 20 cm and 0.05°, respectively. The GLite TSPI system on the C-12C returned position and attitude measurements. However, the GLite TSPI system on the T-38C only returned absolute position measurements. Ultimately, the collected truth data was used to process the data into a relative position error vector and relative attitude error vector. These vectors were computed by subtracting truth data system measurements from algorithm estimates.

TEST AND EVALUATION

OVERALL TEST OBJECTIVE

The overall objective of this project was to assess the performance of a stereo vision relative position and attitude estimating system for automated aerial refueling and collect an inflight dataset for further research and development. The overall test objective was met. A calibrated time stamped imagery dataset was collected with Geodetics RelNav and GLite TSPI truth data sources to support future stereo vision system development. The performance of the Have Double Vision stereo vision system was assessed using the system reported accuracy and precision for both translational and rotational relative position between the pseudo-tanker and pseudo-receiver. Military utility was assessed by determining the calibration sensitivity, airborne system operation, system post processing time, and ICP reported RMS error.

Overall, the error of the system, as well as the unexpected effect of different altitudes and backgrounds resulted in deficient system performance and an overall unsatisfactory rating. The system demonstrated problems in some areas that would negatively affect the military utility such as high sensitivity to calibrations, and an insufficient refresh rate for relative position estimation.

LIMITATIONS AND CONSTRAINTS

There was one limitation affecting ICP accuracy and precision. The truth data output by the ICP algorithm during post processing was expected to be referenced using the left camera reference frame, however an error in the ICP algorithm caused the reporting of data in a different reference frame than expected. All data processing and analysis was accomplished with the assumption that the truth data was reported in reference to the left camera frame. Two weeks prior to report publishing, the customer discovered that the RelNav truth data was not reported in the correct reference frame. This error, as well as the late discovery, prevented reference frame corrections to be made to the analysis in full. A sample of the data was reprocessed with the appropriate reference frame corrections to the ICP algorithm. Details of this evaluation can be seen in Appendix Q.

There were two constraints during the test. First, the IR cameras did not consistently function on the ground or in the air. IR images were collected on flight 1, 5, 6, and 9. All other flights had an IR system failure. The test was delayed by several days while repairs were attempted, however the nature of the malfunction made a permanent fix impractical within the test window. The final determination of the cause of the problem was a very thin wire in the IR camera cable connection having a poor connection to the trigger box due to a poor splice. This connection was repaired on several occasions but not in time to collect a full set of images required for the IR statistical analysis.

Second, the primary visual formation position reference identified during the initial flight was unavailable after flight 4. During flight 4, the strobe light glare shield on the bottom of the aircraft was damaged. Figure 5 shows the location of the damaged visual reference. Detailed descriptions of all other in-flight visual references that were used are located in Appendix E. Since the strobe light glare shield was partially hanging and the risk of it separating from the aircraft existed, the flight 4 mission was terminated. The cause of the damage was either a fatigued strobe light glare shield or the increased turbulent flow due to the camera system which was mounted forward of the strobe light glare shield. The removal of the strobe light glare shield after the flight resulted in less consistency in the contact position during the remaining flights.



Figure 5: Strobe Light Flash Guard Visual Reference

CALBRATED TIME STAMPED IMAGERY

The specific test objective was to collect calibrated time-stamped stereo imagery and formation relative position and attitude truth data in varying environmental conditions.

Test Methods and Conditions:

Two aircraft were flown in close formation with the trailing aircraft flying simulated air refueling maneuvers. This was accomplished over various terrain features at low and high altitude blocks and in varying environmental conditions that caused camera washout, receiver shadowing, glint errors, as well as several other optical challenges. The altitude blocks and background terrain features were defined in Figure 6. The altitude data band was ± 2000 feet. The T-38 mountain high block images were not collected at the stated altitude as a slight descent during a toboggan maneuver was required in order to remain above minimum T-38 airspeed limits. This maneuver began at up to 23,000 feet and was completed by 18,000 feet PA. A sampling of combinations of the following desired variables were conducted:

1. Relative maneuvers:
 - a. Stable astern position
 - b. Closure from astern to contact
 - c. Stable contact position
 - d. Varying contact position (bobble)
 - e. Left/Right contact envelope movement
 - f. Breakaway (high rate separation)
2. Formation maneuvers:
 - a. Straight and level flight
 - b. 20 degree banked level turn
3. Background terrain features:
 - a. Urban
 - b. Desert
 - c. Mountain
 - d. Oceanic
 - e. Clouds

Table 1: Aerial Refueling Maneuver Blocks

Full Maneuver Block	Abbreviated Maneuver Block	Modified Abbreviated Maneuver Block
Stable Astern	Stable Astern	Stable Astern
Closure to Contact	Closure to Contact	Closure to Contact
Stable Contact	Stable Contact	Bobble in Contact
Stabilized 20° Banked Turn	--	Breakaway (High Rate)
Left/Right Contact Limits	--	--
Breakaway (High Rate)	--	--

Table 1 shows a description of the maneuver block terminology used in the test matrix. On several occasions turbulence prevented a full maneuver block from being completed and an abbreviated maneuver block was collected.

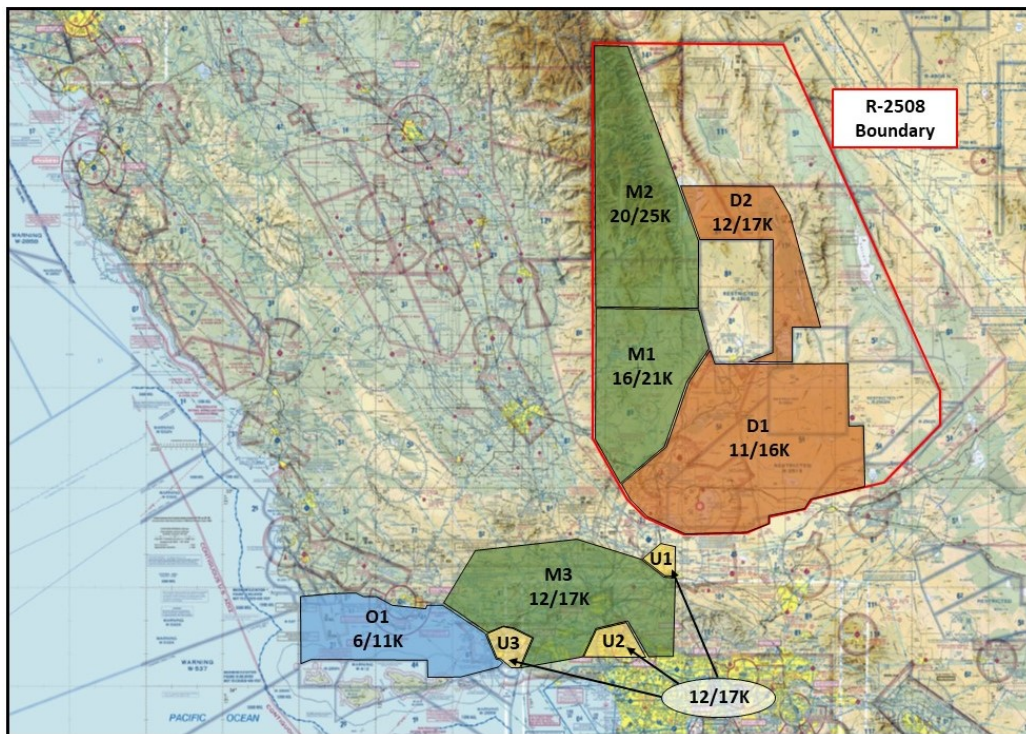


Figure 6: Background Terrain Features and Altitude Blocks

The stereo vision system in the lead aircraft recorded image pairs of the trailing aircraft. The cameras operated at 30 Hz and saved images at 10 Hz. GPS receivers on both aircraft recorded position and attitude for post processing of relative position. Both TSPI and Geodetics RelNav were successfully recorded for all flights.

Test Results

The objective to collect calibrated time stamped data was met. Overall 9 mission were conducted using C-12 and T-38 pseudo-receiver targets. Table 2 shows conditions where data were collected. For a satisfactory collection (green background) the pseudo-receiver completed the full maneuver block at least once at that a specific collection condition. Yellow was given to abbreviated maneuver blocks. T-38 images were only collected with desert and mountain backgrounds at high and low altitude. Images were captured and cataloged for each flight and the system operator notes were included as a reference with

time and image number for each flight. These logs, referenced in Appendix O, contain notes for maneuver start times, as well as unusual features exhibited in the images (such as shadows or glare) as well as unusual events in the real time ICP point cloud. Geodetics RelNav and GLite TSPI materials have also been cataloged by flight number. These materials have been delivered to AFIT for further research and development. The volume of data collected is also displayed in Table 2.

Table 2: Calibrated Time Stamped Imagery Results

Background	Altitude	Maneuver Block EO	Maneuver Block IR
Desert	Low (L) D1: 11K±2K D2: 12K±2K"	Full (C-12 and T-38)	Full (C-12 and T-38)
	High (H) D1: 16K±2K D2: 17K±2K	Full (C-12 and T-38)	Full (C-12 and T-38)
Mountainous	Low (L) M1: 16K±2K M2: 20K±2K M3: 12K±2K	Full (C-12 and T-38)	Full (C-12 and T-38)
	High (H) M1: 21K±2K M2: 25K±2K M3: 17K±2K	Full (C-12 and T-38)	Full (C-12 and T-38)
Urban	Low (L) U1-3: 12K±2K	Full	Full
	High (H) U1-3: 17K±2K	Full	Full
Oceanic	Low (L) 01: 6K±2K	Full	Full
	High (H) 01: 11K±2K	Full	Full
Clouds	Above	Full	Abbreviated
	Below	Full	Abbreviated
Total Images	Total Memory (GB)	EO Pairs	IR Pairs
1,459,968	3,853	436,608	206,735

Images were also collected with snow in the background as well as transitions from different backgrounds. Additionally after experiencing camera washout from clouds and snow, images were also collected with various exposure settings that affected the brightness of the image. After flight 1, EO images were analyzed for the brightness level of the maximum value of the white pixels. When all white areas on the wing of the C-12 were the maximum value of white, minimal detail was visible along the wing. This effect was identified as a possible source of error. After demonstrating exposure setting configuration change on the ground, subsequent flights captured images at a shorter exposure setting to collect images where a gradient of white values along the wing produced more detail in the aircraft in the image. A limited set of sample images were collected at varying exposure settings (with a modified abbreviated maneuver block) until the image was too dark to visually see an aircraft. Images were collected at 15,000 μ s (default), and 10,000 μ s through 1,000 μ s at intervals of every 1,000 μ s. These

appeared to have a positive impact on ICP inflight performance but additional analysis will have to be completed in the future.

ICP ACCURACY AND PRECISION

The specific test objective was to assess the precision and accuracy of the stereo vision relative position and attitude estimating system. The translational and rotational accuracy and precision were compared using the Geodetics RelNav truth source data.

Test Methods and Conditions:

The translational accuracy was measured as the difference in X, Y, Z and R (slant range) compared to the Geodetics RelNav X, Y, Z, and R in the left camera reference frame. The RelNav distance was measured in the RelNav from IMU to IMU for each aircraft and corrected to the left camera frame for the tanker. The ICP algorithm estimated the distance from the left camera frame to the center of mass of the red reference model on the receiver. The test determined whether the accuracy was less than the size of a notional boom envelope (from the KC-10, see appendix D for more information). This was calculated by $X_{\text{Error}} = X_{\text{ICP}} - X_{\text{RelNav}}$. The evaluation criteria are shown with the test results in Table 4 and 5. The overall accuracy was calculated by compiling several repetitions of stabilized flight in the contact window. Once the pilot called stable in the contact position, the test team ensured at least 100 data points were collected (10 seconds of 10 Hz data) during each contact maneuver. These 100 samples were analyzed to determine if more than one independent point could be obtained from each test point. After flight the temporal correlation was determined using the TPS statistics MATLAB toolbox v3.181 to determine how many independent samples could be obtained. Subsequent samples were obtained from the full and abbreviated maneuver blocks with each maneuver beginning from the astern position. To understand what effects the background had on the translational accuracy, the test points used in this analysis were mountain high, mountain low, desert high, and desert low. Other environments were not evaluated.

Translational Accuracy:

Test Results:

The EO translational accuracy was unsatisfactory. The mean accuracy exceeded the notional boom envelope criteria in X and Z, and was marginal in Y. Initial IR translation accuracy appears to be unsatisfactory but cannot be statistically confirmed due to too few samples collected. Statistical confidence is lower due to few independent samples available in the mountain high and low conditions. Based on the samples collected, the 95% confidence interval has a power level of 29% with the mountain low and high conditions. A minimum of 20 samples was required to meet the desired power level of 80%.

Independent samples were obtained as stated using a 10 second contact windows. Post flight analysis using the TPS Statistics toolbox concluded that a single 10 second stabilized window could produce 3 independent samples using the EO or IR images. Further information regarding the correlation is found in Appendix F.

Table 3: Independent Samples Collected

	EO Independent Runs/Samples (#)	IR Independent Runs/Samples (#)
Mountain Low	21/54	8/15
Mountain High	15/41	3/9
Desert Low	20/48	12/36
Desert High	33/98	11/33

The Geodetics RelNav was selected as the truth source for all analysis. The RelNav solution was more easily integrated with the Double Vision system during post processing resulting in a less complex analysis. Additionally the GLite TSPI and Geodetics RelNav relative position solutions were compared side by side resulting in bias. Neither the TSPI nor the RelNav solution was particularly close to the ICP sensed solution, and both resulted in a bias. Therefore, the RelNav was selected due to ease of processing and reduced error from analysis. A more detailed analysis of the difference between the GLite and Geodetics TSPI sources can be found in Appendix J.

Once the independent samples were compiled, the accuracy was computed using mean accuracy of the independent samples. The output of the ICP algorithm produced X, Y, Z, and magnitude relative position in the left camera reference frame from the left camera frame to the center of mass of the reference model. The results were directly compared to the evaluation criteria of a notional KC-10 boom envelope (see appendix D). The satisfactory criteria was 0.76 meters (2.5 feet) in X and Y and 0.30 meters (1 foot) in Z. marginal criteria was 1.52 meters (5 feet) in X and Y and 0.61 meters (2 feet) in Z. The statistical analysis showed that the mean error for different altitude or backgrounds were not equal (see Appendix F). Therefore, the mean error for each data category are shown in Table 4 and Table 5.

Table 4: EO Translational Accuracy Statistical Results

	Evaluation Criteria	Condition	Mean Translational Accuracy (meters)	Standard Deviation	95% Confidence Interval
X (left/right)	Satisfactory 0.76 m	Desert High	1.82	0.43	[0.73,1.91]
		Desert Low	1.64	0.54	[1.48,1.79]
	Marginal 1.52 m	Mountain High	2.43	0.35	[2.32,2.53]
		Mountain Low	2.22	0.41	[2.11,2.33]
Y (up/down)	Satisfactory 0.76 m	Desert High	1.65	0.65	[1.52,1.78]
		Desert Low	1.67	0.67	[1.48,1.87]
	Marginal 1.52 m	Mountain High	1.52	0.62	[1.32,1.71]
		Mountain Low	1.35	0.81	[1.12,1.57]
Z (depth)	Satisfactory 0.30 m	Desert High	-5.58	0.85	[-5.41,-5.75]
		Desert Low	-5.37	1.36	[-4.99,-5.75]
	Marginal 0.61 m	Mountain High	-5.50	1.27	[-5.11,-5.88]
		Mountain Low	-6.07	1.69	[-5.62,-6.53]
R (magnitude)	N/A	Desert High	4.16	1.03	[3.96,4.37]
		Desert Low	4.07	1.36	[3.69,4.46]
		Mountain High	4.30	1.41	[3.87,4.73]
		Mountain Low	4.91	1.95	[4.38,5.43]
95% confidence interval with a 99% power level. Yellow: Marginal, Red: Unsatisfactory					

Table 5: IR Translational Accuracy Initial Results

	Evaluation Criteria	Condition	Mean Translation al Accuracy (meters)	Standard Deviation	95% Confidence Interval
X (left/right)	Satisfactory 0.76 m	Desert High	1.97	0.20	[1.94,2.04]
		Desert Low	1.86	0.16	[1.81,1.91]
	Marginal 1.52 m	Mountain High*	2.84	0.71	[2.38,3.30]
		Mountain Low*	2.55	1.38	[1.86,3.25]
Y (up/down)	Satisfactory 0.76 m	Desert High	1.57	0.20	[1.50,1.63]
		Desert Low	1.47	0.17	[1.41,1.52]
	Marginal 1.52 m	Mountain High*	1.47	0.62	[1.06,1.87]
		Mountain Low*	1.05	1.39	[0.35,1.75]
Z (depth)	Satisfactory 0.30 m	Desert High	-5.73	0.37	[-5.85,-5.60]
		Desert Low	-5.71	0.38	[-5.83,-5.59]
	Marginal 0.61 m	Mountain High*	-5.56	1.19	[-6.34,-4.79]
		Mountain Low*	-5.28	1.64	[-6.11,-4.45]
R (magnitude)	N/A	Desert High	4.34	0.42	[4.19,4.48]
		Desert Low	4.43	0.43	[4.29,4.57]
		Mountain High*	4.46	1.24	[3.65,5.26]
		Mountain Low*	4.52	1.84	[3.59,5.45]
*Due to small sample size the IR accuracy is only reported as an initial results with the 95% confidence with a power level of 29%. Yellow: Marginal, Red: Unsatisfactory					

Overall the EO and IR translational accuracy failed to meet the evaluation criteria. The error discovered was a significant deviation from what the 0.20 meter error expected. The standard deviation was also large due to noise. The confidence interval was small, but with the sufficient number of independent samples the high confidence was expected. During testing, the system operator commented that the EO imagery had more detail than IR imagery and expected better EO performance. This cannot be statistically verified, however initial IR results suggested this may be true. There are four potential contributors to the error observed.

First, the aircraft model utilized by the ICP algorithm did not replicate all features of the actual aircraft, including the spinning propellers that were visible in the EO images.

Second, the aircraft model and the point cloud model did not have known fixed reference points that could be compared. The translational distance between the point cloud model and the aircraft model was calculated using the difference between the center of mass for the reference and the center of mass for the aircraft model as seen in Figure 8. Since these points were not anchored in a known fixed location, and instead calculated by the ICP algorithm via center of point mass distribution, the point track correction between the two models generated error in the sensed relative position. Figure 7 shows an illustration of the problem in simplified terms. **(R1) Improve the ICP model to reduce error.**

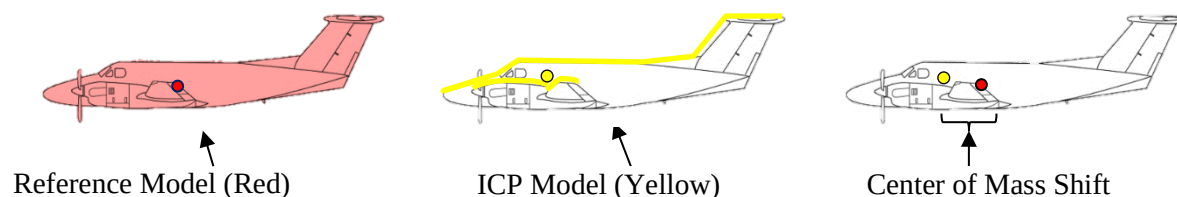


Figure 7: Simplified Center of Mass Shift due to Visible Mass, Side View

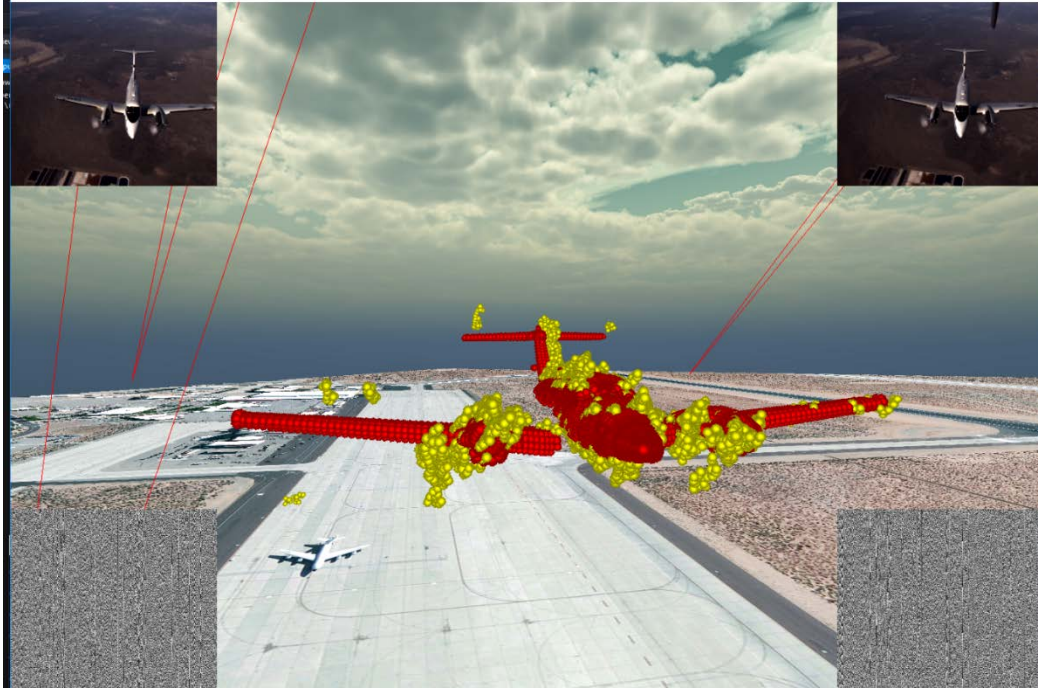


Figure 8: Screenshot of In-flight ICP program (Recreated Post Flight)

Third, the images obtained by the EO and IR cameras lacked optimization. The default camera software settings were not appropriate in bright sunlight, especially when combined with background reflections (i.e. from snow). EO camera adjustments made during later flights with faster exposure times appeared to have improved performance, however insufficient data were collected to make a statistical determination of this effect. The IR camera settings were extremely sensitive, and the required process to make changes in flight made real time adjustments impractical. Figure 9 shows two EO images with different exposure settings where the left image the white in the wing is washed out and no detail can be seen. The right image shows a gradient across the wing which was thought to be favorable to the ICP algorithm. More gradient would enable the ICP algorithm to identify more points in the left and right images to create a better model. A lack of gradient would not present as many points along the wing to match a specific feature in each image pair. Further investigation was required for a definitive answer due to insufficient data for statistical analysis.

(R2) Identify and implement image optimization methods to reduce error in EO and IR cameras.



Figure 9: Camera Exposure Setting Differences from 15,000 μ s to 5,000 μ s

Finally, the noise inherent in the system calculation created unpredictable effects on translational accuracy. Noise was observed where significant relative position changes were present beyond what was

possible in a given time period. For example a stabilized relative position would say the aircraft was wings level at a given distance, and one third of a second later (the next image pair) the aircraft would be have changed position by 30 degrees of bank, the back to wings level by the next camera frame. This seemed to happen at random as observed by the operator. While no noise filtering was used during the statistical analysis, by removing some of the outlier data points, the performance seemed to have significantly better accuracy in the samples observed. Increased noise was found at stabilized points when compared to noise when the pseudo-receiver was transitioning to different positions. The specific cause of the noise was unknown. An initial theory suggested that sun glare was present in one camera but not the other, but analysis of other points suggested that there were accurate sensed estimations with glare present. This is discussed further in the RMS error analysis. **(R3) Mitigate impact of noise in future applications.**

Overall, the bias of the system, as well as the unexpected effect of different altitudes and backgrounds resulted in deficient system performance and an overall unsatisfactory rating.

Rotational Accuracy:

Test Results.

The rotational accuracy was generally tolerable in roll and yaw, however pitch was much greater than desired. The previously reported bias was no longer observed. The EO and IR results are shown in Table 6 and 7. Insufficient IR data points were collected to make an accuracy assessment due to camera malfunctions during flight. The EO accuracy in pitch and roll seemed reasonable, however the yaw error is larger than desired and would likely manifest in borderline to deficient performance. No evaluation criteria was used, however less than a $\sim 2^\circ$ error was considered reasonable by an aerial refueling technical expert.

Table 6: EO Rotational Accuracy Results

EO Rotational Accuracy	Condition	Mean Accuracy (degrees)	Standard Deviation	Confidence Interval (95%)
Roll	Desert High	0.1	5.1	[-0.90,1.12]
	Desert Low	3.3	13.9	[-0.66,7.21]
	Mountain High	-0.4	2.9	[-1.26,0.52]
	Mountain Low	1.4	5.9	[-0.14,3.02]
Pitch	Desert High	5.2	4.4	[4.36,6.12]
	Desert Low	5.1	6.0	[3.37,6.78]
	Mountain High	7.8	4.7	[6.39,9.26]
	Mountain Low	8.1	6.2	[6.48,9.81]
Yaw	Desert High	1.4	4.7	[0.49,2.34]
	Desert Low	0.8	3.1	[-0.13,1.64]
	Mountain High	1.3	1.9	[0.73,1.90]
	Mountain Low	1.4	2.8	[0.66,2.13]
95% confidence interval with a 99% power level.				

Table 7: IR Rotational Accuracy Results

IR Rotational Accuracy	Condition	Mean Accuracy (degrees)	Standard Deviation	95% Confidence Interval
Roll	Desert High	-1.5	1.3	[-1.93,-1.04]
	Desert Low	-2.3	1.3	[-2.78,-1.91]
	Mountain High*	0.4	5.9	[-3.46,4.30]
	Mountain Low*	-13.2	25.8	[-25.98,-0.36]
Pitch	Desert High	3.6	2.4	[2.82,4.42]
	Desert Low	3.6	1.6	[3.12,4.18]
	Mountain High*	5.6	4.0	[2.94,8.23]
	Mountain Low*	4.0	7.1	[0.43,7.63]
Yaw	Desert High	3.8	1.2	[3.43,4.23]
	Desert Low	2.7	1.1	[2.36,3.09]
	Mountain High*	4.7	3.2	[2.62,6.83]
	Mountain Low*	-1.0	8.1	[-5.07,3.12]
*Due to small sample size the IR accuracy is only reported as an initial results with the 95% confidence with a power level of 29%.				

Translational Precision:**Test Methods and Conditions:**

The translational precision data were collected in the same manner as the translational and rotational accuracy. After the image pairs were collected, they were separated into the different contact windows for further analysis. No thinning was conducted to identify independent data points. Success criteria for this analysis required the completion of at least five 10-second stable contact windows in each of the four environments. The success criteria were met for the EO cameras, and for three of the four environments with the IR cameras. Only three contact windows were completed in the Mountain High environment with the IR cameras working.

The test compared the standard deviation of the translational sensed relative position to the standard deviation of the RelNav truth source. The evaluation criteria was for the ICP sensed translational precision to be less than the truth source precision. The standard deviation of the GLite TSPI was not evaluated.

Test Results.

The translational precision was deficient for both the EO and IR camera pairs. Standard deviations of the translational parameters (X, Y, Z, and R) were larger than the RelNav truth source standard deviations for all parameters for both the EO and IR camera pairs. The EO translational precision was close to passing the evaluation criteria for the X direction in the Mountain High environment, where the standard deviations differed by just 1 mm. Similarly, the IR translational precision nearly met the evaluation criteria in the X direction in the Desert Low environment.

Overall the translational precision was deficient resulting in an unsatisfactory rating. Detailed results are shown below in separate tables for the EO and IR translational precision.

Table 8: EO Translational Precision Results

EO Translational Precision	Condition	Number of Contact Windows	Sensed Standard Deviation (m)	Truth Standard Deviation (m)	Error, Sensed - Truth (m)
X (L/R)	Desert High	33	0.26	0.16	0.10
	Desert Low	16	0.35	0.27	0.08
	Mountain High	14	0.218	0.217	0.001
	Mountain Low	18	0.28	0.22	0.06
Y (Up/Down)	Desert High	33	0.27	0.17	0.10
	Desert Low	16	0.35	0.20	0.15
	Mountain High	14	0.36	0.24	0.12
	Mountain Low	18	0.45	0.26	0.19
Z (Depth)	Desert High	33	0.35	0.25	0.10
	Desert Low	16	0.62	0.41	0.21
	Mountain High	14	0.62	0.44	0.18
	Mountain Low	18	0.71	0.47	0.24
R (Magnitude)	Desert High	33	0.40	0.26	0.14
	Desert Low	16	0.66	0.43	0.23
	Mountain High	14	0.68	0.46	0.22
	Mountain Low	18	0.80	0.51	0.29

Table 9: IR Translational Precision Results

IR Translational Precision	Condition	Number of Contact Windows	Sensed Standard Deviation (m)	Truth Standard Deviation (m)	Error, Sensed - Truth (m)
X (L/R)	Desert High	11	0.15	0.14	0.01
	Desert Low	12	0.253	0.252	0.001
	Mountain High	3	0.39	0.20	0.19*
	Mountain Low	5	0.58	0.19	0.39
Y (Up/Down)	Desert High	11	0.21	0.19	0.02
	Desert Low	12	0.20	0.18	0.02
	Mountain High	3	0.38	0.22	0.16*
	Mountain Low	5	0.59	0.24	0.35
Z (Depth)	Desert High	11	0.29	0.23	0.06
	Desert Low	12	0.33	0.27	0.06
	Mountain High	3	1.07	0.49	0.58*
	Mountain Low	5	0.92	0.52	0.40
R (Magnitude)	Desert High	11	0.32	0.28	0.04
	Desert Low	12	0.37	0.30	0.37
	Mountain High	3	1.11	0.52	0.59*
	Mountain Low	5	1.00	0.55	0.45

* Results are shown for IR Mountain High contact windows, but not enough data were collected to make a performance determination. Only three contact windows were completed, but five were required.

Rotational Precision:

Test Methods and Conditions

The same methods and conditions used for the translational precision were used to evaluate the rotational precision. Again, success criteria were not met for the IR cameras in the Mountain High environment.

Test Results.

The rotational precision was deficient. ICP results did not meet the evaluation criteria in any axis. In the contact position, the pilots made minimal changes to the aircraft orientation. Good performance of the algorithm should have shown a small standard deviation. Overall the ICP angular standard deviation was significantly higher than the RelNav truth source. Detailed results for EO and IR rotational precision are shown in tables below. RelNav truth source standard deviations in the roll axis were typically around 0.5°, while the pitch and yaw axis were always below 0.2°. Sensed standard deviations from the ICP algorithm were significantly higher, typically 3-5°. This low precision was seen real time by the system operator, as shown by quick changes in the orientation of the yellow point cloud, and resulting quick changes in the orientation of the red C-12 reference model.

The angular precision was unsatisfactory, however the impact of poor rotational precision will need additional research based on the specific way the system will be used.

Table 10: EO Rotational Precision Results

EO Rotational Precision	Condition	Number of Contact Windows	Sensed Standard Deviation (deg)	Truth Standard Deviation (deg)	Error, Sensed - Truth (deg)
Roll	Desert High	33	2.13	0.46	1.67
	Desert Low	16	4.80	0.57	1.67
	Mountain High	14	2.39	0.56	4.23
	Mountain Low	18	4.11	0.59	1.83
Pitch	Desert High	33	3.14	0.12	3.02
	Desert Low	16	3.53	0.17	3.36
	Mountain High	14	3.20	0.14	3.06
	Mountain Low	18	3.49	0.13	3.36
Yaw	Desert High	33	1.88	0.10	1.78
	Desert Low	16	1.77	0.16	1.61
	Mountain High	14	1.73	0.13	1.60
	Mountain Low	18	2.49	0.12	2.37

Table 11: IR Rotational Precision Results

IR Rotational Precision	Condition	Number of Contact Windows	Sensed Standard Deviation (deg)	Truth Standard Deviation (deg)	Error, Sensed - Truth (deg)
Roll	Desert High	11	1.02	0.38	0.64
	Desert Low	12	1.14	0.49	0.65
	Mountain High	3	4.96	0.46	4.50*
	Mountain Low	5	6.29	0.66	5.63
Pitch	Desert High	11	1.18	0.15	1.03
	Desert Low	12	0.97	0.15	0.82
	Mountain High	3	3.56	0.11	3.45*
	Mountain Low	5	4.65	0.12	4.53
Yaw	Desert High	11	0.86	0.08	0.78
	Desert Low	12	0.77	0.14	0.63
	Mountain High	3	3.26	0.10	3.16*
	Mountain Low	5	7.42	0.15	7.27
* Results are shown for IR Mountain High contact windows, but not enough data were collected to make a performance determination. Only three contact windows were completed, but five were required.					

MILITARY UTILITY FOR AERIAL REFUELING

The specific test objective was to demonstrate the utility of the system for automated aerial refueling. This was accomplished through assessment of calibration sensitivity, airborne operation, system processing time, and ICP Reported RMS Accuracy.

Calibration Sensitivity:

Test Methods and Conditions.

The calibration process created stereo camera calibration settings for use by the ICP algorithm. Calibration images were collected for both EO and IR stereo pairs while using ground power at both the TPS and C-12 parking ramp areas. The calibration events took place before the first flight of each test day and after landing on flight 7. Performing the calibration involved one person below the aircraft holding either an EO or IR checkerboard with squares of a known dimension. The two checkerboards used for the calibration were a small metal board with 25 mm white squares for the stereo IR camera calibration and a printed black and white checkerboard pattern with 30 mm squares printed on plain printer paper and attached to cardboard for the EO cameras and are shown in Figure 10. The person holding the checkerboard slowly tilted and rotated the board while gradually moving in an “S” raster pattern within the shared field of view (FOV) of the cameras. Due to the large FOV of the camera system, the checkerboard was positioned close to the ground at a distance of approximately 8 feet from the cameras when in the lower extremities of the FOV. As the checkerboard was moved to the upper extremities of the FOV during the S-pattern, it was also moved away from the cameras, ending in a position near the trailing edge of the wing. Due to the offset camera mount, the horizontal limits of the checkerboard were the edge of the left side of the fuselage to the right main gear. The system operator at the data computer collected the calibration images and provided feedback for checkerboard placement to ensure the entire checkerboard was visible in all cameras.

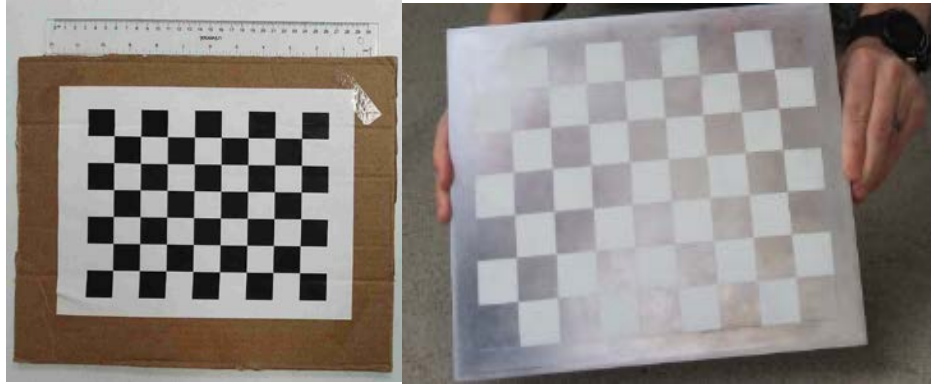


Figure 10: EO Camera Calibration Board (Left) and IR Camera Calibration Board (Right)

Once calibration images were collected they were run through the MATLAB Stereo Camera Calibration Toolbox on processing computers in the lab. The output of the MATLAB toolbox was then run through the AAR script to create 6 input files for the AAR code. These input files were saved in date and flight specific folders so they could be copied into the appropriate folder for processing. The stereo camera calibration reported the average pixel error. Average pixel error was improved when outliers were deleted. An average pixel error for a good calibration was 0.25 pixels or less according to AFIT subject matter experts. Camera calibrations were conducted at various times of day and sun angles, however the full effect of sun angle and lighting conditions was not the focus of this test. Calibration times and sun angles were operationally representative of tanker daytime missions. Further details can be found in Appendix G for post processing instructions.

One variation from the test plan was to adjust the exposure time of the EO camera pair. This improved the image quality of the receiver aircraft in bright sunlight, but created a lower contrast image of the checkerboard in the shadows beneath the pseudo-tanker. If the contrast between the squares on the checkerboard was not high enough, the calibration was generally not usable. A lower limit of 2000 microseconds was used for the EO camera exposure time. Large background contrast from the sunlit and shaded regions of the parking ramp was detrimental to calibrations. Illumination from the sun created a washout effect, especially when the checkerboard was partially illuminated. Another factor in setting up the system properly were the checkerboards used for calibration. The metal boards used for the IR cameras, when heated up, provided good contrast for the IR camera calibration, however did not provide good contrast for the EO camera calibration. As a result, the second checkerboard made of cardboard and printer paper was made and provided good EO average pixel errors as shown in Table 12.

The sensitivity of the calibration was assessed by using a representative sample maneuver block for the receiver maneuvering from astern to contact then back to astern after stable in the contact region. This sample was processed using all calibrations collected. Due to the IR camera malfunctions fewer IR calibrations were collected.

To determine the sensitivity of the ICP algorithm due to calibrations, a maneuver block of flight 6 was processed using every calibration. The average difference in sensed relative X, Y, Z, roll, pitch, yaw and magnitude demonstrated the sensitivity. Additionally a single maneuver block from flight 7 was processed with pre and post flight calibrations to determine how the calibration would drift on a flight.

Test Results

The system was shown to be extremely sensitive to calibration. The time and difficulty to perform an adequate calibration was not excessive, but the requirement to perform this calibration prior to every flight was not appropriate in an operational environment. An abbreviated maneuver block from flight 6 (73.3

seconds) was selected and processed with each calibration. The calibrations with resulting average pixel error are shown in Table 12. Due to IR camera malfunctions the number of IR calibrations was limited.

Table 12: Calibration Average Pixel Error

Flight/Date	Calibration Reference #	EO Pixel Error	IR Pixel Error
Flt 1 (7 Mar 19)	1	0.25	0.25
Flt 2 (8 Mar 19)	2	0.09	0.13
Flt 3 (11 Mar 19)	3	0.11	Not available
Flt 5 (13 Mar 19)	5	0.14	0.18
Flt 7 Pre (14 Mar 19)	7a	0.11	Not Available
Flt 7 Post (14 Mar 19)	7b	0.16	Not Available
Flt 8 (15 Mar 19)	8	0.15	Not Available
Flt 9 (18 Mar 19)	9	0.12	0.1

The EO and IR image pairs collected during the flight 6 sample maneuver were processed using each calibration event. The standard deviation of the translational error demonstrated the average difference from one calibration to another. A large standard deviation meant there was a large variation in the sensed relative position estimate due to changes in calibration events. The average error for each component was shown in Table 13 for EO images and Table 14 for IR images.

The error due to minor differences in calibration demonstrated the system sensitivity. The EO sensitivity was lower than IR, but still had a potential error of 1.723 meters. The accuracy requirement defined by the boom contact envelope (KC-10) was 0.76 meters (2.5 feet). This means a camera system calibration prior to each flight was mandatory to maintain necessary accuracy. Calibration sensitivity for IR cameras was even worse as seen in Table 14.

The calibration effect from a single flight can be seen in Table 15. The error in Y and Z equate to a 16.3 cm error. The sensitivity from a preflight calibration to a post flight calibration is small compared to the required accuracy of 2.5 feet (76.2 cm).

Table 13: EO Calibration Error from Flight 6

Calibration Used For Flight 6	Avg X Error (m)	Avg Y Error (m)	Avg Z Error (m)	Avg Roll Error (degree)	Avg Pitch Error (degree)	Avg Yaw Error (degree)	Avg Magnitude Error (m)
1	1.788	0.010	-8.827	-7.621	11.696	-8.924	8.003
2	1.467	0.978	-5.638	-3.551	11.784	-8.867	4.146
3	1.578	1.778	-4.476	-0.618	7.781	0.693	3.298
5 (Same day)	2.003	1.549	-5.657	-1.414	4.686	0.487	4.497
7a	1.930	2.205	-4.263	-1.233	2.106	1.058	2.959
7b	1.987	2.279	-4.272	-1.447	1.090	1.449	2.945
8	2.059	1.164	-6.487	-3.249	3.930	-0.811	5.411
9	2.132	1.099	-6.771	-0.343	4.401	2.362	5.704
Standard Deviation	0.237	0.741	1.562	2.389	4.086	4.610	1.723
Error computed using Estimated minus RelNav Truth							

Table 14: IR Calibration Error from Flight 6

Calibration Used For Flight 6	Avg X Error (m)	Avg Y Error (m)	Avg Z Error (m)	Avg Roll Error (degree)	Avg Pitch Error (degree)	Avg Yaw Error (degree)	Avg Magnitude Error (m)
1	3.196	-5.385	-19.925	-2.818	14.847	0.051	20.366
2	3.173	-4.720	-19.142	-2.094	13.734	1.304	19.391
5 (Same day)	2.168	1.118	-5.996	-1.875	5.285	3.486	4.977
9	7.381	-5.337	-10.237	26.855	36.046	25.980	12.193
Standard Deviation	2.318	3.147	6.823	14.564	13.094	12.265	7.166
Error computed using ICP minus RelNav Truth							

Table 15: Flight 7 Pre and Post flight Calibration Change

Calibration Used For Flight 7	Avg X Error (m)	Avg Y Error (m)	Avg Z Error (m)	Avg Roll Error (degree)	Avg Pitch Error (degree)	Avg Yaw Error (degree)	Avg Magnitude Error (m)
7a	2.774	1.109	-5.462	0.715	11.006	1.269	4.520
7b	2.786	1.273	-5.624	0.550	9.251	1.194	4.606
Δ from Calibration	-0.012	-0.164	0.163	0.165	1.754	0.075	-0.087
% Difference	-0.43	-13.76	-2.94	26.04	17.33	6.13	-1.90

Overall the calibration sensitivity from day to day seen in Table 13 and Table 14 show a high sensitivity to different calibrations, even if the calibrations are determined to be good. The EO calibration Z (depth) standard deviation of 156.2 cm is not within a reasonable deviation for a notional boom envelope. If an EO calibration was not possible during an early morning flight, the previous day's calibration would cause unacceptable error for use in a refueling mission. Overall the calibration could reasonably be obtained with

an average pixel error less than 0.25. The single day calibration effects were small, and the multi-day calibration effects were more significant resulting in an unacceptable level of deviation. Overall the calibration sensitivity is unsatisfactory due to the high error possible from a non-current calibration.

Airborne System Operation:

Test Methods and Conditions:

The airborne operation of the system was evaluated using several methods. First, while in the contact position, the pseudo-tanker and pseudo-receiver C-12s performed a stabilized 20° bank turn maneuver. From a coordinated time hack, the pseudo-receiver aircraft rolled out to wings level within 2-3 seconds while the pseudo-tanker continued the turn. The time was estimated by the system operator from when the pseudo-receiver aircraft called hack to start its rollout and to when the rollout motion was displayed on the data computer screen. The system operator viewed windows displayed on the data computer screen with streams of the four (4) cameras and the near real time (NRT) generated model running simultaneously using the live stream camera images.

The second method to assess the utility of the system was to complete a Double Vision Questionnaire (Appendix L) which outlined several potential areas of interest. This questionnaire was intended to generate pilot comments during the operation of the system throughout the flight and during required tasks. Both the roll out maneuver and operator comments were collected on several missions.

Test Results:

The Airborne System Operation was deficient due to long ICP pose update rates. For the EO/IR camera stream, no latency was noticeable to the operator for the EO and IR images being displayed. The stability, movement, and movement rate were all discernable from the camera video streams. An operator would not have issues from latency when using this part of the system. The image displayed from the ICP algorithm had ICP pose updates estimated by the operator of 0.5 to 1.5 seconds. There were instances where a significant portion of the pseudo-receiver wing and airframe were not generated by the ICP algorithm. An excerpt of system operator comments from Appendix p, flight 7 is shown below:

“The range stabilized with the aircraft around 81 meters and the range and closure could be seen numerically as well as in the point cloud. Stability and closure were okay, but at distances from astern to contact there were occasionally outliers. While stable in contact, small movements were seen both numerically and in the point cloud. There did appear to be some bias on the point cloud and the reference cloud. Point cloud quality was difficult to assess, but there were times that wing and engine features were clear and stable. At ranges outside of contact [position] the point cloud seemed less stable. EO camera exposure settings seemed to help the performance of the point cloud. There was an update of the ICP model at about 1 Hz while streamed video had no noticeable latency. The utility of the system in the current state was not practical for use, but there is potential for how the numerical information is displayed to offer valuable feedback. The information was useful, however the way the information was displayed was not practical.”

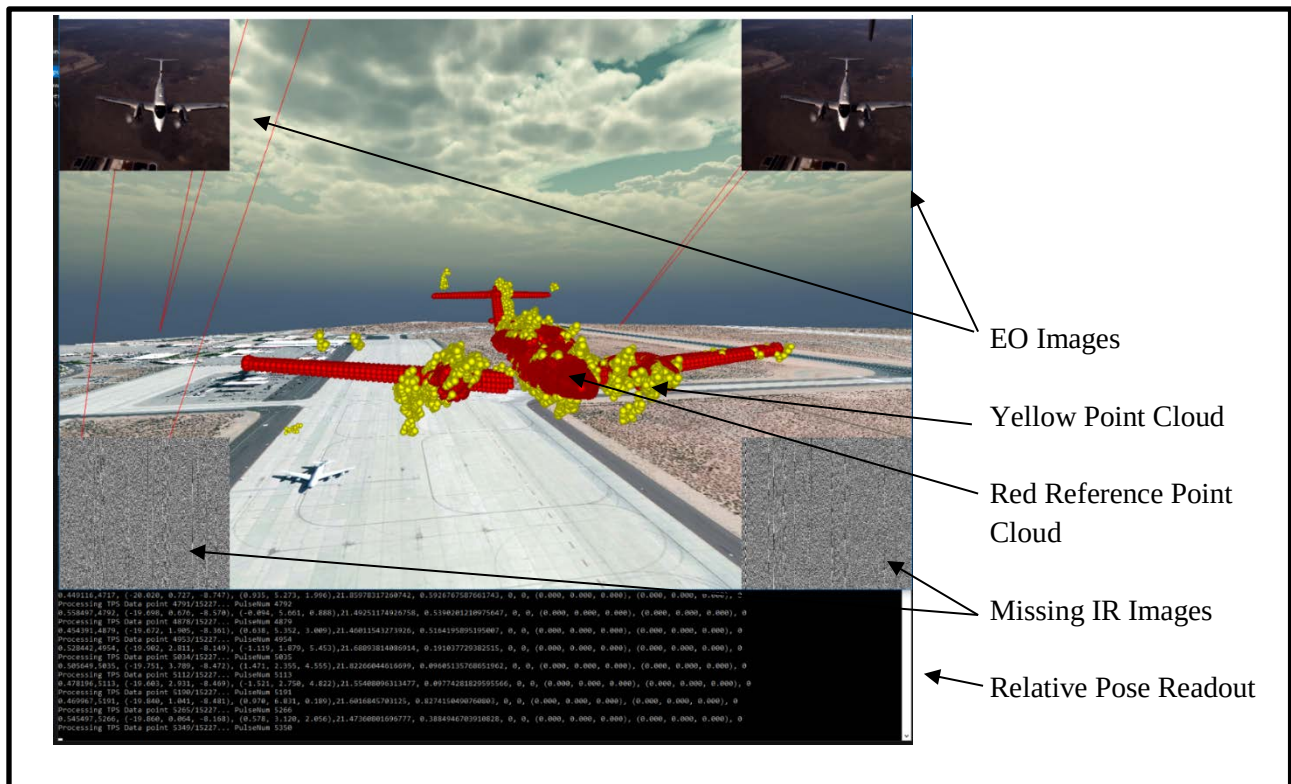


Figure 11: Screenshot of In-flight ICP program with descriptions (Recreated Post Flight)

Figure 11 shows the layout of the in-flight system as well as sample of how the yellow point cloud does not always match the red reference point cloud. The system user interface was cumbersome and not user friendly. The power-up sequence and initialization to begin operations was not objectionable for a single event, but any changes to the system required a shutdown and power up that took too much time for any configuration change. Additionally to operate the system without losing images required strict adherence to procedures where failure to do so would cause permanent loss of data.

The images collected were clear and quick to update with the point cloud and estimation having some delay. The readout of the relative distance and orientation in a scrolling window below the main display resulted in channelized attention to read the appropriate value and observe and changes or rates. The rate that the estimations were displayed was marginally effective with the speed being readable. The challenge was the picking out the correct value out of the long string of text. Overall the system has only integrated minimal user interface considerations and is still a developmental system. The technology has potential to provide useful feedback to a crew, but in its current format the utility was not practical for use.

System Processing Time:

Test Methods and Conditions:

The system processing time was calculated to assess the utility of the system for use in the real time. The purpose of this test was to determine how the Double Vision system performed without saving images to a drive. The version used during flight test required capturing images to build a data set for future research and development. This additional task took considerable processing power from the data processing computer and the concern was that the latency of the relative position estimation due to limited processing would make the algorithm used for near real time relative position estimation unusable. For airborne

operation, a real time version of the algorithm ran at approximately 1 Hz ICP pose refresh rate. This real time version performed the same ICP analysis as the normal version, however it skipped images as necessary to maintain approximately 1 Hz ICP pose refresh rate to compensate for processing speed. The normal version of the algorithm and the real time version were ran in the lab on the post processing machine (see appendix M for computer specifications) to determine a system processing time from a sample set of collected images. A 73.3 second sample with 733 images pairs of an abbreviated maneuver block from flight 6 was processed using EO and IR image pairs. The ratio of collection time (73.3 seconds) to the post processing machine system processing time was compared between the normal and real time versions of the algorithm and are shown in Table 16 i.e. for 1 sec of EO data it took 4.7 sec for the system to process and update the ICP model. The time for the algorithm to initialize and start processing was ignored since this was not required in flight.

Test Results:

The system processing time was a factor of the power of the computer processor and will be an important consideration for future development of the system. As seen in Table 16, while the real time version performed at less than a 1:1 processing time ratio for a sample dataset, the 1 Hz ICP pose update rate was slower than necessary for an aerial refueling mission. The real time algorithm on average skipped 13 image pairs for every image pair processed which provided relative position at approximately 1 Hz and reduced position fidelity. For tanker or unmanned aerial vehicle applications an ICP pose update rate of 5 Hz or greater update rate was recommended by project technical advisors from the 418 FLTS. The 4.7:1 processing time ratio for the normal version of the algorithm meant that a 10 Hz image processing rate was not possible for the normal algorithm given the computing speed of the post processing computer. An improvement in ICP pose update rates and fidelity would be required for use in aerial refueling operations. The EO and IR images were different sizes which explains why the IR performance was slightly better.

Table 16: Post Processing Time for ICP and NRT ICP Variant

	Normal Processing Time (sec)	Processing Time Ratio	Real Time Version Processing Time (sec)	Processing Time Ratio
EO	344.5	4.7:1	56.5	0.77:1
IR	240.3	3.3:1	-	-
Ratio = Processing Time ÷ 73.3 (actual Δt in seconds)				

ICP Reported RMS Accuracy:

Test Methods and Conditions:

The ICP algorithm generated an intrinsic accuracy approximation to quantify the quality of the ICP relative navigation solution. The objective of this test was to determine if this Root Mean Square (RMS) error accurately reported upon the quality of the estimation. To determine the RMS error, the ICP ran a root mean square analysis on the distance the between the red reference point cloud and the closest point in the yellow cloud. The closest distance between each red and yellow dot was squared and summed for all the points in the point cloud. If the distribution of the yellow point cloud overlapped with the reference point cloud the RMS error would be small to none. If the yellow point cloud was asymmetric, rotated away from the red reference point cloud, or the yellow points were not evenly distributed, then the RMS error would be large. The expected performance was that when the receiver aircraft was close the RMS would be small and as the receiver moved further away, the accuracy would be poorer and the RMS error would increase. This intrinsic RMS error would be used like figure of merit (FOM) in GPS.

To evaluate this relationship three flights were sampled using abbreviated maneuver blocks. The details for the maneuver blocks used for analysis can be found in Table 13. Using the known RelNav slant range as the truth source, the RMS error was plotted against slant range distance as well as the slant range error.

Table 17: RMS Sample Runs

Flight #	Time of Day (L)	Heading (Approx.)	Environment/Block
Flight 6	1629	East	Desert Low
Flight 7	1329	South	Mountain Low
Flight 8	0904	East	Desert High

Test Results:

The analysis of the relationship between RMS error, slant range distance, and total slant range error showed some correlation between slant range and total error, and slant range and RMS. However, the noise generated in the system made the RMS error unusable in its current state for the proposed use. The RMS error varied with range as predicted as shown in Figure 12. The higher RMS error appeared to be due to poor angular ICP estimations at close range, as well as higher slant range. A similar noise pattern was observed at the astern position while stabilized. This noise was less while the aircraft moved to and from the contact position and the RMS error relationship was more visible.

**Slant Range Error and RMS from Flight 7
Asteron to Contact to Asteron**

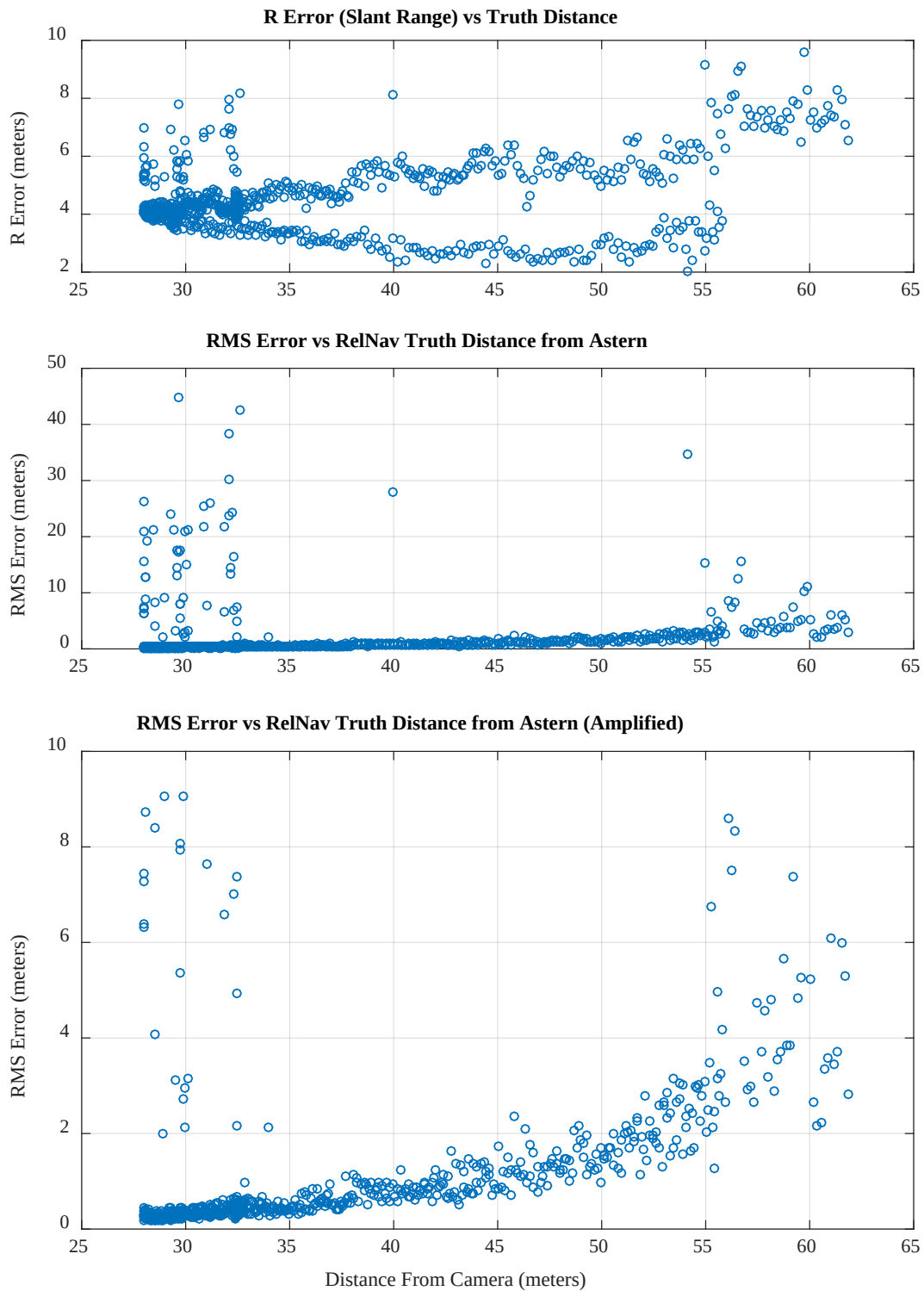


Figure 12: EO Slant Range Error and RMS, Flight 7

Flight 6 Image Pair #161779 L and R, RMS 12.58 meters



Flight 6 Image Pair #161785 L and R, RMS 0.0557 meters

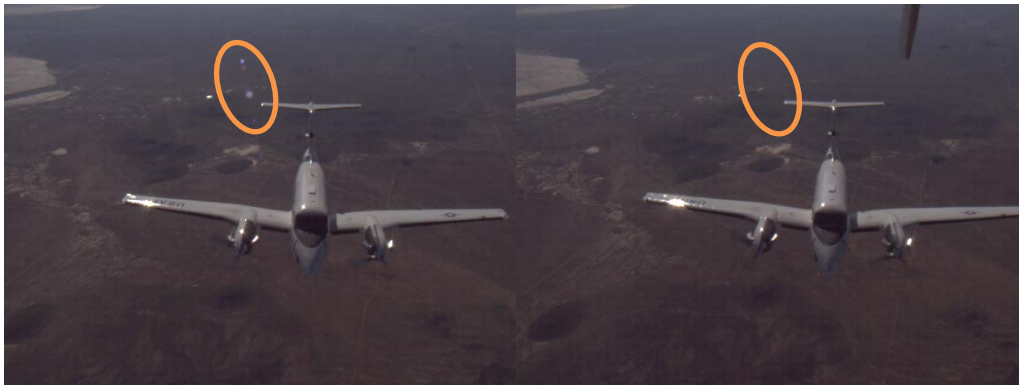


Figure 13: Image Pair with High and Low RMS error showing similar L/R Asymmetry

A closer evaluation of the noise produced no clear cause. For example, Figure 13 shows an example where there is glare in the left camera frame but not the right camera frame for both image pairs. Image 161779 has high RMS error while 161785 has low RMS error. Additional analysis is necessary to determine specifically what is contributing to the translational and rotational error. Overall the RMS error could potentially have use as in intrinsic performance measurement, but is currently only marginally useful.

TEST RESULTS SUMMARY

Overall the Double Vision System was deficient due to unacceptable accuracy and precision resulting in an unsatisfactory rating. Military utility was borderline to deficient based on the criteria used with some key areas of future development required. This result was not unexpected given the early developmental nature of the system. By reducing error and noise, the performance could possibly improve to an adequate level. The interface will also have to be modified for the specific intended use. Using the dataset collected, many of these improvements can be made and verified without additional flight test. Table 14 presents the overall Have Double Vision test results.

Table 18: Overall Have Double Vision Test Results

Title	Descriptor	Ratings
Overall Have Double Vision Test Results	Deficient	Unsatisfactory
Research and Development Dataset Collection	-	Met
Calibrated Time Stamped Data Collection	Complete	
Stereo Vision System Performance	-	Unsatisfactory
Translational Accuracy	Deficient	
Rotational Accuracy	Borderline	
Translational Precision	Deficient	
Rotational Precision	Deficient	
Military Utility for Automated Aerial Refueling	-	Not Rated
Calibration Sensitivity	Deficient	
Airborne System Operation	Deficient	
System Processing Time	Borderline	
ICP Reported RMS Accuracy	Borderline	

The translational and rotational accuracy and precision exhibited bias, noise, and excessive error in both the EO and IR cameras. Overall, the bias of the system, as well as the unexpected effect of different altitudes and backgrounds resulted in deficient system performance and an overall unsatisfactory rating leading to the following recommendations: **(R1) Improve the ICP model to reduce error. (R2) Identify and implement image optimization methods to reduce error in EO and IR cameras. (R3) Mitigate impact of noise in future applications.**

The military utility for automated aerial refueling was not rated but areas warranting future development were identified. The system demonstrated potential, however the performance in calibration sensitivity and refresh rate using the real time ICP algorithm were not appropriate for operational aerial refueling applications. Overall, adjustments are necessary to meet requirements for calibration sensitivity, refresh rate, and processing fidelity. **(R4) Reduce the sensitivity due to calibration differences.**

REFERENCES

1. AFTCI 91-202 Edwards Sup, AFTC Test Safety Review Process, Edwards AFB, California, 5 April 2017.
2. 32 CFR 989, Part 989 – Environmental Impact Analysis Process (EIAP), Volume 6, July 2012.
3. Edwards AFBI 99-105, Test Control and Conduct, 412 TW, Edwards AFB, California, January 2014.
4. ATP-3.3.4.2, NATO Standard Air-to-Air Refueling ATP-56, Edition C, Ver. 1, November 2013.
5. Bouguet, Jean-Yves, *Camera Calibration Toolbox for MATLAB*, 14 October 2015.
<http://www.vision.caltech.edu/bouguetj/calib_doc/>
6. Geodetics Inc., Geo-iNav Commercial User Manual, Document 20134 Rev P, San Diego, CA, 2016.
7. Jorris, Timothy R., MATLAB Stats and DOE App. February 2017.
8. Sofradir-EC, ATOMTM 1024 User Manual, Revision 1.0.33, September 2014.
9. Allied Vision, Prosilica GT Technical Manual, Version 2.8.1, 30 January 2017.
10. AFI 11-202V3, General Flight Results, Headquarters USAF, 10 August 2016.
11. Stuart, Thomas R., Bellingham, S. P., Grace, T. W., Lambach, J. L., and Welch, D.L., *Have Vision Test Plan*, TPS, USAF, August 2017
12. Stuart, Thomas R., Bellingham, S. P., Grace, T. W., Lambach, J. L., and Welch, D.L., *Have Vision Technical Information Memorandum*, TPS, USAF, December 2017
13. AFI 11-2FT-Volume 3, Flight Test Operation Procedures, Headquarters USAF, 1 March 2017
14. Dallmann, William E., *Infrared and Electro-Optical Stereo Vision For Automated Aerial Refueling*, AFIT, USAF, 1 March 2019

This page was intentionally left blank.

APPENDIX A – DETAILED TEST ITEM DESCRIPTION

ICP Algorithm

The ICP algorithm (previously known as R7) outputs an estimate of the observed aircraft's position and attitude in a user-specified frame of interest. For the purposes of this Tanker, the frames of interest are the body frame of the pseudo-tanker and the frame of the left camera within a stereo pair. Required inputs to the algorithm are

1. A set of stereoscopic images captured from a stereo camera pair. These images must have been taken at the same time. For the purposes of this Tanker, these images have a time stamp referenced to the GPS clock.
2. The intrinsic camera calibration results for both cameras in the stereo camera pair. These results must include a camera calibration matrix and a set of distortion parameters.
3. The stereo camera calibration results for the stereo camera pair. These results must include the position of the right camera in the left camera frame and the direction cosine matrix (DCM) describing the rotation from the left camera frame to the right camera frame.
4. The extrinsic camera calibration results for both cameras in the stereo camera pair. These results must include a vector describing the origin of each camera in the frame of interest (for this Tanker, the frame of interest would be the pseudo-tanker body frame) and a DCM describing the rotation from the frame of interest to the frame of each camera. The Cartesian frame used for each camera is shown in Figure A1.

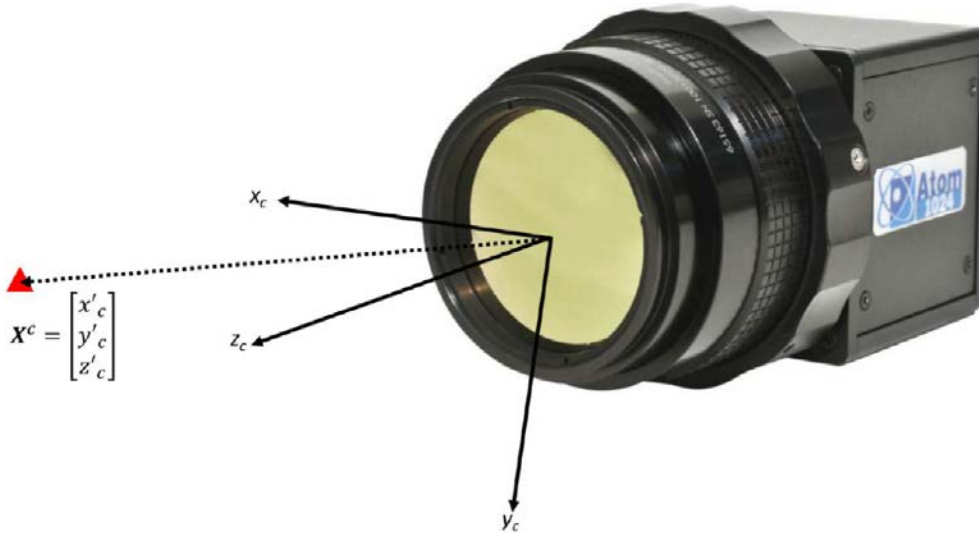


Figure A1: Cartesian Frame Depiction for Each Camera

1. The stereoscopic images are transformed into an observed point cloud. This process is accomplished using the open source computer vision library OpenCV in C++ (reference 11). Multiple sub-routines are required to complete this transformation, the key components of which include:

- The raw camera images are undistorted using the results from the intrinsic camera calibrations. The undistorted images are then rectified based upon the results of the stereo camera calibration. Image rectification consists of transforming the two images in a stereo pair such that common features fall along the same pixel row in both images. The OpenCV function “StereoRectify” undistorts and then rectifies each stereoscopic image pair.
- The algorithm identifies matching pixels between the two images and the location of these matching pixels in both images. Based on the location of a matched pixel in the left camera and right camera images, the separation between these two locations is computed. This separation is termed a disparity. A disparity value for every matched pixel is computed. The OpenCV function “StereoBM” identifies matching pixels and then generates a disparity map.
- Using the results from the stereo camera calibration, the disparities are projected into a real-world depth with units of meters. This depth value corresponds to the matched points’ z-axis locations in the left camera frame. Using the z-values and the matched points’ pixel coordinates, a three dimensional (x, y, z) location for every matched point is computed in the left camera frame. The OpenCV function “reprojectImageTo3D” determines a three dimensional coordinate for all pixels in the disparity map.
- These three-dimensional locations correspond to the observed point cloud.
- This point cloud can be transformed into the frame of interest using the results of the extrinsic camera calibrations.

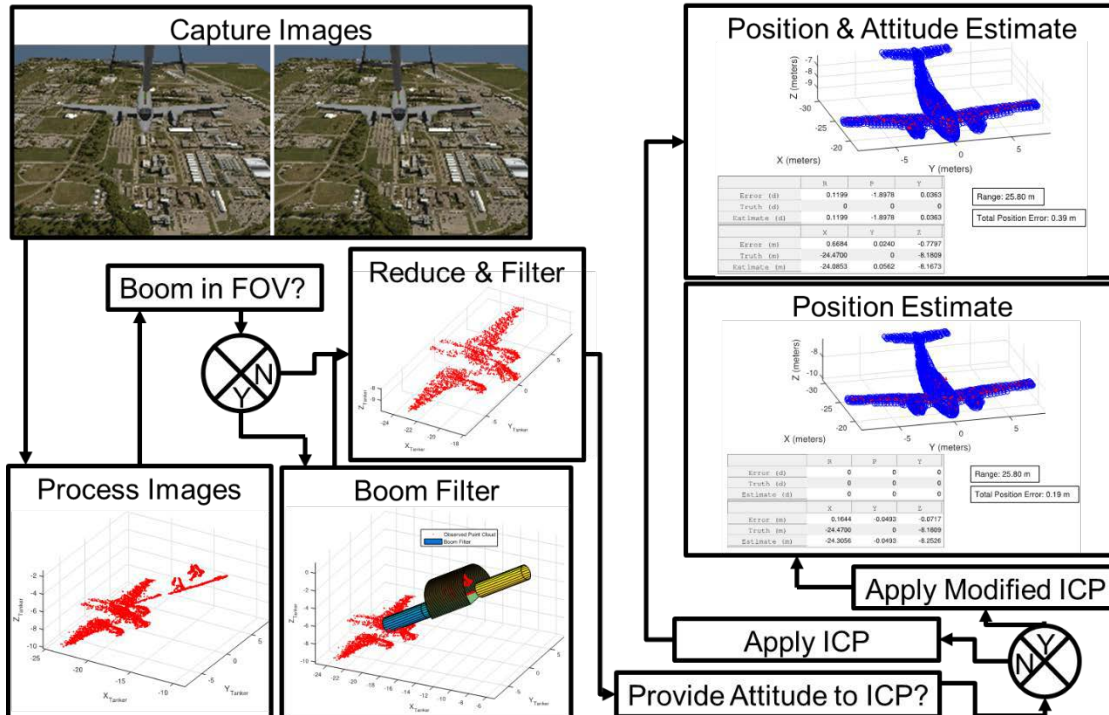


Figure A2: ICP Algorithm Visual Depiction

2. **The observed point cloud is reduced in size and filtered for noise.** Multiple sub-routines are required to complete this process; the key components include:
 - a. Gross outliers are eliminated from the point cloud with a median filter. The median filter eliminates any points whose distance from the median point is greater than a user-specified value (15 meters is used for processing C-12 images).
 - b. The MATLAB function `pcdenoise` is used to remove remaining outliers. This function removes any points whose average distance to its four nearest neighbors is at least one standard deviation larger than the mean average distance to neighbors for all points in the point cloud.
 - c. The remaining point cloud is down-sampled with the MATLAB function `pcdownsample`. This function uses a grid averaging scheme in which the locations of each point within a box of user-specified dimensions is averaged into a single point. The ICP algorithm uses a 0.1 meter-by-0.1 meter-by-0.1 meter box.
3. **The iterative closest point algorithm (ICP) (reference 12) is applied using the filtered observed point cloud and a model point cloud.** The model point cloud is fixed and is independent of the sampled images. For this Tanker, the C-12 model point cloud was generated in BlenderTM from a three-dimensional C-12 created by Dr. Scott Nykl of AFIT in the 3DVW. The three-dimensional model has the same dimensions as the TPS C-12's being used as receivers in this Tanker. BlenderTM allows the user to transform a surface defined object (i.e. the 3DVW C-12 model) from a set of surfaces into a set of points. The ICP algorithm determines the translation and rotation that projects the observed point cloud onto the model point cloud while minimizing the global least squares error between the points in the two point clouds. **This returned translation and rotation correspond to the overall output of the ICP algorithm—the observed aircraft position and attitude in the frame of interest—provided the following conditions are adhered to:**
 - a. The origin of the model point cloud must be defined such that it aligns with the origin of the frame of interest. If the model point cloud origin is defined in this manner, then the translation vector returned by ICP will correspond to the position of the observed aircraft in the frame of interest.
 - b. The model point cloud must be oriented such that its axes are aligned directionally with the frame of interest. If the model point cloud origin is defined in this manner, then the DCM returned by ICP will correspond to the rotation from the frame of interest to the body frame of the observed aircraft.
 - c. To minimize algorithm error, the model point cloud must include point representations of all artifacts that could possibly be present in the observed point cloud. This only applies to aircraft shape or mold line. Paint schemes, etc. are irrelevant. For instance, for a C-12 target, the model point cloud must model the entire aircraft including the wings, fuselage, vertical tail, propeller blades at all possible positions, exhaust stacks, pitot booms, etc.

The ICP algorithm can be configured such that the returned position vector and DCM correspond to different frames. For this Tanker, the position vector will be defined in the left EO or left LWIR camera frame, while the DCM will describe rotation from the pseudo-tanker body frame to the pseudo-receiver body frame.

An example of ICP algorithm output is shown below. The position is returned in the form of a 3- by-1 vector and the DCM in the form of a 3-by-3 matrix in MATLAB.

$$\vec{s}_L = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\mathbf{R}_p^s = \begin{bmatrix} R_1 & R_2 & R_3 \\ R_4 & R_5 & R_6 \\ R_7 & R_8 & R_9 \end{bmatrix}.$$

In this example, ICP returns the position of the observed aircraft in the Cartesian left camera frame (the *L*- frame) and the DCM that describes the rotation from the pseudo-tanker frame (the *p*-frame) to the pseudo-receiver frame (the *s*-frame).

APPENDIX B – ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Abbreviation	Definition	Units
3DVW	Three-Dimension Virtual World	---
σ	Standard Deviation	various
θ	Roll angle	degrees
ϕ	Pitch Angle	degrees
ψ	Yaw Angle	degrees
AFB	Air Force Base	---
AFI	Air Force Instruction	---
AFIT	Air Force Institute of Technology	---
AFRL	Air Force Research Laboratory	---
AFTC	Air Force Test Center	---
AFFTC	Air Force Flight Test Center	---
AFTCI	Air Force Flight Test Center Instruction	---
AAR	Automated Aerial Refueling (AFIT Algorithm Name)	---
AR	Aerial Refueling	---
CD	Compact Disc	---
CDO	Contested Degraded Operations	---
CFR	Code of Federal Regulations	---
CSV	Comma Separated Value	---
CTF	Combined Test Forces	---
DAP	Data Analysis Plan	---
DAS	Data Acquisition System	---
DCM	Direction Cosine Matrix	---
DO	Director of Operations	---
EIAP	Environmental Impact Analysis Process	---
EO	Electro-Optical	---
EPIC	Enhanced Performance Improved Capability	---
FOM	Figure of Merit	---
FOV	Field of View	degrees
FLTS	Flight Test Squadron	---
Geo-RelNav	Geodetics Relative Navigation	---
GPS	Global Positioning System	---
IAW	In Accordance With	---
ICP	Iterative Closest Point	---
ID	Identifier	---
IFR	Instrument Flight Rules	---
IMU	Inertial Measurement Unit	---
IP	Instructor Pilot	---
IRIG	Inter-Rage Instrumentation Group	---
JON	Job Order Number	---
KIAS	Knots Indicated Airspeed	nm/hour
LDTO	Lead Developmental Test Organization	---

LWIR	Long Wave Infrared	---
MOP	Measure of Performance	---
MSL	Mean Sea Level	ft
NM	Nautical Mile	nm
NOTAMS	Notices to Airmen	---
PAR	Program Assessment Review	---
PGM	Portable Graymap	---
PL	Production Level	---
PMF	Probability Mass Function	---
POC	Point of Contact	---
RelNav	Geodetics Relative Navigation	---
RMS	Root Mean Square	---
RQQC	Aerospace Systems Directorate, Control Systems Branch	---
SI	System Instrumentation	---
SRB	Safety Review Board	---
STO	Specific Test Objective	---
TC	Test Conductor	---
THA	Test Hazard Analysis	---
TIM	Technical Information Memorandum	---
TMP	Test Management Project	---
TPS	Test Pilot School	---
TSPI	Time Space and Position Information	---
UAV	Unmanned Aerial Vehicle	---
USAF	United States Air Force	---

APPENDIX C – RATING CRITERIA

Table C1 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

This page was intentionally left blank.

APPENDIX D - TEST EXECUTION

GROUND PROCEDURES

The test team will accomplish the following during pre-flight/ground operations of the Have Double Vision system, the Geodetics RelNav system, and the GLite TSPI system.

- Verify normal operation of the camera and data recording system.
- Capture camera data using intrinsic camera calibration checkerboard (if not blurry).
- Verify GLite TSPI and Geodetics RelNav system are recording.

TEST EXECUTION

Flight test will be carried out in two C-12Cs and a T-38C, with an IP in the trail aircraft. The lead aircraft will be responsible for maintaining the formation within the altitude data band and desired ground track, while respecting local airspace procedures. The trail aircraft will be responsible for flying the test air refueling profile maneuvers. The TC will be responsible for managing the air refueling profile and overseeing the data recording system. The TC will relay profile management radio calls through the pilots.

AIR REFUELING MANEUVER BLOCK

Tankers are capable of establishing contact with receivers in a three-dimensional contact window behind the aircraft. The test team used the dimensions of the KC-10 contact window as illustrated in Figure D1 as a reference for the desired contact window for this test.

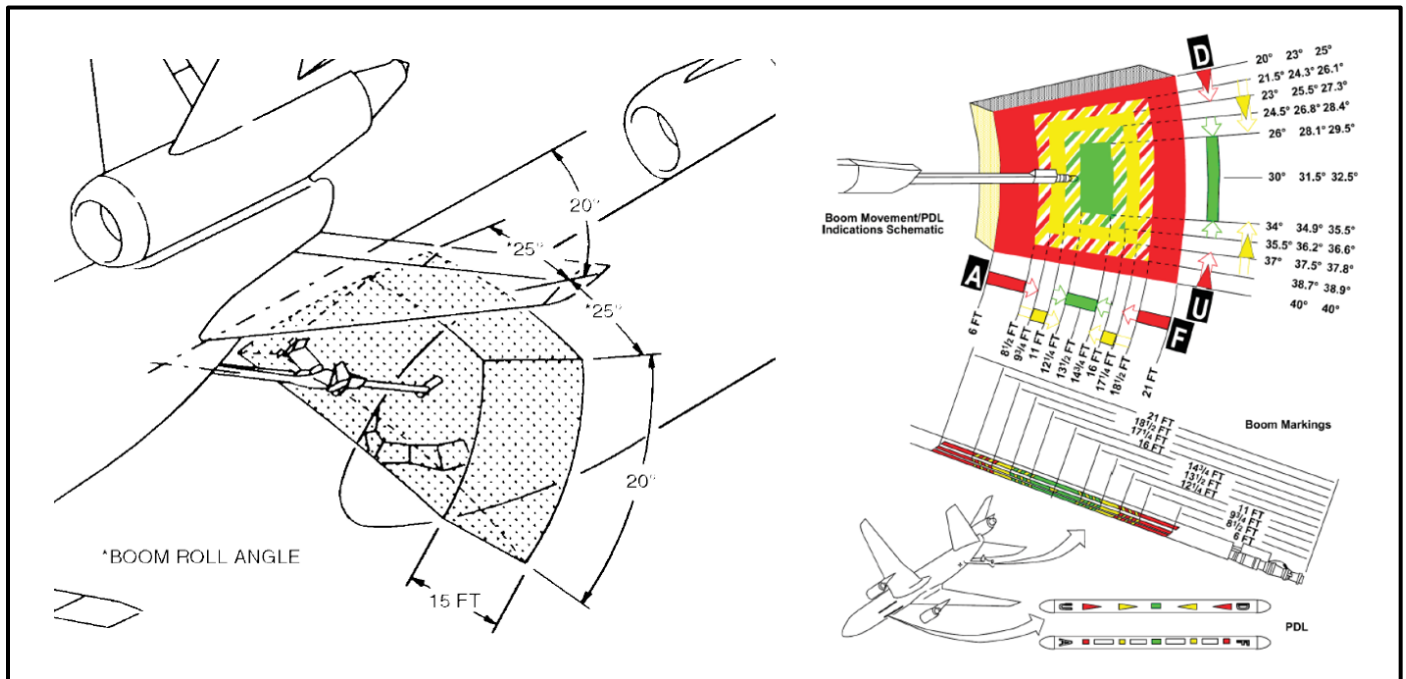


Figure D1: KC-10A Contact and Boom Envelope Window

The contact window and both the minimum and optimum separation requirements for this test are illustrated in Figure D2. Given the intended utilization of the Double Vision stereo vision system, the “Contact” position will be defined within this notional three-dimensional window, and will be the basis for all pseudo-receiver maneuvering. Desired positions are referenced relative to the boom attachment point (approximately two feet aft of the cameras), but safety considerations dictate that nose-tail separation and vertical separation between aircraft be maintained at all times. See Figure D3 for more detail.

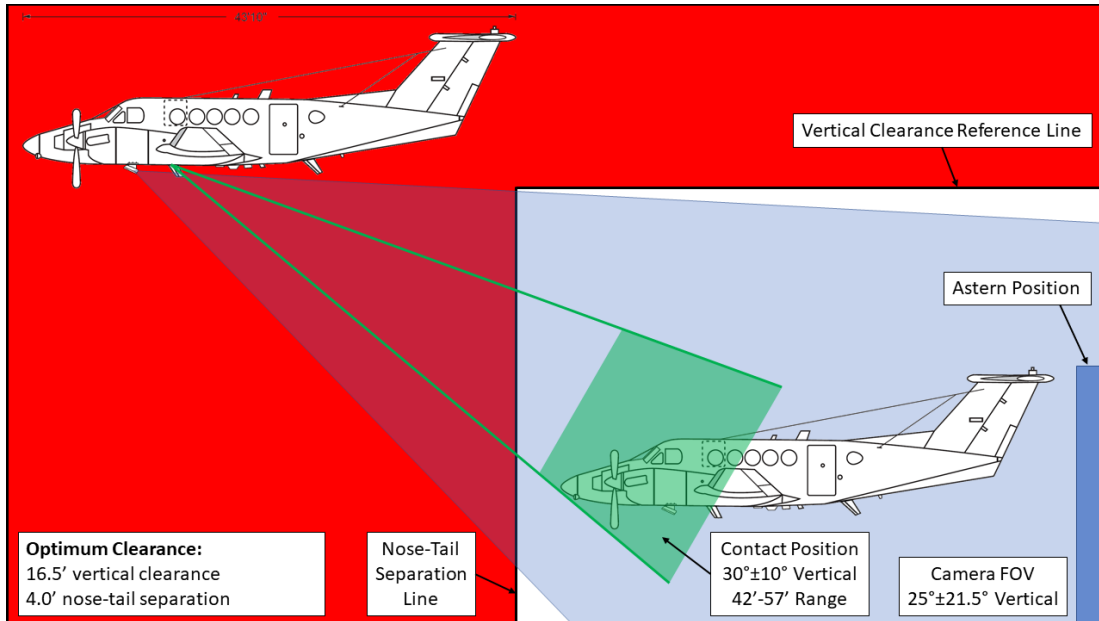


Figure D2: Side View Optimum Pseudo-Receiver Position

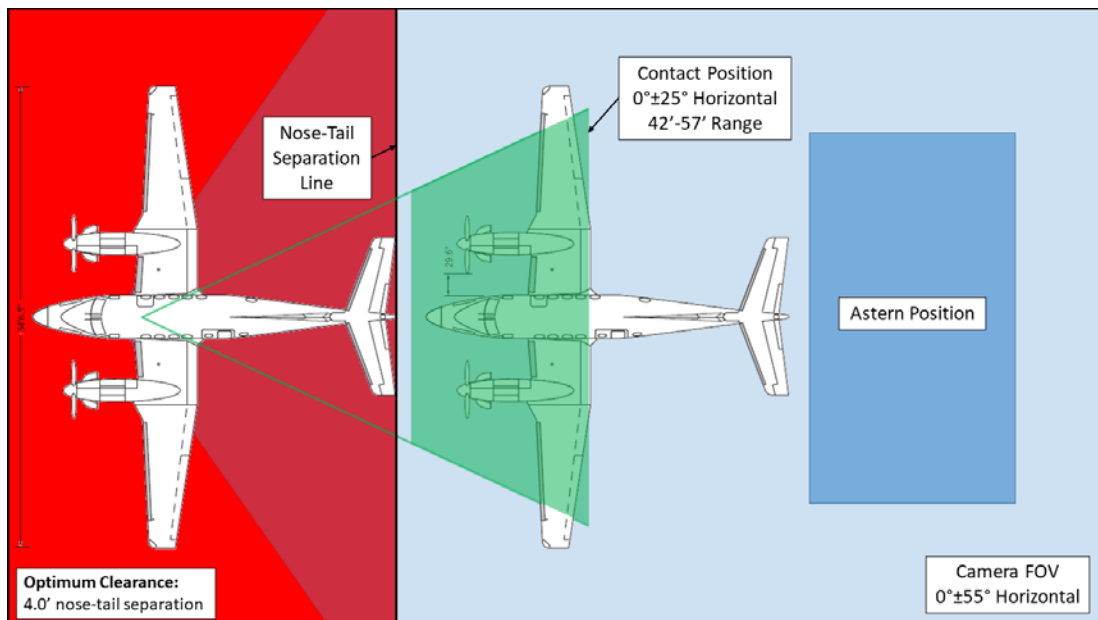


Figure D3: Top View Optimum Pseudo-Receiver Position

Simulated Automated Aerial Refueling formation operations will be conducted in maneuver blocks, defined in Table 3. Within each maneuver block the test aircrew will position the pseudo-receiver at the direction of the TC. In general, the Full Maneuver Block will be used. The Abbreviated Maneuver Block will be used during the maneuver blocks that require data collection for statistical purposes. Overall, the Full Maneuver Block will optimally last between 5 and 10 minutes and the Abbreviated Maneuver Block will optimally last between 2 and 5 minutes. See Appendix A for the planned test matrix.

SETUP

The lead aircraft will start level at the test point altitude and at the test point airspeed (160 -20/+70 KIAS with a C-12C pseudo-receiver or 210±10 KIAS with a T-38C pseudo-receiver). The pseudo-receiver will maintain a route position until the pseudo-tanker is in position. Once cleared by the pseudo-tanker into the astern position, the pseudo-receiver will move from a route position to the astern position using visual reference points on the pseudo-tanker. The pseudo-receiver will accelerate approximately 20 KIAS in order to achieve the desired closure rate. The recommended technique is 10 KIAS of closure at 500 feet below and 0.5 NM in trail; and 5 KIAS of closure 250 feet below and 0.25 NM in trail. The astern position is defined as approximately 50 feet in trail directly behind the pseudo-tanker. The target aircraft will call when established in the astern position. Figure D2 and Figure D3 show the location of the astern position.

STABLE ASTERN

After the pseudo-receiver calls established in the astern position, the TC will direct the start of the maneuvering block. At this time, the pseudo-receiver will remain in a fixed position for a minimum of 30 seconds before beginning the closure to the contact position.

CLOSURE TO CONTACT

The pseudo-tanker will clear the pseudo-receiver into the contact position. The center of the contact window is defined as laterally centered, 50 feet in trail, and 30 degrees below the pseudo-tanker. Dimensions of the contact window are illustrated in Figure D2 and Figure D3. The target aircraft will close from the astern position to the contact position at a maximum rate of approximately 1 foot per second, with the maneuver lasting a minimum of approximately 1 minute. After the pseudo-receiver is established in the contact position without excessive movement, the pseudo-receiver will call when stable.

STABLE CONTACT

Once stable, the pseudo-receiver will maintain the center of the contact window for a minimum of 30 seconds or until the TC has cleared the formation to accomplish the next maneuver. No maneuvering will take place in this position unless required for position maintenance or for safety. The forward limit of the contact position is defined as the nose-tail clearance line. The vertical clearance reference line denotes the upper limit of the contact position, and is defined as a horizontal line extending from the bottom of the prop arc of the pseudo-tanker. This position was determined from minimum slant range of 27 feet (one

half of C-12C wingspan, see Reference 13) from closest point of the pseudo-tanker and a vertical clearance of 8 feet between the top of the pseudo-receiver's tail and the vertical clearance reference line. The minimum clearance position can be identified when the top edge of the pseudo-tanker's propeller arc appears to touch the trailing edge of the wing. If the top edge of the propeller arc appears to rise above the trailing edge of the wing the pseudo-receiver is too high and should initiate a separation maneuver by descending or moving aft. The optimum contact position can be identified when the top edge of the propeller arc appears to touch the leading edge of the wing. If space exists between the top edge of the propeller arc and the leading edge of the wing, the pseudo-receiver is too low. Figure D2 and Figure D3 show the optimum contact position and the minimum clearance references. Additional visual references are found in Appendix H. Prior to the first flight speed tape will be applied to the aft end of the pseudo-tanker to use as a visual reference to aid repeatability for pilots in the receiver.

STABILIZED 20° BANKED TURNS

While in the stable contact position, the pseudo-tanker will initiate a 20° banked turn for 180-360° of heading change to simulate flying anchor refueling pattern. During this time, the pseudo-receiver will maintain the contact position. This maneuver will be counted within the 2 minute requirement of stable contact, The 20° bank turn will not be initiated until at least 10 seconds of straight and level stable contact time has been established and the TC has cleared the formation to execute the maneuver. The 10 second requirement is in place to ensure data requirements for STO 1 have been met.

LEFT/RIGHT CONTACT LIMITS

When the minimum time has passed while the pseudo-receiver is stable in the contact position, the TC will clear the pseudo-receiver to the left and right contact limits. This is defined as the same vertical and fore/aft position as the optimum contact position, and approximately $\pm 25^\circ$ (± 20 feet) laterally. This position can be identified using the same references as the optimum contact position, however the pseudo-receiver will be directly behind the midpoint of the left or right aileron depending the direction of movement. A good reference for this position can be identified by superimposing the nose cone of the opposite engine in line with the trailing edge of the wing root of the wing that the pseudo-receiver is behind. The pseudo-receiver will move towards the left or right limit position at a rate of approximately 1 foot per second and once established in the desired position, the pseudo-receiver will stabilize there for a minimum of 10 seconds. Then pseudo-receiver will then return to the contact position at the same rate and repeat the maneuver in the opposite direction. This portion of the maneuver block will be complete once the pseudo-receiver is re-stabilized in the optimum contact position.

PRACTICE SEPARATION (BREAKAWAY)

Once stable again in the optimum contact position, the pseudo-receiver will advise the TC when they are ready for the practice separation. Since this maneuver is highly dynamic in nature and requires coordinated crew effort, an in-flight review of the procedures that will be executed upon maneuver initiation will be accomplished by the crew in each aircraft. Once both aircraft call ready, the TC will direct the practice separation. The pseudo-receiver will reduce power and initiate descent, initially

targeting 1,000 feet below the pseudo-tanker and targeting 1,000 feet per minute descent rate while maintaining visual contact with the pseudo-tanker. Simultaneously, the pseudo-tanker will advance power and maintain level flight. Once the pseudo-receiver has established safe separation between aircraft, but no earlier than 2 ship lengths separation, the pseudo-receiver will terminate the maneuver and the maneuver block will be complete.

POST-TEST BRIEFING

All personnel associated with the test execution will attend a post test briefing. Items to be discussed at the post test brief may include, but are not limited to: results, analysis, conclusions, recommendations, and lessons learned.

GO/NO-GO

The following items will be constitute Go/No-Go criteria:

- Operational Have Double Vision Stereo Vision System

- Operational Truth Data Source pair on Lead and Trailing Aircraft

This page was intentionally left blank.

APPENDIX E: FORMATION POSITION REFERENCE SLIDES



HAVE Double Vision C-12 Simulated Aerial Refueling Formation Position References

**Maj Erik Hillard
TPS Class 18B
March, 2019**



Overview



1

- **Restrictions**
- **“Contact” Position Definition**
- **Optimum Positions (Side & Top Views)**
- **Reference Markings**
- **Reference Images**
 - **Astern**
 - **Contact**
 - **Left/Right Limits**

2



Restrictions



- **Minimum distance between aircraft = 27 feet**
 - Based on AFI 11-2FT Vol 3, Para A7.3.4
 - Uses closest point of approach for each aircraft
 - Lead: Aft end of fuselage
 - Trail: Top of prop arc
 - This is conservative since the aircraft in this test were “cooperative” aircraft whereas AFI restrictions were for “non-cooperative” aircraft.
 - The minimum “slant range” spacing of $\frac{1}{2}$ the wingspan of the largest aircraft was used in place of the “lateral” spacing defined in the AFI

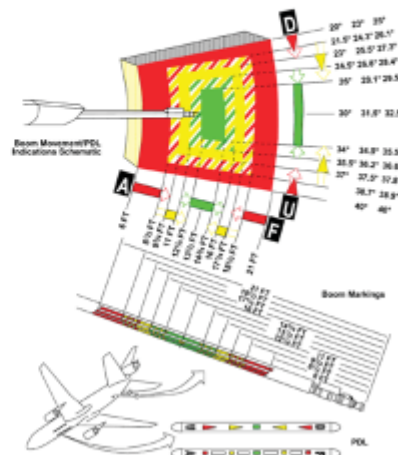
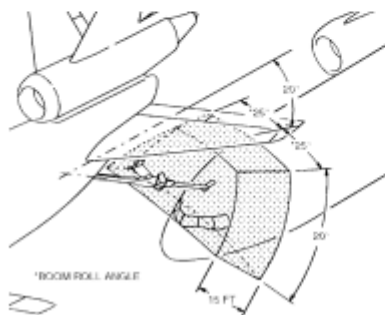
3



Optimum Position Definition



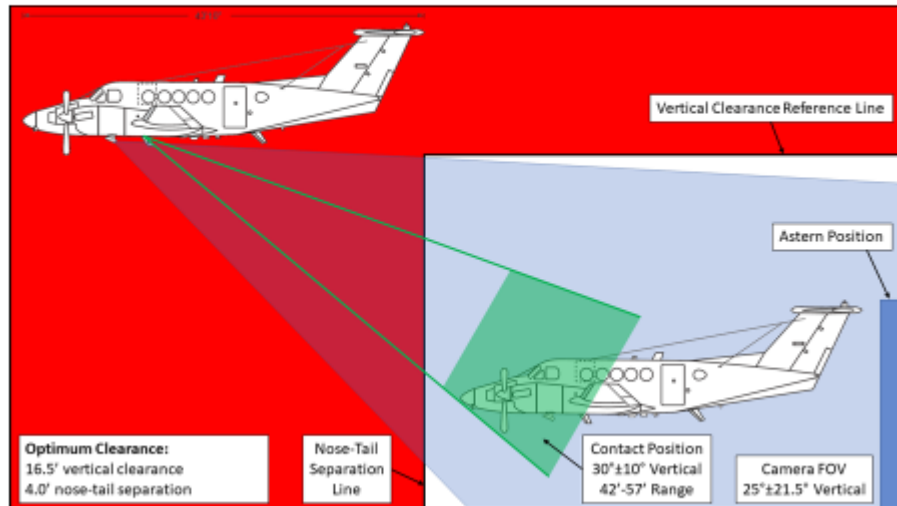
- “Contact” position based on KC-10 envelope
 - Vertical: $30^{\circ} \pm 10^{\circ}$
 - Horizontal: $0^{\circ} \pm 25^{\circ}$
 - Range: $49.5' \pm 7.5'$



4



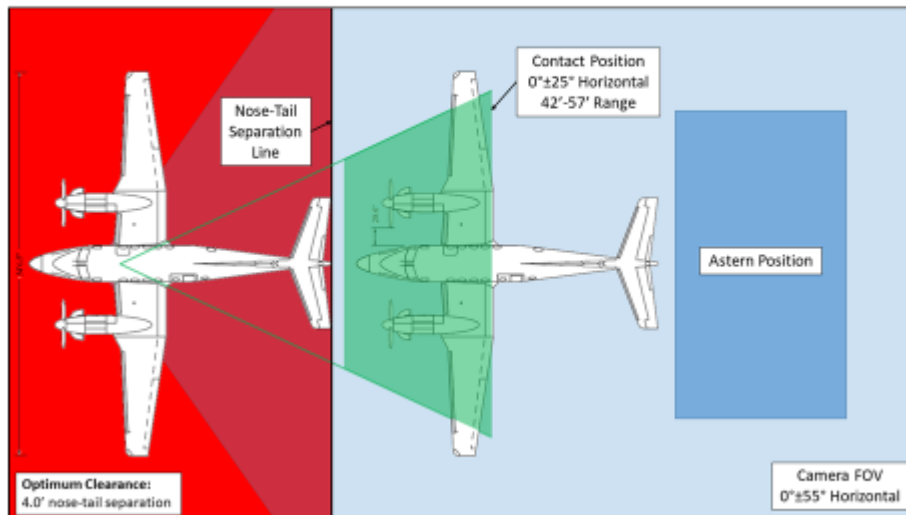
Optimum Position (Side View)



5



Optimum Position (Top View)



6



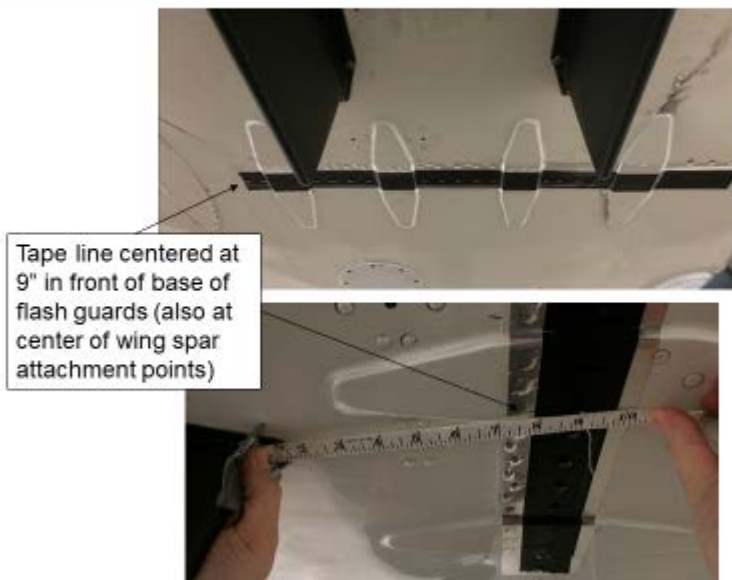
Reference Markings



- Prop arcs with leading or trailing edges of wings
- Speed/Duct tape reference lines on underside of fuselage
 - Speed tape = 3" width
 - Duct tape = 2" width
 - Aft reference = Black flash guards (x2)
 - Tape line = 9" forward of base of flash guards
 - Forward reference = Forward VHF antenna
 - Aft tape line = 12" forward of base of VHF antenna
 - Fwd tape line = 23" forward of base of VHF antenna

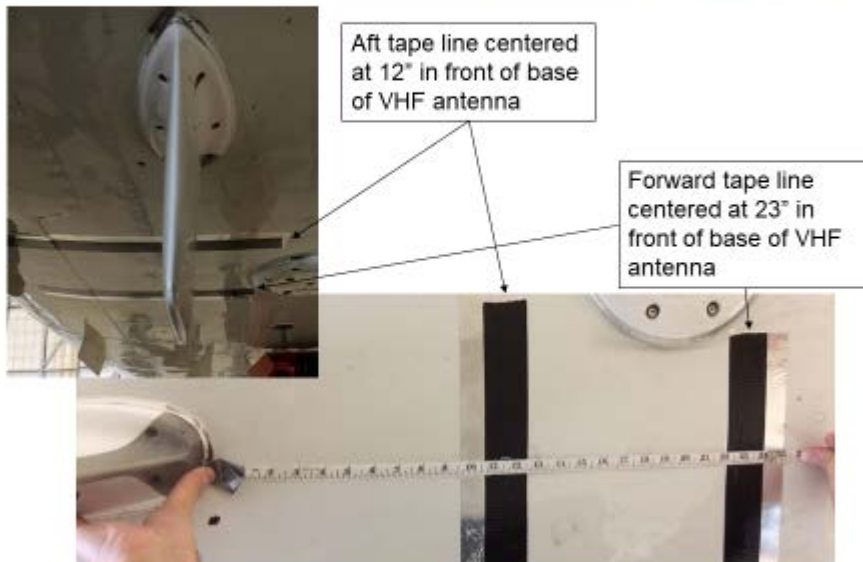


Aft Reference Markings





Forward Reference Markings



9



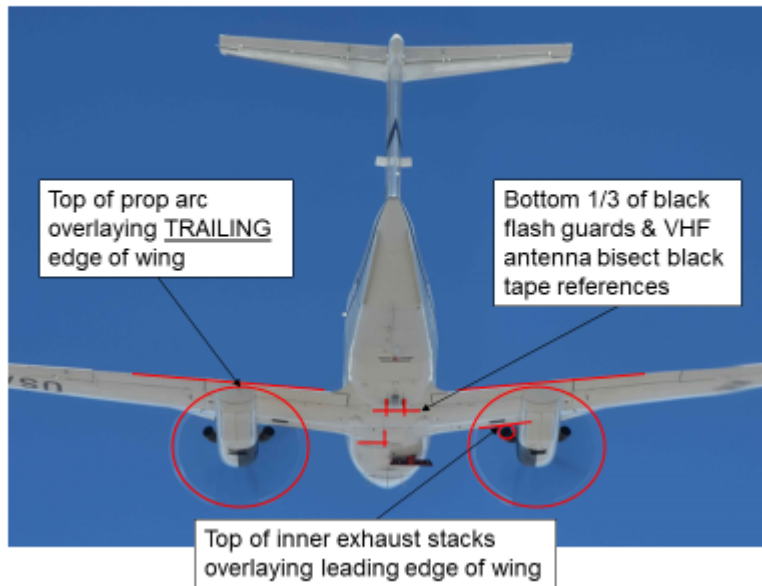
Astern (Optimum)



10



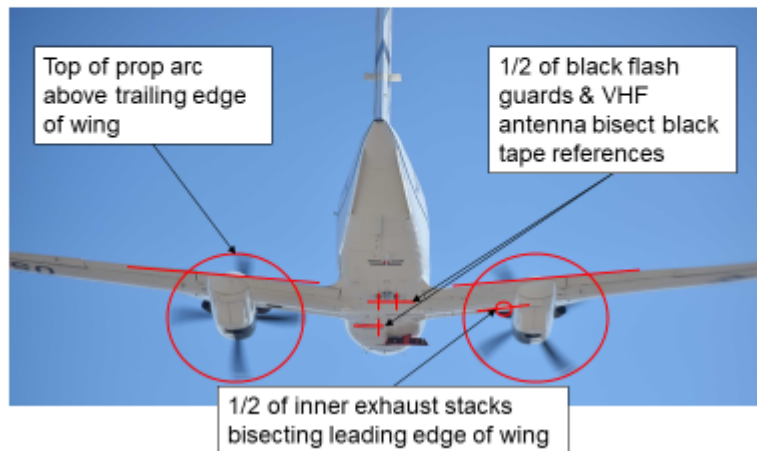
Astern (Optimum)



11



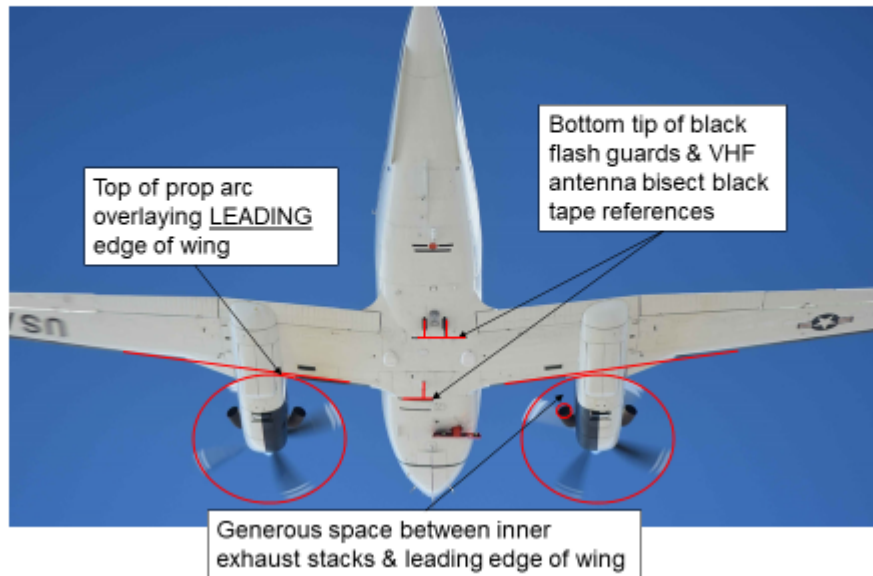
Astern (Too High)



12



Astern (Too Low)



13



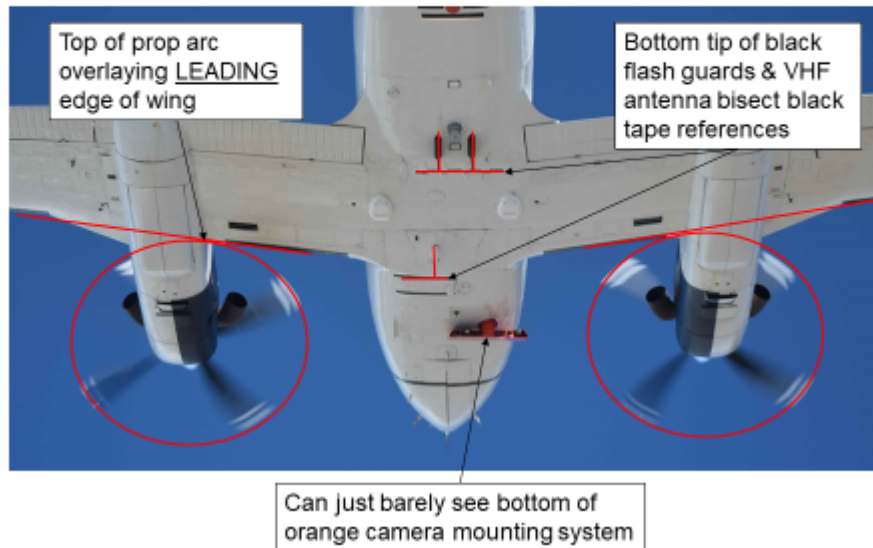
Contact (Optimum)



14



Contact (Optimum)



15



Contact (Copilot View)



This picture makes it look like the contact position is much further away than it really is.

The tail section of the lead aircraft will not be visible unless leaning very far forward in the seat, which is not recommended while flying (have the PNF do this when stable and then give verbal cues).

Depending on sitting height, there won't be much space (if any at all) between the top of the window frame and the trailing edge of the wing of the lead aircraft.

16



Contact (Tail View)



The PF will NOT see this while flying

17



Contact (Tail View)



This is what the PNF should see with the aircraft in the contact position if leaning forward in the seat.

Aft end of the fuselage bisects 1/2 of the ___ antenna on the vertical stabilizer.

The PF will NOT see this while flying

18



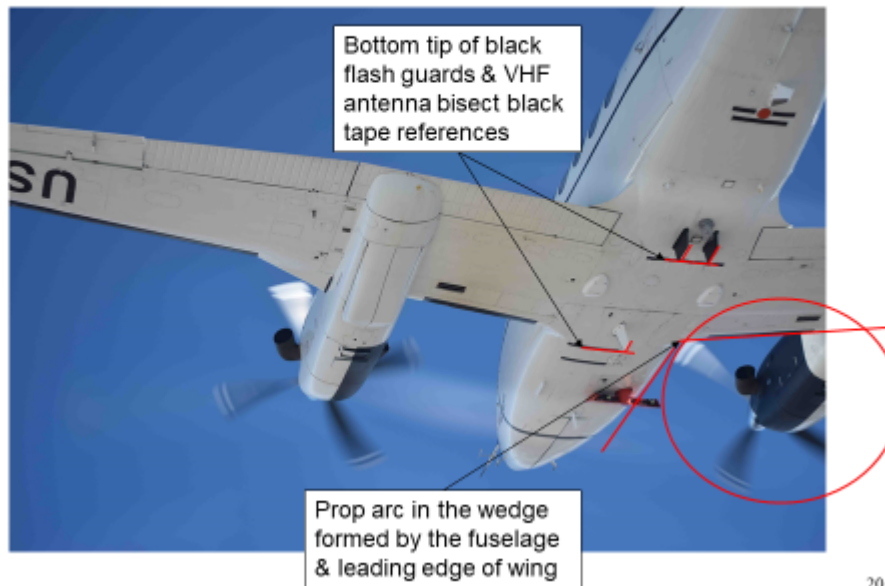
Left Limit (Optimum)



19



Left Limit (Optimum)



20



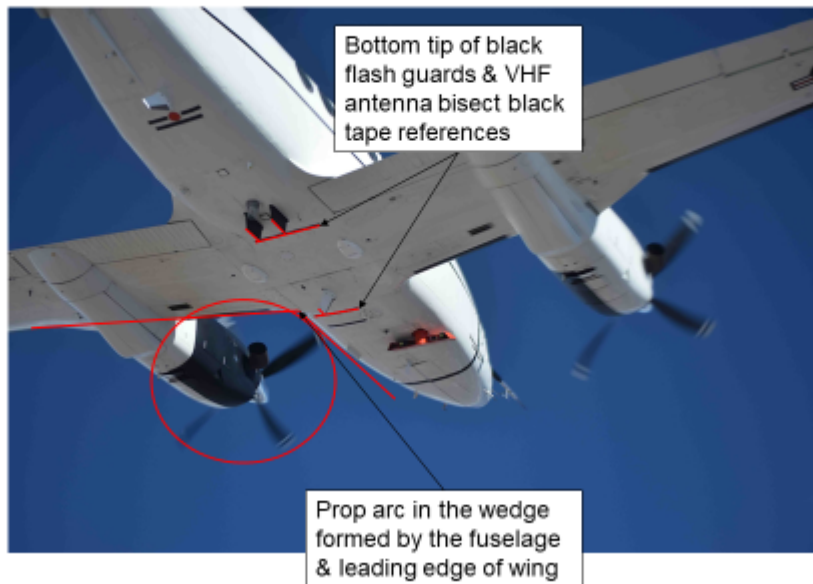
Right Limit (Optimum)



21



Right Limit (Optimum)



22



Left/Right Limit (Copilot View)



Left Limit



Right Limit



23



Summary



- Restrictions
- “Contact” Position Definition
- Optimum Positions (Side & Top Views)
- Reference Markings
- Reference Images
 - Astern
 - Contact
 - Left/Right Limits

24



Questions?



25

This page was intentionally left blank.

APPENDIX F – ICP PERFORMANCE STATISTICAL ANALYSIS

Correlation for data thinning

In order to determine the number of independent samples that could be obtained from a single 10 second stable maneuver, several 10 second points were analyzed with the TPS Stats MATLAB tool using the partial autocorrelation function. This determined that 3 samples from a 10 second window would be independent. For the EO case, we could reasonable select 5 samples and skip every 15-20 image pairs while the IR required skipping 40 image pairs to obtain an independent sample. Since there were only 100 image pairs per 10 second stable window we selected 3 image pairs to be consistent with both the EO and IR case.

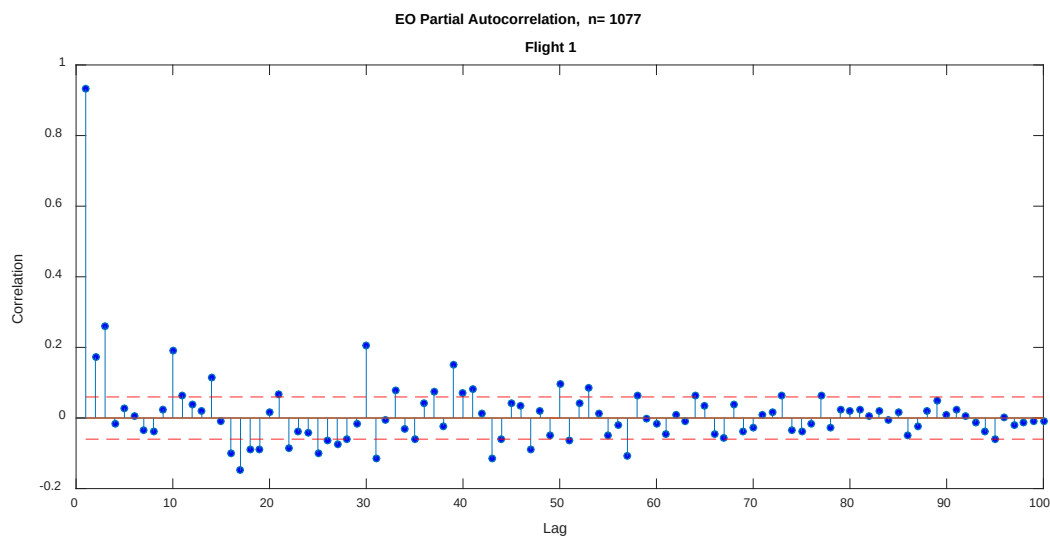


Figure F1: EO Partial Autocorrelation results – Flight 1

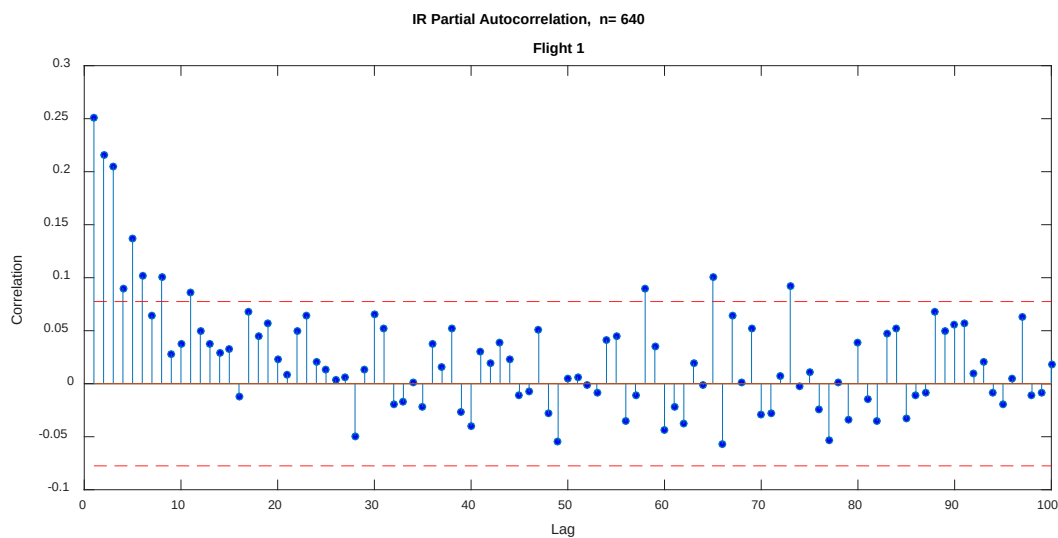


Figure F2: IR Partial Autocorrelation results – Flight 1

IR Low Sample Power Calculations

Figure F3 shows sample power calculations for the EO and IR Mountain High vs Mountain Low conditions. The TPS Statistics toolbox 2015 v3.181 was used. A 2 sample test was used with two tails to determine if we could consider the means equal. The R (slant Range) error was used to determine the standard deviation of the error, and the mean error at each condition. For the limited number of samples collected in IR, the small difference of the means can be compared with a 95% confidence at 29% power level. This was much too low to place statistical confidence in the results. Compared to the EO samples collected for the same data points, 95% confidence can be compared with a 99% power level. For the rest of the

Power for a 2-Sample t-test IR	Power for a 2-Sample t-test EO
Leave a blank for a bold parameter to compute:	Leave a blank for a bold parameter to compute:
sample std dev 1, s_1 Mountain High 1.235	sample std dev 1, s_1 Mountain Low 1.953
sample std dev 2, s_2 Mountain Low 1.841	sample std dev 2, s_2 Mountain High 1.414
True $ \mu - \mu_0 $ 1.01	True $ \mu - \mu_0 $ 1.611
Number of Samples 1, n_1 9	Number of Samples 1, n_1 53
Number of Samples 2, n_2 15	Number of Samples 2, n_2 41
Power 0.28528	Power 0.99279
Significance level, α 0.05	Significance level, α 0.05
Tail, input 1 or 2 2	Tail, input 1 or 2 2
OK Cancel	OK Cancel

Figure F3: Sample Power Calculations for EO and IR, Mountain Low vs Mountain High

Environment Correlation

In order to complete the statistical analysis of the mean error the following statistical analysis was completed in Excel.

1. Set Alpha to 0.05 for 95% confidence.
2. Compute the sample standard deviation using the STDEV.S function for each condition (Desert Low, Mountain High, etc).
3. Calculate n for total number of samples used to determine the degrees of freedom.
4. Calculate the p value for Desert (High versus low), Mountain (High versus low), Low (Desert versus Mountain) and High (Desert versus Mountain) using the TTEST function with two tails and unequal variance.

This used a two sample unpaired T-test for all conditions. The null hypothesis was that mean $X_{\text{mtn_H_error}} = X_{\text{mtn_L_error}}$. The output of the TTEST function (p value) is shown in table F1 and F2.

Table F1. EO/IR Environment Correlation Results - Translational

EO Stats relationship	X (p val)	Y (p val)	Z (p val)	R (mag) (p val)
Desert High v Low	0.043	0.844	0.331	0.690
High Mountain v Desert	8.64e-14	0.256	0.711	0.580
Mountain High v Low	0.009	0.252	0.060	0.079
Low Mountain v Desert	3.25e-8	0.030	0.022	0.013

Table F2. EO/IR Environment Correlation Results - Rotational

EO Stats relationship	Roll (p val)	Pitch (p val)	Yaw (p val)
Desert High v Low	0.132	0.865	0.314
High Mountain v Desert	0.483	0.004	0.855
Mountain High v Low	0.053	0.776	0.866
Low Mountain v Desert	0.399	0.013	0.280

The resulting p value determined whether or not the two conditions mean error could be assumed statistically equal or not. If the p value was lower than 0.05 the null hypothesis (mean $X_{\text{mntn_H_error}} = X_{\text{mntn_L_error}}$) was rejected and the mean error was not equal and independent points could not be combined. A p value higher than 0.05 resulted in a failure to reject the null hypothesis, so the mean error was not assumed to be statistically different. This allowed combining the independent points of those two conditions. The resulting mixture of results for different variables (x,y,z, etc) suggested some trends that the desert and mountain backdrops were statistically different in low altitude, but not high altitude. This would require more analysis to determine at what altitude the difference in background no longer mattered. Since there was not a clear division in conditions that was consistent across all variables, the accuracy and precision for each condition was shown separately.

APPENDIX G – DATA ANALYSIS PLAN

Run Notes for Raw images to data:

Run Camera Calibration

create folder for that date's camera calibration
copy raw calibration images to this folder and separate by EO or IR
convert images to .bmp (see instructions below, may only be necessary for EO and not IR)
sort into different folders for left and right cameras
-> open powershell (LShift + RClick) in the folder with the images
-> command will be (using EO as an example):
move *L_eo.bmp Left
-> can now easily move the remaining right camera images to the proper folder

Open MATLAB

change filepath to the folder named EO or IR for that flight
Open the Stereo Camera Calibrator app from the top menu
Click "Add Images", then browse so Camera 1 = Left, Camera 2 = Right
-> EO = 25 mm, IR = 30 mm, then click ok and let it process for several minutes
-> the program will only keep images where the entire checkerboard was visible, and corners for each individual square are detectable
When done analyzing images, hit the "Calibrate" button, let it run for several minutes, then save the session as .mat file
-> can manually delete some images that look bad and cause outliers, then re-save if desired
Close Stereo Camera Calibrator app
find a copy of stereoParamsToDAT.m and paste it in the EO or IR folder as required
In MATLAB command window, run stereoParamsToDAT.m
-> optional to clear workspace and command window
-> name of calibration file should be: calibrationSession.mat
-> 6 files ending in .dat should appear in the current folder
-> will need to move these 6 files to the appropriate directory before running AAR below

How to select images:

Look at TC Notes for the flight
open pulse reference.xlsx (desktop)

copy stable contact reference pulses into excel for reference

Find images on external hard drive and copy (do not cut + paste) into selected flight folder for both EO and IR

-> Raw images should be at: E:\Edwards March 2019
-> should have exactly 100 images per camera during each 10 second stable contact window

Convert EO images to .BMP

Make a new folder with the selected images if not already done above
example: flight 1 is at G:\HAVE_DOUBLE_VISION\Active\Flight1\images

Copy and paste file location into aftr.conf file for the convert
C:\repos\ABurn\usr\shadows\aarImageProcessing <- use this directory to find the correct aftr.conf file
lines 99 and 101 (make sure file path has / not \
save aftr.conf

open (LeftShift, right click) powershell in C:\repos\ABurn\usr\shadows\aarImageProcessing\cwin64
(location of convert)
up arrow key until the command below is found: then hit enter
./AARImageProcessing.exe convert

verify images in folder were converted.
Delete .rgb files

Convert IR Files to .BMP

within folder with IR images, right click and open Git Bash Here window
hit up arrow so the following command appears, then hit enter:
find ./ -name "*.pgm" -type f -print | xargs -I{} -n1 -P 24 magick mogrify -format bmp {}

Now need to change the name of IR images for processing them "as EO", use WindowsPowerShell (LShift,
Rclick) to run:
dir | rename-item -NewName {\$_.name -replace "ir", "eo"}

Run AAR

open Shadows folder, C:\repos\ABurn\usr\shadows
select EO or IR to process by clicking on the folder ending in EO or IR as required
verify aftr.conf (config) file is updated with:
imagery directory (line 360? and 371)
RelNav file (line 369) (must be the .log_RelNav file from
G:\HAVE_DOUBLE_VISION\Active\FlightXXX)
save aftr.conf file

Verify camera calibration .dat files are copied to the correct directory:
IR C:\repos\ABurn\usr\shadows\AAR-tps-edwards2019-IR\resources\matlabManualIntrinsic
EO C:\repos\ABurn\usr\shadows\AAR-tps-edwards2019-EO\resources\matlabManualIntrinsic
-> calibration .dat files for each flight are saved in desktop folders for each date

Ensure Images are in the correct file referenced in aftr.conf from above

Open AAR.sln file in the appropriate drive
-> IR: C:\repos\ABurn\usr\shadows\AAR-tps-edwards2019-IR\cwin64

-> EO: C:\repos\ABurn\usr\shadows\AAR-tps-edwards2019-EO\cwin64

ctrl + F5 to open the program

LeftShift o (loads config file)

LeftShift [(pauses and allows to jump to a point)

Open output file in:

C:\repos\ABurn\usr\shadows\AAR-tps-edwards2019-IR

C:\repos\ABurn\usr\shadows\AAR-tps-edwards2019-EO

Once complete, navigate to solution file and cut+paste (need to remove from directory before you run another data set) to the desired folder for MATLAB analysis

-> current desired location is on the G:\ drive in the "Flight X" folder at G:\HAVE_DOUBLE_VISION\Active

Open .log file and replace header with:

#ImgNum, SensedPosZ, SensedPosX, SensedPosY, SensedR, SensedP, SensedY, SensedMag, SensedRMS, GPSWeek, GPSSecondsInWeek, TruthPosZ, TruthPosX, TruthPosY, TruthR, TruthP, TruthY, TruthMag

delete all (and)

import to matlab

import and rename

Make AAR run like the aircraft (i.e. nondeterministic)

Use the EO NRT (Near Real Time) version of the code

open C:\repos\ABurn\usr\shadows\AAR-tps-edwards2019-EO -NRT\cwin64

On the left side of the screen expand the AAR tree, then the Source Code Tree

Find GLViewAARBoomOcclusion.cpp and open

Scroll to line 2034 where you will find the following code:

```
2034 //For deterministic replay of every single data point, use a simple monotonically incrementing index counter,
2035 //To match wall clock time, use getNextNearestDatum()...
2036 //this->tpsDataWalker.getNextNearestDatum(); //To O(n) iterate each data point deterministically, change
      .getNextNearestDatum() to static size_t idx = 0; idx++; this->tpsDataWalker.getData().at(idx)
2037 size_t idx = this->tpsDataWalker.getPlaybackLocationIdx();
2038 if( idx < this->tpsPlaybackDataWalkerIdx )
2039     idx = this->tpsPlaybackDataWalkerIdx;
```

On line 2036 make sure the "/" at the beginning is deleted

****MAKE SURE TO UNDO OR CORRECT IF REVERTING--THIS EFFECTS ALL AAR.sln PROGRAMS!!!!**

Aftr.conf example file (see run notes for information)

This file is a reference file for the AAR program to locate the appropriate location for the images and Geodetics RelNav files. This also contained correction factors such as lever arm corrections for the Geodetics IMU to the camera frame of reference. When opened in the native program this also lists line numbers that were used as references.

```
#####
#This file contains variables and values that are stored in the
#ManagerEnvironmentConfiguration. Any variable/value pair can be
#retrieved.
#All variable names and their corresponding values are converted
#to use lower case unless quotes are placed around each element.
#
# Example Aftr.conf body:
#
# playerName="Scott Nykl"
# gameLevel=3
# "EnableGravity"=1
# "DisableBlackholes"=0
# maxVelocity=123.456
# "UserPassword"="Aftr Engine Rocks"
#
# //Inside the module code, retrieve the above values
#
# std::string modelPath = ManagerEnvironmentConfiguration::getSMM() + "/robotModel.3ds";
# std::string playerName = ManagerEnvironmentConfiguration::getVariableValue( "playerName" );
# int level = Aftr::toInt( ManagerEnvironmentConfiguration::getVariableValue( "gameLevel" ) );
# int gravityEnabled = Aftr::toInt( ManagerEnvironmentConfiguration::getVariableValue( "\"EnableGravity\"" ) );
# bool disableBlackHoles = (bool) Aftr::toInt( ManagerEnvironmentConfiguration::getVariableValue(
  "\"DisableBlackHoles\"" ) );
# float maxVel = Aftr::toFloat( ManagerEnvironmentConfiguration::getVariableValue( "maxVelocity" ) );
# std::string userPass = ManagerEnvironmentConfiguration::getVariableValue( "\"UserPassword\"" );
#
#Below are some built in configuration parameters
#####

#-----
#OpenGL Context, Version, and Debugging Settings
#glcontextprofile specifies which profile mode the OpenGL context uses.
# glcontextversion MUST be 3.2 or greater for this to be a value other than "compatibility".
# Valid choices are "compatibility", "core", or "es", defaults to "compatibility".
#glcontextversion Specifies which version of an OpenGL Context to create. A valid OpenGL Version
# must be supplied or context creation may fail.
# Using a value of 2.1 is the most compatible, uses older GLSL built-ins, and does not have Compute Shaders.
# Using a value of 3.2 or later provides "modern OpenGL" context.
# Using a value of 4.3 or later provides compute shaders and is similar to using OpenGL ES 3.1.
# Hardware must support the version. Defaults to 2.1 if not specified.
```

#gldebugmessagecallbackisenabled determines if glDebugMessageCallback is enabled or not. When set to a value other than 0 or false, OpenGL Debug Information will be printed to standard out. Defaults to 0 (false)

glContextProfile=compatibility

glContextVersion=4.3

glDebugMessageCallbackIsEnabled=0

#-----

#####

General Settings

#####

showCamFrusta=1

showGlobalAxes=0

showStereoFBOs=0

#Turns on and off the 4 stereo displays that show TPS footage (or images loaded from file/directory)

showTPSStereoFBOs=1

#When replaying TPS data from disk, these FBOs show the image.

#Size is determined where 1.0 is full width of screen. Since there are two,

#max size ought to be 0.5.

TPSStereoFBOHorzSize=0.20

showTankerBoom_Normal=0

#showTankerModel=KC46

showTankerModel=C12

#showTankerModel=DallmannWagonTanker

showGeodeticsPrimaryUnit=0

showGeodeticsSecondaryUnit=0

OutputVecTankerToRecvInTankerBodyFrame=0

showTerrainWPAFB=0

#Zoom18 is lower res imagery over a larger area

showTerrainWPAFBZoom18=0

#UpdateTerrainPoseRelativeToTanker is helpful when you are playing back a log file and

#want some terrain to remain below the tanker during flight.

#This will cause the altitude of the terrain to be incorrect as the terrain is shifted to

#approximate the aircraft's altitude.

UpdateTerrainPoseRelativeToTanker=0

showTerrainEdwardsAFB_All=0

showTerrainEdwardsAFB_A=1

showTerrainEdwardsAFB_B=0

showTerrainEdwardsAFB_C=0

showTerrainEdwardsAFB_D=0

showfps=0

playbackSpeed=4.0

enableSolutionLoggingToFileAndConsole=1

#####

Shadow Volume Settings

#####

showLeftLightVolume=0

showRightLightVolume=0

```

showLeftShadowVolume=0
showRightShadowVolume=0
showLeftSilhouettePoints=0
showLeftSilhouetteRing=0
showRightSilhouettePoints=0
showRightSilhouetteRing=0

#####
#      Terrain Settings      #
#####
#For WPAFB Zoom 18 use 3900
tankerAltitudeAboveTerrainMeters=1500
#For WPAFB Zoom 18 use 3600
tankerHorzOffsetFromTerrainCenterMeters=0

#####
#  Settings for Image Processing  #
#####
#Size of each point graphic for point cloud
pointSizeInMetersXY=0.55

#Enable or disable 3DVW auto calibration file (reads in
AAR\resources\calibrationOutputData\3DVWCheckerboardAutoCal.yml)
#This value must be set to zero to ignore 3DVWCheckerboardAutoCal.yml and use external sources like Matlab and
Veneable's code
#Loads (Q,R1,R2,P1,P2,M1,M2,D1,D2)
useCalibrationFileAutoGeneratedFrom3DVWCheckboard=0
#Number of calibration images to use
numberCalibrationImages=10
#Show calibration images
showCalibrationCorners=0
#Show disparity map each frame
showDisparityMap=0

#Number of disparities must be a multiple of 16 - 256 for EO
numDisparities=256
#SAD Window Size needs to be odd - 11 for EO
SADWindowSize=11

#Show ICP Reference Point Cloud
showReferencePC=1

#Perform ICP every iteration
performICP=1

#####
#  Settings for Boom Occlusion  #
#####
performBoomOcclusion=0

```

```

#Zach's boom occlusion loads 3 booms. The "normal boom" is the original KC10 .3ds model that is properly texture
mapped.
#The "convex boom" is composed of 12 sub meshes where each mesh is a convex hull for silhouette computation
and point inclusion.
#The "intersection boom" is the "big or scaled boom" that was manually enlarged to capture a larger silhouette to
avoid sensing
#yellow dots on the surface/ silhouette edge of the normal boom when trying to filter those out for boom occlusion.
showTankerBoom_Convex=0
#TODO SLN: Ensure that convex boom (when tube is extended & retracted) perfectly matches the normal boom
(when tube is extended & retracted)
showTankerBoom_Intersection=0
intersectAgainstScaled=0
showRays=0

#####
#   Settings for Reference Model   #
#####
#Which reference model to use only one should be set true
#Set all to 0 for wings and nose model
useFullReferencePC=0
useShelledReferencePC=1
useWingsOnlyShell=0
useDallmannWagonReferencePC=0

useCalibrationFileAutoGeneratedFrom3DVWCheckboard=0
#Set above flag to zero and this flag to one to indicate that calibration parameters will be loaded from a separate
external source(s)
useCalibrationFileFromExternalSource=1

#(Prereq: useCalibrationFileFromExternalSource must be 1)
#Choose a source for the corresponding camera calibration inputs: MAT, VEN, TPS,
CALCULATE_VIA_OPENCV
#MAT:../resources/matlabManualIntrinsic/
#VEN:../resources/venableManualCal/
#TPS:../resources/tps/
##      double rms = cv::stereoCalibrate(objectPoints, imagePoints[0], imagePoints[1],
##                                     inM1, inD1, inM2, inD2, inImageSize, outR, outT, outE, outF, ... );
##      cv::stereoRectify( inM1, inD1, inM2, inD2, imageSize, inR, inT,
##                        outR1, outR2, outP1, outP2, outQ, ... );
#VEN or MAT
cali_intr_M1M2D1D2=MAT
#VEN, TPS, or MAT - This is also known as R_R_L
cali_stereo_R=MAT
#TPS or MAT - This is also known as l_T_r
cali_stereo_T=MAT
#VEN or TPS - This is also known as p_R_L, also loads L_p
cali_extr_R=TPS
#CALCULATE_VIA_OPENCV

```

```
cali_extr_R1R2P1P2Q=CALCULATE_VIA_OPENCV
```

```
TPS_Test_Image_Left=../resources/stereoimages/226L_ir.pgm
TPS_Test_Image_Right=../resources/stereoimages/226R_ir.pgm
#TPS_Test_Image_Left=../resources/stereoimages/1L_ir.pgm
#TPS_Test_Image_Right=../resources/stereoimages/1R_ir.pgm
```

```
#####
# Settings for Calibration Checkerboard #
#####
#Number of Chekerboard Corners (used with WOCheckerboard)
checkerboardCornersX=16
checkerboardCornersY=17
```

```
#####
```

```
#####
# Feature Extraction & Truth Output #
#####
ExtrinsicTruthPoseWithFeatureOutputDir=../capExtrinTruthPose/
ExtrinsicTruthPoseWithFeatureOutputFileName=features.txt
#####
```

```
#Set minimum time per frame. 16 ms is roughly 60 FPS
minmillisecperframe=16
```

```
#Explicitly tell SDL to turn Vsync off (vsync=0) or on vsync=1
#vsync=1
```

```
#Double Render into Oculus-compliant FBO for viewing with rift
#useOculusRift=1
```

```
##Width and Height, in pixels, of the window.
##Setting width and height to 0 will set the resolution to match
##the current resolution.
#Uncomment the line below and set to desired value.
```

```
#Keep these values matched to the Sofraidr LWIR cameras or EO Prosilica Cameras, depending on use
#width=1920
#height=1080
width=800
height=600
```

```
#Choose to either calculate EO results or IR results. One variable is used for both EO and IR to prevent a user from
accidentally trying to
#produce EO and IR results at the same time
#Use 0 to calculate EO results
#Use 1 to calculate IR results
calculateEOorIRResults=0
```

```

#calculateEOorIRResults=1

#-----
#Stereoscopic Camera Configuration for Tanker
#Specify Frustum Info for stereo cameras
stereoFrustumLensFocalLengthMM=16.44

#For Prosilica it is 1280x960 (This resolution must be set properly when using
cali_extr_R1R2P1P2Q=CALCULATE_VIA_OPENCV (not performing auto camera calibration))
#For ATOM 1024 it is 1024x768
stereoFrustumHorzSensorPixels=1280
stereoFrustumVertSensorPixels=960
#stereoFrustumHorzSensorPixels=512
#stereoFrustumVertSensorPixels=384

stereoFrustumHorzFOVDeg=56.0
stereoFrustumNearPlaneMeters=1.0
#36.225 meters is close to the edge of the floating TVs (this value will become irrelevant in the near future, but
saved for right now
#This was originally 5000m, but changed to 15000m to accommodate larger terrains
stereoFrustumFarPlaneMeters=15000.0
#Physical Separation of cameras
stereoBaselineSeparationMeters=0.5

#Location where the stereo camera "platform" is attached to the tanker.
#The cameras are 1/2 the baseline away from this point in a direction
#perpendicular to this vector aligned to the tanker's wings. (x,y,z).
#Camera mount point used for KC 46 without Wheels: #stereoAnchorPointInParentSpaceMeters=(-8.784, 0.0, -
6.492)
#Camera mount point used for C12 beneath co-pilot chair: #(3.49006, -0.23335, -1.73803)
#Camera mount point used for Will Dallmann's wagon pushing at AFIT (when using wagon_receiverxyz.3ds):
(...,...,...)
#These variables are used when showTankerModel= "KC46", "C12", or "DallmannWagonTanker", respectively.
stereoAnchorPointInParentSpaceMeters=(-8.311, 0.0, -7.031)
stereoAnchorPointInParentSpaceMetersWhenTankerIsC12=(3.49006, -0.23335, -1.73803)
#For Dallmann Wagon, EO Anchor Point is (-0.4355, 0.0525, -0.2603) and IR Anchor Point is (-0.4355, -0.045, -
0.2499)
stereoAnchorPointInParentSpaceMetersWhenTankerIsDallmannWagon=(-0.4355, 0.0525, -0.2603)

#For real TPS data, this can be set to what is bore sighted or other calibration data.
stereoCameraLeftRollPitchYawInDegInTankerBodyFrame= (0,-25,180)
stereoCameraRightRollPitchYawInDegInTankerBodyFrame=(0,-25,180)
#stereoCameraLeftRollPitchYawInDegInTankerBodyFrame= (0.0945465409761694,-
24.6275642167481,178.537500407622)
#stereoCameraRightRollPitchYawInDegInTankerBodyFrame=(0.226926581399621,-
24.6265014948131,178.215995462774)

#The location of the GPS antenna in the virtual world local body frame (North-West-Up) of the model (receiver or
tanker respectively)

```

```

receiverGPSLocationLocalBodyFrame=(-5.0633, 0.0, 1.6751)
tankerGPSLocationLocalBodyFrame=(6.03541, 0.04416, -0.83239)

#The lever arm measurement from the IMU to the GPS. This input must be local body frame (North-West-Up) and
not P-frame
receiverIMUtoGPSLocalBodyFrame=(-7.943, -0.234, 3.483)
tankerIMUtoGPSLocalBodyFrame=(3.3997, -0.512, 0.887)

boomAngleDegreesFromHorizontal=-30.0
#This boom offset is constant across both the KC46 and C12 as the tanker model
boomOffsetFromStereoAnchorPointInParentSpaceMeters=(-5.50100040, 0, 0.48050022)
#MAX_TUBE_EXT_METERS = 6.705m
#MIN_TUBE_EXT_METERS = 1.0524m... (6.705 - 1.0524) / 2 = 2.8263m
#boomExtensionInMeters=-2.8263

loadF15SEAtStartup=0
loadX47BAtStartup=0
loadC12AtStartup=1
loadDallmannWagonAtStartup=0
loadCheckerboardAtStartup=0

# The KC-46 position (8.311, 0.25, 7.031) puts the left camera center point origin at the center of the world frame
KC46Position=(8.311, 0, 7.031)
F15SEPosition=(18.95, -1.6, 34.80)
X47BPosition=(19.5, 2.8, 33.80)
C12Position=(-20.67, 0, -7.78089)
DallmannWagonPosition=(-20.67, 0, -7.78089)
CheckerboardPosition=(-18.0, 0, -9.75)

#C12 Options
showC12NoseMarker=0
showBladesOnThePropellers=0
C12NoseLocationBodyFrame=(6.67, 0.000, -1.21911)
C12AntennaLocationBodyFrame=(3.19,0.00,0.04)
C12PropLeftLocationBodyFrame=(5.25, 2.59,-0.90)
C12PropLocalRotPoint=(0, 0.00389, -0.22919 )
C12PropRotationVelDegPerSec=3
#EdwardsAFB_C12_Tail_158_Boresight=coordFrame_IMU_C12_Tail_158_EdwardsAFB_March2019.conf
EdwardsAFB_C12_Tail_161_Boresight=coordFrame_IMU_C12_Tail_161_EdwardsAFB_March2019.conf

#####
# Data Traversal: Log Playback Config #
#####
####Determines which type of log file to play back. Options listed below. Restart module after changing this.
#absolute - This plays back a BlueMax tanker/receiver log file (.tdf), probably one of Dan Johnson's files. This
replay the both absolute tanker / receiver tdf files.
#relative - Replay a single relativeLogFile; expects log file to contain relative position between tanker/recv versus
two absolute tdf files

```

#tps_data - Plays back MetaLog data which contains images and truth data indexed via a MetaLog file produced from AARImageProcessing

This could be data collected in Sept 2017 at Edwards AFB via Tom Stuart's (JIFKO) TPS experiments (HAVE VISION)

or Will Dallmann's "Pushing the Wagon through AFIT's parking lot"

or in the March 2019 at Edwards AFB via (HAVE DOUBLE VISION)

#dir_of_Images - Plays back images in a directory without trying to parse a log file (a MetaLog file)

#logFilePlaybackType=relative

#logFilePlaybackType=absolute

#logFilePlaybackType=live_stream_via_netmsg

logFilePlaybackType=tps_data

#logFilePlaybackType=dir_of_images

#When replaying a MetaLog truth file, the Geodetics system only gives high accuracy for the relative

#distances between the tanker (primary) and receiver (secondary). In other words, the tanker's GPS location

#drifts by a few meters here and there -- this is annoying. By uncommenting these settings AND using

#the setting "logFilePlaybackType=tps_data", the tanker get placed and oriented as specified below.

#If one only needs to override the primary position, only uncomment the Lat/Lon/Alt (LLA), if only

#need to override the pitch or roll, only uncomment out those. So far, it doesn't seem like overriding

#yaw (heading) is necessary. TPS data and Dallmann data will likely want to use these for certain processing

#parts. This overriding actually takes place within the WOGeoRelNav::updatePoseFromRelNavMsg0x06(const AfrLogDataRYORelNav0x06& msg)

#method. All settings are populated normally, but then the values below override the primary unit's pose.

#Use this position for the actual parking lot LLA

TPSData_OverrideTankerPosLLA=(39.782529, -84.081495, 296.9)

#Use this position for the Edwards AFB TPS Hangar

TPSData_OverrideTankerPosLLA=(34.91461414, -117.89657349, 804.79388453)

#Use this position to get correct ICP results per conversation on 18 Jan 2019

#TPSData_OverrideTankerPosLLA=(39.78533041, -84.09112284, 0.51723236)

#TPSData_OverrideTankerRollDeg=0

#TPSData_OverrideTankerPitchDeg=10

#For AFIT Parking lot using Dallmann trailer, use 274 deg

#For Edwards AFB TPS hangar, use around 300 deg

TPSData_OverrideTankerYawDeg=240

#For AFIT Parking lot using Dallmann trailer Nov 25 data set, use -9 deg

TPSData_GeoRelNavYawCorrection=-9

TPSData_CameraLocationWhileStreamingImagery=(-527.253479, -14.716530, 1021.408203)

TPSData_CameraLookDirWhileStreamingImagery=(0.989494, -0.069217, 0.127012)

#####

#####

This Section Handles replaying data from files stored on a disk, including TPS Data

#This points to a MetaLogger generated .log file produced from a data collect.

#When using logFilePlaybackType=Dir_of_Images

#Dir_Of_Images_PlaybackDirectory=D:/Flight Test Data/13 Sep/3. 13 Sep Mountains Contact/BMPs/Subset for Processing/Test Subset

#Dir_Of_Images_PlaybackDirectory=C:/repos/aBurn/usr/shadows/AARImageProcessing/AAR Sample EO Data Collect With Log file and rgb images/Color/imgs/

```

#Dir_Of_Images_PlaybackDirectory=C:/repos/aBurn/usr/shadows/AAR_rectify/resources/stereoImages/
Dir_Of_Images_PlaybackDirectory=G:/HAVE_DOUBLE_VISION/Active/Flight3/startupimages

#Following 3 attributes are used when "logFilePlaybackType=tps_data", if the *_Images are set to
# empty, ie "EO_Images=", then the path specified in the meta log file will be used; otherwise,
# the path leading up to the filename will be replaced by the path specified here.)
TPS_PlaybackLogFile=C:/repos/aBurn/usr/shadows/AAR_tps_IR/resources/dallmann/Data_25Nov_official_1/2018
.Nov.25_20.44.25.6667097.UTC.log_relnav
TPS_PlaybackLog_IR_Images=C:/repos/aBurn/usr/shadows/AAR_tps_IR/resources/dallmann/Data_25Nov_official_1/IR
TPS_PlaybackLog_EO_Images=C:/repos/aBurn/usr/shadows/AAR_tps_IR/resources/dallmann/Data_25Nov_official_1/EO

TPS_PlaybackLogFile=G:/HAVE_DOUBLE_VISION/Active/Flight3/2019.Mar.11_17.36.14.0280162.UTC.log_relnav
TPS_PlaybackLog_IR_Images=G:/HAVE_DOUBLE_VISION/Active/Flight3/startupimages
TPS_PlaybackLog_EO_Images=G:/HAVE_DOUBLE_VISION/Active/Flight3/startupimages

#TPS_PlaybackLogFile=C:/repos/aBurn/usr/shadows/AAR_rectify/resources/Collection_27Sep/Data_Collect_One_27Sep/2018.Sep.27_14.51.38.6388996.UTC.log
#TPS_PlaybackLog_IR_Images=C:/repos/aBurn/usr/shadows/AAR_rectify/resources/Collection_27Sep/Data_Collect_One_27Sep/Collect_One_IR
#TPS_PlaybackLog_EO_Images=C:/repos/aBurn/usr/shadows/AAR_rectify/resources/Collection_27Sep/Data_Collect_One_27Sep/Collect_One_EO

#Dir_Of_Images_PlaybackDirectory=C:/repos/aburn/usr/shadows/aarImg/data/imgs/
#Set the starting and ending frame number. They are processed inclusively when using
logFilePlaybackType=dir_or_images
Beginning_FrameNum_In_Dir_Of_Images_Playback=87139
Ending_FrameNum_In_Dir_Of_Images_Playback=104005
#####

receiverLogFile=../Receiver_0927.tdf
tankerLogFile=../Tanker_0927.tdf
#relativeLogFile=../RelativeRecv_0927.tdf

showReceiverRibbon=0
showTankerRibbon=0
receiverRibbonLengthDataPts=30000
tankerRibbonLengthDataPts=30000
savePointCloudDataFromLog=0

#####
# Settings for Image Processing #
#####
#Enable line below to have this process be the video sink (receiver of images)
#live_stream_isVideoStreamReceiver=1
#NetServerListenPort=12680
###

```

```

#Enable the line below to begin streaming from the WOVideoStreamViewer to the server
#Don't forget to enable at least EO or IR imagery, too
#live_stream_StreamToRemoteServer=127.0.0.1:12680
#live_stream_Stream_Time_msec_BetweenNextImageSend=0
#Enable the line below to stream EO to RemoteServer
#live_stream_StreamEO=1
#Enable the line below to stream IR to RemoteServer
#live_stream_StreamIR=1
#####

#-----
##Specify the relative path from the Module's .exe to the shared
##multimedia folder and the local multimedia folder.
#Uncomment the line below and set to desired value.
#sharedmultimedpath can be quickly accessed via ManagerEnvironmentalConfiguration::getSMM()
#localmultimedpath can be quickly accessed via ManagerEnvironmentalConfiguration::getLMM()
#sharedmultimedpath="../../shared/mm/"
#localmultimedpath="../../mm/"

```

Translational and Rotational Accuracy and Precision:

The following MATLAB code was completed and adjusted for X, Y, Z, Roll, Pitch, and Yaw.

```

% Double Vision Data Analysis
% May 2019
% Drew Petry

clear all
close all
clc
format compact

% right click on .log or .xlsx filename, click import data, click import selection
% once data loads to workspace, click dropdown arrow and save as .mat file

% load data structure
Desert_Low_EO = load('Desert_Low_EO.mat');
Desert_Low_IR = load('Desert_Low_IR.mat');

Desert_High_EO = load('Desert_High_EO.mat');
Desert_High_IR = load('Desert_High_IR.mat');

Mountain_Low_EO = load('Mountain_Low_EO.mat');
Mountain_Low_IR = load('Mountain_Low_IR.mat');

Mountain_High_EO = load('Mountain_High_EO.mat');
Mountain_High_IR = load('Mountain_High_IR.mat');

% find error between sensed and truth position
diff_Desert_Low_EO = Desert_Low_EO.SensedMag-Desert_Low_EO.TruthMag;

```

```

diff_Desert_Low_IR = Desert_Low_IR.SensedMag-Desert_Low_IR.TruthMag;

diff_Desert_High_E0 = Desert_High_E0.SensedMag-Desert_High_E0.TruthMag;
diff_Desert_High_IR = Desert_High_IR.SensedMag-Desert_High_IR.TruthMag;

diff_Mountain_Low_E0 = Mountain_Low_E0.SensedMag-Mountain_Low_E0.TruthMag;
diff_Mountain_Low_IR = Mountain_Low_IR.SensedMag-Mountain_Low_IR.TruthMag;

diff_Mountain_High_E0 = Mountain_High_E0.SensedMag-Mountain_High_E0.TruthMag;
diff_Mountain_High_IR = Mountain_High_IR.SensedMag-Mountain_High_IR.TruthMag;

% find mean and standard deviation of error
mean_Desert_Low_E0 = mean(diff_Desert_Low_E0)
std_Desert_Low_E0 = std(diff_Desert_Low_E0)

mean_Desert_Low_IR = mean(diff_Desert_Low_IR)
std_Desert_Low_IR = std(diff_Desert_Low_IR)

mean_Desert_High_E0 = mean(diff_Desert_High_E0)
std_Desert_High_E0 = std(diff_Desert_High_E0)

mean_Desert_High_IR = mean(diff_Desert_High_IR)
std_Desert_High_IR = std(diff_Desert_High_IR)

mean_Mountain_Low_E0 = mean(diff_Mountain_Low_E0)
std_Mountain_Low_E0 = std(diff_Mountain_Low_E0)

mean_Mountain_Low_IR = mean(diff_Mountain_Low_IR)
std_Mountain_Low_IR = std(diff_Mountain_Low_IR)

mean_Mountain_High_E0 = mean(diff_Mountain_High_E0)
std_Mountain_High_E0 = std(diff_Mountain_High_E0)

mean_Mountain_High_IR = mean(diff_Mountain_High_IR)
std_Mountain_High_IR = std(diff_Mountain_High_IR)

% plots
figure
plot(diff_Desert_Low_E0, '-*')
hold on
plot(1:length(diff_Desert_Low_E0),diff_Desert_Low_E0*0+mean_Desert_Low_E0,'k--')
grid on
title('Desert Low Error, E0 Camera')
xlabel('Pulse Count')
ylabel('Error, (Sensed - Truth), m')
legend('Error', 'Mean')

figure
plot(diff_Desert_Low_IR, '-*')
hold on

```

```

plot(1:length(diff_Desert_Low_IR),diff_Desert_Low_IR*0+mean_Desert_Low_IR,'k--')
grid on
title('Desert Low Error, IR Camera')
xlabel('Pulse Count')
ylabel('Error, (Sensed - Truth), m')
legend('Error','Mean')

figure
plot(diff_Desert_High_E0,'-.*')
hold on
plot(1:length(diff_Desert_High_E0),diff_Desert_High_E0*0+mean_Desert_High_E0,'k--')
grid on
title('Desert High Error, E0 Camera')
xlabel('Pulse Count')
ylabel('Error, (Sensed - Truth), m')
legend('Error','Mean')

figure
plot(diff_Desert_High_IR,'-.*')
hold on
plot(1:length(diff_Desert_High_IR),diff_Desert_High_IR*0+mean_Desert_High_IR,'k--')
grid on
title('Desert High Error, IR Camera')
xlabel('Pulse Count')
ylabel('Error, (Sensed - Truth), m')
legend('Error','Mean')

figure
plot(diff_Mountain_Low_E0,'-.*')
hold on
plot(1:length(diff_Mountain_Low_E0),diff_Mountain_Low_E0*0+mean_Mountain_Low_E0,'k--')
grid on
title('Mountain Low Error, E0 Camera')
xlabel('Pulse Count')
ylabel('Error, (Sensed - Truth), m')
legend('Error','Mean')

figure
plot(diff_Mountain_Low_IR,'-.*')
hold on
plot(1:length(diff_Mountain_Low_IR),diff_Mountain_Low_IR*0+mean_Mountain_Low_IR,'k--')
grid on
title('Mountain Low Error, IR Camera')
xlabel('Pulse Count')
ylabel('Error, (Sensed - Truth), m')
legend('Error','Mean')

figure
plot(diff_Mountain_High_E0,'-.*')

```

```

hold on
plot(1:length(diff_Mountain_High_E0),diff_Mountain_High_E0*0+mean_Mountain_High_E0,'k-')
grid on
title('Mountain High Error, E0 Camera')
xlabel('Pulse Count')
ylabel('Error, (Sensed - Truth), m')
legend('Error', 'Mean')

figure
plot(diff_Mountain_High_IR, '-*')
hold on
plot(1:length(diff_Mountain_High_IR),diff_Mountain_High_IR*0+mean_Mountain_High_IR,'k-')
grid on
title('Mountain High Error, IR Camera')
xlabel('Pulse Count')
ylabel('Error, (Sensed - Truth), m')
legend('Error', 'Mean')

```

Published with MATLAB® R2015b

Camera Calibration Sensitivity:

<Insert Run Notes Here>

After MATLAB Stereo Camera Calibration is complete run the following script to create inputs into AAR

CONVERT STEREO PARAMS FROM MATLAB'S CAMERA CALIBRATOR APP TO DAT FILES

@author Will Dallmann @date 15 November 2018

```

clearWorkspace = input('\nDo you want to clear your current Workspace? (y/n): ', 's');
clearWindow = input('\nDo you want to clear your current Command Window? (y/n): ', 's');

if clearWorkspace == 'y'
    clc
end

if clearWindow == 'y'
    clear
end

calibrationFileName = input('\nEnter the name of the calibration file: ', 's');

```

```

load(calibrationFileName);

%Save k1, k2, p1, p2, and k3 for the left camera so they can be written to d1.dat
L_k1= calibrationSession.CameraParameters.CameraParameters1.RadialDistortion(1);
L_k2 = calibrationSession.CameraParameters.CameraParameters1.RadialDistortion(2);
L_p1 = calibrationSession.CameraParameters.CameraParameters1.TangentialDistortion(1);
L_p2 = calibrationSession.CameraParameters.CameraParameters1.TangentialDistortion(2);
L_k3 = 0;

% k3 is set to zero unless MATLAB outputs a value for k3
if
calibrationSession.CameraParameters.CameraParameters1.NumRadialDistortionCoefficients
== 3
    L_k3 = calibrationSession.CameraParameters.CameraParameters1.RadialDistortion(3);
end

%Write k1, k2, p1, p2, and k3 to d1.dat
leftCameraDistortion = fopen('d1.dat', 'w');
fprintf(leftCameraDistortion, '%.14f %.14f %.14f %.14f %.14f',L_k1, L_k2, L_p1, L_p2,
L_k3);
fclose(leftCameraDistortion);

%Save k1, k2, p1, p2, and k3 for the right camera so they can be written to d2.dat
R_k1= calibrationSession.CameraParameters.CameraParameters2.RadialDistortion(1);
R_k2 = calibrationSession.CameraParameters.CameraParameters2.RadialDistortion(2);
R_p1 = calibrationSession.CameraParameters.CameraParameters2.TangentialDistortion(1);
R_p2 = calibrationSession.CameraParameters.CameraParameters2.TangentialDistortion(2);
R_k3 = 0;

% k3 is set to zero unless MATLAB outputs a value for k3
if
calibrationSession.CameraParameters.CameraParameters2.NumRadialDistortionCoefficients
== 3
    R_k3 = calibrationSession.CameraParameters.CameraParameters2.RadialDistortion(3);
end

%Write k1, k2, p1, p2, and k3 to d2.dat
rightCameraDistortion = fopen('d2.dat', 'w');
fprintf(rightCameraDistortion, '%.14f %.14f %.14f %.14f %.14f',R_k1, R_k2, R_p1, R_p2,
R_k3);
fclose(rightCameraDistortion);

% Save the Intrinsic matrix for the left camera into M1.dat
leftCalibrationMatrix = fopen('M1.dat', 'w');
fprintf(leftCalibrationMatrix, '%.14f %.14f
%.14f\n',calibrationSession.CameraParameters.CameraParameters1.IntrinsicMatrix);
fclose(leftCalibrationMatrix);

```

```

% Save the Intrinsic matrix for the right camera into M2.dat
rightCalibrationMatrix = fopen('M2.dat', 'w');
fprintf(rightCalibrationMatrix, '%.14f %.14f
%.14f\n', calibrationSession.CameraParameters.CameraParameters2.IntrinsicMatrix);
fclose(rightCalibrationMatrix);

%Save the Translation vector into T.dat
translationMatrix = fopen('T.dat', 'w');
fprintf(translationMatrix, '%.14f %.14f
%.14f\n', calibrationSession.CameraParameters.TranslationOfCamera2);
fclose(translationMatrix);

%Save the Rotation matrix into R.dat
rotationMatrix = fopen('R.dat', 'w');
fprintf(rotationMatrix, '%.14f %.14f
%.14f\n', calibrationSession.CameraParameters.RotationOfCamera2);
fclose(rotationMatrix);

```

Published with MATLAB® R2015b

The output was 6 .dat files that are moved to the appropriate folder to for AAR processing.

Accuracy Data Analysis Methodology

1. Collect Images
2. Extract stable contact images from contact envelope according to operator notes in Appendix O.
3. Convert and process images in accordance with instructions listed in appendix G (convert to BMP, run AAR, etc)
4. Using AAR output .csv file, organize and decimate points to create condensed table of independent points grouped by condition (ex Mountain High)
5. Calculate Error (ϵ) (using Excel) using $\epsilon_i = \text{Sensed}_i - \text{Truth}_i$. (sensed and truth listed as column names) Calculate Error for all variables (X, Y, Z, R, Roll, Pitch, Yaw)
6. Using Excel, calculate the Mean error and standard deviation using the AVERAGE and STDEV.S functions for all variables.
7. Calculate the confidence interval for the mean error using the CONFIDENCE formula in Excel.

This page was intentionally left blank.

APPENDIX H – COORDINATE FRAMES

Table H1: Coordinate Frame Descriptions

Frame Name	Shorthand	Origin	X-direction	Y-direction	Z-direction
Pseudo-tanker body frame	P-frame	Top of TSPI IMU	Aircraft longitudinal axis (forward = positive)	Aircraft lateral axis (right = positive)	Aircraft directional axis (down = positive)
Pseudo-receiver body frame	S-frame	Top of TSPI IMU	Aircraft longitudinal axis (forward = positive)	Aircraft lateral axis (right = positive)	Aircraft directional axis (down = positive)
Right camera frame	R-frame	Center of camera focal plane	Camera right	Camera down	Camera forward
Left camera frame	L-frame	Center of camera focal plane	Camera right	Camera down	Camera forward

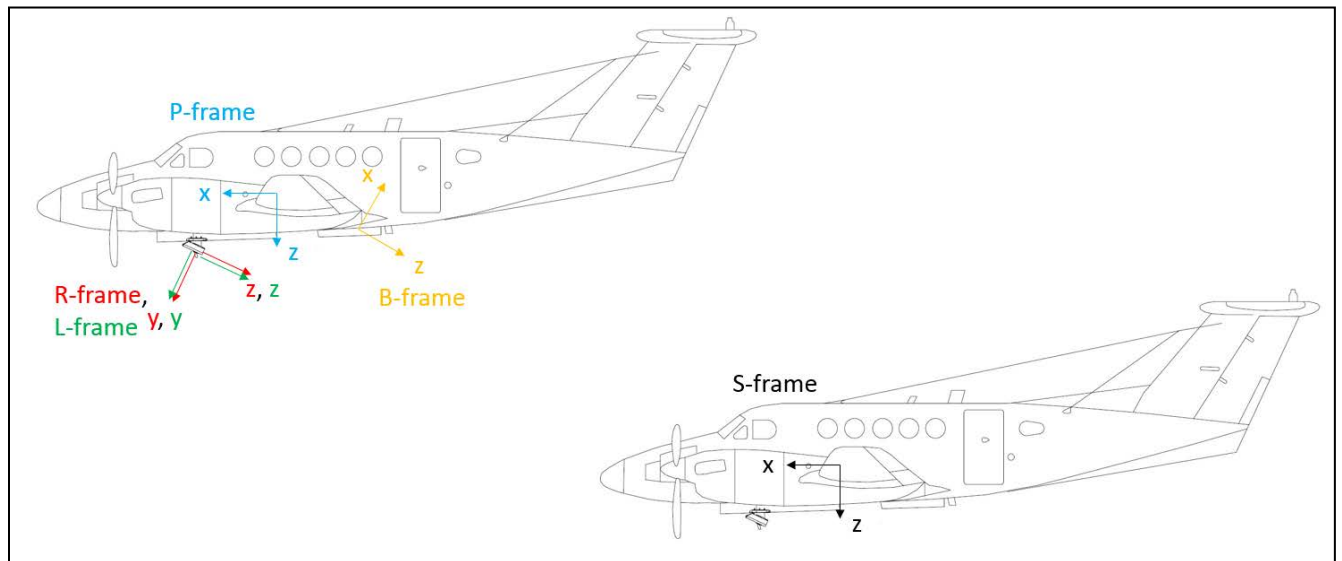


Figure H1: Coordinate Frames

This page was intentionally left blank.

APPENDIX I – SUPPLEMENTAL DATA

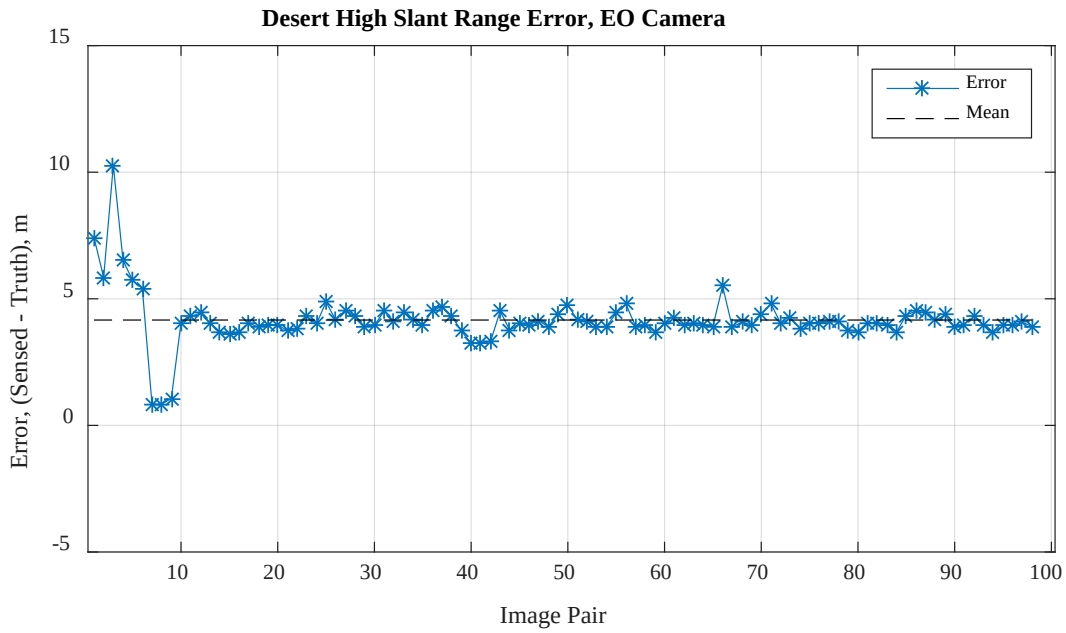


Figure I1: Desert High Slant Range Error, EO Camera

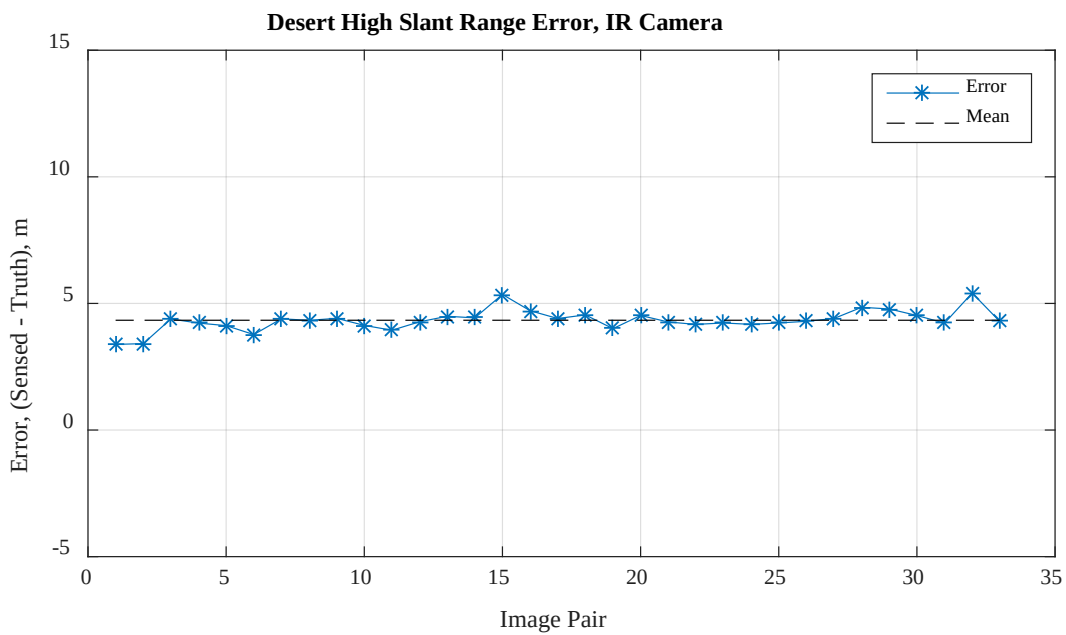


Figure I2: Desert High Slant Range Error, IR Camera

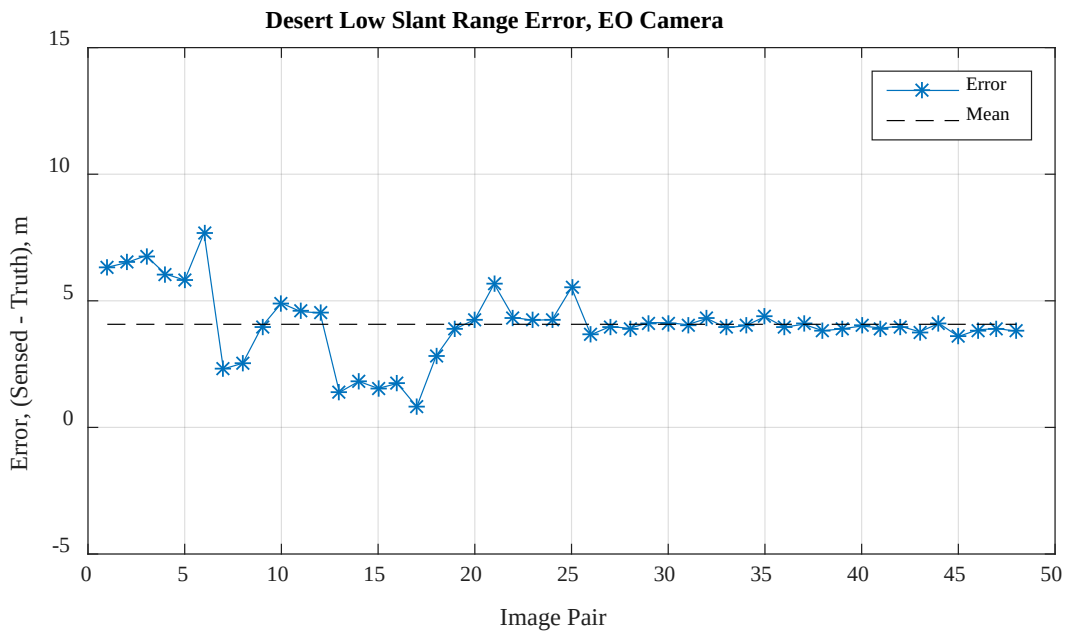


Figure I3: Desert Low Slant Range Error, EO Camera

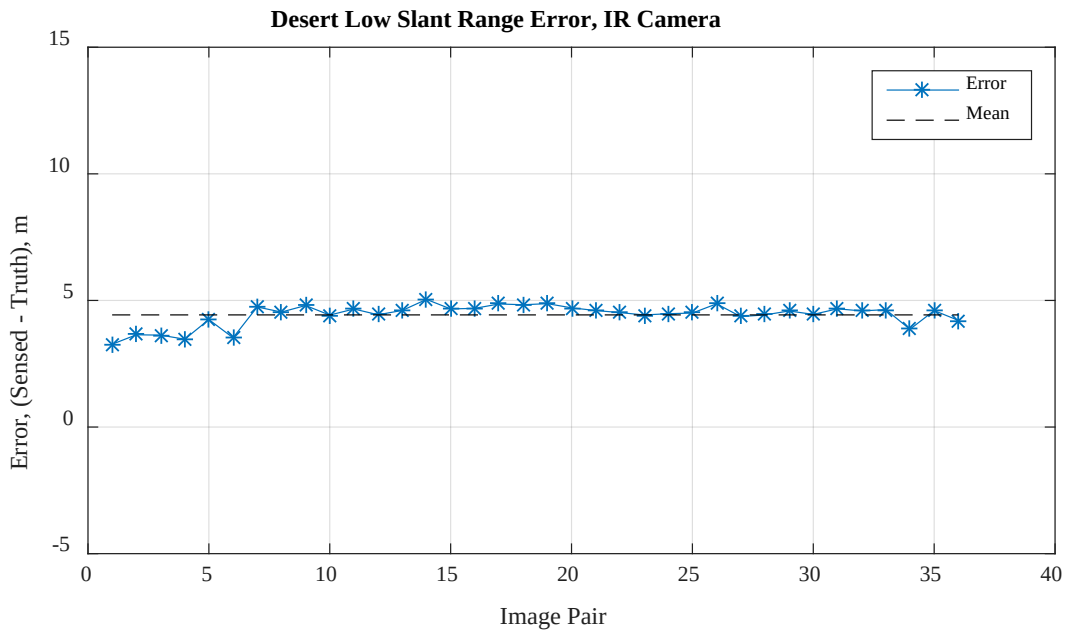


Figure I4: Desert Low Slant Range Error, IR Camera

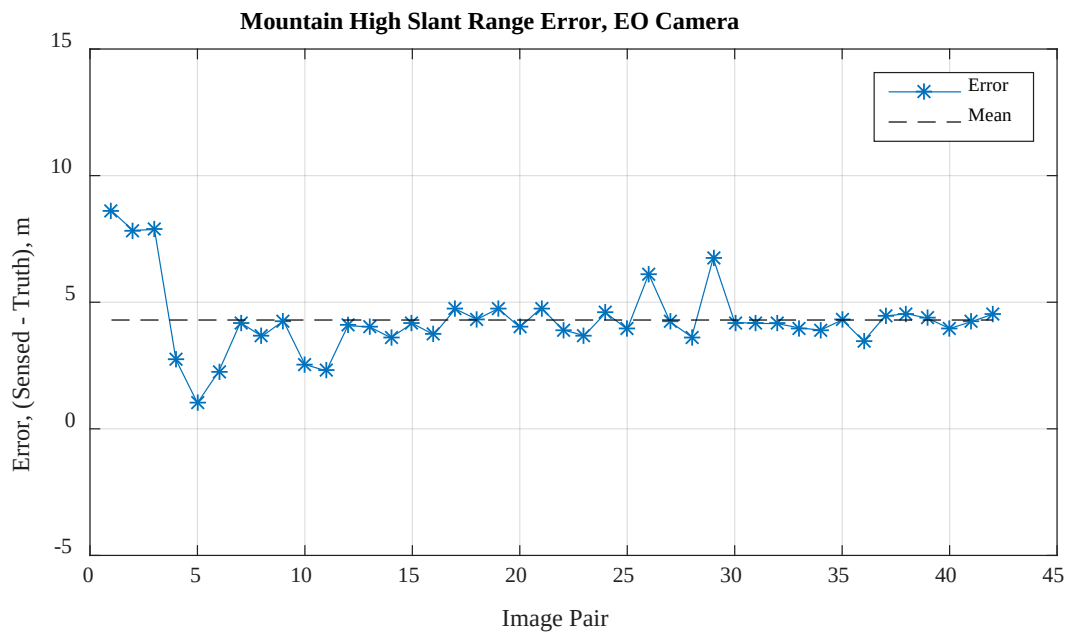


Figure I5: Mountain High Slant Range Error, EO Camera

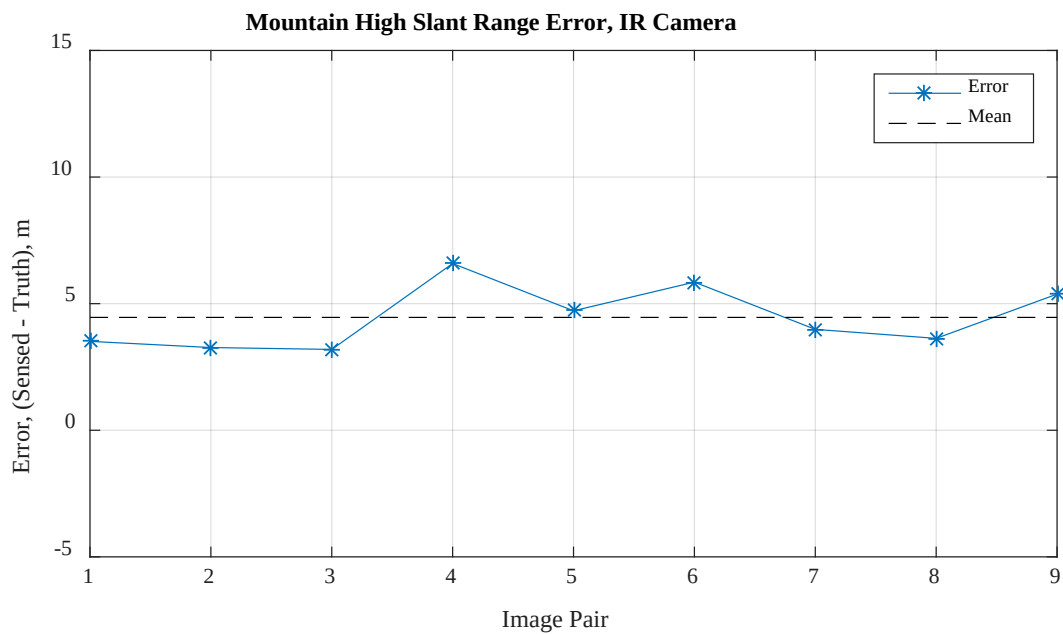


Figure I6: Mountain High Slant Range Error, IR Camera

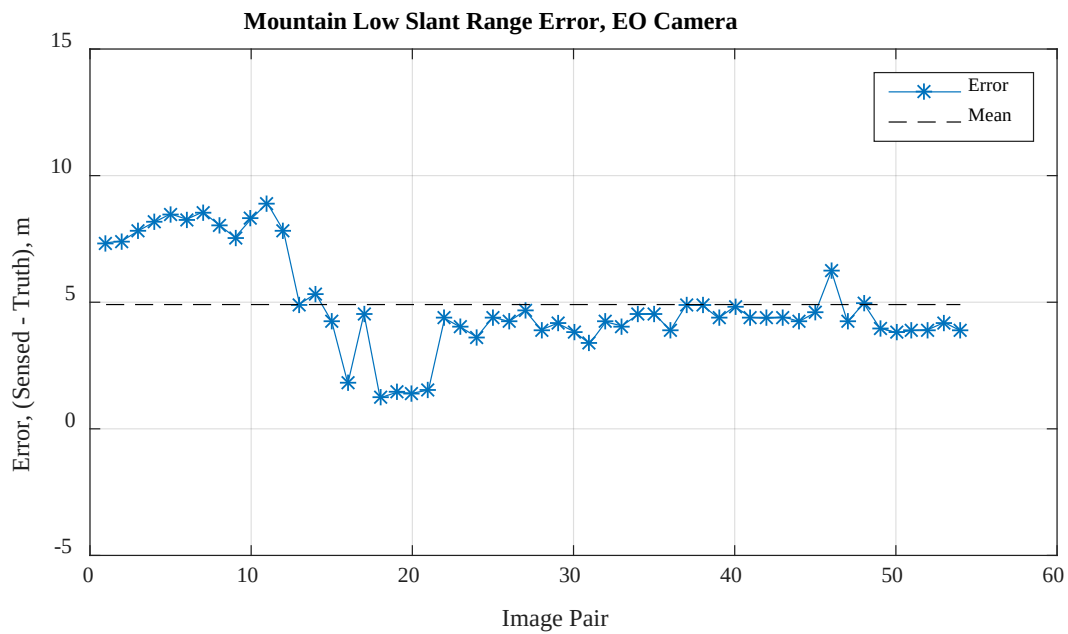


Figure I7: Mountain Low Slant Range Error, EO Camera

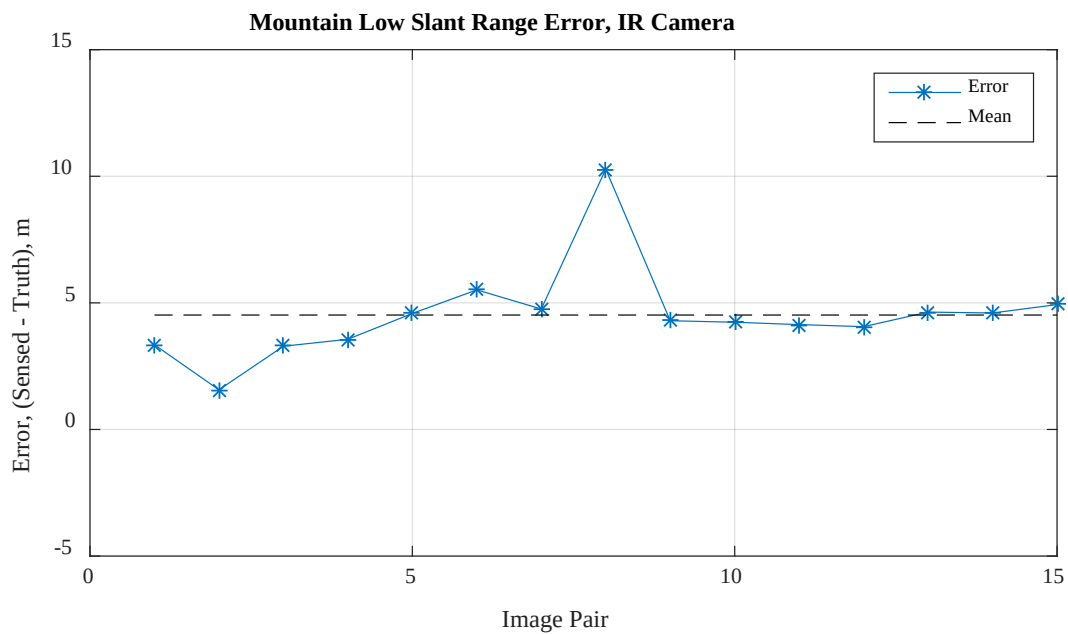


Figure I8: Mountain Low Slant Range Error, IR Camera

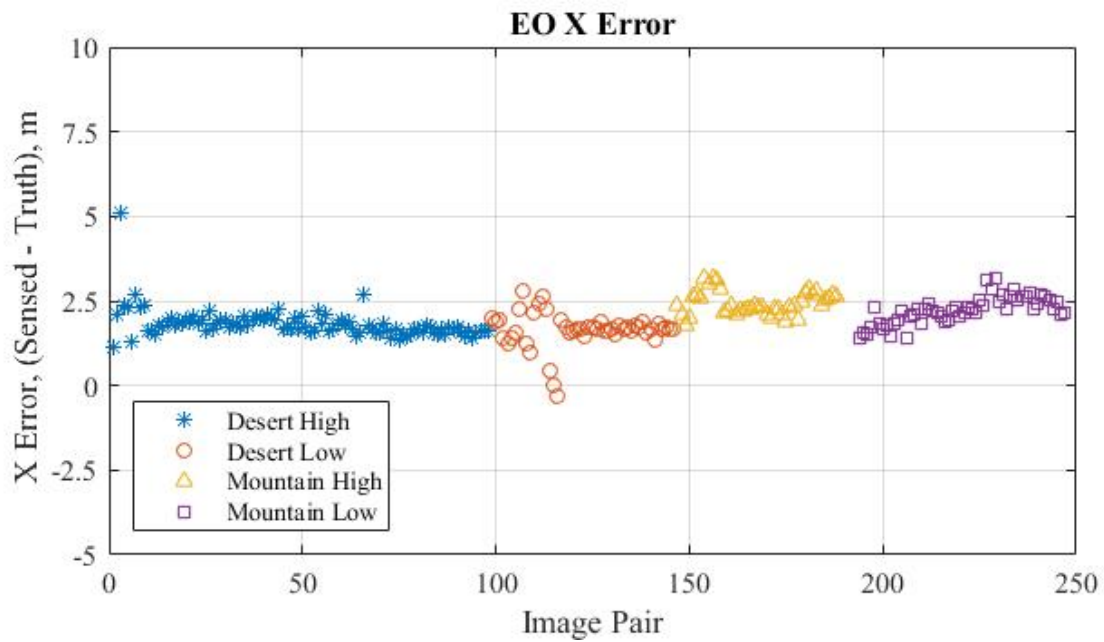


Figure I9: EO Translational X (Camera Frame) Error for All Conditions

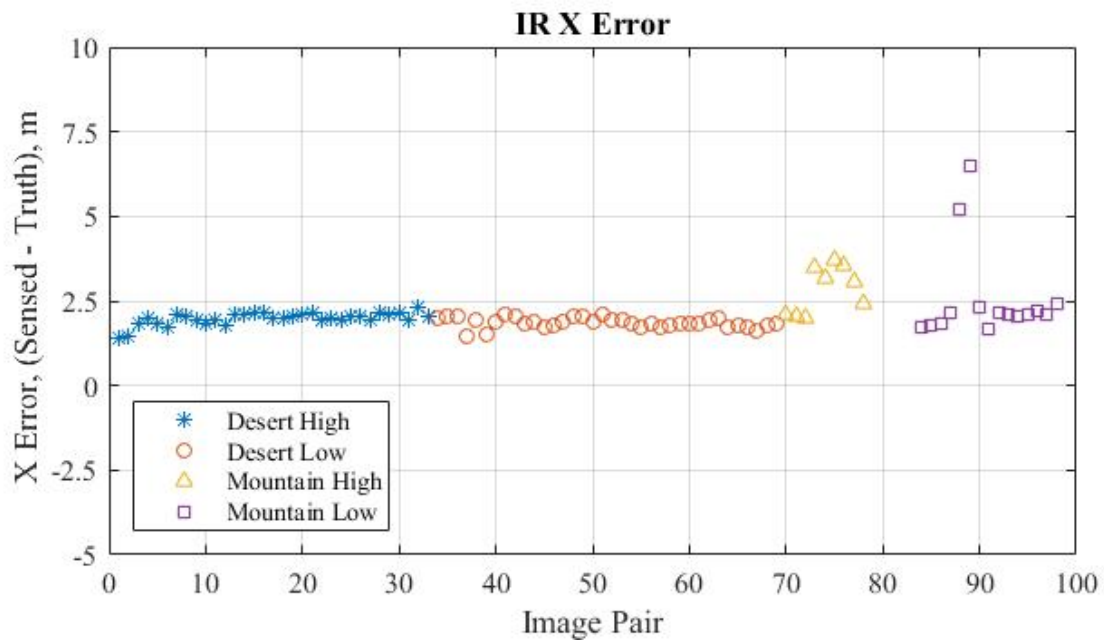


Figure I10: IR Translational X (Camera Frame) Error for All Conditions

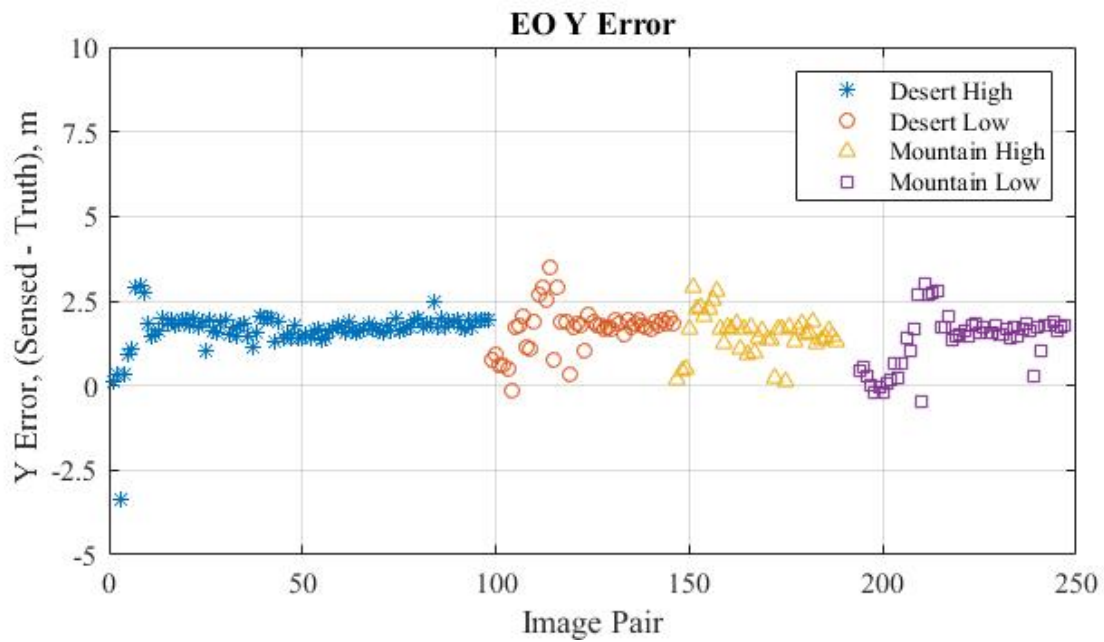


Figure I11: EO Translational Y (Camera Frame) Error for All Conditions

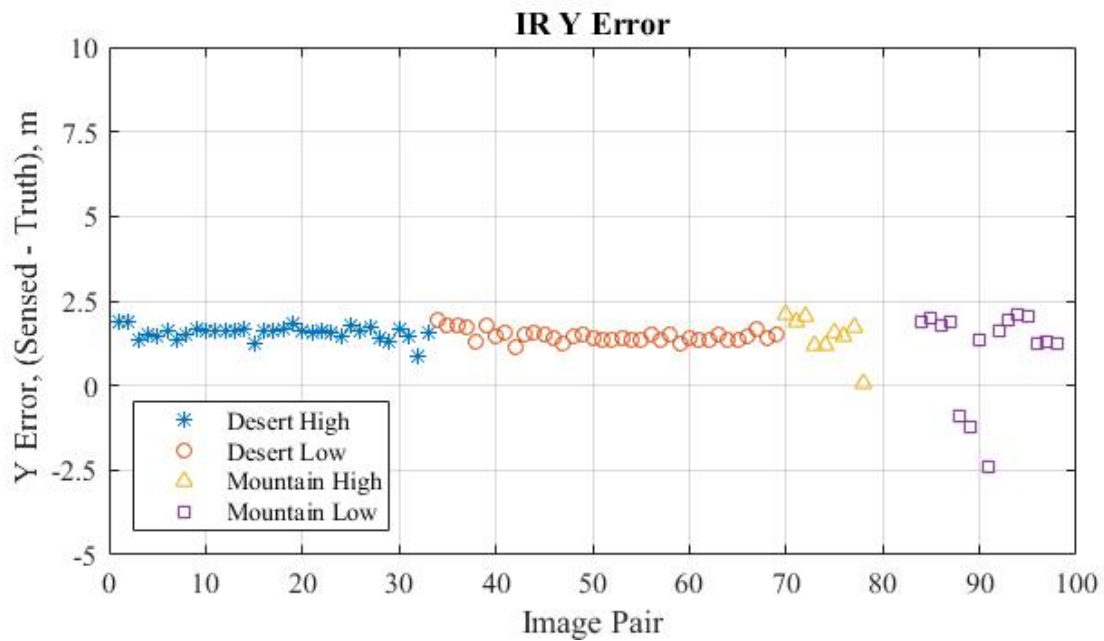


Figure I12: IR Translational Y (Camera Frame) Error for All Conditions

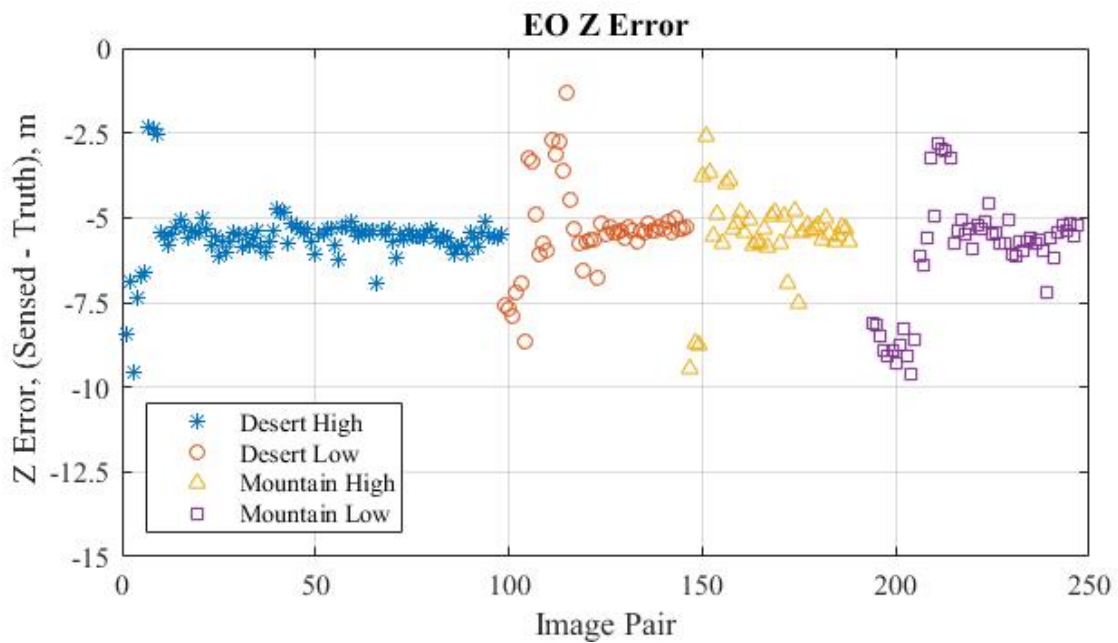


Figure I13: EO Translational Z (Camera Frame) Error for All Conditions

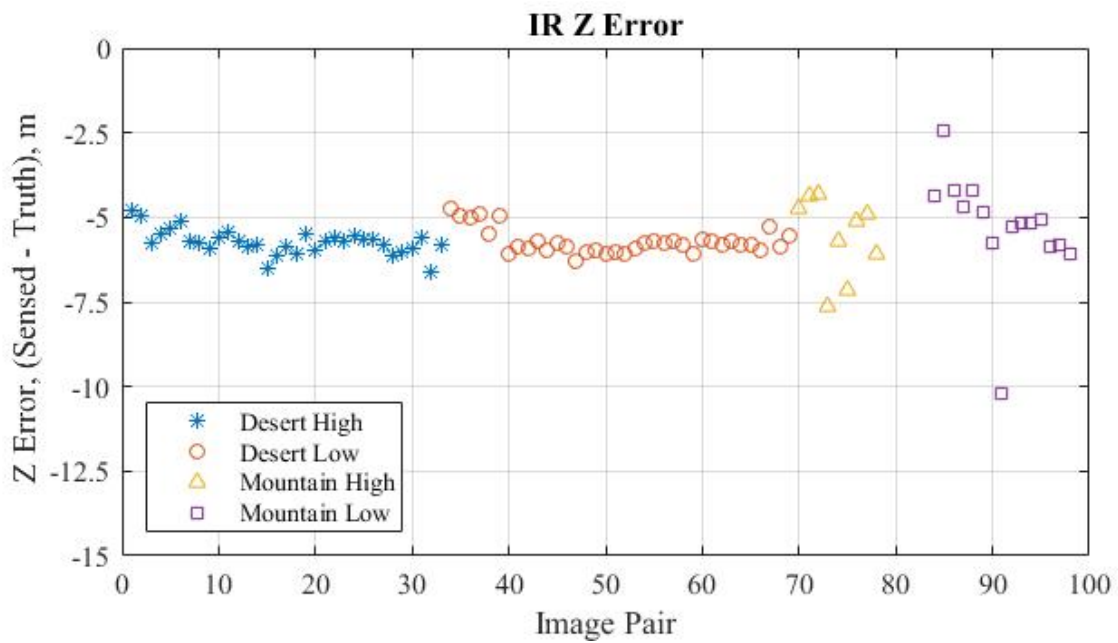


Figure I14: IR Translational Z (Camera Frame) Error for All Conditions

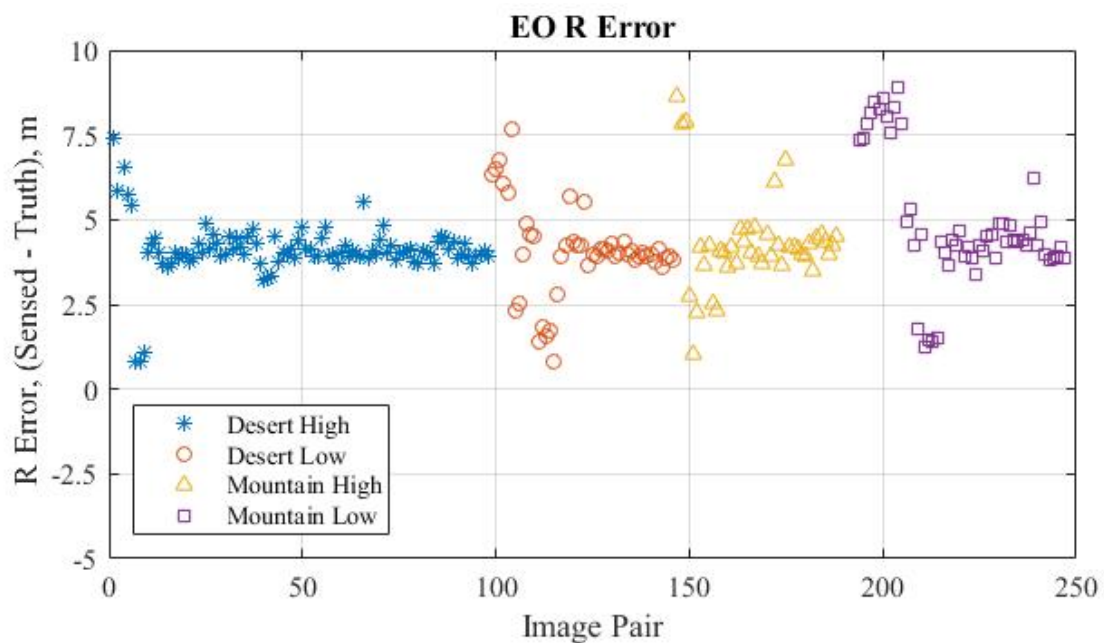


Figure I15: EO Translational R –Slant Range (Camera Frame) Error for All Conditions

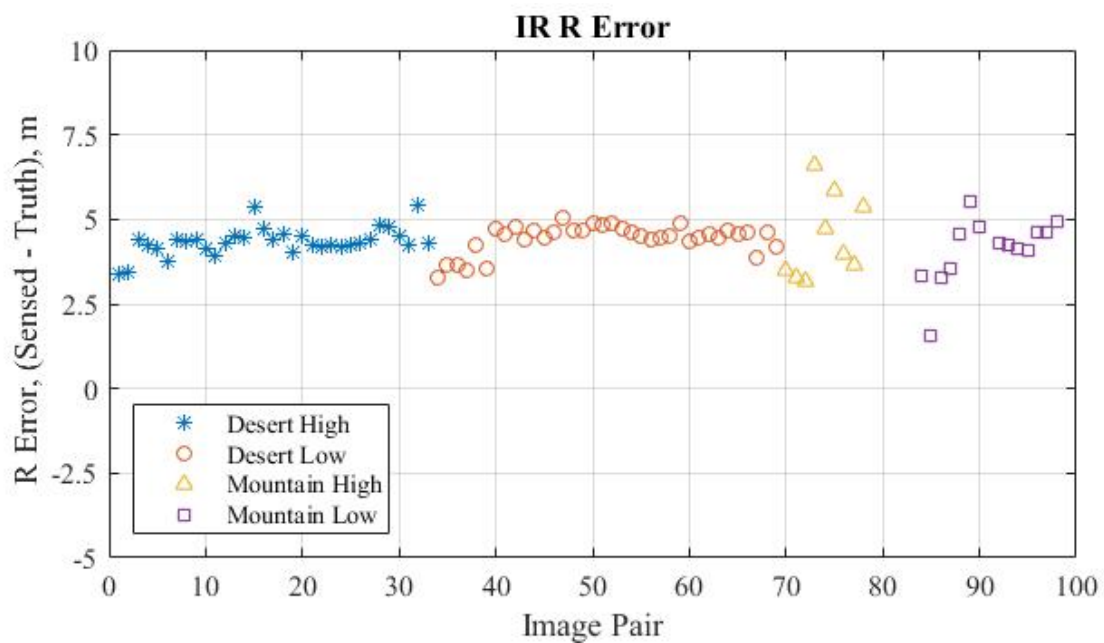


Figure I16: IR Translational R Slant Range (Camera Frame) Error for All Conditions

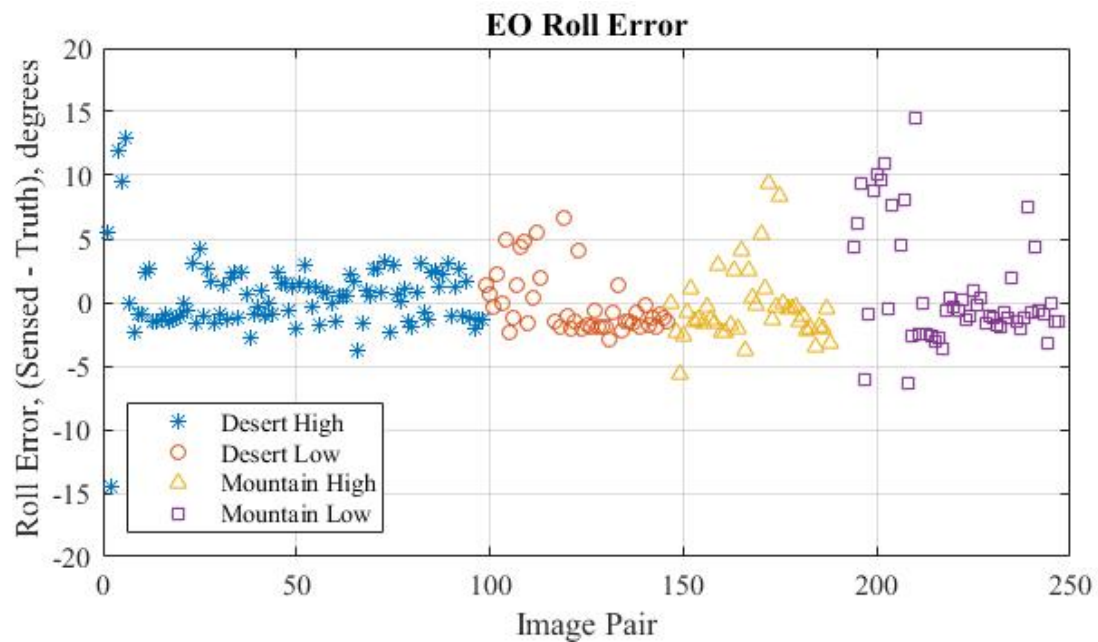


Figure I17: EO Rotational Roll (Camera Frame) Error for All Conditions

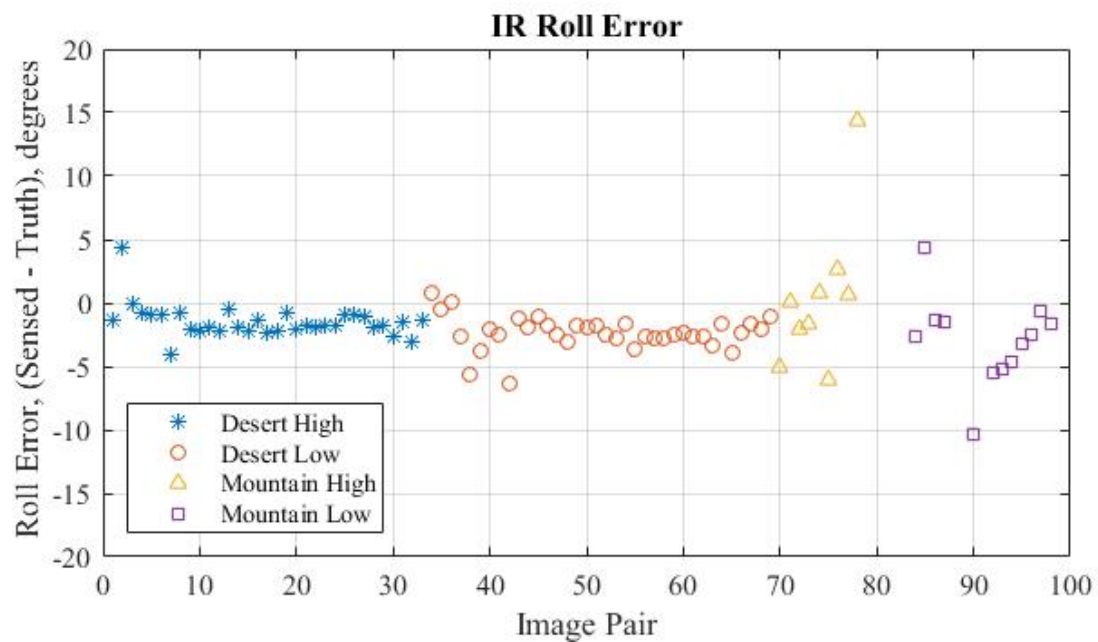


Figure I18: IR Rotational Roll (Camera Frame) Error for All Conditions

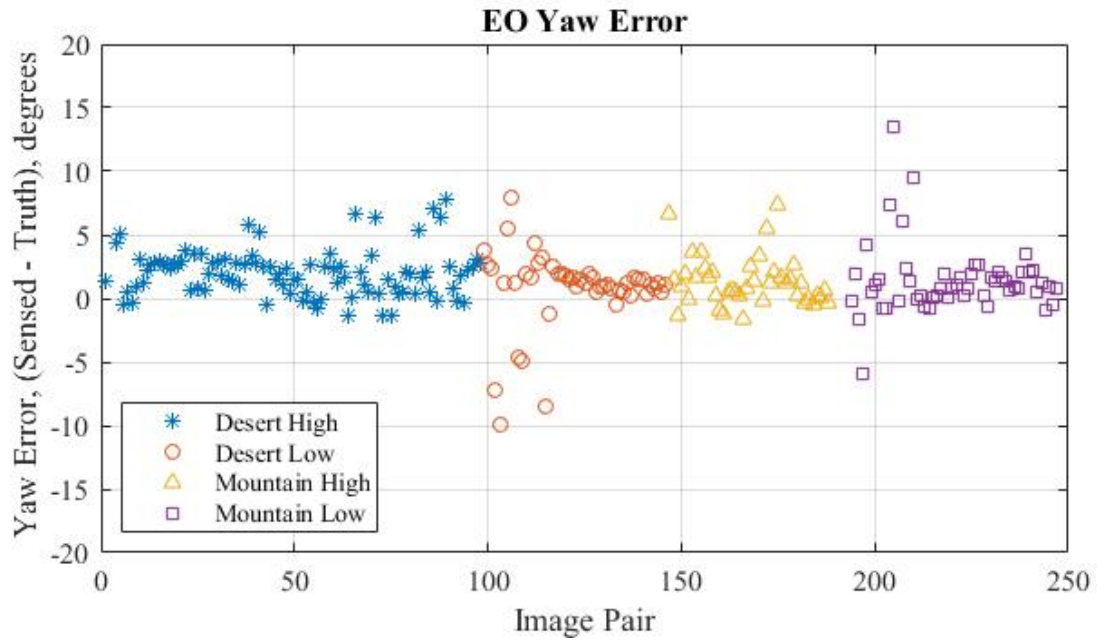


Figure I19: EO Rotational Yaw (Camera Frame) Error for All Conditions

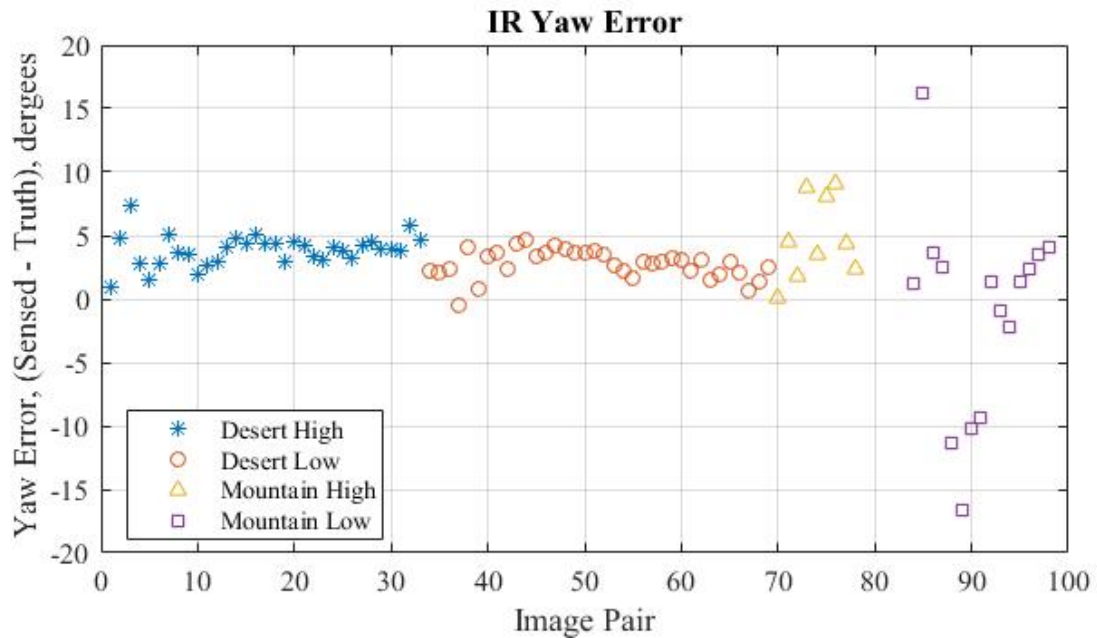


Figure I20: IR Rotational Yaw (Camera Frame) Error for All Conditions

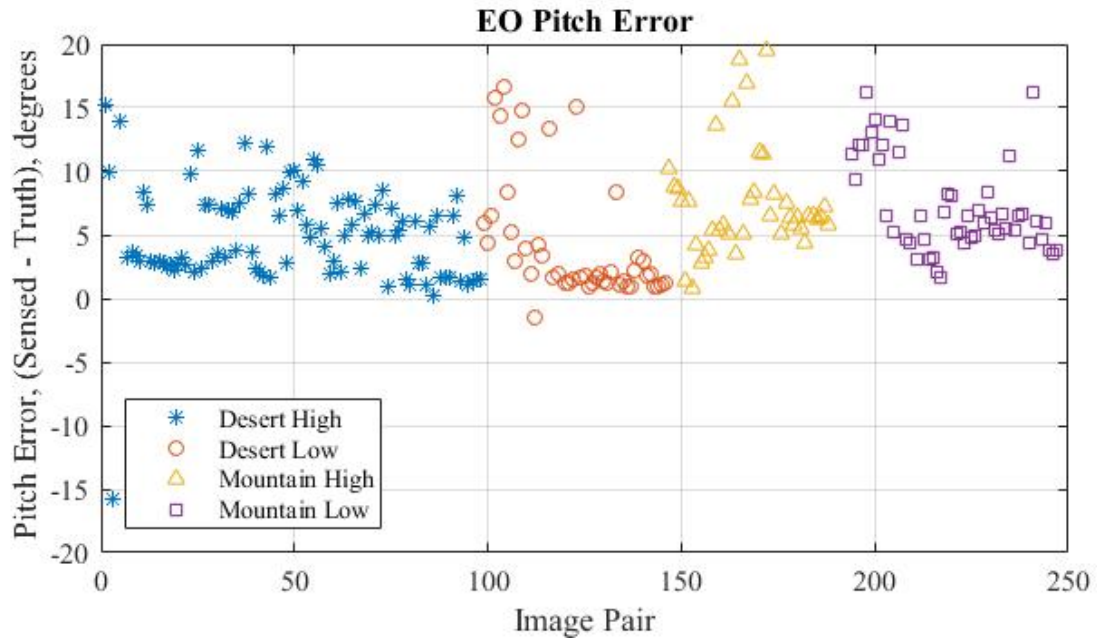


Figure I21: EO Rotational Pitch (Camera Frame) Error for All Conditions

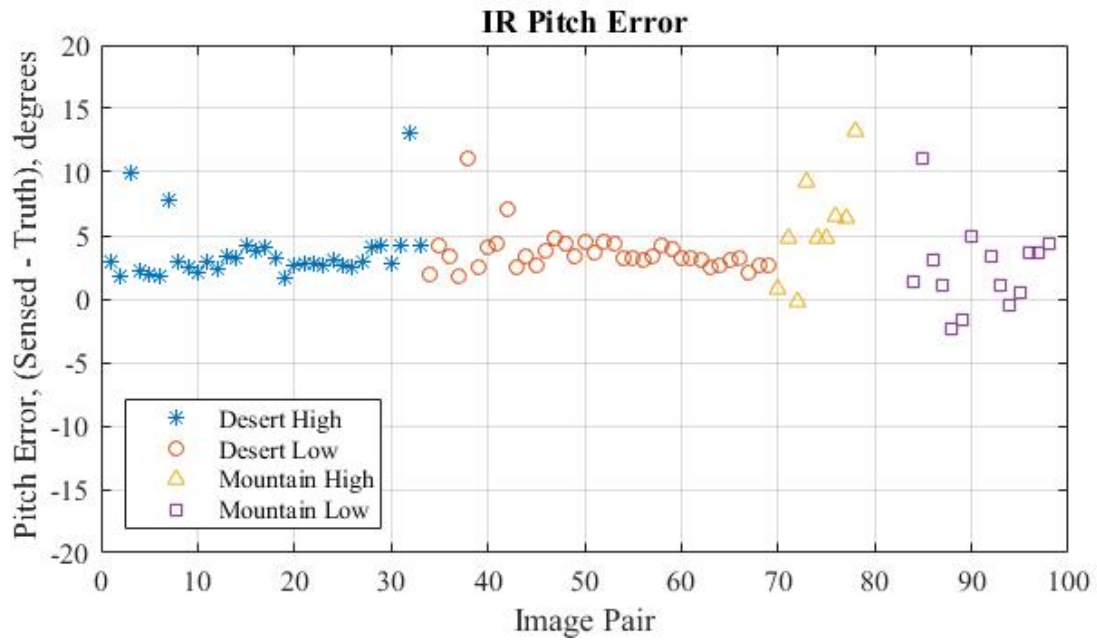


Figure I22: IR Rotational Pitch (Camera Frame) Error for All Conditions

**Slant Range Error and RMS from Flight 7
Asteron to Contact to Asteron**

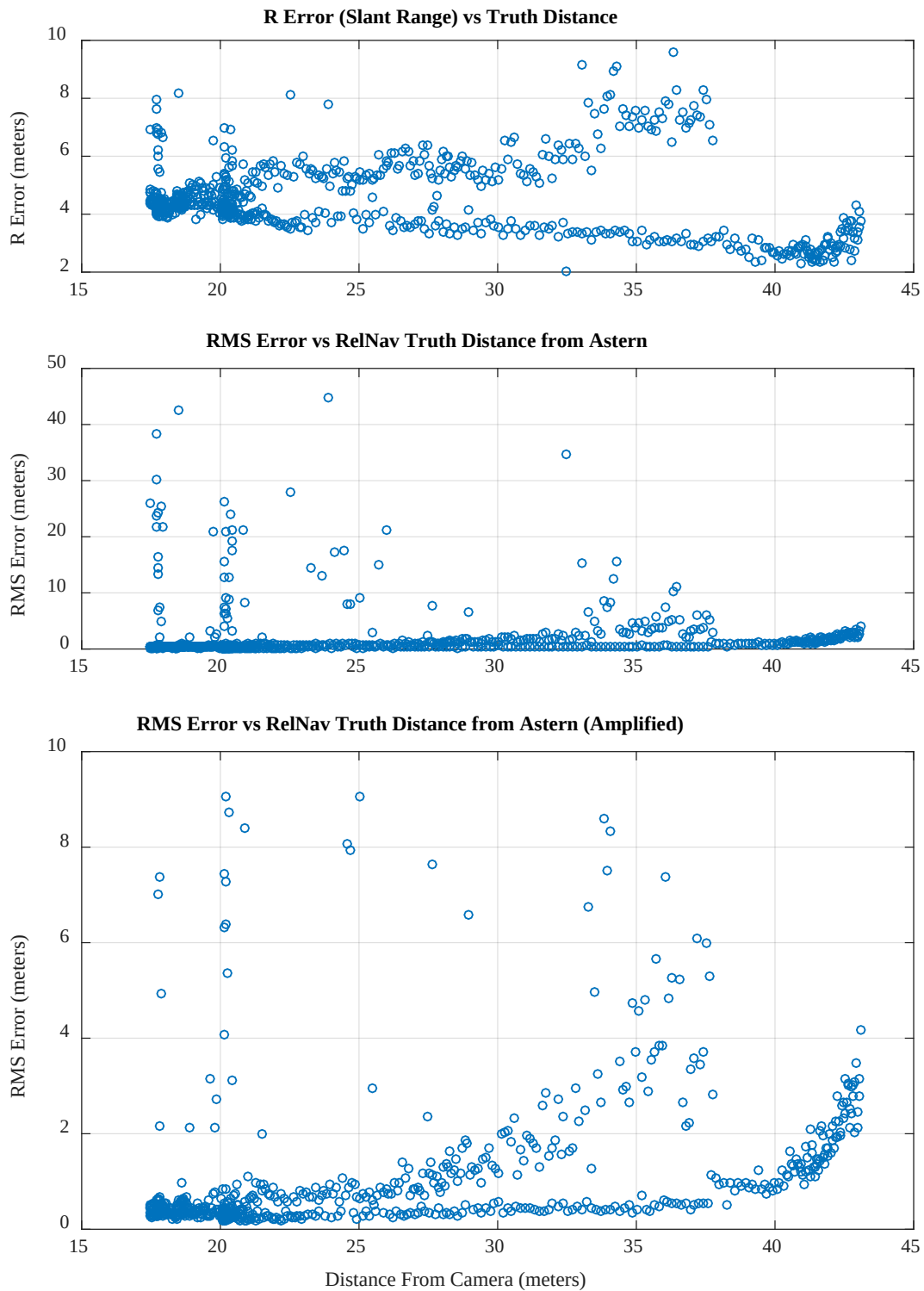


Figure I23: RMS Error IR, Flight 7

**Slant Range Error and RMS from Flight 7
Asteron to Contact to Asteron**

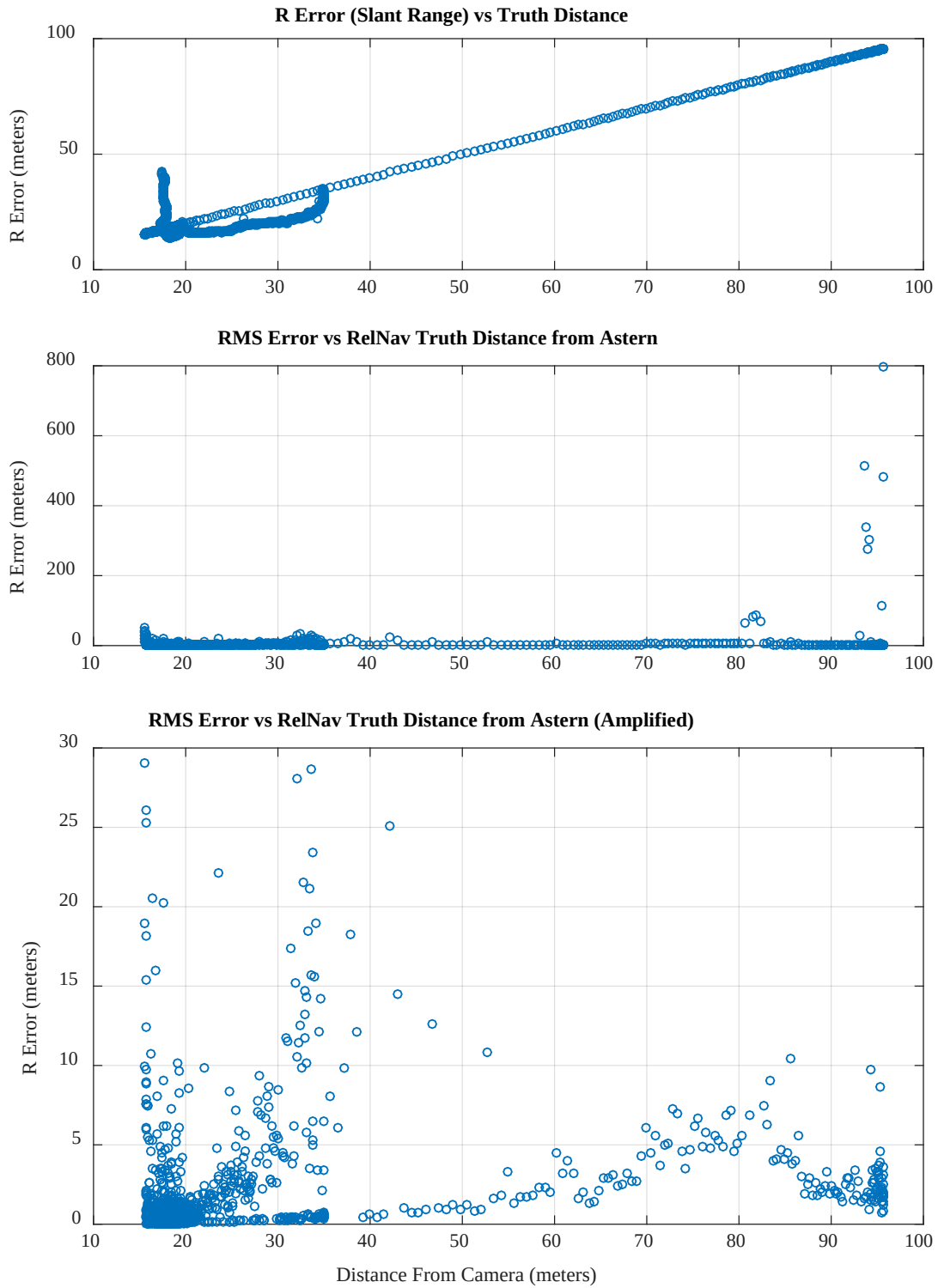


Figure I24: RMS Error EO, Flight 8

This page was intentionally left blank

Appendix J - Geodetics RelNav and GLite TSPI Comparison

The Have Double Vision system contained two truth sources due to the original Have Vision Geodetics malfunctions. While the Geodetics system operation was well known, this was the first time it had been used in this manner at TPS. The difference from the previous setup was the lack of real time connection between the geodetics systems. Instead, the Geodetics was post processed from two independent systems in a similar manner to the GLite TSPI. Since the operation of the system in this manner was in question the GLite TSPI was recorded as a secondary truth source. In order to verify the two truth sources were in agreement, the two truth sources were compared to each other. The differences in the two truth sources can be attributed to lever arm corrections used in each system. Throughout the two flights (flight 1 and flight 3) the bias between the systems was consistent. Both of these were offset from the ICP results. Due to this the Geodetics RelNav was determined to be valid for use as a truth source.

To compare the two systems the 30 Hz GLite TSPI data was converted from GPS Day, Day seconds to GPS week, week seconds using a 18 second offset (added to TSPI to correct to RelNav).

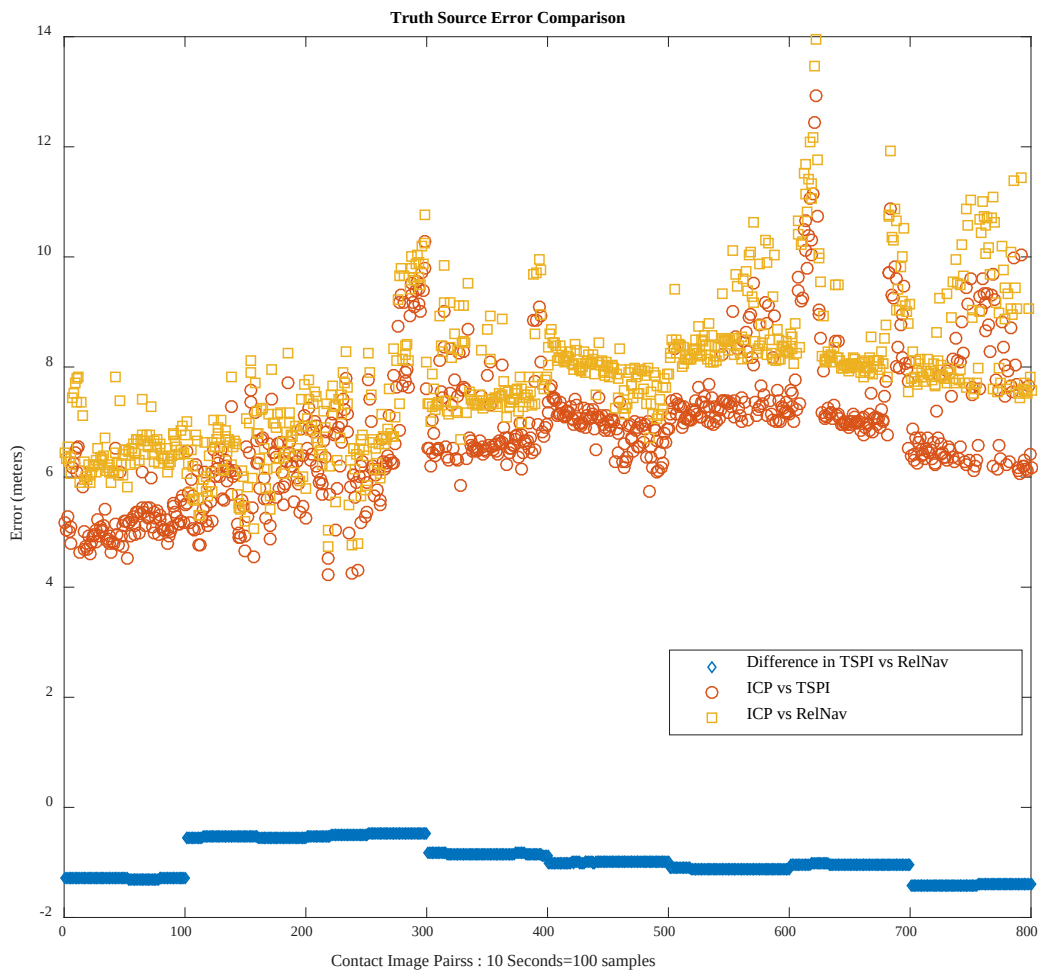


Figure J1: RelNav and TSPI vs ICP relative Solution and Error

This page was intentionally left blank.

Appendix K – Lessons learned

1. Completing a flight check of the system proved to be very valuable since one of the IR cameras was not operating correctly during flight. Specifically, one of the IR cameras (S/N: 53122) froze shortly after becoming airborne. Following the event, the grounding wires to the trigger board were combined to ensure a more stable ground connection since that was assumed to be a problem based on Have Vision's test results and the two IR cameras were swapped in position on the mounting rack. Since the camera positions were swapped and the computer software was not updated with the new IP/MAC addresses for the swap, the team was able to narrow down the issue to the camera and not the wiring after a second flight check of the system. The cameras were sent back to the manufacturer for repair during the week prior to the test window. The manufacturer performed visual inspections, cold soak operations testing, imaging testing, and signal voltage measurements in order to correct the deficiency and ensure proper operation of the cameras. The manufacturer determined that the IR camera (S/N: 53122) had a floating pin, which caused a low variable voltage of 2V to 2.5V to be applied to the internal camera trigger depending on conditions. The internal camera trigger required a stable 3V to operate correctly. In addition, the manufacturer determined that both of the IR cameras were incorrectly built and had missing elements such as circuit protection diodes and various resistors. Once both of the IR cameras were fixed and properly configured, they were sent back to the team for reinstall prior to the test window. A third flight check of the system on the day prior to the test window confirmed that both of the IR cameras were operating properly after some troubleshooting and reconfiguration on the ground.
2. In addition to the camera problems discovered during the preflight checks the wiring harness had a defect that introduced intermittent failure of the IR camera that was attached to that cable. The hairline wire was difficult to sufficiently connect resulting in a poor solder connection. This worked on flight 1 but when it failed on flight 2 we thought the cameras defect had returned. Further inspection showed that it was the connection and a repair was made. This repair took more than 12 hours to repair. The camera worked on flights 5 and 6, but failed on flight 7. Due to the limited test window we proceeded with the test without the cameras. The repair over the weekend provided a functional camera for the final flight. These cables were critical to the operation of the system. Because of the sensitivity of the connection, overtightening the wiring harness or sharply turning the wiring harness contributed to failures.
3. Having the researchers (Dr. Nykl and Capt Dallmann) on location during the beginning of the test window proved to be invaluable since they knew exactly how the system worked and could help troubleshoot issues directly. The team did not have enough working knowledge of the system to perform any advanced troubleshooting steps, so between the first and second flight checks of the system, troubleshooting had to be guided remotely by the researchers, which was difficult since system operation was much more complicated than the test team had initially anticipated. During the third checkout flight, the IR cameras were initially not working on the ground, but by having both of the researchers on the aircraft on MESP status, they were able to troubleshoot system operation directly. They were able to fix the issues and the third flight check of the system was successful.
4. Not being experts in the system under test limited the test team's ability to foresee potential issues with system operation. Not only did this include the cameras and the associated computer

software, but also the Geodetics RelNav system. While troubleshooting camera operation during the third flight check of the system, the Geodetics RelNav system was determined to be operating incorrectly as well. The test team was unable to troubleshoot the Geodetics RelNav system on the aircraft during either of the two previous flight checks due to a lack of knowledge in how the system operated. There was not enough time in the flight to perform any troubleshooting of the Geodetics RelNav system. The first issue that was determined was that each Geodetics RelNav unit was equipped with a backup battery that operated continuously even with external power disconnected in order to supply power to the real-time clock. The operations manual explained that a fully charged backup battery would discharge in approximately 2 months and that a fully discharged battery requires about 12 hours to charge. The consequence of removing power from a backup battery with insufficient charge was the potential for the SD card or the processor board becoming corrupt which would have resulted in complete data corruption if that were to occur. When the researchers arrived, they were unsure about the status of the charge of the two Geodetics RelNav units and expressed their concerns about the backup batteries failing during the test window. This prompted the team to request the Geodetics RelNav units be uninstalled to allow off-aircraft charging through the night prior to the test window. The Geodetics RelNav units were then reinstalled after verifying that the power LEDs were solid, which indicated that both contained more than a 50% charge.

5. Camera calibration procedures and techniques were not well understood in detail by the test team prior to execution, resulting in a suboptimal camera calibration for the first calibration conducted on 7 March. Lighting conditions, camera settings, and calibrator techniques are major factors involved in the camera calibration, and the camera calibration techniques are not a simple process. Camera calibration is extremely dependent on physical camera settings such as the physical aperture setting of the lens on the camera. After the first successful data flight and during the initial data review, the test team found that the aperture of the EO cameras was inadvertently set differently with one EO camera set with a fully closed aperture and the second EO camera set with a more open aperture (the dial was turned by ~10 degrees) resulting in one of the cameras having a brighter image than the other. The aperture setting was fixed for later flights, however this required a different calibration due to the physical camera settings changing between test flights. In addition, the sun angle had a large effect on the calibration. For the first calibration, the aircraft was pointed to the West with the sun being positioned low on the horizon in East during the morning, and therefore providing too much backlighting for the calibration. The ground was very bright in the picture and the individual performing the calibration along with the calibration checkerboard were very dark due to this backlighting effect. The EO cameras did not have an auto-dim feature so the darkness of the board contrasting with the sunlit background could not be improved, and was determined to be a partial cause of the poor calibration. Other possible causes for the poor calibration were the lack of depth of the calibration board. While on the ground, it was impossible to place the calibration board at the proper focal distance of the cameras which were set to be focused at infinity. During lab camera calibrations at AFIT, the researchers placed the board 10 feet away from the cameras. During ground calibrations with the cameras installed on the aircraft, the test team was forced to place the board approximately 4 feet from the cameras instead of a more ideal distance away, resulting in a slightly out of focus checkerboard. The camera calibration toolset automatically identifies images that work well for calibration. Out of 300 total images, the toolset only accepted 19 EO image sets as being good enough to use while the rest were determined to be invalid due to factors such as the entire calibration board not being visible in the camera FOV or the lighting conditions being suboptimal. A total of 19 images were

not enough images to give a good calibration since approximately 30 images were generally required for a good calibration. For the IR cameras, there were approximately 150 useable image sets for the calibration, which was more than ideal, however the toolset accepted some of the “bad” IR images, which negatively affected the overall calibration if they were left as a part of the overall calibration image set. The “bad” images had to be removed individually to improve the overall calibration if a lot of images were accepted by the program. The calibration toolset image acceptance algorithm depended on the technique of moving the checkerboard in different lighting conditions and on the ability of the camera to see the checkerboard. After the calibration tool was run, the average value of 0.25 was determined to be the adequate calibration threshold with 0.15 being the desired calibration threshold and lower values being optimal. The first calibration resulted in an EO calibration value of 0.35 and an IR calibration value of 0.25, which was outside of the adequate calibration threshold.

6. In all of the initial flight tests, the EO camera was determined to be taking pictures in which the aircraft and underlying background were both too bright, making distinguishable features of the aircraft unable to be seen. In order to correct this issue, it was determined that the EO camera exposure settings could be changed via the Vimba Viewer. Instead of having the exposure setting set to the default of 15,000 μ s, the exposure setting was reduced to 5,000 μ s, allowing much better views of distinguishable features of the aircraft in comparison to varying backgrounds. The backgrounds that were troublesome were snow covered mountains and underlying clouds, both of which were very close to the color of the aircraft itself. The operable IR camera was able to see the aircraft clearly in comparison to background terrain without having to adjust any camera settings.
7. On the fourth test sortie, one of the black strobe light glare shields that was being used for external formation references was found to be broken upon entering the contact position. The sortie was terminated to avoid the potential of the strobe light glare shields from falling off of the lead aircraft and into the trail aircraft. After landing, maintenance removed both strobe light glare shields in order to prevent the occurrence from happening again. They speculated that the camera mounting system was causing turbulent flow around the strobe light glare shields and therefore premature fatigue for the mostly plastic and foam components. This required reversion to other references for formation position keeping.
8. A boresight of the aircraft with the TSPI GLite and Geodetics RelNav systems installed was not planning on being conducted by the test team since the modification of the aircraft was identical to the previous Have Vision modification. The range TSPI processing squadron refused to process any TSPI data without a new calibration. This was accomplished after the test window before the aircraft modifications were removed. This caused significant delay in the TSPI truth
9. The GLite initialization was a significant element in the preflight actions. In order to initialize the system the metal cover over the IMU units had to be removed by special instrumentation personnel, then replaced after the initialization was complete. This had to occur on both aircraft which delayed the aircraft startup on several occasions. The only reason to remove the cover was to plug a cable into the GLite IMU. If this were accessible without removing the cover significant delay could be avoided.

10. Pulling C-12 receiver Gear & Stall Warning CBs to eliminate nuisance low power setting audible warnings was very beneficial to flying the receiver aircraft. Ensure the correct circuit breakers are known and included in the procedures and cards.
11. The speed differences for the C-12 and T-38 were significant enough that at high altitudes the C-12 could not maintain the heavyweight approach speeds for the T-38 resulting toboggan maneuver to fly the points in a slight descent.
12. The time server that connected the data acquisition computer and synchronized the system clock was a known item, however the process was unknown. This led to poor planning in the test plan and some confusion in execution until all operators understood the system procedure.
13. The Geodetics data processing timeline was longer than advertised, but still faster than the local Range TSPI shop.
14. The out and back mission was a big success. The data collection was much more efficient than if the same amount of data needed to be collected on a single flight. This did cause confusion for the TSPI squadron despite prior coordination but was easily corrected.
15. The TSPI shop will give you exactly what you ask for, however the language they use is different than expected. If we wanted the relative solution presented to avoid post processing then ensuring that they filled out the request form would have been a better plan. Plain English did not work and the result was data that needed additional steps to complete any processing.

APPENDIX L – DOUBLE VISION QUESTIONNAIRE

Sample questionnaire for flight comments

Double Vision Questionnaire	
For use by Double Vision system operator to demonstrate military utility during flight and post processing (as applicable). This does not limit what qualities the operator would like to address. Any additional user comments are acceptable.	
During operation or post processing: Images, Point Cloud, Relative Position Estimate feedback	
Can you assess stability?	
Can you assess movement?	
Can you assess movement rate?	
Are there any correlations in point cloud quality and image quality (i.e, shadows on receiver, receiver out of the FOV)	
Does the output have any latency issues (time difference from actual to processed position estimate)?	
How fast does the estimation update (refresh rate)?	
Additional Comments	

This page was intentionally left blank.

APPENDIX M – EQUIPMENT SPECIFICATION SHEETS

Prosilica GT1290, GT1290C

Feature	Specification	
Resolution	1280 (H) x 960 (V) 1.2 MP	
Sensor	GT1290: Sony ICX445ALA with EXview HAD CCD™ technology	GT1290C: Sony ICX445AQA with EXview HAD CCD™ technology
Sensor type	Interline CCD, Progressive Scan	
Sensor size	Type 1/3 6.0 mm diagonal	
Cell size	3.75 µm x 3.75 µm	
Lens mount	Standard: C-Mount Optional: See the Modular Concept	
Housing	Standard format	
Optical filter ¹	GT1290: No optical filter	GT1290C: IRC30 IR cut filter
Maximum frame rate at full resolution	33.3 fps	
Maximum image bit depth	14-bit (monochrome), 12-bit (color)	
Image buffer	128 MB	
StreamHoldCapacity	Up to 53 frames at full resolution	
Monochrome formats	GT1290: Mono8, Mono12, Mono12Packed, Mono14	GT1290C: Mono8
Color formats (YUV)	GT1290: N/A	GT1290C: YUV411Packed, YUV422Packed, YUV444Packed
Color formats (RGB)	GT1290: N/A	GT1290C: RGB8Packed, BGR8Packed
RAW formats	GT1290: N/A	GT1290C: BayerRG8, BayerRG12, BayerRG12Packed
Exposure control	12 µs to 77.3 s, 1 µs increments	
Gain control	0 to 29 dB	
Binning	Horizontal: 1 to 8 columns Vertical: 1 to 14 rows	
Decimation X/Y	Horizontal and vertical: 1, 2, 4, 8 factor	
Sensor taps	Single-tap	
TTL (non-isolated) I/Os	1 input, 2 outputs	
Opto-isolated I/Os	1 input, 2 outputs	
RS232	1 Tx/D, 1 Rx/D	
Voltage requirements	7 to 25 VDC; PoE	
Power consumption	2.9 W @ 12 VDC; 3.5 W PoE	
Trigger latency	2 µs	
Trigger jitter	20 ns	

Table 2: Prosilica GT1290, GT1290C model specifications

Figure M1. Prosilica GT 1290C Specifications (Sheet 1 of 4)

Feature	Specification
Propagation delay (t_{pd})	30 ns for non-isolated I/O; 70 ns for isolated I/O
Operating temperature	-20 °C to +65 °C ambient temperature (without condensation)
Storage temperature	-20 °C to +70 °C ambient temperature (without condensation)
Operating humidity	20 to 80% non-condensing
Body dimensions (L x W x H)	86 x 53.3 x 33 mm
Mass	211 g
Interface	IEEE 802.3 1000BASE-T/100BASE-TX, IEEE 802.3af (PoE)
Interface standard	GigE Vision® Standard V1.2
Regulations	CE, RoHS, REACH, WEEE, FCC, ICES
Temperature monitoring	Available for main board and sensor board. Resolution: 0.031; Accuracy: ± 1 °C
¹ For more information on available optical filters see the Modular Concept.	

Table 2: Prosilica GT1290, GT1290C model specifications (continued)

Figure M2. Prosilica GT 1290C Specifications (Sheet 2 of 4)

Absolute QE

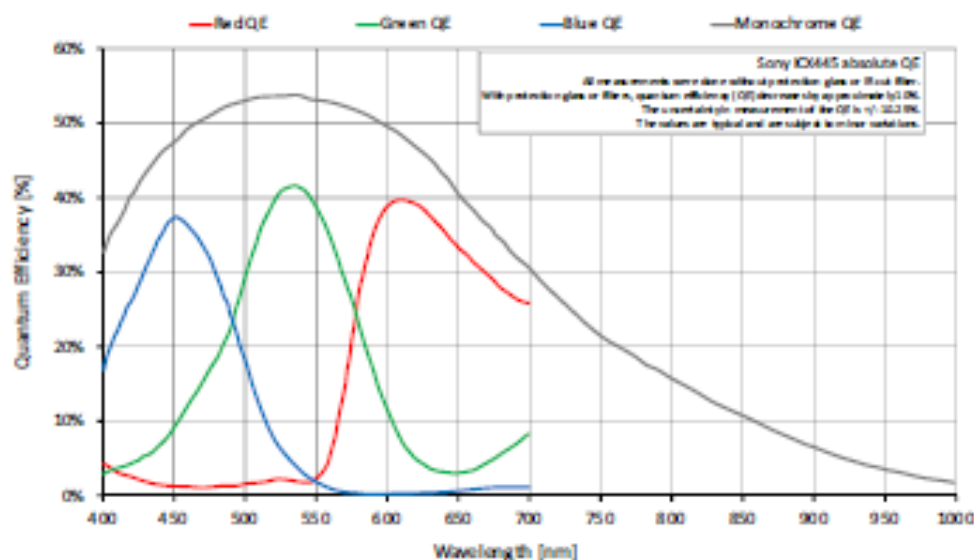


Figure 1: Prosilica GT1290, GT1290C (Sony ICX445) absolute QE

Spectral response

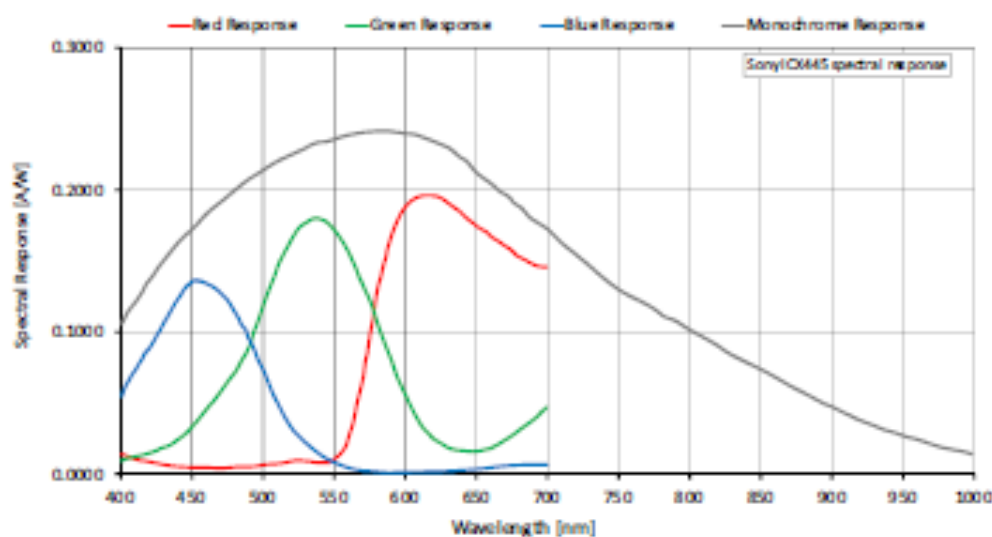


Figure 2: Prosilica GT1290, GT1290C (Sony ICX445) spectral response

Figure M3. Prosilica GT 1290C Specifications (Sheet 3 of 4)

ROI frame rate

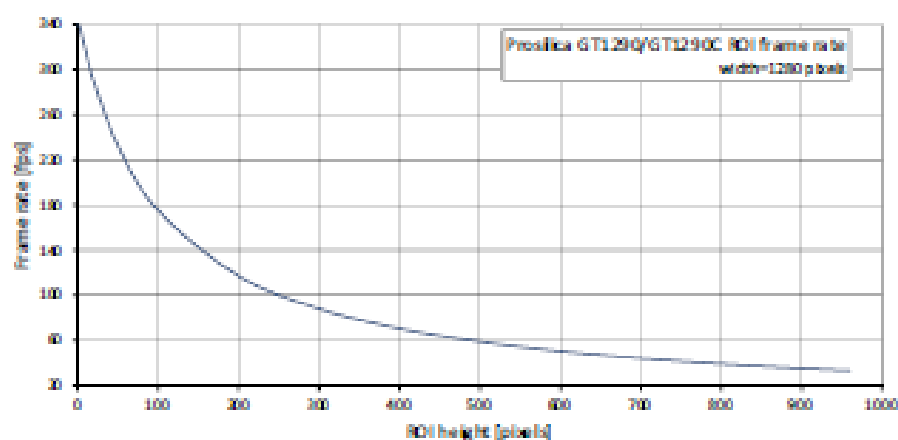


Figure 3: Frame rate as a function of ROI height

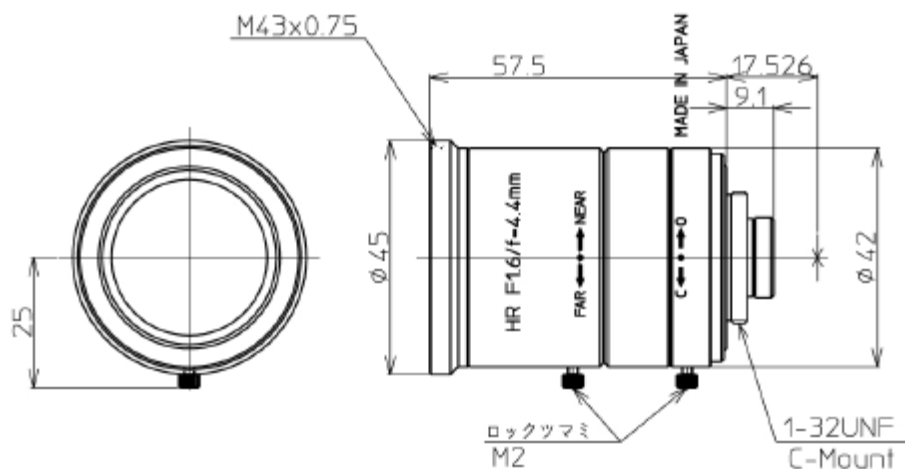
Height [pixels]	Frame rate [fps]	Height [pixels]	Frame rate [fps]
960	33.3	300	88
900	35.3	200	117.1
800	39.2	100	175
700	44.1	50	232.4
600	50.4	20	289.5
500	58.8	10	315.2
400	70.5	2	339.4

Table 3: Frame rate as a function of ROI height table

The following table shows how binning affects frame rate.

BinningVertical	Height [pixels]	Frame rate [fps]	BinningVertical	Height [pixels]	Frame rate [fps]
2	480	60.8	8	120	158.3
3	320	83.8	9	106	168.7
4	240	103.3	10	96	176.9
5	192	120	11	86	185.1
6	160	134.5	12	80	191.9
7	136	147.8			

Table 4: Frame rate as a function of ROI height with vertical binning enabled



SPECIFICATION

1. USE		1/1.8" to 1/3" MEGA CAMERA					
2. FOCAL LENGTH		4.4mm					
3. MAX. DIA. RATIO		F1.6					
4. IRIS RANGE		F1.6-F16					
5. IMAGE SIZE		ø9 5.4x7.2mm					
6. BACK FOCAL LENGTH		8.75 in air					
7. FLANGE FOCAL LENGTH		17.526mm in air					
8. FOCUS RANGE		0.1 m					
9.FIELD ANGLE	VER.	118°	61.2°	112°	55.5°	113°	43.0°
	HOR.		76.6°		70.1°		55.5°
	DIA.		89.4°		82.5°		66.7°
10.LENS CONSTRUCTION		7 GROUPS 9 ELEMENTS					
11.CLEAR APERTURE	FRONT	ø30.0					
	REAR	ø8.0					
12.EXIT PUPIL POSITION		-61.4mm					
13.MOUNT		C-MOUNT					
14.FILTER SCREW SIZE		M4.3x0.75					
15.TV DISTORTION		118°	-0.2%	112°	-0.1%	113°	-0.13%
16.WEIGHT		150 g					



尺 寸	1/1	承 造	八木	製 造	富永
1/1.8" F1.6 f=4.4mm					
LM4NCM					

Figure M5. Kowa Lens (EO Camera) Specification Sheet

12 Specifications

<i>Infrared Engine Model</i>	<i>ATOM 1024</i>
FPA	Uncooled ASi Microbolometer
Size	1024 x 768
Pixel Pitch	17 μ m
Frame Rate (full frame)	30 Hz
Thermal Time Constant	< 10 ms
Digital Output	LVTTL (L model), Gigabit Ethernet (G model), Camera Link (C model)
Size: (W x H x D) (w/o lens, Camera Link option)	81 x 89 x 68mm (2.4" x 2.7" x 2.6")
Weight (w/o lens, LVTTL option)	< 250g
Weight (w/o lens, Camera Link option)	< 300g
Weight (w/o lens, Gigabit Ethernet option)	< 500g
Input Voltage	8 – 12 VDC
Power Consumption	< 1.7W LVTTL; < 2.2W Camera Link < 3.6W Gigabit Ethernet
Detector Thermal Sensitivity ¹	< 50 mK
Time to First Image	< 4 sec
Video Processing	Non-uniform Correction
Operational Temperature	-40°C to 60°C
Non-operation Temperature	-45°C to 70°C

¹ Normalized to unity transmission and f1.0 lens

Figure M6. Atom 1024G Specification Sheet.

16.44mm (f1.0) Athermal Fixed Focus Lens Dimensions

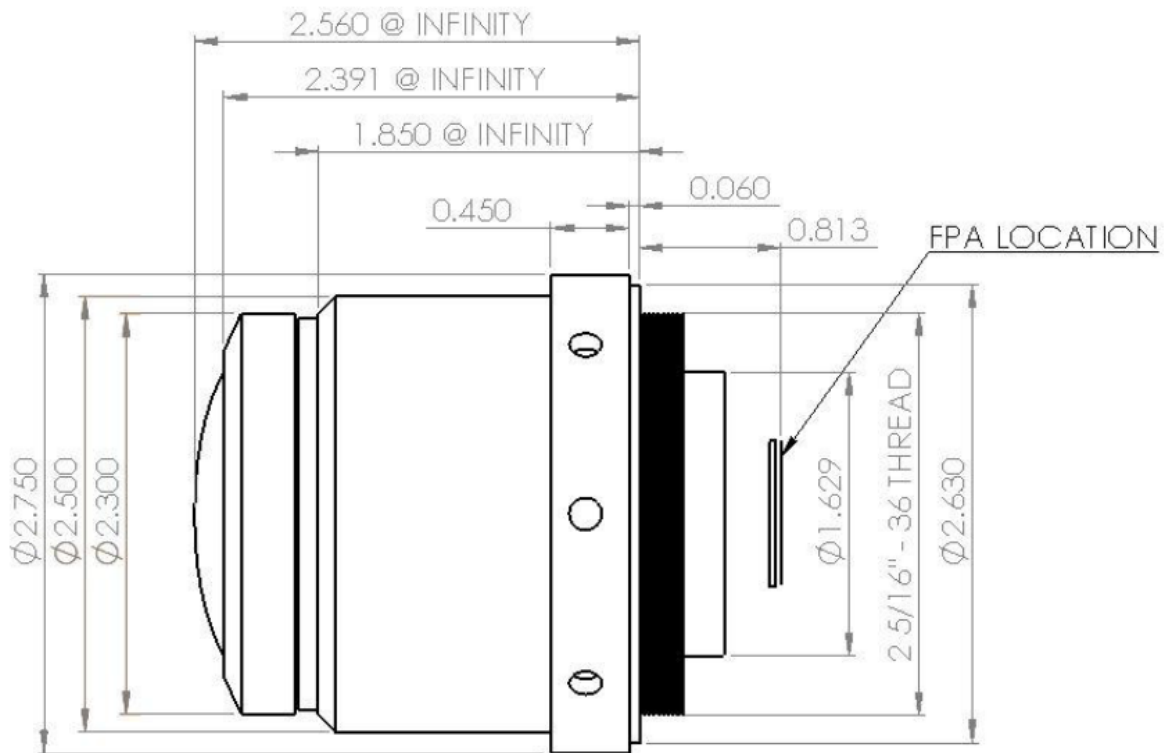


Figure M7. Atom 1024G 16.44mm Fixed Focus Lens.



News

September, 2015: Geodetics to present UAV Navigation paper at ION 2015: [See Abstract](#)

June, 2015: Geodetics offers KVH IMU's for navigation systems [See White Paper](#)

[See More News](#)

Geo-RelNAV®

High-Accuracy, Real-Time Relative Positioning and Orientation System

Geo-RelNAV® is a high-accuracy, real-time relative positioning and orientation system. Geo-RelNAV provides precise relative position and orientation between moving platforms such as manned or unmanned air and ground vehicles. This information can be used for applications such as autonomous aerial refueling, autonomous landing and collision avoidance. Geo-RelNAV offers a variety of processing, GPS and IMU options and can be configured to cover a broad performance spectrum.

- + Completely autonomous - no external reference is needed for relative information
- + Not sensitive to magnetic field
- + 1-2 centimeter relative positioning accuracy*
- + 0.01-0.02 degree relative orientation accuracy*
- + Small footprint - 33.8 cubic inches (without external IMU). Size of IMU enclosure depends on IMU used
- + Light weight - 20 oz. (without external IMU). Weight of IMU enclosure depends on IMU used
- + Internal TDMA data link optional
- + 3 RS-232 ports and 1 Ethernet port
- + On-board data logging of all raw and solution data
- + Powered by Precise Instantaneous Network (PIN) positioning, based on Geodetics' Epoch-by-EPOCH® technology, a new network-based real-time methodology not requiring multi-epoch initialization and re-initialization
- + Mil-Spec ruggedization
- + Configurable with single or dual-frequency GPS receivers
- + Configurable with various grade IMU's

*Accuracy is dependent upon GPS satellite system performance, ionospheric conditions, IMU type, data link and other factors

Relative navigation applications include:

- + Autonomous landing systems for UAV's
- + Autonomous aerial refueling for UAV's
- + UxV collision avoidance
- + UxV Swarming
- + UxV Leader/Follower Formations

Navigation Systems

- Geo-iNAV® Tactical
- Geo-iNAV® Advanced
- Geo-RelNAV®
- Geo-Pointer™
- Geo-hNAV™
- Geo-PNT®
- Geo-MMS™

Embedded Systems

- Geo-eBox™

Software Solutions

- RTD-Data
- RTD-Guest
- RTD-Net
- RTD-Post
- RTD-Pro
- RTD-Rover
- RTD-Vector

Geo-RelNAV® Brochure w/ Tech Specs



Figure M8. Geodetics Geo-RelNav Specification Sheet



Sensor Accuracy Chart

TSPI Capability Name	TSPI system type	Describe ground-based portion of system	Describe player instrumentation	Real-time accuracy	Post-mission accuracy
GLite KGPS Config C1	KGPS, 12 channel, kinematic, single frequency. On board control and data recording. Post mission processing only.	GPS reference receiver station (CR3)	PC-104 stack with CPU, GPS receiver, status display, recorder, optional data interface		Pos=1.5 ft, Vel=0.5 ft/s, Acc=0.5 ft/s/s
GLite KGPS+IMU Config C2B	KGPS+IMU, onboard control and data recording. Post mission processing only. GPS: 12 channel, kinematic, single frequency. IMU: HG-1700	GPS reference receiver station (CR3)	PC-104 stack with CPU, GPS receiver, IMU, status display, recorder, optional data interface		Pos=1.5 ft, Vel=0.02 ft/s, Acc=0.02 ft/s/s, Att=0.1 deg

1/21/2019

1

Figure M9. GLite Specification Sheet

The C-12 will be equipped with a C2B and the T-38 will be equipped with a C1.

Data Acquisition Computer

The Data Acquisition Computer has 2 Intel Xeon E5-2620 processors with 6 cores and 12 threads each for a total of 12 cores and 24 threads. The processors are x64-based. There is also 32 GB of RAM installed and 4 TB of solid state drive storage. A minimal amount of storage is used for Windows 10, applications, and the code.

Data Processing Computer (Lab)

OS Name Microsoft Windows 10 Education
Version 10.0.17134 Build 17134
Other OS Description Not Available
OS Manufacturer Microsoft Corporation
System Name DESKTOP-IDFCOR8
System Manufacturer Hewlett-Packard
System Model HP Z840 Workstation
System Type x64-based PC
System SKU F5G73AV
Processor Intel(R) Xeon(R) CPU E5-2695 v3 @ 2.30GHz, 2301 Mhz, 14 Core(s), 28 Logical Processor(s)
BIOS Version/Date Hewlett-Packard M60 v02.29, 11/8/2016
SMBIOS Version 2.8
Embedded Controller Version 255.255 BIOS Mode Legacy
BaseBoard Manufacturer Hewlett-Packard
BaseBoard Model Not Available
BaseBoard Name Base Board
Platform Role
Hardware Abstraction Layer Version = "10.0.17134.765"
Installed Physical Memory (RAM) 128 GB
Total Physical Memory 128 GB
Available Physical Memory 124 GB
Total Virtual Memory 147 GB
Available Virtual Memory 143 GB

This page was intentionally left blank.

APPENDIX N – TSPI PARAMETER LIST

The highlighted fields are requested from the Range Operations Squadron

TSPI PRODUCT SPECIFICATION SHEET (Page 1 of 5)

TPS HAVE DOUBLE VISION					
INCLUDE (Please X this column.)	NO	* WEATHER AFFECTED; REQUIRES WEATHER BALLOON	NAME	UNITS	PARAMETER DESCRIPTION
Time and Index					
X	1		HMS	HMS	Time of Day (Hours, Minutes, Seconds)
	2		ELAPS	Sec	Elapsed time since zero time
	3		INDEX	N/A	Index Number
X	4		SECS	Sec	Time of Day (Total Seconds)
XYZ Coordinates *same values as Geocentric parameters 107-108-109 (PG4) if REF PT is ECEF					
X	8		XSM	Feet	X-Coordinate of Position
X	9		YSM	Feet	Y-Coordinate of Position
X	10		ZSM	Feet	Z-Coordinate of Position
Geodetic Coordinates *same values as Geodetic parameters 107, 108, 109 (PG4) - LAT84, LONG84, HGT84					
X	11		LAT	Deg	Latitude (+ North)
X	12		LONG	Deg	Longitude (+ WEST)
X	13		HGT	Feet	Ellipsoid Height
Altitude Above Mean Sea Level					
X	110		ALT	Feet	MSL Altitude
Atmospheric Parameters					
	14	*	RHO	SI/Ft3	Air Density
	15	*	PA	MBS	Ambient Pressure
	16	*	TA	Deg C	Ambient Temperature
Wind Parameters					
	17	*	WD	Deg	Direction Wind is Blowing From (+ Clockwise from North)
	18	*	WV	Ft/Sec	Wind Velocity
	19	*	WX	Ft/Sec	X-Component of Wind Velocity
	20	*	WY	Ft/Sec	Y-Component of Wind Velocity
	5	*	WZ	Ft/Sec	Z-Component of Wind Velocity
Velocity Parameters					
X	21		VX	Ft/Sec	X-Component of Velocity
X	22		VY	Ft/Sec	Y-Component of Velocity
X	23		VZ	Ft/Sec	Z-Component of Velocity
X	24		ROC	Ft/Sec	Rate of Climb
	25	*	VWX	Ft/Sec	Wind-Corrected X-Component of Velocity
	26	*	VWY	Ft/Sec	Wind-Corrected Y-Component of Velocity
	6	*	VWZ	Ft/Sec	Wind-Corrected Z-Component
Acceleration Parameters					
X	27		AX	Ft/Sc2	X-Component of Acceleration
X	28		AY	Ft/Sc2	Y-Component of Acceleration
X	29		AZ	Ft/Sc2	Z-Component of Acceleration
X	30		AV	Ft/Sc2	Vertical Acceleration
	31	*	AWX	Ft/Sc2	Wind-Corrected X-Component of Acceleration
	32	*	AWY	Ft/Sc2	Wind-Corrected Y-Component of Acceleration
	7	*	AWZ	Ft/Sc2	Wind-Corrected Z-Component of Acceleration
Miscellaneous					
	33		SR	Feet	Slant Range
	34		HR	Feet	Horizontal Range
	35		AZY	Deg	Azimuth with Respect to the Y-Axis (+ Clockwise)
	36		AZN	Deg	Azimuth with Respect to North (+ Clockwise)
	37		EL	Deg	Elevation Angle
	38		ROD	Ft/Sec	Rate of Descent

TSPI PARAMETER LIST.Revised 25SEP15.xls

TSPI PRODUCT SPECIFICATION SHEET (Page 2 of 5)

TPS HAVE DOUBLE VISION					
INCLUDE (Please X this column.)	NO	* WEATHER AFFECTED; REQUIRES WEATHER BALLOON	NAME	UNITS	PARAMETER DESCRIPTION
Miscellaneous					
	39	*	RDMSL	Ft/Sec	Mean Sea Level Rate of Descent
Velocity Parameters (Other)					
	40		VT	Ft/Sec	Total Velocity
	41		VH	Ft/Sec	Horizontal Velocity
	42		VG	Ft/Sec	Ground Velocity
	43	*	TAS	Ft/Sec	True Air Speed
	44	*	VHA	Ft/Sec	Horizontal Velocity, Wind Corrected
	45	*	VGA	Ft/Sec	Ground Velocity, Wind Corrected
Cumulative Distances					
	46		HORD	Feet	Horizontal Distance
	47		ARCD	Feet	Arc Distance
	48		ACCGD	Feet	Accumulated Ground Distance
Attitude Angles - NO LONGER AVAILABLE; if chosen, values will be ZERO (0)					
N/A	49		AZATT	Deg	Azimuth Attitude Angle (+ Clockwise)
N/A	50		ELATT	Deg	Elevation Attitude Angle
N/A	51		VATT	Deg	Vertical Attitude Angle
Miscellaneous					
	52		HV	Deg	Heading With Respect to the Y-Axis (+ Clockwise)
X	53		HVN	Deg	Heading With Respect to North (+ Clockwise)
	54		DVA	Deg	Dive Angle
	55	*	HVA	Deg	Wind Corrected Heading with Respect to the Y-Axis (+ Clockwise)
	56	*	HVNA	Deg	Wind Corrected Heading with Respect to North (+ Clockwise)
	57	*	DVAA	Deg	Wind Corrected Dive Angle
	58	*	VS	Ft/Sec	Velocity of Sound
	59	*	MACH	N/A	Mach number
X	60		GRAV	Ft/Sc2	Acceleration due to Gravity
	61	*	QDP	Lb/Ft2	Dynamic Pressure
	62	*	QC	Lb/Ft2	Impact Pressure
	63	*	PITCH	Deg	Pitch Angle
	64	*	YAW	Deg	Yaw Angle
	65	*	FPA	Deg	Flight Path Angle
North-East Parameters					
	66		RN	Feet	Range North
	67		RE	Feet	Range East
	68		VN	Ft/Sec	Northward Velocity
	69		VE	Ft/Sec	Eastward Velocity
	70	*	RB	Deg	Bearing of Origin with Respect to HVNA
At the Object Parameters					
	71		VNO	Ft/Sec	Northward Velocity at the Object
	72		VEO	Ft/Sec	Eastward Velocity at the Object
	73		VZO	Ft/Sec	Upward Velocity at the Object
	74		HVO	Deg	Heading from North at the Object (+ Clockwise)
	126		ANO	Ft/Sc2	Northward Acceleration at the Object
	127		AEO	Ft/Sc2	Eastward Acceleration at the Object
	128		AZO	Ft/Sc2	Upward Acceleration at the Object
Acceleration Parameters (Other)					
	75		AM	Ft/Sc2	Total Acceleration

TSPI PARAMETER LIST.Revised 25SEP15.xls

TSPI PRODUCT SPECIFICATION SHEET (Page 3 of 5)

TPS HAVE DOUBLE VISION					
INCLUDE (Please X this column.)	NO	* WEATHER AFFECTED; REQUIRES WEATHER BALLOON	NAME	UNITS	PARAMETER DESCRIPTION
Acceleration Parameters (Other)					
	76		AT	Ft/Sc2	Tangential Acceleration
	77		AN	Ft/Sc2	Normal Acceleration
	78	*	AMA	Ft/Sc2	Wind Corrected Total Acceleration
	79	*	ATA	Ft/Sc2	Wind Corrected Tangential Acceleration
	80	*	ANA	Ft/Sc2	Wind Corrected Normal Acceleration
Total Velocity Intercepts					
	81		XINV	Feet	X-Coordinate of VT Intercept with XY-Plane
	82		YINV	Feet	Y-Coordinate of VT Intercept with XY-Plane
Velocities Relative to SR Vector (Right-Handed System)					
	83	*	VXP	Ft/Sec	Velocity along SR Vector
	84	*	VYP	Ft/Sec	Velocity Horizontally Perpendicular to SR Vector
	85	*	VZP	Ft/Sec	Velocity Upwardly Perpendicular to SR Vector
Accelerations Relative to TAS Vector (Right-Handed System)					
	86	*	AXP	Ft/Sc2	Acceleration along TAS Vector
	87	*	AYP	Ft/Sc2	Acceleration Horizontally Perpendicular to TAS Vector
	88	*	AZP	Ft/Sc2	Acceleration Upwardly Perpendicular to TAS Vector
	89	*	RLF	Ft/Sc2	Radial Acceleration
	90	*	KAPPA	Deg	Direction of Radial Acceleration (+ Clockwise from Vertical)
	91	*	RLD	N/A	Lift-to-Drag Ratio Valid for Unpowered Flight only
	92	*	CDS	SQFT	Drag Area
	93	*	CD	N/A	Coefficient of Drag
	94	*	KD	N/A	Ballistic Coefficient of Drag
Problem Plane Parameters					
	95		DPP	Feet	Range in Problem Plane
	96		VPP	Ft/Sec	Velocity in Problem Plane
	97		APP	Ft/Sc2	Acceleration in Problem Plane
	98		OMGT	DG/Sec	Angular Rate of Pull-Up in Problem Plane
	99		SIGT	Deg	Elevation Angle in the Problem Plane (Target Angle)
	100		PTCHPP	Deg	Pitch Angle in the Problem Plane
	101		YAWPP	Deg	Yaw Angle from the Problem Plane (+ Clockwise)
	102		BETA	Deg	Horizontal Angle Between the VT and SR Vectors (+ Clockwise)
	103		THETA	Deg	Vertical Angle between the VT and SR Vectors in the Problem Plane (+ Clockwise)
	104		PHI	Deg	Space Angle between the VT and SR Vectors
	105	*	VAPP	Ft/Sec	Air Speed in the Problem Plane
	106	*	PRALT	Feet	Pressure Altitude
"NAD-27" Geodetic Coordinates					
	107		LAT27	Deg	"NAD-27" Latitude
	108		LONG27	Deg	"NAD-27" Longitude
	109		HGT27	Feet	"NAD-27" Altitude
"WGS-72" Geodetic Coordinates					
	107		LAT72	Deg	"WGS-72" Latitude
	108		LONG72	Deg	"WGS-72" Longitude
	109		HGT72	Feet	"WGS-72" Altitude
"WGS-84" Geodetic Coordinates					
	107		LAT84	Deg	"WGS-84" Latitude
	108		LONG84	Deg	"WGS-84" Longitude
	109		HGT84	Feet	"WGS-84" Altitude

TSPI PARAMETER LIST.Revised 25SEP15.xls

TSPI PRODUCT SPECIFICATION SHEET (Page 4 of 5)

TPS HAVE DOUBLE VISION					
INCLUDE (Please X this column.)	NO	* WEATHER AFFECTED; REQUIRES WEATHER BALLOON	NAME	UNITS	PARAMETER DESCRIPTION
Geocentric Coordinates *same values as Parameters 8-9-10 (PG1) if REF PT is ECEF					
	107		U	Feet	Geocentric U-Coordinate
	108		V	Feet	Geocentric V-Coordinate
	109		W	Feet	Geocentric W-Coordinate
Lambert Coordinates					
	107		E-LAM	Feet	Lambert Easting
	108		N-LAM	Feet	Lambert Northing
	109		U-LAM	Feet	Lambert Up
UTM Coordinates					
	107		E-UTM	Meters	UTM Easting
	108		N-UTM	Meters	UTM Northing
	109		U-UTM	Meters	UTM Up
Topocentric XYZ Coordinates					
	107		X-TPC	Feet	Topocentric X-Coordinate
	108		Y-TPC	Feet	Topocentric Y-Coordinate
	109		Z-TPC	Feet	Topocentric Z-Coordinate
Local Geocentric XYZ Coordinates					
	107		X-LGC	Feet	Local Geocentric X-Coordinate
	108		Y-LGC	Feet	Local Geocentric Y-Coordinate
	109		Z-LGC	Feet	Local Geocentric Z-Coordinate
Spherical Coordinates					
	107		SPHI	Deg	Phi (Geocentric Latitude)
	108		STHETA	Deg	Theta (Longitude)
	109		RADIUS	Feet	Radius from Center of Earth
Topocentric RAE Coordinates					
	107		EL-TPC	Deg	Topocentric Elevation Angle
	108		AZ-TPC	Deg	Topocentric Azimuth Angle
	109		RG-TPC	Feet	Topocentric Range
Local Geocentric RAE Coordinates					
	107		EL-LGC	Deg	Local Geocentric Elevation Angle
	108		AZ-LGC	Deg	Local Geocentric Azimuth Angle
	109		RG-LGC	Feet	Local Geocentric Range
Position, Velocity, and Acceleration Uncertainties					
X	111		SX	Feet	X Position Sigma
X	112		SY	Feet	Y Position Sigma
X	113		SZ	Feet	Z Position Sigma
X	114		RSSP	Feet	RSS Position Sigma
X	115		SVX	Ft/Sec	X Velocity Sigma
X	116		SVY	Ft/Sec	Y Velocity Sigma
X	117		SVZ	Ft/Sec	Z Velocity Sigma
X	118		RSSV	Ft/Sec	RSS Velocity Sigma
X	119		SAX	Ft/Sc2	X Acceleration Sigma
X	120		SAY	Ft/Sc2	Y Acceleration Sigma
X	121		SAZ	Ft/Sc2	Z Acceleration Sigma
X	122		RSSA	Ft/Sc2	RSS Acceleration Sigma
INU Attitude Angles					
X	123		ITHD	Deg	INU True Heading in Degrees (+ Clockwise from North)
X	124		IPITCH	Deg	INU Pitch Angle (+ Counter Clockwise)

TSPI PARAMETER LIST.Revised 25SEP15.xls

TSPI PRODUCT SPECIFICATION SHEET (Page 5 of 5)

TPS HAVE DOUBLE VISION					
INCLUDE (Please X this column.)	NO	* WEATHER AFFECTED; REQUIRES WEATHER BALLOON	NAME	UNITS	PARAMETER DESCRIPTION
INU Attitude Angles					
X	125		IROLL	Deg	INU Roll Angle (+ Counter Clockwise)
Uncertainties (Other)					
X	15		SLAT	Feet	Latitude Sigma
X	16		SLON	Feet	Longitude Sigma
X	17		SHGT	Feet	Ellipsoid Height Sigma
X	18		SALT	Feet	MSL Altitude Sigma
	22		SVE	Ft/Sec	East Velocity Sigma
	23		SVN	Ft/Sec	North Velocity Sigma
	24		SVU (SVD)	Ft/Sec	Up (Down) Velocity Sigma
	28		SAE	Ft/Sc2	East Acceleration Sigma
	29		SAN	Ft/Sc2	North Acceleration Sigma
	30		SAU (SAD)	Ft/Sc2	Up (Down) Acceleration Sigma
	49		SAX	Ft/Sc2	X Acceleration Sigma
	50		SAY	Ft/Sc2	Y Acceleration Sigma
	51		SAZ	Ft/Sc2	Z Acceleration Sigma
Dilution of Precision (DOP) Parameters (currently unavailable with GLITE units - values will be 0)					
Standard Parameters					
			GDOP		Geometric DOP
			PDOP		Position DOP
			TDOP		Time DOP
			HDOP		Horizontal DOP
			VDOP		Vertical DOP
			EDOP		East DOP
			NDOP		North DOP
			UDOP		Up DOP
Weighted Parameters					
			WGDOP		Geometric DOP
			WPDOP		Position DOP
			WTDOP		Time DOP
			WHDOP		Horizontal DOP
			WVDOP		Vertical DOP
			WEDOP		East DOP
			WNDOP		North DOP
			WUDOP		Up DOP

This page was intentionally left blank.

APPENDIX O– DAILY FLIGHT REPORTS

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE C-12C	2. SERIAL NUMBER 76-00158
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO 4320-1/2	B. FLIGHT NO / DATA POINT Have Double Vision Flight #1	C. DATE 7 March 2019	
D. FRONT COCKPIT (<i>Left Seat</i>) Whitebread	E. FUEL LOAD / OPERATING WEIGHT / MOMENT 2.6 / 10.0	F. JON MT18B600	
G. REAR COCKPIT (<i>Right Seat and rest of crew</i>) Lorax / Slayer / BIFF / Nykl	H. START UP GR WT / MOMENT 12.5 / 19.7	I. WEATHER SCT 040	
J. TO TIME / SORTIE TIME 0846 / 2.0	K. CONFIGURATION / LOADING Have Double Vision Camera Config	L. SURFACE CONDITIONS 47°F / 24019G23	
M. CHASE ACFT / SERIAL NO 76-00161	N. CHASE CREW Billy / Faruk / Evil / Dish / Dallmann	O. CHASE TO TIME / SORTIE TIME 0846 / 2.0	
4. PURPOSE OF FLIGHT / TEST POINTS			
The purpose of this flight was to collect data to meet specific test objectives 1 and 2 in accordance with the Have Double Vision Test Plan in the high and low altitude blocks for areas D1 and M1. Additionally the formation position was clarified and visual references updated. "Near real-time" functionality was unavailable but some comments were obtained for utility in accordance with specific test objective 3. Points completed were C12.D1.L.F, C12.D1.H.F, C12.M1.L.F, C12.M1.H.F, C12.C.A.A, and C12.M1.L.A.			
5. RESULTS OF TESTS (<i>Continue on reverse if needed</i>)			
The flight 1 objectives were to complete full maneuver blocks of for desert high, desert low, mountain high, and mountain low points. Additionally the pilots in the test aircraft spent time familiarizing and standardizing formation position. The planned sequence of test points was Camera Calibration, start taxi, truth data calibration, takeoff, C12.D1.L.F, C12.D1.H.F, C12.M1.L.F, C12.D1.H.F, landing. Clouds in D1 were encountered and prioritized after the desert low block. Ground Ops: Camera calibrations were completed on external power. The camera calibrations proved to be questionable do to lighting on the EO cameras (backlit from the sun). The low contrast made the individual grids difficult to distinguish. IR camera calibration sensors were potentially more acceptable due to good warming of the calibration board. It is important to ensure all squares of the grid are visible in the field of view. Outliers should not be included in the camera calibration. To ensure the time server was correctly synced to the computer clock the current time had to be changed by 2-3 min to allow the correction to work. The time server correctly worked after this was completed. The coarse alignment was also completed before the aircraft was ready to taxi. Both aircraft taxied single ship after coarse alignment was complete and fine alignment was complete after passing the T-38 sun shades enroute to 22-R. No fine alignment maneuvers were required. All blocks were flown at 160 KIAS. Systems worked correctly with zero dropped frames throughout the flight. C12.D1.L.F Desert Low - Completed level at 11,000 feet. The formation position was stable and centered in all frames of the camera. Shadows from the lead aircraft were observed. Maneuver points were collected on an eastward heading. All systems were working and data quality was good. C12.C.A.F (in D1) Above Clouds - Clouds were encountered at approximately 4,000 feet (aircraft at 11,000 feet). An abbreviated block was completed above the clouds. Astern to contact, contact, left and right limits, and a single turn were completed. The EO cameras were very washed out and the white C-12 was difficult to clearly identify. IR cameras looked good. An additional above cloud block should be low priority. Continued			
6. RECOMMENDATIONS			
Consider adjusting the exposure on the EO cameras using VIMBA to allow better images over snow and clouds.			
COMPLETED BY Baxter, David T, Capt, USAF		SIGNATURE \\signed\dtb\7Mar19\	DATE 7 March 19

C12.D1.H.F Desert High - Completed level at 16,000 feet. The formation position was stable and centered in all frames of the camera. Some shadows from the lead aircraft were observed. Maneuver points were collected on a westward heading. All systems were working and data quality was good.

C12.M1.L.F Mountain Low - Completed level at 16,000 feet. The formation position was stable and centered in all frames of the camera. Lots of clouds were present resulting in poor data quality. Maneuver points were collected on a northward heading. All systems were working and data quality was marginal.

C12.M1.H.F Mountain High – Completed level at 21,000 feet. The formation position was stable and centered in all frames of the camera. Maneuvering around clouds ensured better data quality. Some of the maneuver was completed with snow in the background. Maneuver points were collected on a southward heading. All systems were working and data quality was good.

C12.M1.L.F Mountain Low - Completed level at 16,000 feet. The formation position was stable and centered in all frames of the camera. Maneuvering around clouds ensured better data quality. Some of the maneuver was completed with snow in the background. An additional abbreviated point was also completed. Maneuver points were collected on a southward heading. All systems were working and data quality was good.

Landing and ground ops were uneventful. All data was collected to backup drives without incidence.

End of Report.

Date: 7 MAR 19 TC Name: BIFF

Flight #: 1

Page #: 1/4

Takeoff Time: 0846L

Land Time: 1045

Overall WX Conditions: mostly
Sunny Some
SKT cloudsTime TC hit "g": 1627Z
0827LTime TC stopped recording: 1040L
1840Z

Test Point ID from test matrix	Start Time (local)	Start Ballpark Pulse Number (current Pulse)	End Time	Comments
C-12.D1.L.F	0851	2012	0900	Example—good full desert low maneuver block. Clear skies. Saw washout on EO cameras. Light turbulence caused receiver to bobble in contact position.
Elimbout	0847	38300		Some Image flicker OCL OA R IR
ASTERN	0851	44200		plane in camera FOV ~8K' MSL
CONTACT Position Start	0855	52000		plane starting to come into contact position, in full
C12.D1.L.F somewhere in here Tanker A/C shadows on RWR A/C				frame of all cameras
	0858	55700		Stable contact
	0900 (1200 comp time)	60,000		20 deg turn (Left)
	0903	65,400	0905	20 deg R turn
	0906	70,100	0907	R FRAME edge limit 1/4 wingtip gone
	0907	72,000	0908	not quite out of frame at mid air continued to 1/4 (R) wingtip out of L frame
Clouds Low	0908	74000	0910	entered clouds
Clouds	0910	77,300	0912	20° L turn, clouds are broken

Date: 7 MAR 19 TC Name: BIFF

Flight #: 1

Page #: 2/4

Takeoff Time:

Land Time:

Overall WX Conditions:

Time TC hit "g":

Time TC stopped recording:

Test Point ID from test matrix	Start Time	Start Ballpark Pulse Number	End Time	Comments
C-12.D1.L.F	0851	2012	0900	Example—good full desert low maneuver block. Clear skies. Saw washout on EO cameras. Light turbulence caused receiver to bobble in contact position.
Clouds Low	0913	81,700		L limit. 1/2 A/C L wingtip gone out of Rgt Frame
	0914	83,500		R limit 1/2 A/C R wingtip gone, out of L frame
INFO (Transition)	0915	86,800		clouds starting to clear off
D1. L. breakaway	0916	87,900	0917	Practice Separation, no more clouds, just on edges
back ASTERN	0918	92,800		
Stable contact	0919	97,000		
D1. H ASTERN	0921	100,000	0923	
D1. H contact	0923	102,000	0924	Stable
	0924	104,000	0925	L limit 3/4 wing A/C out Rgt of frame Comm: "Stable" Time 1:50
	0925	106,300		R limit 1/2 wing out L frame

debrief

Date: TC Name: Flight #: Page #: 3/4
 Takeoff Time: Land Time: Overall WX Conditions:
 Time TC hit "g": Time TC stopped recording:

Test Point ID from test matrix	Start Time	Start Ballpark Pulse Number	End Time	Comments
C-12.D1.L.F	0851	2012	0900	Example—good full desert low maneuver block. Clear skies. Saw washout on EO cameras. Light turbulence caused receiver to bobble in contact position.
D1.4 TURNS	0926	187,700	0928	20° R TURN. Some clouds/ water reflections from lakebed near Alc tail
	0928	112,100	0928	20° L TURN
D1.4 Breakaway	0929	114,200	0930	cleared out of bottom of frame
INFO	0934	122,800	0936	Some terrain entering (low mtns) less flare on EOs. Came back into desert
M1.L 16k'	0939	131,500		moving to astern
Stable contact	0942 :05	135,400		Alc aft more than prev.
Limit	0943	137,500		Alc to L. Limit (R. frame)
	0944	139,800		Alc to R. Limit (L. frame)
TURNS	0945	141,600	0946	20° L TURN Lake; clouds brown → white tops
	0946	145,000		white mountains, complete EO washout.
	0947	146,800	0948	20° R TURN. half brown/white tops

Date: 7 Mar 19 TC Name: BIFF

Flight #: 1

Page #: 4/4

Takeoff Time:

Land Time:

Overall WX Conditions:

Time TC hit "g":

Time TC stopped recording:

Test Point ID from test matrix	Start Time	Start Ballpark Pulse Number	End Time	Comments
				IR NUKES close to firing window
C-12.D1.L.F	0851	2012	0900	Example—good full desert low maneuver block. Clear skies. Saw washout on EO cameras. Light turbulence caused receiver to bobble in contact position.
M1. L separation	0950	150,600		hard for EO w/ snow
M1. H	0955	159,000		Some clouds, brown/green tops
M1. H	0957	163,000		Astern to contact
Contact stable	0959:30	165,800		brown/green tops [For time]
L Limit	1000	167,700		3/4 wing out
R Limit	1000	169,500		1/2 wing out
R 20° turn	1002	171,700		Low Mtns in background
L 20° turn	1002	173,000	1004	Few clouds
→ Separation	1005	177,300	1005	Med/High Mtns + desert in backgnd
M1. L	1010	187,000		moving to contact position
Stable contact	1012:20	189,800		Some low mtn + desert in background
" "	1014:15	193,000		better mtns, IR NUKE
L Limit	1015	194,500		full wing part of fuselage
R Limit		196,200	1016	1/2 wing out
20° L Turn	1016	197,700		few clouds
Stable	1018:55	201,200		Good mtns, no cloud
20° R Turn		202,800	1020	
Separation	1020	204,200		some EO wash out, desert/brown mtn tops
Desert ~ mtns	1028	214,800		in frame, low alt
stable astern	1030	225,000	1034	

1033 over mtns

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE C-12C	2. SERIAL NUMBER 76-00158
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO 4321-1/2	B. FLIGHT NO / DATA POINT Have Double Vision Flight #2	C. DATE 8 March 2019	
D. FRONT COCKPIT (<i>Left Seat</i>) Whitebread	E. FUEL LOAD / OPERATING WEIGHT / MOMENT 2.6 / 10.0	F. JON MT18B600	
G. REAR COCKPIT (<i>Right Seat and rest of crew</i>) Starr / Dish / Slayer / Dallmann	H. START UP GR WT / MOMENT 12.5 / 19.7	I. WEATHER SCT 080 – LGT/MOD TURB	
J. TO TIME / SORTIE TIME 0907 / 1.9	K. CONFIGURATION / LOADING Have Double Vision Camera Config	L. SURFACE CONDITIONS 47°F / 24019G23	
M. CHASE ACFT / SERIAL NO 76-00161	N. CHASE CREW Billy / Faruk / Evil / Biff / Nykl	O. CHASE TO TIME / SORTIE TIME 0907 / 1.9	
4. PURPOSE OF FLIGHT / TEST POINTS			
The purpose of this flight was to collect data to meet specific test objectives 1 and 2 in accordance with the Have Double Vision Test Plan in the high and low altitude blocks for areas D1, D2, and M1. “Near real-time” functionality was unavailable but some comments were obtained for utility in accordance with specific test objective 3. Points completed were C12.D1.L.F (twice), C12.D1.H.F, C12.D2.H.F (at 21000 MSL) and C12.C.B.A. An additional maneuver block was flown at 16000 MSL on an East heading in the northern half of R-2505 over foothill terrain.			
5. RESULTS OF TESTS (<i>Continue on reverse if needed</i>)			
The objectives for flight 2 were similar to those of flight 1, with a focus on more independent data sets in the desert and mountain backgrounds. No points were planned in the M2 region due to widespread snow cover on the mountains. The general flow was a clockwise route around KNID. Clouds were seen in region D1 near the California City airport and an abbreviated maneuver block was completed approximately 1500 ft below the scattered clouds. Moderate turbulence prevented the completion of a full maneuver block. Ground Ops: Both aircraft were hooked up to external power on the ground. The G-Lite TSPI was initialized on tail 161. On tail 158, both the G-Lite and computer/camera system were booted up. The #1 IR camera did not turn on and did not appear on the EBus program. The camera successfully booted up after re-seating the power cable and ground ops continued with a good camera calibration. Geodetics fine alignment was again completed on Taxiway F just east of the F-16 sunshades. The SI Master Power was inadvertently turned off after the co-pilot mistakenly hit the engine start switch while taxiing onto runway 22R. The SI system was rebooted and the aircraft performed a fine alignment maneuver on the hammerhead between 22R and 22L. A standard interval takeoff was performed from Runway 22L. The same IR camera that previously had issues on the ground froze immediately after takeoff. The cause was investigated but not found in flight, and the team decided to proceed knowing the EO camera pair was operating well. All formation maneuvers were flown at 160 KIAS. Full maneuver blocks were completed in desert region #1 in Black Mountain for the high and low altitude blocks. The camera operator noted several occasions where clouds or shadows from the lead aircraft were present in the field of view. After turning to a westbound heading, the TC directed the pilot to descend to attempt a maneuver block below a scattered cloud deck at about 8000 ft MSL near Cal City. Only an abbreviated maneuver block was completed due to constant moderate turbulence from the interaction between wind and the mountains north of Mojave. A full maneuver block was also completed on the east side of the mountain ridge along the west side of Owens Valley. The formation was turned on an eastbound heading to cut across R-2505 at 16000 ft MSL over interesting terrain contrasts. Light snow on foothills occasionally made it difficult to distinguish the trail aircraft on the EO cameras, but it was still possible to see on the one working IR camera. Continued.			
6. RECOMMENDATIONS			
COMPLETED BY Andrew K. Petry, Captain, USAF		SIGNATURE //signed—akp//	DATE 8 Mar 19

Another full maneuver block was flown at 21000 ft MSL in the D2 region, on a course roughly aligned with points J through M. The last maneuver block was flown in the D1 region at 12000 ft MSL.

Landing and ground ops were uneventful. All data were transferred to backup drives.

End of Report.

Date: 8 MAR 19 TC Name: PETR-1

Flight #: 2

Page #: 1/3

T/O:

Land: 1103L

Overall WX: F6W/SCt 9000ft.

Time TC hit "g": (L) 902L (Z) 1702Z Recording Stop: (L) 909 (Z) 1709Z ^{NOT} FINAL

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
P	0855	27100		COMPUTER SHUTDOWN RESTART COMPLETE
	907	9000		240 14 G20 TAKEOFF
CAMERA FRUSTRATE	908			LEFT CAMERA STOPPED WORKING IR (FROZE)
	910 L 1710 Z	0		LEFT IR NOT WORKING
	912 L			STOPPED
RESTART SYSTEM	917 1717			BUFFERS REINITIATED (WARNING) IN CBUS PLAYER
OUTBOARD IR STOPPED		NO IR ↓		WARNING PROCESS IMAGE RETURN FALSE (AAR PROCESSING)
D1.L	919	3600		ASTERN
CONTACT	922 10	8000		STABLE CONTACT DRIFTED AFT
CONTACT LIMITS	923	9000		CONTACT L/R LIMITS
TURNS	924	12400 13600		TURNS (LEFT) OVER BLACK MTN (RIGHT) - GROND CONTRAST
	927 928	15000		OVER BLK MTN CLOUDS
TURN	929			TURN FOR BLK MTN
	932	25700		EO CUT IN HALF B-T CONTRAST
	933	29000	0934 D1.L complete	SEPARATION RIGHT OVER CLOUDS
D1.H	940	40800		ASTERN
CONTACT	941.33	42900		

Date: 8 MAR 19 TC Name:

Flight #: 2

Page #: 2/3

T/O:

Land:

Overall WX:

Time TC hit "g": (L)

(Z)

Recording Stop:(L)

(Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L/ L frame limit	0851	(current pulse #)	0900	R (IN BOARD) 60 APPLES WASHED OUT Example—Clear skies. Saw washout on EO cameras. ^{MORE THAN} TERRAIN change. 1/2 ac's L wing out of top R frame. ^{BEFORE}
D1. H LIMITS	942	443 45100		L Lim (DISAPPEARS) R Lim
TURN	943	46100 47500		R TURN - some clouds L TURN
SEPARATION	944	49700		
C12 C.B.A ASTERN	952	62000		
CONTACT	954			NO STABLE CONTACT, GOOD 10° COMPLETE
	955	69000		TERMINATED FOR TURBULENCE
M1. L	1005	86000		ASTERN TO CONTACT SOME CLOUDS
CONTACT	1006	87800	1007	SOME CONTACT, TURBULENCE POSSIBLY ABANDONED COMPLETE
MX, L	1010	95000		ASTERN
CONTACT	1013	99000		MOUNTAINS, ADJUSTING CONTACT POSITION, CLOSE
STABLE CONTACT	10 14:15	101700		
LIMITS	10 14 10 15	102500 105000		L Lim DESERT/MTN MIX R Lim
URNS	1017 1018	108000 109600		R. CLOUD WASHOUT L GOOD MTN
SEP	1019	112900		STAYED IN FOV, GOOD RATE
MX, H (02)	1026	123800		STABLE ASTERN
CONTACT	10 27:24	126500		
L/R LIMITS	1028	127100 127900		WASHED OUT CONTACTED L Lim R Lim WASHED OUT FROM CONTACT

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE C-12C	2. SERIAL NUMBER 76-00158
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO 4756-1/2	B. FLIGHT NO / DATA POINT Have Double Vision Flight #3	C. DATE 11 March 2019	
D. FRONT COCKPIT (<i>Left Seat</i>) Whitebread	E. FUEL LOAD / OPERATING WEIGHT / MOMENT 2.6 / 9.8	F. JON MT18B600	
G. REAR COCKPIT (<i>Right Seat and rest of crew</i>) Billy / BIFF / Dish	H. START UP GR WT / MOMENT 12.4 / 19.7	I. WEATHER SCT 080	
J. TO TIME / SORTIE TIME 1055 / 2.1	K. CONFIGURATION / LOADING Have Double Vision Camera Config	L. SURFACE CONDITIONS 41°F / VRB 06	
M. CHASE ACFT / SERIAL NO 76-00161	N. CHASE CREW Faruk / Lorax / Slayer / Nykl	O. CHASE TO TIME / SORTIE TIME 1055 / 2.1	
4. PURPOSE OF FLIGHT / TEST POINTS			
<i>Note that this was the first flight after Daylight Savings Time began, so the new local to zulu correction is 7 hours.</i> The purpose of this flight was to collect data to meet specific test objectives 1 and 2 in accordance with the Have Double Vision Test Plan in the high and low altitude blocks for areas D1, M1, M2, and near clouds. "Near real-time" functionality was used for the first time, and subsequent flights should complete the airborne system operator questionnaire. One IR camera was again inoperative, so the team flew with two working EO cameras. The system operator changed the EO camera exposure settings from 15000 µs to 5000 µs in an effort to avoid saturating the cameras due to bright white conditions. Points completed were: - C12.C.B.F in the D1 region - C12.D1.L.F - C12.D1.H.F - C12.C.A.F in the D1 region - C12.M1.L.F - C12.C.A.F in the M1 region - C12.M2.L.F - C12.M1.H.F			
5. RESULTS OF TESTS (<i>Continue on reverse if needed</i>)			
The objectives for flight 3 were similar to those of the previous two flights. The team flew within the R-2508 complex in the D1, M1, and M2 regions. Puffy cumulus clouds were initially few at 8000 ft AGL and cover increased to scattered from KMHV north over the Isabella MOA. A high cirrus layer was rolling in during RTB. The general flow was to complete more full maneuver blocks in the D1, M1, and M2 regions and to take advantage of clouds where possible. Ground Ops: Both aircraft were hooked up to external power on the ground. The G-Lite TSPI was initialized on tail 161. On tail 158, both the G-Lite and computer/camera system were booted up. Both IR cameras worked during an early morning test in the C-12 hangar, but the #1 camera stopped working once the aircraft was towed out to the C-12 parking ramp. The team troubleshooted the issue in conjunction with SI technicians and the AFIT representatives. The issue was traced to the "pigtail" splice that connects the trigger line to the camera. The team decided to press on with two working EO cameras, with the understanding that the flight for 12 Mar 19 would likely be canceled to give SI an estimated 4-5 hours to fix the issue. No camera calibration was completed because the AFIT representatives wanted to wait until later in the day when the sun was at a more favorable angle. Engine start was normal and the Geodetics fine alignment was completed on Taxiway F just east of the F-16 sunshades. Takeoff was normal and the vision system was unpaused shortly after takeoff. All formation maneuvers were flown at 160 KIAS. Continued.			
6. RECOMMENDATIONS			
COMPLETED BY Andrew K. Petry, Captain, USAF		SIGNATURE //signed—akp//	DATE 12 Mar 19

C12.C.B.F in D1 region, starting at 1101L near pulse 45300

Flight planning was orchestrated with SPORT to shift from the initial plan of Cords Road to a block underneath a long cloud south of Highway 58. A full maneuver block was completed at about 8000 ft MSL, about 1500 ft below the cloud base. A left turn was completed during the left/right contact limits to stay under the clouds which were becoming more intermittent. A right turn was not completed.

C12.D1.L.F, starting at 1111L near pulse 62000

The formation moved over to Cords Road to complete a low altitude maneuver block. Small, wispy clouds were in the camera FOV as the test aircraft moved to the astern position during the climb to 11000 ft MSL. 20 degree bank turns were flown over the mines in Boron, which caused interesting washout on the EO cameras around pulse 71000. The rest of the full maneuver block was completed normally.

Experimenting with exposure settings

The vision system was shut down at about 1120L to change the EO exposure settings. The system operator closed the AAR recording GUI, then renamed the D:\imagery folder to avoid overwriting the images captured earlier in the flight. Vimba Viewer was used to change one of the camera exposures from 15000 μ s to 7500 μ s. The vision system was turned back on at 1126L/1826Z and the new exposure setting was compared to the old one. It was now possible to see more detail on the test aircraft, and one closure to contact was performed at 1127L. The team decided to lower the exposure even more to 5000 μ s in both cameras, with a new system start time of 1130L/1830Z. The images looked much better, and the system operator could see the black USAF insignia on the top wing surface. Hopefully the increase in detail visible on the AAR viewer will help the ICP algorithm avoid being washed out.

C12.D1.H.F, starting at 1131L near pulse 2700

A full maneuver block was completed at 16000 ft MSL using the new exposure settings. Note that the pulse count was reset once the exposures were changed.

C12.C.A.F in D1 region, starting at 1140L near pulse 18600

This maneuver block was flown at 11000 ft MSL in the southwest corner of R-2515 between EDW and MHV. The formation maneuvered over a cloud street that was at about 9000-10000 ft MSL. The clouds were in the camera FOV for the contact phase and left/right turns. A second closure to contact was completed, followed by left/right contact limits again with clouds in the background. The practice separation was flown as clouds left the FOV.

Real-time viewer

The real-time viewer was brought up in the transit to the Isabella MOA at 1150L. The text file directions on the computer desktop were useful. The system displayed the range to the test aircraft if the range was under 100 meters. The contact position was typically at about 36-38 meters slant range. Range was measured from the camera tray on 158 to the point cloud center of mass on 161. Yellow point cloud dots were concentrated on the fuselage and engine nacelles. More points were located near the USAF markings on top of the wings, which was a good sign that the lower exposure settings were helpful. The ICP algorithm tried to match a red colored C-12 reference model to the point cloud. This match was pretty good for position, but was quite jumpy for attitude. Future systems using ICP could augment the attitude calculation with smoothing inputs from the ownship IMU (or other techniques) to keep the system from matching to obviously incorrect attitudes. One issue noted with matching the aircraft position was that yellow point cloud dots were occasionally placed on background clouds or snowy mountains. These far away dots were small in number, but their large distance from the centroid of the other points caused the red C-12 reference model to jump aft by up to 5 meters or so as displayed on the real-time viewer. The system operator didn't notice if the range readout was also jumping around. Future flights should continue to use the real-time viewer and should complete the airborne systems operator survey. See Figure 1 for a photo of the point cloud and reference model.



Figure 1. C-12 Reference Model and Point Cloud.

C12.M1.L.F, starting at 1151L near pulse 38000

Flown at 14000 ft MSL over the Isabella MOA, starting over the windmills northeast of MHV. The maneuver block was completed uneventfully, with the exception of a few small clouds in the background which showed up as yellow dots in the real-time viewer point cloud as discussed above.

C12.C.A.F in M1 region, starting at 1159L near pulse 53000

Flown in Isabella MOA at 14000 ft. Clouds were in the camera FOV for the full duration of the maneuver block. The clouds were scattered cumulus with mountains and occasional snow in the background.

C12.M2.L.F, starting at 1216L near pulse 83700

Flown at 20000 ft MSL. Specifically targeted background mountains with extensive snow cover to test out the new exposure settings. The practice separation was flown on a southerly heading with the tanker aircraft's shadow covering the test aircraft's nose and windshield at the start of the maneuver. The shadows had no obvious impact on the point cloud in the real-time viewer.

C12.M1.H.F, starting at 1224L near pulse 97500

Crossed a few large puffy cumulus clouds during the maneuver block. Also flew directly over Lake Isabella with no obvious impact on the point cloud.

Landing and ground ops were uneventful. All data were transferred to backup drives.

End of Report.

Date: 11 Mar 19 TC Name: Haggberg

Flight #: 3

Page #: 1/4

T/O: 1054L

Land: 1255L

Overall WX: FEW 4000, FEW 8000, BKN Cirrus 20000

Time TC hit "g": (L) 10:36:15 (Z) 17:36:15

Recording Stop: (L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
climbout	1054	33000		unpaused recording
in view	1059	41000		moved to 8-10k block over the airfield to stay under clouds
cleared astern	1100	43000		
stable astern	1101	45300		start of C12.C.B.F just south of Hwy 58
cleared contact	1103	49000		about 8000 ft MSL
contact	1104:00	49800		10 seconds
L/R limits	1104	50900	1107	intermittent cloud cover flew left turn, never right
practice separation	1107	56700	1108	moved to cords Road after for DILF
moving to astern	1111	62000	1112	clouds in view... very wispy during climb to 11000
cleared contact	1113	658000		DILF!
contact	1113:53	67800		
L/R limits	1114	68500	1115	
turns	1115	70500	1117	strange washout from miles in the background on EO
practice separation	1117	73500		
closed to re-do	the exposure settings @ 1120, pulse 80500			
original was	15000, reset to	7500 with new		
"start recording"	time of	1126 L, 1826 Z		

Date: TC Name: Flight #: Page #: 2/4
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
Contact	1127:00	1800		experimented w/ exposure settings 4000 at 15000, one at 7500
Reset exposures				Reset exposures to 5000
cleared to contact	1131	2700		new start time 1130
contact	1132:00	3400		image looks much better... can see USAF insignia on wing top
L/R limits	1132	4000	1133	L, then R
Turns	1133	6000	1136	Right 180°, then small left turn
practice separation	1136	10700	1136	end of DIHF @ 16000 MSL
cleared astern	1140	18600		start of points above broken cloud layer between EDW and MHV
cleared contact	1141	20200		flew at 11000 MSL, clouds were about 9-10k MSL
Contact	1142:10	21700		clouds in view!
turns	1142	22000		Right turn w/ clouds in background
cleared to contact	1144	25300		
contact	1145:00	27000		few clouds
L/R limits	1145	27600		L, then R, clouds in view
practice separation	1146	29600	1147	clouds went out of view slightly before maneuver
				brought up real time viewer while flying into Isabella

Date: TC Name: Flight #: Page #: 3/4
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
—	1150			started real time viewer
cleared contact	1151	38000		14000 ft MSL, over the windmills, start of M1LF
contact	1151:50	39000		
turns	1152	39800		left first real time view saw clouds far away
L/R limits	1153	41600		
turns	1155	45000		right turn w/ small clouds in view
practice separation	1156	47900		
cleared astern	1159	53000		start of C.A.F over Isabella Mountains at 14000 ft
cleared contact	1202	57200		
contact	1203:21	59700		clouds in view below
L/R limits	1203	60400		clouds ✓
Turns	1203	63200		yellow points ok, but a few were on for clouds and pulled the model off
practice separation	1209	70000	1210	clouds in view
cleared astern	1216	83700		start of M2LF, targeting snowy mtns w/ low exposure 20000 MSL
cleared contact	1217	85400		
contact	1218:00	86100		
L/R limits	1218	86700		Right first for snow, then L

Date: TC Name: Flight #: Page #: 4/4
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.
turns	1219	88800	1221	Right first, then left very small clouds, lots of snow
practice separation	1222	95000	1223	our shadow right on their windshield
cleared astern	1224	97500		small puffy clouds intermittent
cleared contact	1226	101500		start of M/HF
contact	1227:00	102500		
L/R limits	1227	103000		left first, then right crossed over a large cloud
turns	1228	104600		left, then right crossed Lake Isabella at frame 110000
practice separation	1232	112000		
started shutdown	1250	143000		

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE C-12C	2. SERIAL NUMBER 76-00158
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO 4984-1/2	B. FLIGHT NO / DATA POINT Have Double Vision Flight #4 (almost)	C. DATE 11 March 2019	
D. FRONT COCKPIT (<i>Left Seat</i>) Whitebread	E. FUEL LOAD / OPERATING WEIGHT / MOMENT 2.6 / 9.8	F. JON MT18B600	
G. REAR COCKPIT (<i>Right Seat and rest of crew</i>) Faruk / Slayer / BIFF	H. START UP GR WT / MOMENT 12.4 / 19.7	I. WEATHER SCT 040/080/120/200	
J. TO TIME / SORTIE TIME 1539 / 0.6	K. CONFIGURATION / LOADING Have Double Vision Camera Config	L. SURFACE CONDITIONS 41°F / 03012G18	
M. CHASE ACFT / SERIAL NO 76-00161	N. CHASE CREW Billy / Lorax / Dish / Dallman	O. CHASE TO TIME / SORTIE TIME 1539 / 0.6	
4. PURPOSE OF FLIGHT / TEST POINTS The purpose of this flight was to collect data to meet specific test objectives 1 and 2 in accordance with the Have Double Vision Test Plan in the high and low altitude blocks for areas D1, M1, M2, and D2. "Near real-time" functionality was available. Additionally the real time algorithm was assessed for operational utility in accordance with specific objective 3.			
5. RESULTS OF TESTS (<i>Continue on reverse if needed</i>) This flight was terminated due to a damage strobe light glare shield that was discovered by the test aircraft during the first approach into the contact position. This was determined to be a safety risk for the test aircraft and contact position collection was terminated at this point. The formation landed and taxied back without losing the glare shield. Maintenance noted that this damaged part could be removed and the flight could be continued without the glare shield. This was not expected to impact further test operations. Ground Ops After flight 3 determined the IR camera was unusable for the flight, the decision was made to collect as much data as possible with the EO cameras before grounding aircraft 158 to attempt a repair. When the preflight power up of the have double vision system confirm the IR camera continued to malfunction, a calibration of only the EO cameras was completed on the ground. It is notable that further aft positions (8-10 feet from the cameras) were used than previous calibrations. This decision was made due to the results of the flight 2 camera calibration results. A short rain shower also occurred on the ground while maintenance replaced the auxiliary battery in tail 158. The cameras were checked before engine start and were determined to be dry enough to continue. The camera exposure was set to 5,000 during ground ops (default 15,000) resulting in dark image with the aircraft clearly visible. Engine Start and Taxi The ground was generally dry by the time taxi operations started. The fine alignment was completed by the time the aircraft was in the runway 04L hammerhead. This was further than expected and ramp space was coordinated for fine alignment turns but ultimately not used. Takeoff was uneventful. The desert 1 low block was attempted at 8,000 feet below the clouds. One abbreviated maneuver was completed with an approach from astern to contact where the glare shield was noted. Test was subsequently put into a safety chase position and the formation terminated the mission. Landing, taxi back, and shutdown were uneventful. End of Report.			
6. RECOMMENDATIONS Set 5,000 on the manual exposure settings in VIMBA for daytime operations, consider 7,500 for low light conditions.			
COMPLETED BY Baxter, David T. Capt, USAF		SIGNATURE //signed/dtb/11Mar19//	DATE 11 Mar 19

Date: 11 MAR

TC Name: BIFF

Flight #: 4

Page #: 1/1

T/O: 1540 L

Land: 1611 L

Overall WX: overcast, winds 030@14

Time TC hit "g": (L) 1522

(Z) 2222

Recording Stop:(L)

(Z)

Urpang 1943

~ 1600 L

[illegible]

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE C-12C	2. SERIAL NUMBER 76-00158
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO 4760-1/2	B. FLIGHT NO / DATA POINT Have Double Vision Flight #5	C. DATE 13 March 2019	
D. FRONT COCKPIT (<i>Left Seat</i>) Whitebread	E. FUEL LOAD / OPERATING WEIGHT / MOMENT 2.5 / 9.8	F. JON MT18B600	
G. REAR COCKPIT (<i>Right Seat and rest of crew</i>) Cain'n / Dish / BIFF	H. START UP GR WT / MOMENT 12.4 / 19.7	I. WEATHER CLR	
J. TO TIME / SORTIE TIME 1743 / 2.5	K. CONFIGURATION / LOADING Have Double Vision Camera Config	L. SURFACE CONDITIONS 49°F / VRB 06	
M. CHASE ACFT / SERIAL NO 76-00161	N. CHASE CREW Billy / Faruk / Lorax / Slayer	O. CHASE TO TIME / SORTIE TIME 1743 / 2.5	
4. PURPOSE OF FLIGHT / TEST POINTS			
The purpose of this flight was to collect data to meet specific test objectives 1 and 2 in accordance with the Have Double Vision Test Plan in the high and low altitude blocks for areas U1, U2, U3, M3, and O1. "Near real-time" (NRT) Iterative Closest Point (ICP) functionality was available. Additionally the real time algorithm was assessed for operational utility in accordance with specific objective 3. Both pairs of EO and IR cameras were operational. Points completed were: - C12.M3.H.F - C12.U2.H.F - C12.U3.H.F - C12.O1.H.F - C12.O1.L.F			
5. RESULTS OF TESTS (<i>Continue on reverse if needed</i>)			
Overall flight The NRT ICP yellow dots would frequently lock onto outlier points from objects in the distance similar in the off-white color of the trail aircraft (ocean sun reflection, and white buildings, plots of land) which were lower and further back from the point cloud being generated from the actual aircraft. This would cause the red model to drop its tail to a more nose up attitude to account for a mean distance location between all the points. The nose of the red model aircraft would also frequently align one of the nacelles of the yellow point cloud. Dr Nykl informed the team after the flight that future iterations of the model would be better able to account for these outliers. Ground Ops A ground EO and IR calibration took place at parking near 0930L using default EO and IR camera settings for exposure (15000 µS) and Automatic Gain Control (ACG) – Level & Gain: Automatic; Cutoff – Cold: 1, Hot: 5. Engine Start and Taxi After engine start, the system was started in accordance with the startup procedures. The NTP time offset was synched to within 0.0005s (System vs GPS offset). The EO camera exposure value was set to 5000 as this showed better pixel definition in previous sorties. The Geodetics fine alignment was completed on Taxiway F just east of the F-16 sunshades. Takeoff was normal and the vision system was unpaused just prior to takeoff at 1041L to witness system operation during takeoff in the event the IR cameras stopped working and no other Air Force aircraft were nearby. The system was paused again shortly after takeoff at 1046L once away from Edwards and the receiver aircraft came into view. Takeoff was uneventful. Overflight of Palmdale (U1) was skipped to fly direct route to U2. Continued.			
6. RECOMMENDATIONS			
Setting 2,000 on the manual EO exposure settings in VIMBA over the water to block out breaking waves and sun reflections. Automatic gain and level changes kept the IR video similar in contrast. The same IR manual gain and brightness settings will make one camera's video appear brighter than the other, which likely won't be good for the algorithm.			
COMPLETED BY Haggborg, Joseph S. Capt, USAF		SIGNATURE //signed/jsh/15Mar19//	DATE 15 Mar 19

C12.M3.H.F starting at 1053L near pulse 53000

A full maneuver block was completed at 17,000 MSL for about 4 minutes. The right banked turn had a U2 and M3 mix. The cameras faced the SW side of the mountains and essentially no snow was visible. Between U2 and U3 there was 1 minute of collection in the stable contact position (pulse 73000)

C12.U2.H.F starting at 1059L near pulse 63500

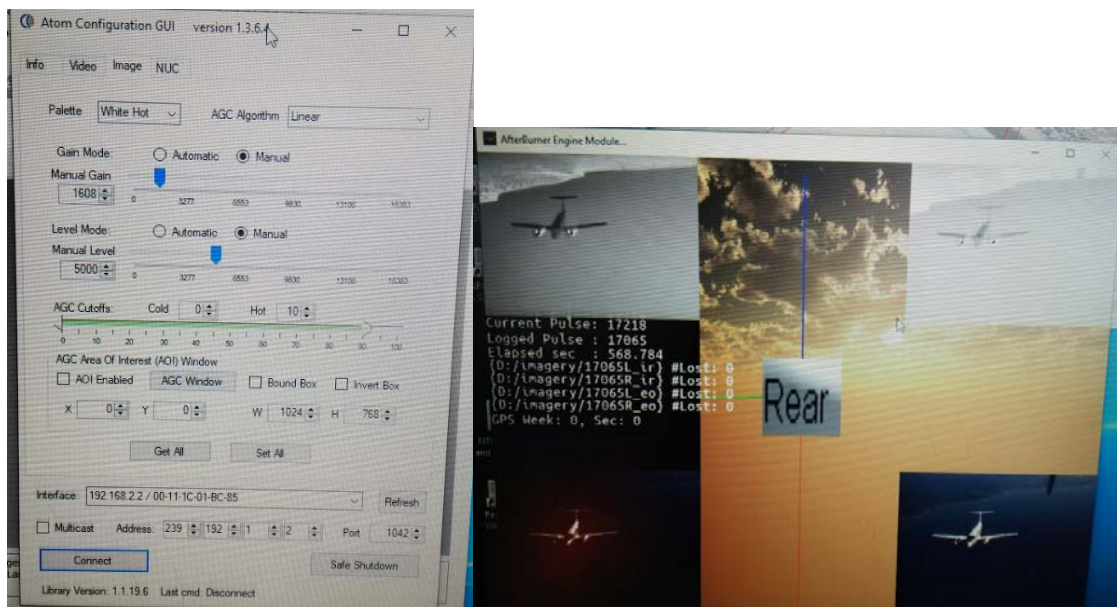
Portions of the full maneuver block were completed at 17,000 MSL for about 5 minutes. Did not get turns due to ATC flight path dictation. Limits, separation, and one astern to contact were completed with suburbs and industrial buildings near Burbank in the camera FOV. NRT ICP appeared to continue populating well with aircraft with some occasional yellow dots on white colored buildings.

C12.U3.H.F starting at 1106L near pulse 75800

The area in the FOV was in Ventura County near Camarillo, CA which consisted of a mix of coastal valley and highland terrain and included a good mix of housing development, populated highways, shopping centers and some plots of farm land. There were several areas with 100+ acre square plots of canopied farm land. These canopies were white with a sheen which would create additional points (even more so with sun reflection) in the ICP that would significantly alter the model on the NRT model depiction. This is definitely an area that should be investigated in post-flight data analysis.

C12.O1.H.F starting at 1119L near pulse 92400 (17K' MSL)

The plane passed over the coast near the start of the time listed above and the NRT ICP generated several points from the breaking waves along the coast line. When the plane was fully over the water, the plane caught some sun reflections. The plane was very black in the IR so the settings were changed in AtomConfig to those found in the picture below.



Having both IR cameras set to the same manual settings caused the camera in the top right frame to appear much lighter. The plane did get a much better gradient of black and gray on the wings which Dr. Nykl suggested would be better for the algorithm to generate ICPs. A full maneuver block was flown with these settings.

The EO cameras exposure settings were then changed from 5000 μ S to 2000 μ S which made the overall EO images darker and provided better contrasting pixels on the trail C12 (Note: better images of the camera changes and differences can be found from the image pair camera data). The EO setting changes did create more NRT ICPs on the wings and nacelles and generated less ICP dots from the waves breaking on the beach and the sun reflections.

C12.O1.L.F starting at 1207L near pulse 19600 (6K' MSL)

A full maneuver block was completed. Interesting sun reflections on the aircraft and water during right turn near pulse 33200. During left turn a significant amount of ICP dots were generated near pulse 37000 possibly due to sun reflection. Five (5) airborne system operation evaluations were conducted and the aircraft ICPs were observed to move in less than a second of the "hack" being called. Video of the maneuver and echoing the radio calls was recorded on Dish's phone near pulse 66300.

Formation breakup occurred at 1242L for a full stop landing at KCMA (Camarillo, CA). The landing, taxi back, and shutdown were uneventful.

End of Report.

Date: 13 MAR TC Name: BIFF Flight #: 5 Page #: 1/3
T/O: 1043 L Land: 1301 L Overall WX: Clear
Time TC hit "g": (L) 10:24 (Z) 17:24 Recording Stop: (L) 1244 (Z) 1944
un paused 1041

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
				EO Exposure 5000 1K ACG cutoff Cold 5 Hot 1
D1.L/ L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
	1036			after eng start, good sys start up. NTP Offset 0.0005
	1046 1049	39000 45600		Paused un paused RACE coming into view
	1056	47000		Astern. ICP Yellow pts tracking, red model aligning
M3.H.F No L turn	1053	53000		Some mtn terrain 16K
	1053:20 1057	56000 59400	1058 60000	10s stable contact Limits @ ~1054 separation
M2.H.A	1059	63500		mtn urban mix R. turn
	1101: 1101	64500 65800 66500		stable contact Limits
	1102 1103	67300 67600 70300	1102	separation Astern
	1104	71200		Contact
M3.H	1105	73000		Contact
7K' M3.H.F Same mtns	1106	75800		R. Limit stable holding over urban, still all frames
	1107	77200		L. Limit 1/2 wing gone airplane crossed under
	1108 1110	79300 79900 83300		separation Astern → some farm plots while moving astern
	1110 1111	84000 85000 85800		Contact 10s v L. turn
		86400 87300		R. turn
	1114	89700		Some lgt farm plot of land
	1115	91500 92400		mtn urban mix passing coast, sun reflection, Limits
17K'	1119	97900		Plane fully over water

Date: TC Name: Flight #: Page #:
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
O. A. F	1134 1136	1400 4500		Astern IR settings changed Contact top R IR in window lighter
		5100		L turn channel islands in background
	1137	6600		Limits. Calm sea state no caps
	1138 1140	8700 + 9400 12200		Separation Astern
	1140	13200		L turn Sun reflection and coast/ terrain in background
				seems to pick up waves breaking on beach
CAMERA	1142	15800 16300		Contact Limits
SETTING CHANGE	1143	18000 - 18700		Separation
	1158	2000		EO 2000. stable contact IR sett on phone
		3600 - 5200		Limits
	1159	5700		L turn
	1201	7500 - 8200		Separation
O1.L.F	1207 1208	14600 20700		Astern Contact
		21200		Limits 1/4 L wing gone L limit
	1210	23400 - 24000		Separation
	1212 1213	28800 29700 / 30700		Contact Limits
	1214 1214	31800 33200		R turn. Sun reflections in turn ch AIC & water
	1217	35600 37600		L turn bit off on pts on lower left, Sun reflection?
	1218	38800 - 39400		Separation

01. L
6K'

45800

1.6

Airborne Sys opn

50,400 Stable contact

51,800 ASD.

< 1.0 saw bank change w/ yellow points

red model nose aligning w/ eng

56,000 Stable contact

56,800 L turn

1228 57,000

ASD

< 1.0 good mvr

1232 63100

Astern

66300

ASD good mvr → video on Dish phone

1235 69300

Astern

70500

Contact

1236 72000

ASD good mvr

1238 75000

ASTERN

dragging over channel island

77100

Stable

rejecting more of the white water break on coast of Island

79700

R Limit

80200

L Limit

1242 81400 - 81900

Separation

1242 formation breakup

84200 out of frame ED1 lost in IR much earlier..

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE C-12C	2. SERIAL NUMBER 76-00158
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO 4760-3/4	B. FLIGHT NO / DATA POINT Have Double Vision Flight #6	C. DATE 13 March 2019	
D. FRONT COCKPIT (<i>Left Seat</i>) Whitebread	E. FUEL LOAD / OPERATING WEIGHT / MOMENT 2.6 / 9.8	F. JON MT18B600	
G. REAR COCKPIT (<i>Right Seat and rest of crew</i>) Cain'n / Dish / BIFF	H. START UP GR WT / MOMENT 12.4 / 19.7	I. WEATHER CLR	
J. TO TIME / SORTIE TIME 1510 / 2.1	K. CONFIGURATION / LOADING Have Double Vision Camera Config	L. SURFACE CONDITIONS 69°F / VRB 06	
M. CHASE ACFT / SERIAL NO 76-00161	N. CHASE CREW Billy / Faruk / Lorax / Dish	O. CHASE TO TIME / SORTIE TIME 1510 / 2.1	
4. PURPOSE OF FLIGHT / TEST POINTS			
The purpose of this flight was to finish collecting data points over the ocean and urban areas during the return leg from KCMA to KEDW. Both pairs of EO and IR cameras worked for the entire flight duration. The near real-time display also worked. The EO camera exposure time was set to 2000 μs. The IR camera settings were adjusted to Cold = 1, Hot = 5, and Auto. Settings were left unchanged throughout the flight. Points completed included: - O1.L.F x2 - O1.H.A - O1.H.F with a coast crossing - M3.L.F x2 - M3.L.A x2 - U1.F at 7500 MSL - U1.F at 6500 MSL x2 - U1.A at 6500 MSL - D1.L.A x10 - D1.H.A x10			
5. RESULTS OF TESTS (<i>Continue on reverse if needed</i>)			
The objectives of this flight were the same as flight #5 which occurred earlier the same day, with the addition of many abbreviated maneuver blocks in the D1 region to gain a statistically useful set of data with the EO exposure time set to 2000 μs. General sortie flow involved a takeoff on KCMA runway 26 followed by the completion of several ocean maneuver blocks. After the ocean blocks were completed, the formation flew on a nearly direct path from Santa Barbara to the western end of the Antelope Valley. Lancaster and Palmdale were used as urban backgrounds before reentering R2515 for many abbreviated maneuver blocks in the D1 region along Cords Road. Ground Ops Ground Ops occurred on the ramp at the Sun Air FBO at the Camarillo Airport, KCMA. No G-Lite initialization was performed because it was already completed before departing KEDW earlier in the morning. No camera calibration was performed because no external power carts were available. Both aircraft completed a Geodetics fine alignment during normal taxi operations from the Sun Air ramp to the runway. Takeoff was normal and the vision system was unpaused shortly after takeoff. All formation maneuvers were flown at 160 KIAS. Ocean Maneuver Blocks, starting at 1514L near pulse 26500 Crossed over the coastline at pulse ~28100. Saw the real-time viewer have several yellow points along waves breaking at the shore, which pulled the tail of the red C-12 model down and caused the nose to appear to yaw to the left. On the second O1.L.F near pulse 37600, we saw yellow point cloud place dots along both propeller arcs as the propellers glinted in the bright sunlight. The C-12 reference model doesn't account for the spinning propellers, which likely introduced some error in the pose estimation. Saw shadows from the pseudo-tanker hit the pseudo-receiver near pulse 47000.			
6. RECOMMENDATIONS			
R1: Use a C-12 reference model which includes the propeller disc.			
COMPLETED BY Andrew K. Petry, Capt, USAF		SIGNATURE //signed-akp//	DATE 16 Mar 19

Ocean Maneuver Blocks, continued

Crossed over the coast near Santa Barbara when the pseudo-receiver was in the contact position near pulse 68500. The practice separation flown near pulse 71900-72200 was flown differently than on previous maneuver blocks. LA Center Air Traffic Control required both aircraft to maintain constant altitude due to high traffic volume, so the practice separation was performed with the pseudo-receiver pulling power to idle, then staying at a constant altitude while sliding aft relative to the pseudo-tanker.

R1: Use a C-12 reference model which includes the propeller disc.

Mountain Maneuver Blocks, starting at 1541 near pulse 74000

There was little or no snow present on the mountains in this region. The practice separation at pulse 80000-80400 was again flown with the pseudo-receiver holding a constant altitude instead of descending. Saw sun glint off the right wing near pulses 77200 and 83500 with no obvious impact to the yellow point cloud on the real-time viewer. Saw very bright sun reflection off a mountain stream that appeared to pass beneath the pseudo-receiver near pulse 86000, again with no detrimental impact on the point cloud. A large cloud passed near the right wing at pulse 98000 during a climb from 11000 MSL to 12000 MSL. Practice separations for the rest of the flight were flown according to the standard procedure.

Urban Maneuver Blocks, starting at 1603 near pulse 114000

Had to descend to 7500 MSL, then 6500 MSL and cancel our IFR flight plan in order to fly over the Antelope Valley without interfering with other aircraft being controlled by Joshua Approach. These maneuver blocks were flown along a north-south line near Highway 14, followed by a turn towards eastern Palmdale to avoid direct flight over the mountains at the southern end of the Antelope Valley. Several maneuver blocks included a mix of urban, desert, and mountain backgrounds due to the numerous turns made to try to stay over the urban area. During one maneuver block over Lancaster, the formation was flying on a 360° magnetic heading that looked parallel to several north-south running roads in the background. Near pulse 137000, the algorithm seemed to place several points along one of these roads.

Desert Low Abbreviated Maneuver Blocks, starting at 1624 near pulse 151800

Ten abbreviated maneuver blocks were flown in an easterly heading along Cords Road at 11000 ft MSL. Each maneuver block consisted of a movement from astern to contact, stable contact, then a retreat to the astern position. One of the blocks was flown with the large Boron mine in the background near pulse 164500 with the pseudo-receiver in the contact position. The algorithm placed points in several of the retaining ponds near the mine, which were reflecting the sun as it got low in the sky in the late afternoon.

Desert High Abbreviated Maneuver Blocks, starting at 1645 near pulse 190400

Ten more abbreviated maneuver blocks were flown in a westerly heading along Cords Road at 16000 ft MSL. Each maneuver block consisted of a movement from astern to contact, stable contact, then a retreat to the astern position. There were several instances of shadows from the elad aircraft falling on the pseudo-receiver, most notably near pulse 199400. Near pulse 201800 as the aircraft was moving out from contact to astern, there was a large sun glint of the solar farm north of the Four Corners Hwy 395/Hwy 58 intersection.

Landing and ground ops were uneventful. All data were transferred to backup hard drives.

End of Report.

Date: 13 Mar 19 TC Name: Petry Flight #: 6 Page #: 1/8
T/O: 1510 Land: 1712 Overall WX: sky clear
Time TC hit "g": (L) 1500 (Z) 2200 Recording Stop: (L) 1700 (Z) 0000

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L/ L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
startup	1500	—		started w/ EO exposure 2000 ns IR cold=1, hot=5, auto
climbout	1511	21000		all 4 cameras working
cleared astern	1514	26000		
stable astern	1514	26500		Start of 01.L.F @ 6k ft
cleared contact	1515	27000		red model often yaws nose left relative to point cloud
contact	1515:30	28100		Crossed from land to ocean
L/R limits	1516	28000		fully ocean, westbound 270°
Left turn	1518	33000		
practice sep	1519	35000	35600	
stable astern	1520	37500		another 01.L.F @ 6k ft
cleared contact	1520	37600		point cloud occasionally places dots on the propeller arc as they glint in the sun
contact	1521:22	38700		
Left turn	1526	47000		270° to 090°, apparent IR saw 158's shadow cross 161
contact in climb 6-8k	1527	50000		red model pulled down and toward right wing by sunlight on waves
Left turn @ 8k	1530	55000	56700	turn 090° to 010°
climb in contact	1531	56700	62200	climb 8-11k, ocean background
cleared astern	1534	63000		start 01.H.A

Date: TC Name: Flight #: Page #: 2/8
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.
Contact	1535:34	64200		[01.H.A] complete
cleared astern	1536	66300		[01.H.F] → some in M3L
cleared contact	1537	67600		
Contact	1538:14	68500		crossing over coastline into M3 region #2
L/R limits	1539	69800		
practice separation	1539	71900	72200	Stayed same altitude per ATC instructions
cleared contact	1541	74000		[M3.L.F] at 11000 MSL
contact	1541:36	75100		No snow on mountains
L/R limits	1542	75600	77100	left, then right
Right turn	1542	77200		some sun glint off right wing 010° to 065°
practice separation	1544	80000	80400	level per ATC restrictions
cleared astern	1545	81400		start of another [M3.L.F]
contact	1546:14	83500		sun glint off right wing tip, no apparent impact on point cloud
L/R limits	1546	84000		
Turns	1548	87700	90000	saw sun reflection off stream below us at 86000-87000, 89300
practice separation	1550	90100	90500	end of M3.L.F
cleared contact	1553	95300		start of M3.L.A

Date: TC Name: Flight #: Page #: 3/8
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.
contact	1553:15	96000		end of M3.L.A
cleared astern	1554	98000		climb from 11-12K cloud near right wing @ 98000
cleared contact	1556	101600		entered Antelope Valley, another M3.L.A
contact	1557:00	103000		cancelled IFR to maneuver
practice sep	1557	103600	103800	standard practice sep
safety chase	1558	106000	111000	descent from 11-7.5KMSL with 161 maneuvering in trail
cleared astern	1601	111300		
cleared contact	1603	114000		start of U1.Fat 7500 MSL
contact	1603:43	115000		Longaster in view
L/R limits	1604	115500		
Turns	1605	117100		descended to 6500 MSL mix of urban and mountain
practice sep	1606	118700		
cleared astern	1607	121700		mix of urban and mountains
cleared contact	1608	123000		Start U1.F at 6500 MSL
contact	1608:47	124000		South end of Palmdale
Left turn	1609	125000		from 080° to 255°
L/R limit	1610	127400		shadow interaction at right contact limit

Date: TC Name: Flight #: Page #: 4/8
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.
practice sep	1611	129500		mix of urban/desert background
cleared astern	1612	130000		end of U.I.F at 6500 MSL
cleared contact	1613	131400		continuous light turbulence
contact	1613:50	133100		start of another <u>U.I.F</u> at 6500
Right turn	1614	133700		mix of urban/desert/mtn
L/R limits	1616	137000		Saw points in background on a N/S road, 360° hdg
practice sep	1617	139700	140200	end of U.I.F at 6500
cleared contact	1618	141800		<u>U.I.A</u> at 6500 + L/R limits
contact	1619:06	142600		
L/R limits	1619	143500	145300	Northbound abeam Rosamond Dry Lake
Right turn	1621	146500		
—				reentered 2515 for Cords Rd
stable astern	1624	151800		start of many <u>D1.L.A</u> blocks at 11000 MSL
cleared contact	1625	153500		
contact	1626:25	155555		
cleared astern	1627	157000		end of D1.L.A #1
cleared contact	1627	158200		start of D1.L.A #2

Date: TC Name: Flight #: Page #: 5/8
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.
contact	1628:25	159300		all on Cords Rd, eastbound
cleared astern	1628	159800		end of D1.L.A #2
cleared contact	1629	160900		start of D1.L.A #3
contact	1629:45	161800		
cleared astern	1630	162200		end of D1.L.A #3
cleared contact	1630	163200		start of D1.L.A #4
contact	1631:16	164500		point cloud had some reflections from ponds near the mines
cleared astern	1631	16500		end of D1.L.A. #4
cleared contact	1632	165800		start of D1.L.A #5
contact	1632:25	166666		
cleared astern	1632	167100		end of D1.L.A. #5
cleared contact	1633	168100		start of D1.L.A #6
contact	1633:54	169200		
cleared astern	1634	169800		end of D1.L.A #6
cleared contact	1635	171200		start of D1.L.A #7
contact	1635:45	172600		
cleared astern	1636	173000		end of D1.L.A #7

Date: TC Name: Flight #: Page #: 6/8
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.
Cleared contact	1636	174200		start D1.L.A #8
Contact	1637:31	175700		Harper's Dry Lake in fov
Cleared astern	1637	176300		end of D1.L.A #8
Cleared contact	1638	177500		start D1.L.A #9
contact	1639:00	178400		
Cleared astern	1639	179000		end D1.L.A #9
Cleared contact	1639	180000		start D1.L.A #10
contact	1640:27	181000		
Cleared astern	1640	181400		end D1.L.A #10, climb to 16k
—				turned left to Hdg 270°
Cleared contact	1645	190400		start of D1.H.A #1 at 16k, westbound
contact	1646:16	191500		
Cleared astern	1646	192100		end of D1.H.A #1
Cleared contact	1647	193400		start D1.H.A #2
contact	1647:55	194500		
Cleared astern	1648	194800		end D1.H.A #2
Cleared contact	1648	195800		start D1.H.A #3

Date: TC Name: Flight #: Page #: 7/8
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.
contact	1649:19	197000		
cleared astern	1649	197500		end D1.H.A #3
cleared contact	1650	198300		start D1.H.A #4
contact	1650:37	199400		shadow on right wingtip
cleared astern	1650	200000		end D1.H.A #4
cleared contact	1651	200800		start D1.H.A #5
contact	1651:48	201500		
cleared astern	1652	201800		end D1.H.A #5 saw sun reflection off solar panels
cleared contact	1652	202800		start D1.H.A #6
contact	1653:06	203900		
cleared astern	1653	204600		end D1.H.A #6
cleared contact	1653	205100		start D1.H.A #7
contact	1654:30	206300		
cleared astern	1654	206700		end D1.H.A #7
cleared contact	1655	207500		start D1.H.A #8
contact	1655:44	208600		
cleared astern	1656	209000		end D1.H.A #8

Date:

TC Name:

Flight #:

Page #: 8 / 8

T/O:

Land:

Overall WX:

Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

(Z)

Recording Stop:(L)

(Z)

[illegible]

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE C-12C	2. SERIAL NUMBER 76-00158
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO 4759-1	B. FLIGHT NO / DATA POINT Have Double Vision Flight #7	C. DATE 14 March 2019	
D. FRONT COCKPIT (<i>Left Seat</i>) Whitebread	E. FUEL LOAD / OPERATING WEIGHT / MOMENT 2600	F. JON MT18B600	
G. REAR COCKPIT (<i>Right Seat and rest of crew</i>) Billy / Slayer	H. START UP GR WT / MOMENT 12.2/19.7	I. WEATHER Few 100	
J. TO TIME / SORTIE TIME 1139L 2.5	K. CONFIGURATION / LOADING Have Double Vision Camera Config	L. SURFACE CONDITIONS Altimeter 30.23 Winds 010/03	
M. CHASE ACFT / SERIAL NO 76-00161 // 64-03302	N. CHASE CREW Faruk/Lorax/BIFF; Sonic / Dish	O. CHASE TO TIME / SORTIE TIME 1139 2.5; 1153 1.2	
4. PURPOSE OF FLIGHT / TEST POINTS			
The purpose of this flight was to experiment collect full maneuver blocks with the T-38 in desert and mountain terrain backgrounds. After completing T-38 collection abbreviated points with the C-12 were flown to increase the number of independent data points for statistical accuracy. The IR cameras were inoperative. The airspace plan was to start with both C-12s at 22,000 feet MSL in Isabella with the T-38 delaying takeoff. If the C-12 tanker was unable to maintain 210 KIAS then the maneuver would be completed in slight descent to allow the T-38 to maintain minimum speeds. The descent was continued into the desert block with the same method. After the T-38 abbreviated maneuvers were completed with an EO camera setting of 2000 microseconds was set for C-12 mountain high and low blocks. Test points: T38.M1.H.F T28.M1.L.F T38.D1.H.F C12.M1.H.A x10 C12.M1.L.A x10			
5. RESULTS OF TESTS (<i>Continue on reverse if needed</i>)			
Overall The flight went as planned and required a slight descent for tail 158 to maintain 207-210 KIAS in a descent. This resulted in a combined mountain high and low block (began at 22,000 feet and was completed at 18,000). The C-12 was able to maintain 210 in level flight at 16,000 feet and the 18,000-16,000 foot block was used in the desert high area. During the camera change the T-28 images were overwritten due to a failure to rename the collection folder. The T-38 data from this flight is not available. The C-12 mountain high and low abbreviated block points were collected using 2,000 microsecond EO camera exposure and resulted in good data points. Ground Ops Both aircraft were hooked up to external power on the ground. The G-Lite TSPI was initialized on tail 161. On tail 158, both the G-Lite and computer/camera system were booted up. T-38 tail 302 G-Lite was initialized on the ground. One of the IR cameras didn't work. EO camera calibration and setup was completed. . Geodetics fine alignment was completed during normal taxi from parking to takeoff on Runway 4L. The fine alignment was achieved just after the aircraft stopped in the 4L hammerhead for the engine run-up. Takeoff was normal and the vision system collection was resumed shortly after takeoff. Maneuver Blocks T38.M1.H.F T28.M1.L.F The T-38 maneuver block began at 22,000 feet in a slight descent to maintain minimum T-38 airspeeds. There was scattered snow during several of the turns, however most of the scene was generally uniform in terrain varying from bare hillsides to trees. The T-38 was visible on both EO and IR cameras and the real-time worked despite using a C-12 model. The left and right contact limits were much further than the C-12 due to shorter wingspan. These points were flown until the wings on the T-38 were partially obscured. The T-38 was flown with 40 degrees flaps. The EO cameras were set to 5,000 microseconds. Continued.			
6. RECOMMENDATIONS			
Repeat all T-38 points.			
COMPLETED BY Baxter, David T, Capt, USAF	SIGNATURE \\Signed\dtb\18Mar\\	DATE 18 Mar 19	

T38.D1.H.F

After completing the mountain block the desert full maneuver block was conducted from 18,000 to 16,000 feet. The left and right limits were flown over the mines. Several images were collected from the C-12 in the photo-safety chase position.

The C-12 receiver (161) switched roles with the T-38 and the T-38 collected images of the C-12 in the contact position.

C12.M1.H.A x10

C12.M1.L.A x10

The C-12 receiver was then cleared to the abbreviated maneuver blocks in mountainous terrain using an EO exposure setting of 2,000 microseconds. The image of the C-12 was darker than normal in the EO cameras but contrast was still visible on the wings. The NRT ICP seemed to work well.

The airborne operation (STO 3) was also conducted. The following comments were collected: The range stabilized with the aircraft around 81 meters and the range and closure could be seen numerically as well as in the point cloud. Stability and closure were okay, but at distances from astern to contact there were occasionally outliers. While stable in contact small movements were seen both numerically and in the point cloud. There did appear to be some bias on the point cloud and the reference cloud. Point cloud quality was difficult to assess, but there were times that wing and engine features were clear and stable while at ranges outside of contact the point cloud seemed less stable. EO camera exposure settings seemed to help the performance of the point cloud. There was not noticeable latency, but the ~1 Hz update rate made latency difficult to assess for time less than 1 second. The utility of the system on the current state are not practical for use, but there is potential for how the numerical information is displayed to offer valuable feedback. The information was useful, the way the information was displayed was not practical.

Landing and ground ops were uneventful. All data were transferred to backup hard drives.

End of Report.

Date: 14 MAR 19 TC Name: SLAYER

Flight #: 7

Page #: 116

T/O: 1140 L Land:

Overall WX: SKC CLR

Time TC hit "g": (L) 1131:23 (Z) 1431:23 Recording Stop: (L) 1349 (Z) 2049
IR NOT WORKING

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
~~UNPAUSED~~				WOULD NOT UNPAUSE
STARTED & UNPAUSED	114610 184610	0		CLIMBOUT TO 22,000
MT 1 AREA CLZ.M.H.A	1201	28400		- CLZ TO ABEAM
MT 1 H F T-38 ASTERN	1209	41700		T-38 TO ASTERN
CLIMBOUT CONTACT	1210	44400		
STABLES CONTACT	121235	48000		
LIMITS R CONTACT L	1213	50700 51700		SNOW DURING LIMITS
CENTER CONTACT	1215	52500		
RETURN	1215	53400		SNOW IN TURN
SAP.	1219	59600		SOME SNOW
CLR ASTERN	1219			
CRN CONTACT	1221			
STABLES CONTACT	1223 24:50			
DEPART CLR ASTERN	1226	72800		
CLR STABLES				
STABLES CONTACT	122734	74700		
L TURN	1229	78300		

Date: TC Name: Flight #: Page #: 2/6
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit ~~DESCRIBE T38~~	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
R LIM L LIM	1231 1231	81100 81900		OVER MOUNTAINS
P. 9&P.	1232	84100		
R TURN/ASTERN	1236	90000		
CLIN ASTERN	1238	94000		
CIL / T38 SWAP	1239			
C12 H.A CLIN ASTERN	1240	97400		
STABIN CONTACT	124450	10500		PHOTOS w/ EDWARDS
ASTERN	1254	123200		MANEUVER TO MTN HIGH BACK
	130354	141223		STOPPED, CHANGED to to 2000
RESTART	1306	0		2000ms
ASTERN	1307	4000		High MTN
CLIN CONT	1307	4200		
	130815	5200		DARK IMAGE.
C. ASTERN	1308	5900		
C CONTACT	1308	6400		
S. CONTACT	130926	7200		
C. ASTERN	1309	8000		

Date: TC Name: Flight #: Page #: 3/6
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments	
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.	
C CONTACT	1310	9000			
S CONTACT	1310 41	9600			3
C ASTERN	1311			TURN FOR AIRSPACE	
C CONTACT	1313	14200			
S CONTACT	131336	14800			4
C ASTERN	1313	15400			
C CONTACT	1314	16000			
S CONTACT	131504	17500			5
C ASTERN	1315	18200			
C CONTACT	1315	18500			
S CONTACT	131623	19700			6
C ASTERN	1316				
C CONTACT	1317	20900			
S CONTACT	131735	22100			7
C ASTERN	1317	22600		180 TURN FOR AIRSPACE	
C CONTACT	1319	25600			
S CONTACT	132009	26600			8

Date: TC Name: Flight #: Page #: 4/6
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments	
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.	
C ASTERN	1320	27560			
C CONTACT	1320	27900			
S CONTACT	1321 58	29800			9
C ASTERN	1322	30400			
C CONTACT	1322	30900			
S CONTACT	132320	32300			10
C ASTERN	1323	33200		DESCENT TO LOW BLOCK	
ASTERN	1324	44300			
C CONTACT	1324	44300			
S CONTACT	1330 31	45200			1
C ASTERN	1331	46200			
C CONTACT	1331	46700			
S CONTACT	1331 51	47600			2
C ASTERN	1332	48400			
C CONTACT	1332	48900			
S CONTACT	133307	50000			3
C ASTERN	1334	51700		180° TURN	

Date: TC Name: Flight #: Page #: 516
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments	
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.	
C CONTACT	1335	54400			
S CONTACT	133639	56500			4
C ASTERN	1337	56900			
C CONTACT	1337	57700			
G CONTACT	133809	58900			5
C ASTERN	1339	60500			
C CONTACT	1339	61000			
S CONTACT	133955	62200			6
C ASTERN	1340	62700			
C CONTACT	1340	63800			
S CONTACT	134123	64800			7
C ASTERN	1341	67700			
C CONTACT	1342	65800			
S CONTACT	134221	66900			8
C ASTERN	1342	67300		180° turn for AIRSPACE	
C CONTACT	1344	70500			
S CONTACT	134523	72000			9

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE C-12C	2. SERIAL NUMBER 76-00158
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO 4758-1	B. FLIGHT NO / DATA POINT Have Double Vision Flight #8	C. DATE 15 March 2019	
D. FRONT COCKPIT (<i>Left Seat</i>) Whitebread	E. FUEL LOAD / OPERATING WEIGHT / MOMENT 2.6 / 9.6	F. JON MT18B600	
G. REAR COCKPIT (<i>Right Seat and rest of crew</i>) Faruk/Dish	H. START UP GR WT / MOMENT 12.2 / 19.7	I. WEATHER CLR	
J. TO TIME / SORTIE TIME 1500 / 1.9	K. CONFIGURATION / LOADING Have Double Vision Camera Config	L. SURFACE CONDITIONS 35°F / VRB 06	
M. CHASE ACFT / SERIAL NO 76-00161	N. CHASE CREW Billy / Vulcan / Slayer	O. CHASE TO TIME / SORTIE TIME 1500 / 1.9	
4. PURPOSE OF FLIGHT / TEST POINTS			
The purpose of this flight was to experiment with different EO camera exposure times. The IR cameras were inoperative. The plan was to stay over Cords Road in the D1 background and complete hybrid maneuver blocks with different EO exposure times, which varied from 10000 μs to 1000 μs. During RTB once the pseudo-receiver was out of the camera FOV, the operator lowered the exposure time to just 100 μs, which made the images appear nearly pitch black. Test points: - D1.H.F x2 with exposure set to 10000 μs - D1.H.F x2 with exposure set to 9000 μs - D1.H.F x2 with exposure set to 8000 μs - D1.H.F x2 with exposure set to 7000 μs - D1.H.F x2 with exposure set to 6000 μs - D1.H.F x2 with exposure set to 5000 μs - D1.H.F x2 with exposure set to 4000 μs - D1.H.F x2 with exposure set to 3000 μs - D1.H.F x2 with exposure set to 2000 μs - D1.H.F x2 with exposure set to 1000 μs			
5. RESULTS OF TESTS (<i>Continue on reverse if needed</i>)			
Ground Ops Both aircraft were hooked up to external power on the ground. The G-Lite TSPI was initialized on tail 161. On tail 158, both the G-Lite and computer/camera system were booted up. One of the IR cameras didn't work, but this flight seemed to be worse than previous flights because the camera appeared to not even receive power. This made booting up the system tricky, and the system operator needed assistance to prevent the AAR GUI from crashing. It was noted that the standard "1, 2, 3, 4, g" commands didn't work if not all cameras had power. Instead, the startup command was just "3, 4, g" which skipped the IR cameras. Geodetics fine alignment was completed during normal taxi from parking to takeoff on Runway 4L. The fine alignment was achieved just after the aircraft stopped in the 4L hammerhead for the engine runup. Takeoff was normal and the vision system was unpaused shortly after takeoff. Maneuver Blocks The overall plan was to stay at 16000 ft MSL and complete hybrid maneuver blocks which were effectively just as useful as the full maneuver blocks flown on previous flights, but much more efficient. Each block consisted of closure from astern to contact, stable contact, bobbles in the contact position, and a practice operation. The bobbles were intended to introduce small and rapid changes in pseudo-receiver roll/pitch/yaw attitude to see how well the algorithm responded to fast attitude changes. One maneuver block was flown to the east (toward the rising sun) followed by a second maneuver block toward the west, away from the sun. After both blocks were completed, the vision system operator stopped the recording to change exposure settings in the Vimba Viewer. Exposure times were stepped down in 1000 μs increments from 10000 μs to 1000 μs. This data set will be used by AFIT researchers to fine-tune the EO exposure time to optimize algorithm performance—it is desired that the exposure time be long enough to capture good detail, but short enough that the sensor isn't saturated by bright sunlight. Landing and ground ops were uneventful. All data were transferred to backup hard drives. End of Report.			
6. RECOMMENDATIONS			
COMPLETED BY Andrew K. Petry, Capt, USAF		SIGNATURE //signed-akp//	DATE 16 Mar 19

Date: 15 Mar 19 TC Name: Petry

Flight #: 8

Page #: 1/7

T/O: 0815L Land: 1007L Overall WX: skies clear

Time TC hit "g": (L) 0806 (Z) 1506 Recording Stop: (L) 1000 (Z) 1700

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
startup	0806	—	—	EO exposure 10000 μ s IR broken
overall plan				Fly Desert 1 at 16000 MSL, complete maneuver blocks w/ contact, bobble, and practice sep.
				both into and away from direct sunlight, then step down the EO exposure time setting and repeat
climbout	0817	19000		unpaused recording
cleared contact	0821	27700		start of D1.H.F #1 eastbound exposure 10000 μ s
contact	0823:06	30000	30400	
bobble	0823	30600	32200	
practice separation	0826	35200	35500	end of D1.H.F #1 16k ft MSL
cleared astern	0826	36400		start D1.H.F #2 westbound
cleared contact	0828	39000		saw noticeably fewer point cloud dots near wingtips when pointed away from the sun. Saw sun glint along wings.
contact	0828:30	39900	40200	
bobble	0829	40500	42200	
practice sep	0830	42600	42900	end D1.H.F #2
—				changed exposure to 9000 μ s
—	0833	0		restarted recording

Date: TC Name: Flight #: Page #: 2/7
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
cleared contact	0834	2700		start D1.H.F #3 eastbound exposure 9000 ns
contact	0835:00	3800	4200	
bobble	0835	4400	6100	
practice sep	0836	6400	6700	end D1.H.F #3, turned west
cleared astern	0836	7200		start D1.H.F #4 westbound
cleared contact	0838	9200		
contact	0838:40	10300	11100	
bobble	0839	11600	13500	shadow on fuselage
practice sep	0840	13800	14000	end D1.H.F #4
restart camera 0842		0		changed exposures to 8000 ns
cleared astern	0843	1000		start D1.H.F #5 eastbound
cleared contact	0844	2000		
contact	0844:11	2500	3100	
bobble	0844	3300	5200	left wingtip just out of frame
practice sep	0845	5400	5900	end D1.H.F #5, turn to west
cleared astern	0846	6100		start D1.H.F #6
cleared contact	0847	8500		

Date: TC Name: Flight #: Page #: 3/7
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
contact	0848:25	10200	10900	shadow on fuselage
bobble	0849	10300	13300	
practice sep	0850	13400	13700	end D1.H.F #6, turn east
restart	0852	0		changed to 7000 μ s
cleared contact	0853	1000		start D1.H.F #7 eastbound
contact	0854:05	2400	3100	
bobble	0854	3200	5000	
practice sep	0855	5300	5700	end D1.H.F #7, turned west
cleared astern	0856	5900		start D1.H.F #8, westbound
cleared contact	0857	8600		
contact	0858:20	9900	11800	sun glint on left wing
bobble	0859	12000	13900	shadow on fuselage
practice sep	0900	14100	14500	end D1.H.F #8, turned east
restart	0903	0		changed to 6000 μ s
cleared contact	0904	3000		start D1.H.F #9, eastbound
contact	0905:30	4200	4700	
bobble	0906	4800	6800	building at Boron mine in FOV

Date: TC Name: Flight #: Page #: 4/7
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.
practice sep	0907	7000	7400	end D1.H.F #9, turned west
cleared astern	0907	7800		start D1.H.F #10, westbound
cleared contact	0908	10000		
contact	0909:40	11600	12100	sun glint on left wing
bobble	0910	12200	14100	
practice sep	0911	14400	14900	end D1.H.F #10, turned east
restart	0914	0		changed to 5000 μ s exposure
cleared contact	0914	1200		start D1.H.F #11 eastbound
contact	0915:10	2400	3100	shadow near left wingtip
bobble	0915	3200	5100	
practice sep	0916	5300	5800	end D1.H.F. #11, then turned west
cleared astern	0917	5900		start D1.H.F #12, westbound
cleared contact	0918	8300		
contact	0919:05	9400	10200	
bobble	0919	10400	12500	sun glint on left wingtip, plus glint off ponds at mines
practice sep	0921	12900	13300	end D1.H.F #12, then turned east
restart	0923	0		changed to 4000 μ s exposure

Date: TC Name: Flight #: Page #: 5/7
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. ½ ac's L wing out of top R frame.
cleared contact	0924	2500		start D1.H.F #13, eastbound 4000 μ s exposure
contact	0925:06	3600	4100	Shadow on left wing
bobble	0925	4300	6300	
practice sep	0926	6600	7100	end D1.H.F #13, then turned to west
cleared astern	0927	7200		start D1.H.F #14, westbound
cleared contact	0928	9800		
contact	0929:00	10700	11200	sun glint on left wing
bobble	0929	11400	13400	
practice sep	0930	13700	14200	end D1.H.F #14, then turned east
restart	0933	0		reset exposure to 3000 μ s
cleared contact	0933	1000		Start D1.H.F #15, eastbound
contact	0934:20	2500	3100	
bobble	0934	3200	4900	shadow on left wing
practice sep	0935	5200	5800	end D1.H.F #15, then turned west
cleared astern	0936	5900		start D1.H.F #16, westbound
cleared contact	0937	8200		Sun glint might still be saturating the EO sensors
contact	0938:15	9500	10100	

Date: TC Name: Flight #: Page #: 6/7
T/O: Land: Overall WX:
Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
bobble	0938	10300	12000	
practice sep	0939	12200	12700	end D1.H.F #16, turned east
restart	0941	0		reset exposure to 2000 μ s
cleared contact	0942	500		start D1.H.F #17, eastbound
contact	0942:30	1500	2100	no apparent saturation
bobble	0943	2200	3600	shadow on left wing
practice sep	0944	3800	4200	end D1.H.F #17, then turn to west
cleared astern	0944	4300		start D1.H.F #18, westbound
cleared contact	0945	6500		potential saturation on engine exhaust stack and left wing tip
contact	0945:50	7300	7800	
bobble	0946	7900	9600	
practice sep	0947	9800	10300	end D1.H.F #18, then turn east
restart	0949	0		reset exposure to 1000 μ s
cleared contact	0949	400		start D1.H.F #19, eastbound
contact	0949:39	1200	1600	no apparent saturation
bobble	0950	2000	3200	
practice sep	0950	3300	3800	end D1.H.F #19, then turned west

Date: TC Name: Flight #: Page #: 7/7
 T/O: Land: Overall WX:
 Time TC hit "g": (L) (Z) Recording Stop:(L) (Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
cleared astern	0951	4000		start D1.H.F #20, westbound
cleared contact	0952	6200		image looks pretty dark, but can still see sun glint on exhaust stacks
contact	0952:48	6800	7400	
bobble	0953	7600	9100	Sun reflections in FOV off of ponds near mms
practice sep	0954	9300	9900	end D1.H.F #20
complete	→ formation broke up during return to base			
restart	0956	0		reset exposure to 100 μ s,
stopped recording	1000	7000	—	No C-12 in background, just terrain
				image looks <u>very</u> dark,
				maybe pure black

DAILY/INITIAL FLIGHT TEST REPORT		1. AIRCRAFT TYPE C-12C	2. SERIAL NUMBER 76-00158
3. CONDITIONS RELATIVE TO TEST			
A. PROJECT / MISSION NO 5021-1	B. FLIGHT NO / DATA POINT Have Double Vision Flight #9	C. DATE 18 March 2019	
D. FRONT COCKPIT (<i>Left Seat</i>) Whitebread	E. FUEL LOAD / OPERATING WEIGHT / MOMENT 2.6 / 9.6	F. JON MT18B600	
G. REAR COCKPIT (<i>Right Seat and rest of crew</i>) Faruk/Dish/Slayer/Fug	H. START UP GR WT / MOMENT 12.5 / 19.7	I. WEATHER CLR	
J. TO TIME / SORTIE TIME 1459 / 1.5	K. CONFIGURATION / LOADING Have Double Vision Camera Config	L. SURFACE CONDITIONS 74°F / VRB 06	
M. CHASE ACFT / SERIAL NO 64-13189	N. CHASE CREW Billy / Speed	O. CHASE TO TIME / SORTIE TIME 1517 / 1.3	
4. PURPOSE OF FLIGHT / TEST POINTS			
The objective of flight 9 was to collect T-38C images as a pseudo-reciever. This supports objective 2 to collect a diverse dataset with truth data. The planned points were T-38.M1.H.F, T-38.M1.L.F, T-38.D1.H.F, and T-38.D1.L.F. A camera calibration was also conducted in support of objective 3.			
5. RESULTS OF TESTS (<i>Continue on reverse if needed</i>)			
Overall The flight was conducted in good weather with all planned systems operational. Data was collected in all planned points. The GLite data will be used as the truth source. DAS data was collected and processed for attitude information. The initial data points were collected in a slight descent for speed inconsistencies. Ground Ops A Glite initialization was completed on both test aircraft. Images for an EO and IR camera were collected for calibration of both cameras. Coarse and fine alignment were completed on the geodetics relnav despite no geodetics on the T-38 for standardization with other flights. The data recorder was started and paused on the ground. Data Points T-38.M1.H.F Mountain High block in M1 The data collection started with the test in the safety position transitioning to astern at 23,000 feet. A slight descent was initiated to maintain 205-208 KIAS with a 500-600 fpm descent. The complete altitude block was completed using north to south and reciprocal headings. Some snow was present in the background. IR and EO cameras worked as planned. The EO camera was set to 5,000 microseconds for all data points on the flight. Some Tanker shadows were intermittently seen on the test aircraft. T-38.M1.L.F Mountain Low block in M1 The low block was initiated passing 18,000 feet and completed within the altitude band. This block was completed in a slight descent at 208 KIAS with a 200-300 fpm descent. Some snow and scattered clouds were observed in the background. T-38.D1.H.F Desert High block in D1 The full block was started at 16,000 -17,000 feet. This was done in level flight at 208 KIAS and all points were completed on east or west trending headings. Shadows were observed on the test aircraft during the maneuvers. Continued			
6. RECOMMENDATIONS			
Build a Model of the T-38 to use in the ICP processing.			
COMPLETED BY Baxter, David T, Capt, USAF	SIGNATURE \\signed\dtb\19Mar19\\	DATE 19 Mar 19	

T-38.D1.L.F Desert Low block in D1

The full block was started at 10,000 -11,000 feet. This was done in level flight at 208 KIAS and all points were completed on east or west trending headings. Shadows were observed on the test aircraft during the maneuvers.

Additional comments

The realtime ICP program was also observed with the T-38 as the test aircraft. Despite the mismatch in models the ICP showed a stable point cloud and provided relative position and attitude estimations. These were not expected to be valid or accurate. The point cloud was observed to be responsive and close to the T-38 shape throughout maneuvers in the contact window.

Post Flight

Landing, taxi, and shutdown were uneventful. All data was collected and maintained.

End of Report.

Date: 18 MAR 19 TC Name: BAXTER

Flight #: 9

Page #: 4/2

T/O: 1459

Land: 1627

Overall WX: SKC FEW100

Time TC hit "g": (L) 143959 (Z) 213959 Recording Stop: (L) 160500 (Z) 230500

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
TAKOFF	1459	32000		TEST TO ENSURE CAMERA IS WORKING
UNPAUSE		50000		
T-38 IN FOV	1528	96800		ISABE LIA 23,000 LOCAL ALT 29.97
CLR CONTACT	1529	88900		STARTED ~ 21,000
STABLE CONTACT	152948 133012	89800 90500		IN CONTACT, SLIGHTLY LOW, ADJUSTED
R TURN	1530	91500		
L LIM	1533	95700		
R LIM	1534	97400		
BUBBLE	1535	99000		
SEPARATION	1536	100900		FILMED SCREEN
CLR ASTERN	1536	101800		TURNED IN ASTERN 104100 CLOUDS ✓
CLR CONTACT	1539	107300		START @ 19K
STABLE CONTACT	153924	107900		
L LIM	1540	108900		
R LIM	1541	110100		
R TURN	1542	11200		SHADOW ON T38
L TURN	1542	113400		
SEPARATION	1544	116000		

High MTD

Date: 18 MAR 19 TC Name: BAXTER

Flight #:

Page #: 2/2

T/O:

Land:

Overall WX:

Time TC hit "g": (L)

(Z)

Recording Stop:(L)

(Z)

Test Pt ID or Maneuver	Start (Local)	Start Ballpark Pulse Number	End Time	Comments
D1.L / L frame limit	0851	(current pulse #)	0900	Example—Clear skies. Saw washout on EO cameras. Terrain change. 1/2 ac's L wing out of top R frame.
DESERT 1 HIGH 1916	15216			T38 IN ASTERN
CLR ~~CONTACT~~ ASTERN	1548	123200		
CLR CONTACT	1548	123800		
STABLE CONTACT	154933	125300		
L LIM	1550	126200		OUTER MINGS
R LIM	1550	126700		+ L TO RIGHT END 127100
CONTACT	1551	128200		
L TURN	1551	129200		
R TURN	1552	130600		
SEPARATION	1553	131900		
CLR ASTERN	1558	140700		MOVING TO DESERT LOW BLACK
CLR CONTACT	1559	143000		TURBULENCE (LIGHT → MOD)
STABLE CONTACT	155952	143900		SHADOW ON WING
L LIM	~~144700~~ 1600	144700		
R LIM	1600	145300 - 145800		SHADOW DURING LIMIT TRANSITION
CENTER	1601	146700		
R TURN	1602	147700		SOLAR FARM REFLECTION
L TURN	1602	148800		HARPER'S CAICED
SEPARATION	1603	149900		
PAUSED 1604		152281		T38 CLEARED OFF

1605 270000

APPENDIX P– RECOMMENDATIONS FOR FUTURE RESEARCH

1. How does the accuracy change with the formation in a bank?
2. What is the limit where background type no longer matters?
3. What is the cause of the noise in the system?
4. How accurately does the T-38 relative position show with the C-12 Model?
5. Is the 0.25 pixel error “good” enough or is there a better calibration quality measure?

APPENDIX Q– CUSTOMER ERROR CORRECTION

After publishing and reviewing the report, the customer discovered an error in the ICP algorithm that affected the geodetics algorithm output used during the analysis for the accuracy, precision, calibration sensitivity, and RMS error analysis. They reported that the following was not included:

X: 0.55616 meters

Y: -1.71939 meters

Z: 2.63571 meters

This offset was for the geodetics output in the tanker's frame. Specifically, it is the tanker's lever arm offset. To correct this error the reported truth data was reverted to the tanker frame from the camera frame, then the correction was applied and the truth source data was corrected back to the camera frame. A subset of the results was recalculated using this correction to determine what effect this correction would have on the reported results. The correction was applied in the tanker frame then a rotation matrix was used to project the new Geodetics RelNav data. Since most of the data collected was in the Desert High condition, this was processed and compared to the original results.

$$Rotation (ROT) = \begin{bmatrix} -1 & 0 & 0 \\ 0 & \cos(25^\circ) & \sin(25^\circ) \\ 0 & -\sin(25^\circ) & \cos(25^\circ) \end{bmatrix}$$
$$\begin{bmatrix} X^{Corrected} \\ Y^{Corrected} \\ Z^{Corrected} \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} * ROT^{-1} + \begin{bmatrix} 0.55616 \\ -1.71939 \\ 2.63571 \end{bmatrix} * ROT$$

Overall the data improved, however the new accuracy did not change the analysis that the system accuracy did not meet the evaluation requirements. Figure Q-1 shows the Desert High translational accuracy error plots. Both X and Y improved enough to be within marginal criteria, but the Z error remained unacceptably high. The system rating is still unsatisfactory, however there is potential in the system and continued development should be pursued.

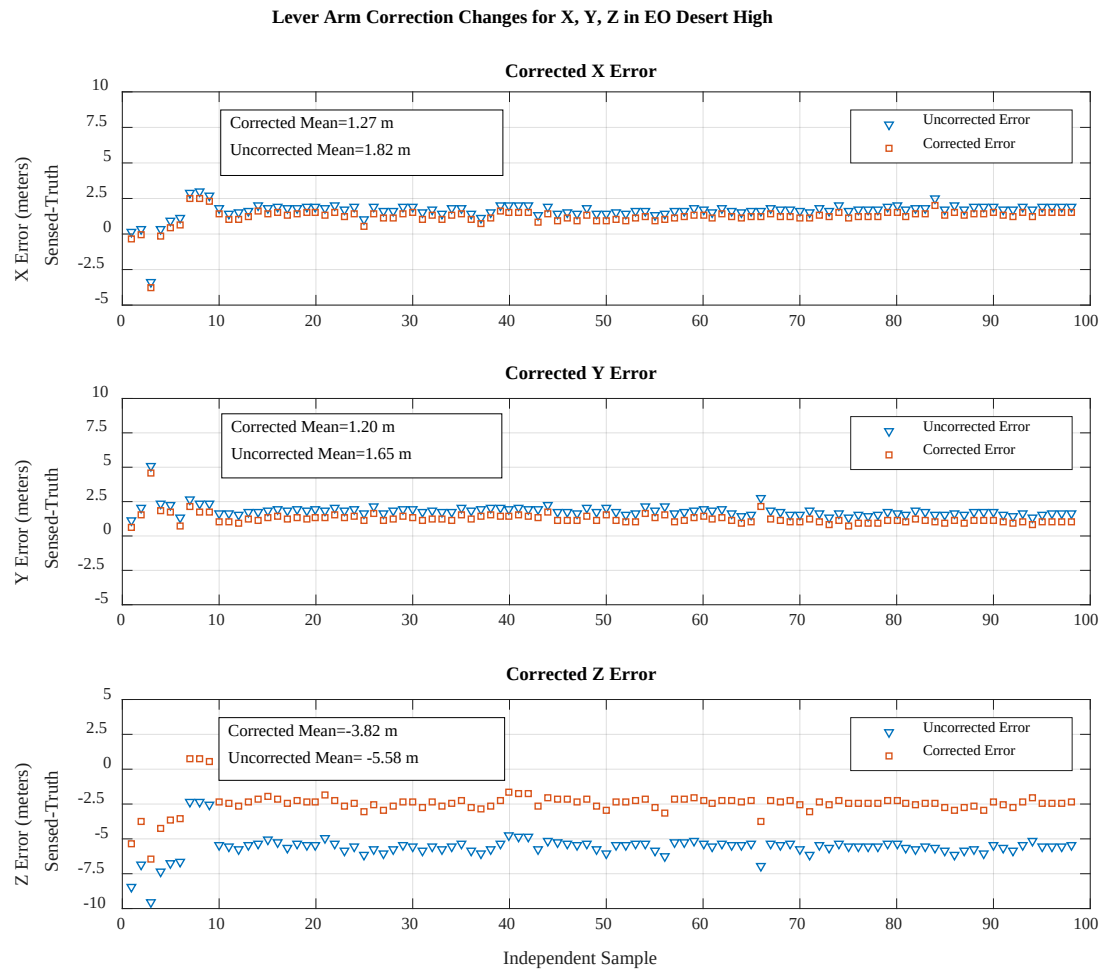


Figure Q-1: Accuracy Changes based on Lever Arm Corrections.

APPENDIX R– DISTRIBUTION LIST

<u>Onsite</u>	<u>Number of Copies</u>		
	<u>E-mail</u>	<u>Digital</u>	<u>Paper</u>
USAF Test Pilot School			
Attn: Andrew Freeborn	1	0	0
Jeremy Cookson	1	0	0
David Vanhoy	1	0	0
David Baxter	1	0	1
Mailing Address:			
220 South Wolfe Ave			
Edwards AFB, CA 93524			
 <u>Offsite</u>			
Dr. Scott Nykl	1	0	0
Email: scott.nykl@us.af.mil			
Mailing Address:			
Attn: Dr. Scott Nykl, AFIT/ENG			
AFIT/ENG			
2950 Hobson Way			
Wright-Patterson AFB, OH 45433			
 Mr. Ba Nguyen	 1	 0	 0
Email: ba.nguyen@us.af.mil			
Mailing Address:			
Attn: Mr. Ba Nguyen			
Control Systems Branch, AFRL/RQQC			
2210 Eighth Street			
Wright-Patterson AFB, OH 45433			
 Mr. Daniel Schreiter	 1	 0	 0
Email: daniel.schreiter@us.af.mil			
Mailing Address:			
Attn: Mr. Daniel Schreiter			
Control Systems Branch, AFRL/RQQC			
2210 Eighth Street			
Wright-Patterson AFB, OH 4543			