

USAFTPS-TIM-19-03



U  
S  
A  
F  
T  
P  
S

## A LIMITED CHARACTERIZATION OF ADVANCED RECEIVER AUTONOMOUS INTEGRITY MONITORING AND DUAL POLARIZED ANTENNA

(Project Have DRAGON)



**CHRISTOPER P. FULTON, Capt, USAF**  
Project Manager / Project RPA Test Pilot

**TRISTAN A. ATKINS, FLT LT, RAAF**  
Project Flight Test Engineer

**DALLAS M. WRIGHT, Maj, USAF**  
Project RPA Test Pilot

**JOSHUA C. RIVEY, Capt, USAF**  
Project Flight Test Engineer

**GREGORY D. EASTBURG, LT, USN**  
Project Test Pilot

**SHAWN J. WHITNEY, Capt, USAF**  
Project Flight Test Engineer

**DECEMBER 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.

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

This technical information memorandum (USAFTPS-TIM-19A-03, *Project Have DRAGON Limited Characterization of Advanced Receiver Autonomous Integrity Monitoring (ARAIM) and Dual Polarized Antenna (DPA)*) was submitted under job order number MT19A300 by the Commandant, USAF Test Pilot School, Edwards AFB, California 93524-6485.

Prepared by:

This memorandum has been reviewed and is approved for publication:

---

CHRISTOPHER P. FULTON  
Captain, USAF  
Project Manager/RPA Test Pilot

---

CHIAWEI N. LEE  
NH-03, DAF  
Staff Advisor, USAF Test Pilot School

---

DALLAS M. WRIGHT  
Major, USAF  
Project RPA Test Pilot

---

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

---

GREGORY D. EASTBURG  
Lieutenant, USN  
Project Test Pilot

---

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

---

TRISTAN A. ATKINS  
Flight Lieutenant, RAAF  
Project Flight Test Engineer

---

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

---

JOSHUA C. RIVEY  
Captain, USAF  
Project Flight Test Engineer

---

SHAWN J. WHITNEY  
Captain, USAF  
Project Flight Test Engineer

# 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.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> 12-11-2019		<b>2. REPORT TYPE</b> Final Technical Information Memorandum		<b>3. DATES COVERED (From - Through)</b> 06 September – 18 September 2019	
<b>4. TITLE AND SUBTITLE</b>  Project Have DRAGON A Limited Characterization of Advanced Receiver Autonomous Integrity Monitoring and Dual Polarized Antenna				<b>5A. CONTRACT NUMBER</b> N/A	
				<b>5B. GRANT NUMBER</b> N/A	
				<b>5C. PROGRAM ELEMENT NUMBER</b> N/A	
<b>6. AUTHOR(S)</b> Atkins, Tristan A., Flight Lieutenant, RAAF Eastburg, Gregory D., Lieutenant, USN Fulton, Christopher P., Captain, USAF Rivey, Joshua C., Captain, USAF Whitney, Shawn J., Captain, USAF Wright, Dallas M., Major, USAF				<b>5D. PROJECT NUMBER</b> MT19A300	
				<b>5E. TASK NUMBER</b> N/A	
				<b>5F. WORK UNIT NUMBER</b> N/A	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Air Force Test Center 412 <sup>th</sup> Test Wing USAF Test Pilot School Edwards AFB CA 93524-6485				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  USAFTPS-TIM-19A-03	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Stanford GPS Laboratory, Aeronautics & Astronautics Department 496 Lomita Mall Stanford, CA 94305				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> N/A	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> N/A	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b> <b>Distribution A.</b> Approved for public release; distribution is unlimited.					
<b>13. SUPPLEMENTARY NOTES</b> SC: 012100                      CA: Air Force Test Center, Edwards AFB, CA                      Print this document in <b>COLOR</b> .					
<b>14. ABSTRACT</b> This report documents testing results of an Advanced Receiver Autonomous Integrity Monitoring (ARAIM) algorithm and Dual Polarized Antenna (DPA) under the project name Have Detect, Recognize, and Adapt to Global Positioning System (GPS) Overt Noise (Have DRAGON). Testing was requested by the Stanford University GPS Lab, Stanford University, CA in support of Federal Aviation Administration (FAA) objectives. The lead developmental test organization was the Air Force Test Center, Edwards AFB, California. The executing test organization was Class 19A of the USAF Test Pilot School, Edwards AFB. Testing was conducted from 6 September 2019 to 18 September 2019 and comprised of 4.5 ground test hours and 8 sorties totaling 17.6 flight test hours. The overall test objective was to investigate ARAIM and DPA's capability for improving airborne GNSS system robustness. All test objectives were met.					
<b>15. SUBJECT TERMS</b> AFB(Air Force Base); AV(air vehicle); AFTC(Air Force Test Center); FAA(Federal Aviation Administration); GPS(Global Positioning System); GNSS(Global Navigation Satellite System); RAIM(Receiver Autonomous Integrity Monitoring)					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> Same as Report	<b>18. NUMBER OF PAGES</b> 95	<b>19A. NAME OF RESPONSIBLE PERSON</b> Sherman Lo
<b>a. REPORT</b> U	<b>b. ABSTRACT</b> U	<b>c. THIS PAGE</b> U			<b>19B. TELEPHONE NUMBER (INCLUDE AREA CODE)</b> 626-215-9642

This page was intentionally left blank.

## EXECUTIVE SUMMARY

This report presents the results for the Have Detect, Recognize, and Adapt to Global Positioning System (GPS) Overt Noise (Have DRAGON) test management project (TMP). Specifically, this evaluation characterized an Advanced Receiver Autonomous Integrity Monitoring (ARAIM) algorithm and a Dual Polarized Antenna (DPA) system. Stanford University requested USAF TPS support to evaluate Federal Aviation Administration (FAA) objectives. The Lead Developmental Test Organization (LDTO) was the Air Force Test Center (AFTC), Edwards AFB, California. The executing test organization was Class 19A of the United States Air Force Test Pilot School (USAF TPS), Edwards AFB, CA working in partnership with Stanford University in support of Federal Aviation Administration (FAA) objectives. Testing was conducted in the 586<sup>th</sup> Flight Test Squadron's C-12J, S/N 86-0080, from 6 September 2019 to 19 September 2019. Testing included eight test sorties totaling 17.6 flight hours under the Job Order Number MT19A300.

The overall test objective was to characterize ARAIM and DPA for improving airborne GNSS system robustness. The overall test objective was met.

Navigation errors jeopardized safety, potentially inducing flight into terrain. In addition to natural and environmental causes of GPS error, GPS jamming and spoofing were becoming more prevalent due to technology maturation and proliferation. Denied GPS would reduce military effectiveness by degrading employment of GPS-reliant weapons and producing poor navigational solutions. Both capabilities were critical for military operations. For both military and civilian aviation, degraded navigational solutions could lead to hazardous situations such as controlled flight into terrain (CFIT) or mid-air collisions.

The first system under test was an ARAIM algorithm used in post-flight data processing. The current system, Receiver Autonomous Integrity Monitoring (RAIM), provided characterization of GPS receiver accuracy. The product of RAIM was a horizontal protection level (HPL) which bounded possible system error within a very high probability. HPLs functioned as a guarantee of system accuracy. While RAIM was limited to the GPS constellation, ARAIM advanced the technology by incorporating multiple constellations. As a result, ARAIM provided improved HPL performance over RAIM and a usable Vertical Protection Level. In 10,445 independent data points, ARAIM error values remained bounded throughout all flight regimes with no error value exceeding the protection level. ARAIM protection degraded during steep bank angle turns (>30 degrees) and in jammed environments, but generally proved more resilient than RAIM. ARAIM demonstrated improved resilience to environment interference and hostile jamming.

The second system under test was a dual polarized antenna (DPA) system that correlated signal polarization to the direction of arrival (DOA). DPA provided a potential solution to mitigate GPS jamming through the determination of DOA that could be coupled with null steering algorithms, which allows receivers to ignore false signals. The DPA system demonstrated the ability to determine the azimuth of the satellite with an average azimuth error of 30°. DPA did not demonstrate elevation-dependent error, except within 8° of the vertical. DPA was promising as a potential control system for a null-steering algorithm.

The tested configuration included three antennas secured to mounts on a C-12J aircraft. One generated position data from four major constellations for ARAIM analysis, while the other two were DPA. The 586<sup>th</sup> Flight Test Squadron Ultra-High Accuracy Reference System served as the truth source for comparison. Data were collected in a variety of flight regimes, including benign maneuvering, limited tactical maneuvering (60° angle of bank turns, 1,000 feet per minute climbs and descents), mountainous terrain and overwater overflight, and at night. The test occurred concurrently with NAVFEST, an exercise that employed GPS jamming. Both systems were tested in uncontested and GPS-degraded environments. Testing during cruise portions occurred between 1,500 feet above ground and 21,500 feet pressure altitude, between 110 and 200 knots indicated airspeed. Low level testing occurred at 200 feet on the Tower Fly-By line, and above 500 feet modified contour above ground level in mountainous terrain and overwater.

This page was intentionally left blank.

# TABLE OF CONTENTS

EXECUTIVE SUMMARY .....	i
TABLE OF CONTENTS.....	iii
LIST OF FIGURES .....	vi
LIST OF TABLES .....	vii
INTRODUCTION .....	1
BACKGROUND .....	1
ERRORS IN GLOBAL NAVIGATION SATELLITE SYSTEMS .....	1
ADVANCED RECEIVER AUTONOMOUS INTEGRITY MONITORING .....	2
DUAL POLARIZED ANTENNA .....	3
TEST ITEM DESCRIPTION .....	6
ARAIM ANTENNA, RECEIVER, AND SOFTWARE .....	6
DPA .....	8
OVERALL TEST OBJECTIVE .....	10
CONSTRAINTS .....	10
TEST AND EVALUATION .....	11
GENERAL METHODOLOGY .....	11
TEST SETUP.....	11
ARAIM IN BENIGN MANEUVERING .....	12
TEST METHODS AND CONDITIONS.....	12
ARAIM VERTICAL PROTECTION LEVEL ACCURACY .....	12
ARAIM HORIZONTAL PROTECTION LEVEL ACCURACY.....	13
DIFFERENCE BETWEEN ARAIM AND RAIM HORIZONTAL PROTECTION LEVEL.....	14
ARAIM IN LIMITED TACTICAL MANEUVERING .....	16
TEST METHODS AND CONDITIONS.....	16
ARAIM VERTICAL PROTECTION LEVEL ACCURACY .....	17
ARAIM HORIZONTAL PROTECTION LEVEL ACCURACY .....	18
DIFFERENCE BETWEEN ARAIM AND RAIM HORIZONTAL PROTECTION LEVEL.....	19
ARAIM IN GPS JAMMED ENVIRONMENT.....	20
TEST METHODS AND CONDITIONS.....	20
ARAIM VERTICAL PROTECTION LEVEL ACCURACY .....	22

ARAIM HORIZONTAL PROTECTION LEVEL ACCURACY .....	24
DIFFERENCE BETWEEN ARAIM AND RAIM HORIZONTAL PROTECTION LEVEL .....	24
DPA DIRECTION OF ARRIVAL ACCURACY .....	26
TEST METHODS AND CONDITIONS .....	26
DPA AZIMUTH DIRECTION OF ARRIVAL ERROR .....	27
TEST RESULTS SUMMARY .....	33
REFERENCES .....	37
APPENDIX A – DETAILED TEST ITEM DESCRIPTION .....	A-1
DUAL POLARIZED ANTENNA .....	A-1
APPENDIX B – RATING CRITERIA .....	B-1
APPENDIX C – DATA ANALYSIS .....	C-1
ARAIM DATA ANALYSIS .....	C-1
ARAIM FILE PROCESSING .....	C-1
ARAIM PARAMETER OUTPUTS AND SEGMENTATION .....	C-2
INDEPENDENT POINT CALCULATION .....	C-2
VERTICAL AND HORIZONTAL ERROR LEVEL CALCULATION .....	C-2
ARAIM TO RAIM HORIZONTAL PROTECTION LEVEL .....	C-4
DPA DATA ANALYSIS .....	C-5
DPA PARAMETER OUTPUTS AND SEGMENTATION .....	C-5
DPA ROTATION AND TRANSLATION MATRICES .....	C-5
UHARS AZIMUTH POINTING VECTOR .....	C-6
DPA AZIMUTH SOLUTION PER DOA COMPARISON .....	C-7
APPENDIX D – DAILY FLIGHT REPORTS .....	D-1
APPENDIX E – TEST POINT SUMMARY .....	E-1
ARAIM IN BENIGN MANEUVERING .....	E-1
ARAIM IN LIMITED TACTICAL MANEUVERING .....	E-1
ARAIM VERTICAL PROTECTION LEVEL ACCURACY .....	E-1
ARAIM HORIZONTAL PROTECTION LEVEL ACCURACY .....	E-2
DIFFERENCE BETWEEN ARAIM AND RAIM HORIZONTAL PROTECTION LEVEL .....	E-3
ARAIM IN GPS JAMMED ENVIRONMENT .....	E-4
ARAIM VERTICAL PROTECTION LEVEL ACCURACY .....	E-4
ARAIM HORIZONTAL PROTECTION LEVEL ACCURACY .....	E-5
DIFFERENCE BETWEEN ARAIM AND RAIM HORIZONTAL PROTECTION LEVEL .....	E-6

APPENDIX F – LESSONS LEARNED.....	F-1
APPENDIX G – FTT MATRIX AND INDEPENDENT DATA POINTS.....	G-1
APPENDIX H – ABBREVIATIONS, ACRONYMS, AND SYMBOLS.....	H-1
APPENDIX I – DISTRIBUTION LIST .....	I-1

## LIST OF FIGURES

Figure 1. Stanford University Dual Polarized Antenna Ground Test: LHCP Response.....	5
Figure 2. ARAIM Hardware Setup .....	7
Figure 3. ARAIM Software Architecture .....	7
Figure 4. C-12J Harris C-146 Multi-Frequency Antenna .....	8
Figure 5. C-12J Under-Mounted DPA Plate (Left) and Top-Mounted DPA Plate (Right) .....	8
Figure 6. DPA uBlox Mode Configuration.....	9
Figure 7. DPA SDR Mode Configuration.....	9
Figure 8. ARAIM and Position Error Vertical Comparison – Benign Maneuvering .....	13
Figure 9. ARAIM, RAIM, and Position Error Horizontal Comparison – Benign Maneuvering .....	16
Figure 10. ARAIM and Position Error Vertical Comparison – Tactical Maneuvering .....	17
Figure 11. ARAIM and Position Error Vertical Comparison – Mountainous and Over-Water .....	18
Figure 12. ARAIM, RAIM, and Position Error Horizontal Comparison – Tactical Maneuvering.....	19
Figure 13. ARAIM, RAIM, and Position Error Horizontal Comparison – Mountainous and Over-Water	20
Figure 14. NAVFEST Jamming Projection at 12,000 feet Mean Sea Level .....	21
Figure 15. GNSS L1 Band and Intended Jamming Profile .....	22
Figure 16. GNSS L2 Band and Intended Jamming Profile .....	22
Figure 17. ARAIM and Position Error Vertical Comparison – Benign Maneuvering in Jamming.....	23
Figure 18. ARAIM and Position Error Vertical Comparison – Tactical Maneuvering in Jamming .....	24
Figure 19. ARAIM, RAIM, and Position Error Horizontal Comparison – Benign Maneuvering in Jamming .....	25
Figure 20. ARAIM, RAIM, and Position Error Horizontal Comparison – Tactical Maneuvering in Jamming .....	26
Figure 21. DPA DOA Azimuthal Error (Uncontested GPS Environment, 30° Increments) .....	27
Figure 22. DPA DOA Azimuthal Error (Uncontested GPS Environment, 10° Increments) .....	28
Figure 23. DPA DOA Azimuthal Error, High-Elevation Satellites (Uncontested, 4° Increments) .....	28
Figure 24. DPA Performance in Tracking PRN 28 on Flight 7, 17 and 18 September 2019 .....	30
Figure 25. DPA Performance on Flight 7, 17 and 18 September 2019.....	31
Figure 26. DPA DOA Azimuthal Error (Contested GPS Environment, 30° Increments) .....	32
Figure 27. DPA Error, GPS Contested (Left: Top-Mounted DPA, Right: Bottom-Mounted DPA) .....	32
Figure A1. Major Components of the DPA .....	A-1
Figure C1. ARAIM Processing Flow Chart.....	C-1
Figure C2. DPA Processing Flow Chart .....	C-5
Figure C3. 3-D Projection of Satellite Ephemeris Data onto the DPA Antenna Reference Frame .....	C-7
Figure C4. 2-D Satellite Ephemeris Projection onto the DPA Reference Frame .....	C-8
Figure D1. Flight 1 FTTs Accomplished .....	D-2
Figure D2. Flight 2 FTTs Accomplished .....	D-4
Figure D3. Flight 3 FTTs Accomplished .....	D-6
Figure D4. Flight 4 FTTs Accomplished .....	D-8
Figure D5. Flight 5 FTTs Accomplished .....	D-10
Figure D6. Flight 6 FTTs Accomplished .....	D-12
Figure D7. Flight 7 FTTs Accomplished .....	D-13
Figure D8. Flight 8 FTTs Accomplished .....	D-14

## LIST OF TABLES

Table 1. Major GNSS Channels and Frequencies.....	3
Table 2. UHARS System Accuracy without Ground-Based Position Reference .....	6
Table 3. ARAIM Vertical Protection Level Accuracy in Benign Maneuvering.....	12
Table 4. ARAIM Horizontal Protection Level Accuracy in Benign Maneuvering .....	14
Table 5. Difference between ARAIM and RAIM in Benign Maneuvering.....	15
Table 6. RAIM and ARAIM Data Point Drop-Outs.....	33
Table 7. ARAIM Test Results.....	34
Table B1. 412 <sup>th</sup> Test Wing Rating Criteria .....	B-1
Table E1. ARAIM Vertical Protection Level Accuracy in Limited Tactical Maneuvering .....	E-1
Table E2. ARAIM Horizontal Protection Level Accuracy in Limited Tactical Maneuvering .....	E-2
Table E3. Difference between ARAIM and RAIM HPLs in Limited Tactical Maneuvering .....	E-3
Table E4. ARAIM Vertical Protection Level Accuracy in the GPS Jammed Environment.....	E-4
Table E5. ARAIM Horizontal Protection Level Accuracy in the GPS Jammed Environment.....	E-5
Table E6. Difference between ARAIM and RAIM HPLs in the GPS Jammed Environment.....	E-6
Table F1. Major Operations Limitations Differences between the C-12C and C-12J.....	F-2
Table G1. FTT Maneuver Matrix .....	G-1
Table G2. Benign FTT Independent Data Points.....	G-2
Table G3. Limited Tactical FTT Independent Data Points.....	G-2
Table G4. Low-Level FTT Independent Data Points.....	G-3
Table G5. GPS Jamming FTT Independent Data Points .....	G-4

This page was intentionally left blank.

# INTRODUCTION

This report presents the results for the Have Detect, Recognize, and Adapt to Global Positioning System (GPS) Overt Noise (Have DRAGON) test management project (TMP). Specifically, this evaluation characterized an Advanced Receiver Autonomous Integrity Monitoring (ARAIM) algorithm and a Dual Polarized Antenna (DPA) system. Stanford University requested USAF TPS support to evaluate Federal Aviation Administration (FAA) objectives. The Lead Developmental Test Organization (LDTO) was the Air Force Test Center (AFTC), Edwards AFB, California. The executing test organization was Class 19A of the United States Air Force Test Pilot School (USAF TPS), Edwards AFB, CA working in partnership with Stanford University in support of Federal Aviation Administration (FAA) objectives. Testing was conducted in the 586<sup>th</sup> Flight Test Squadron's C-12J, S/N 86-0080, from 6 September 2019 to 19 September 2019. Testing included eight test sorties totaling 17.6 flight hours under the Job Order Number MT19A300.

## BACKGROUND

### ERRORS IN GLOBAL NAVIGATION SATELLITE SYSTEMS

To reduce operating cost, the FAA intended to reduce the number of ground-based navigation aids, further increasing aviation reliance on global navigation satellite systems (GNSS), such as the US-owned Navigation Signal Timing and Ranging (NAVSTAR) GPS. The FAA's "Navigation Programs Strategy called for a reduction in 30% of the active Non-Directional Beacons (NDB) facilities. From 2016 to 2020, the FAA shut down 74 Very-High Frequency (VHF) Omnidirectional Range (VORs), and will shutter 234 more from 2021 to 2024.<sup>11</sup> Commercial GPS was still reliant on the Wide Area Augmentation System (WAAS) to provide corrections to positioning solutions and ensure sufficient navigational precision. WAAS was a large system of ground facilities that provide timing corrections for GPS users. Satellite navigation system errors can jeopardize aviation safety, inducing controlled flight into terrain or contributing to an unintentional departure from cleared airspace. Limitations in position accuracy also could have prevented desired future capabilities, such as completing a precision instrument approach with no ground aids.

Each GNSS emitted a signal with satellite position information and timing information. The signal from the satellite traveled through the atmosphere and arrived at the GNSS antenna some time later. When the antenna received the satellite signal, the GNSS receiver used the signal delay to calculate a distance (known as pseudorange) from the antenna to the satellite. By using the intersection of ranges from multiple satellites with known locations, the receiver determined its location. GNSS receivers required a minimum of four independent satellite signals to determine their 3-dimensional position and GPS time. However, the atmosphere, especially the ionosphere, attenuated the signal and introduced some variation into the calculated path length from the receiver to the satellite.

Other than the ionosphere, other factors reduced the ultimate precision and accuracy of the GNSS solution is affected by multiple sources of errors. The configuration of the constellation was one major source of error. Multiple satellites overlapping in the same area of the sky provide less position refinement than satellites spread across the entire sky. The GPS constellation operated on a 12 hour cycle, so the satellite configuration changed consistently through that time period as more or less satellites become visible and their line of sight angles to the receiver changed. Error due to the dynamically changing satellite geometry was called dilution of precision (DOP) and was a major factor in the variance of GPS accuracy, causing navigational accuracy to vary by a factor of 3 over the course of the 12 hour cycle.

Other environmental factors affected GPS accuracy. One impact on military operations in low-level environments is multipath. Multipath occurs when a GPS signal impacts the ground, reflects, and then is

accepted as a valid signal by a receiver. The additional path length of the GPS signal induced by the multipath effect would add time delay to the signal, and would degrade the GPS system accuracy.

Another environmental factor that affected GPS performance was interference, whether incidental or hostile. GPS jamming had become more prevalent as the technology became more widespread, cheaper and desirable. GPS jamming and spoofing had become more widespread and resulted in degraded operational capacity for GNSS-reliant weapon and navigation systems. Traditional anti-US jamming systems typically targeted either the L1 or both L1 and L2 frequencies used by military GPS receivers. Jammers attempted to deny GNSS acquisition (prevent the receiver from locking onto the correct frequency and time delay) or to degrade the modulation of positioning data from the satellite. However, jamming also affected civilian airports in Israel, Egypt and Turkey.<sup>1,2</sup>

## **ADVANCED RECEIVER AUTONOMOUS INTEGRITY MONITORING**

Receiver Autonomous Integrity Monitoring (RAIM) provided characterization of a GPS receiver accuracy. The RAIM algorithm analyzed information from all visible GPS satellites to determine the precision of the location solution. RAIM estimated the effect of the errors in the GNSS constellation including DOP, clock errors, broadcast satellite position, multipath, atmospheric effects, and space weather. The output of a RAIM process created a protection level (PL), which bounds the possible error of an associated position solution. A protection level was a guarantee of an error rate, which meant that the probability of actual position error exceeding the provide PL was less than  $10^{-7}$ . In navigation operations, pilots used RAIM to validate their maximum GNSS accuracy. RAIM was limited to providing horizontal protection levels (HPL) and RAIM also relied entirely on the US GPS system which limited RAIM effectiveness due to the potential for electromagnetic interference, satellite drop-outs, and increased DOP. ARAIM extended conventional RAIM by incorporating multi-frequency and multiple satellite constellations across GNSS creating four main advantages over RAIM.

First, ARAIM was intended to generate improved HPLs over RAIM HPLs. The ARAIM antenna received positioning information from the United States' GPS, EU's Galileo, Russian GLONASS, and Chinese BeiDou Navigation Satellite System. All four satellite systems worked under similar principles for real-time position determination. While both RAIM and ARAIM provided PLs that equated to an error rate of  $10^{-7}$ , ARAIM was expected to report much smaller HPLs.

Second, ARAIM was expected to generate vertical protection levels (VPL) where RAIM did not. Any vertical protection level calculated using the RAIM algorithm produces a VPL so large that it was unusable. Utilizing additional satellites, ARAIM VPLs were expected to provide increased accuracy.

Third, ARAIM was predicted to be more resilient to service drops out due to integrating multiple constellations in its position solution. The increased number of satellites provide a more resilient network, resistant to drop outs such as Galileo's complete loss of service in July 2019<sup>3</sup>, and frequency denial tactics. ARAIM used information from all available satellite constellations collectively to determine the antenna's position. As an additional benefit, ARAIM did not suffer from variable DOP inherent in the GPS system alone. Having access to multiple satellite constellations improved the opportunity of a having satellite signals from all directions, and DOP was expected to both more favorable and more consistent.

Fourth, ARAIM was designed to be more resistant to jamming due to using multiple frequencies from multiple constellations. The ARAIM system was expected to be extremely resilient to jamming of the US GPS frequencies. Jamming L1 and L2 may have completely denied access to the US Military GPS system, but the Galileo, BeiDou, and GLONASS all used different signal frequency ranges (See Table 1). Despite some overlapping frequency ranges, access to multiple satellites expanded the usable frequency band. Signals from different constellations provided up to 27 MHz of frequency separation from L1; 20 to 51

MHz of frequency separation from L2, and 15 or more MHz of frequency separation from L5. If a frequency band is jammed, the ARAIM algorithm would still provide accurate position information by utilizing other constellations in other frequency bands. Figure 15 and 16 provide a graphic depiction of the frequency overlap and bandwidth.

Table 1. Major GNSS Channels and Frequencies

	Channel	Frequencies
US GPS	L1	1567.75 - 1583.09 MHz
	L2	1222.10 – 1233.10 MHz
	L5	1170.20 – 1182.70 MHz
EU Galileo	E1	1563.14 – 1587.70 MHz
	E5	1166.22 – 1217.37 MHz
	E6	1258.29 – 1299.21 MHz
GLONASS	G1	1598.06 – 1603.38 MHz
	G2	1242.94 - 1248.63 MHz
BeiDou	B1C	1559.05 – 1563.15 MHz
	B2a	1195.14 – 1219.14 MHz
	B3I	1256.52 – 1280.52 MHz

Stanford University GPS Labs have already explored ARAIM performance in the aviation environment.<sup>7</sup> Late August of 2016, Stanford Labs installed a multi-frequency antenna array on a Global 5000 jet owned by the William J. Hughes FAA Technical Center. The test aircrew in the Global 5000 executed test maneuvers at straight and level flight, in “Figure-8” banking patterns using approximately 30° angle of bank, and in missed approaches. During the entire test period, except during initialization, ARAIM produced VPL and HPL under 50 meters, with an approximate average of HPL 20 meters. A nominal RAIM HPL value would be 150 meters. In addition to observing improved ARAIM HPL performance, Stanford noted that in bank, ARAIM would occasionally lose lock with low-elevation satellites. Aircraft body masking prevented exploitation of horizon satellites, and caused instantaneous ARAIM drop-outs.

### **DUAL POLARIZED ANTENNA**

The Dual Polarized Antenna (DPA) designed by Stanford University was intended to reduce the effects of both multipath and GPS jamming. Ultimately, the DPA attempted to determine a signal direction of arrival (DOA). Multi-pathed signals would have a false DOA that failed to agree with ephemeris, and could then be discounted. To counter jamming several techniques could have been employed, such as null

steering, but those techniques required a source location. The DPA system attempted to correlate signal polarization with DOA. Normal GPS signals were transmitted as Right-Hand Circular Polarized (RHCP). When the signal arrived at a receiver, it may have components of both RHCP and Left-Hand Circular Polarization (LHCP), and the magnitude of each depended on the receiver orientation. The signal phase for both RHCP and LHCP signals changed in opposite directions as the receiver azimuth changed so the phase of each signal was correlated to the DOA for the GPS signal. The DPA system measured both RHCP and LHCP components of the GPS signal, and in post-processing compared those signals to determine the angle at which a minimum (or null) LHCP signal occurs. The null angle was classified as the DOA. However, since the phase difference of LHCP and RHCP rotated  $720^\circ$  in a full  $360^\circ$  sweep, the DPA antenna generated a false positive  $180^\circ$  azimuth from the true signal.

For GPS signals that arrived from a high elevation, the null azimuth of the LHCP signals became more difficult to determine as the polarization effects blend together. This effect was predicted to reduce the accuracy of higher elevation satellite signal DOA estimations. Figure 1 shows the results from a ground test that took place at Stanford University.<sup>5</sup> The figure depicts the LHCP response to three different satellites, one near the horizon, one at a moderate elevation and one at high elevation. For each satellite, DPA generated a plot of Carrier-to-Noise ( $C/N_0$ ) ratio observed as the azimuth changed. Below the  $C/N_0$  charts, a spider plot displays the true location of the target satellites. The spider plot shows azimuth as a left or right angle from the vertical, and elevation angle as a radial distance, where the edge of the plot is the horizon, and the exact center is directly overhead.

The signals used to produce the plots were from GPS satellites, and did not pass through any ground masking, so the assumption that the source was primarily RHCP was valid. The DPA electronically swept through  $360^\circ$  in azimuth, and recorded the magnitude of the LHCP response. As shown in Figure 1, the LHCP response dropped dramatically for the low elevation satellites when the DPA was aligned directly toward and directly away from the satellite (shown on the middle  $C/N_0$  ratio chart at  $110^\circ$  and  $290^\circ$  azimuth). The nulls agreed well with the satellite location at  $290^\circ$  azimuth, depicted in the spider plot portion of Figure 1. The DPA continued to sweep multiple times, producing several nulls that agree with the previous DOA determination. Higher elevation satellites have a less distinguishable response, but DOA estimations still were inferred. All sweeps produced two nulls in  $360^\circ$ , including one that was directed at the satellite and the false positive that was exactly opposite.

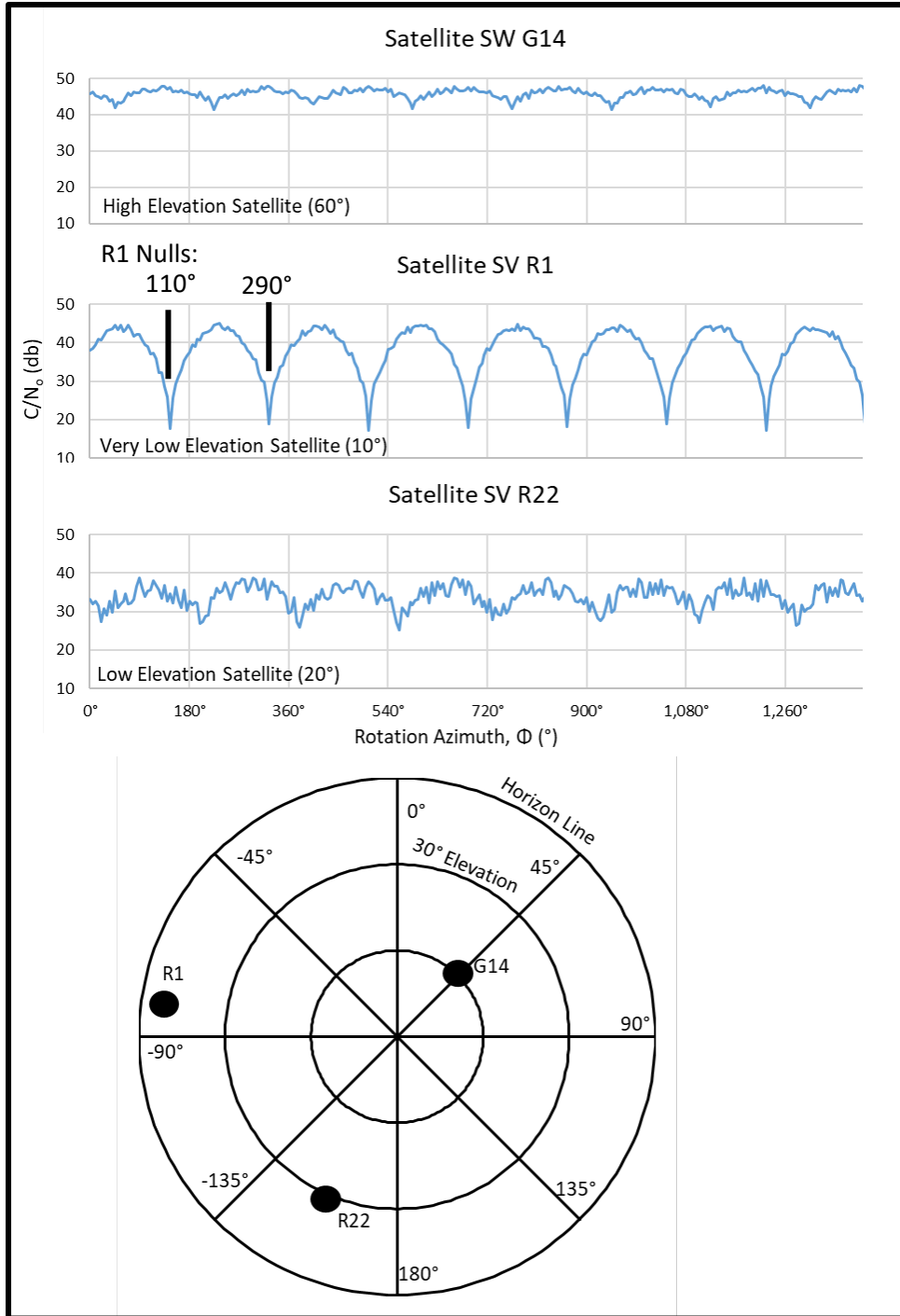


Figure 1. Stanford University Dual Polarized Antenna Ground Test: LHCP Response

Stanford University has tested several DPA systems under different configurations but has not conducted flight test. On 12 May, 2015, Stanford built a DPA system to detect and characterize a spoofed signal. They learned that jammers become more effective as the depression angle from their simulated aircraft to the jammer decreases. For aviation applications, banks towards the jamming system may further degrade a Stanford DPA. Additionally, during this test Stanford observed that moderate jamming-to-signal power ratios quickly saturated the DPA. DOA estimations became unreliable when the DPA was saturated.

## TEST ITEM DESCRIPTION

The test management project assessed two distinct systems, the ARAIM algorithm and the DPA. The two systems were installed simultaneously on the test aircraft but were tested and analyzed as isolated systems that did not interact or interfere with each other. The ARAIM algorithm processed signals received from a dedicated antenna separate from the DPA. In previous tests, Stanford has installed multi-frequency antennas on an FAA Global 5000 aircraft to test the ARAIM algorithm, but has only assessed the system in take-off, holding, and approach phases.<sup>7</sup> This test exposed the ARAIM system to low altitude, moderate airspeed navigation, multipath, and high-powered GPS jamming. Stanford has also employed a DPA system on a test stand, and observed the effects of spoofing on the DPA, but prior to this test, they have not been able to assess DPA performance in flight.

The test aircraft was a 586<sup>th</sup> Flight Test Squadron (FLTS) C-12J (USAF S/N 86-0080), based at Holloman Air Force Base. The aircraft was modified extensively to perform as a system testbed with internal truss assemblies and palletized racks for computer equipment, and it was further modified for this test. Three additional antennas were added for this test, including one top-mounted DPA, one bottom-mounted DPA, and one more top-mounted multi-frequency Harris C-146 antenna to provide GNSS signals for ARAIM analysis. Finally, the aircraft was configured to host the Ultra-High Accuracy Reference System (UHARS). The UHARS system combined a precise inertial navigation system (INS) with a GNSS-receiver. The same Harris multi-frequency antenna used for ARAIM analysis provided GNSS signals to the UHARS to generate a navigation solution. The UHARS system was used throughout the test to provide a truth source for comparison. When operating at the test range at Edwards Air Force Base, UHARS boosts the accuracy reported in Table 2.

Table 2. UHARS System Accuracy without Ground-Based Position Reference

	Environment	Horizontal Position Accuracy (each axis)	Vertical Position Accuracy
UHARS	Clear-air	0.1 m	0.2 m
	High-powered (90+ Open-air S/N ratio) GPS Jamming Levels	4 m	20 m

## ARAIM ANTENNA, RECEIVER, AND SOFTWARE

The hardware setup to test ARAIM is depicted in Figure 2. Stanford University GPS Labs developed the ARAIM algorithm, and flew an arrangement similar to that depicted in Figure 2 on a Global 5000 jet in August 2016<sup>7</sup>. To implement the proposed ARAIM algorithm, the standard L1/L2 Harris antenna on the C-12J was replaced with a matching form factor L1/L2/L5 C-146 Harris antenna. The raw GNSS signal was received by a Trimble BX940-INS. The Trimble BX940-INS receiver is capable of tracking all major GNSS satellite constellations, including support for triple frequency GPS (L1, L2, L5) and GLONASS (G1 and G2) in addition to dual frequency capability for Galileo (E1 and E5a) and BeiDou (B1 and B2), as well as WAAS (L1). The system was also INS capable, but the test did not use the INS functionality. The Trimble BX940 produces a proprietary .T04 file format for position information in addition to Receiver Independent Exchange Format (RINEX) data formats.

C-146 Harris Multi-Frequency Antenna  
GPS, GLONAS, Galileo, BeiDou

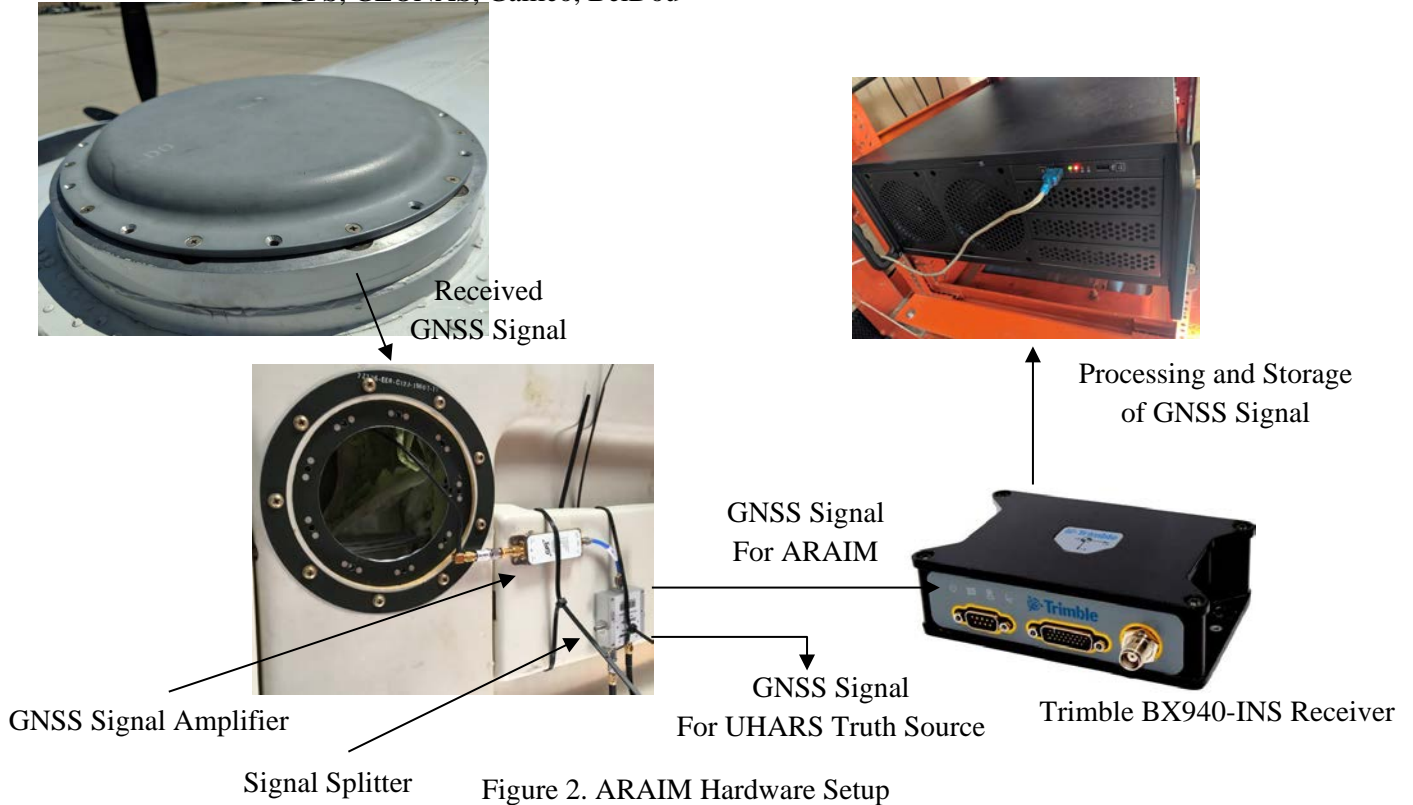


Figure 2. ARAIM Hardware Setup

Figure 3 details the data processing flow for the ARAIM software. The data were provided to the ARAIM software from the Trimble BX-940 by means of an Ethernet connection. The ARAIM software extracted the GNSS time and position data from the .T04 file. Once extracted, the data were converted to a standard RINEX format. Using Stanford University provided MATLAB scripts, the observation (obs.txt), ephemeris (.ephemeris.txt) and position (pos.txt) files were generated. The ARAIM software output included time, VPL, HPL and a position solution. The time aligned position solution were compared to the “truth” solution provided by the UHARS. A detailed description of the data processing and MatLab scripts is provided in Appendix C – Data Analysis. The multifrequency antenna, as it was installed on the C-12J, is visible as Figure 4.

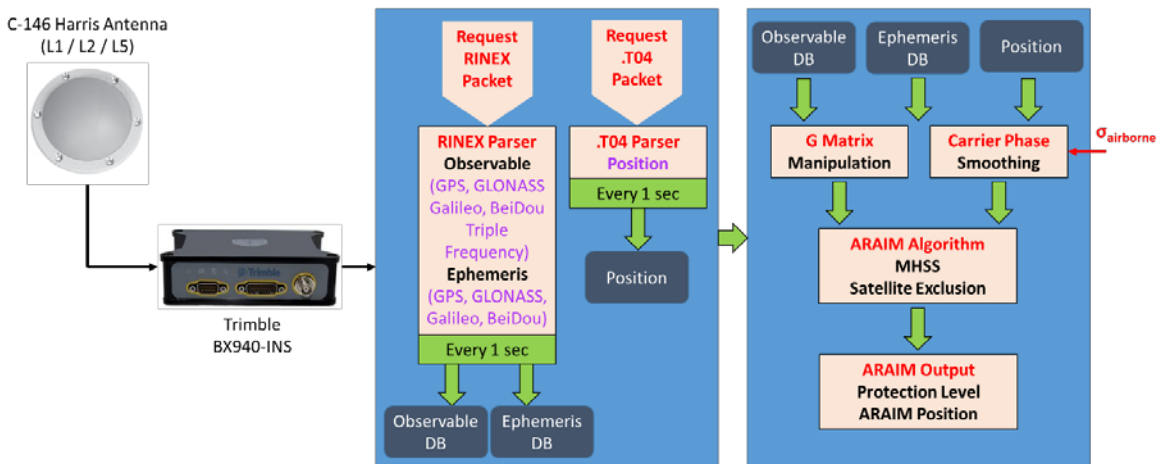


Figure 3. ARAIM Software Architecture



Figure 4. C-12J Harris C-146 Multi-Frequency Antenna

### DPA

The DPA was an immature antenna and hardware system that has undergone ground testing at Stanford University. Both antennae, as they were mounted for this test, are displayed in Figure 5. Stanford University GPS Labs designed both DPA, while the 586<sup>th</sup> FLTS at Holloman Air Force Base manufactured and mounted the equipment. The antenna was developed using a miniaturized printed circuit board (PCB) that houses the radio frequency (RF) components and circuitry.



Figure 5. C-12J Under-Mounted DPA Plate (Left) and Top-Mounted DPA Plate (Right)

Two different DPA receiver configurations were tested, with different methods for accounting for the LHCP signal. A uBlox 8 was the first receiver connected to the DPA (see Figure 6). uBlox 8 was a commercial-off-the-shelf (COTS) GPS-only receiver that could only process one signal at a time. In this limitation, direct comparison of the RHCP and LHCP could not occur. Stanford University GPS Labs countered this restriction by combining the LHCP with a phase-shifted RHCP, producing a single composite signal. This single signal was dependent on an assumed azimuth, so by electronically scanning 360°, the uBlox 8 receiver was able to map the composite signal. When the composite signal achieves a “null”, the LHCP is minimal, and the null azimuth is an estimate for the signal DOA. The results of a uBlox DPA scan are depicted in Figure 1.

### uBlox Mode

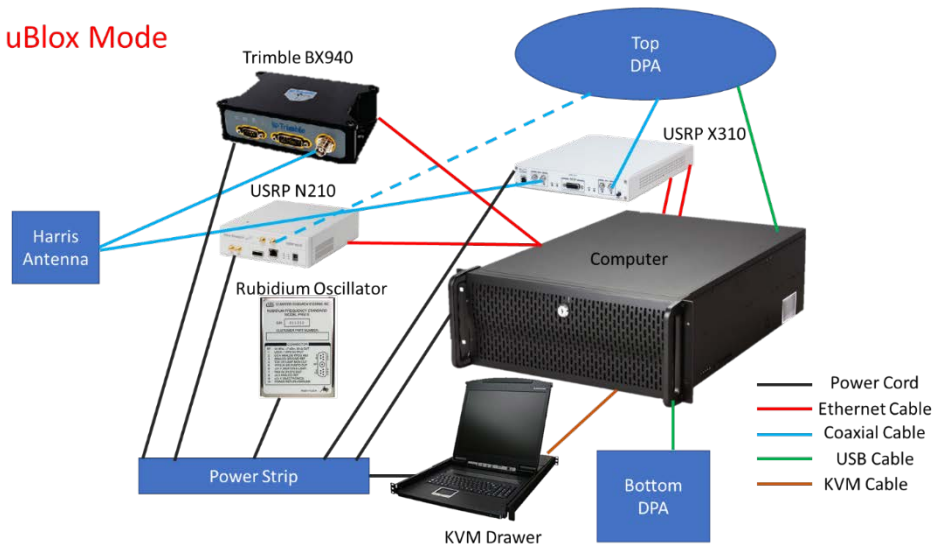


Figure 6. DPA uBlox Mode Configuration

The DPA also used a Stanford University GPS Labs proprietary Software-Defined Radio (SDR) receiver (see Figure 7). The SDR used an analog-to-digital converter to convert received GPS signals to electronic signals. The software then could record and manipulate signals independently and individually. The primary advantage of SDR was that RHCP and LHCP could both be recorded and directly compared without the specialized hardware necessary for uBlox 8. However, the SDR was a custom built program, not a COTS system, and was installed directly at the antenna. Due to antenna mounting safety requirements, the recording device could not be accessed during the test, and analysis could not begin until the SDR recording card was received at Stanford University.

### SDR Mode

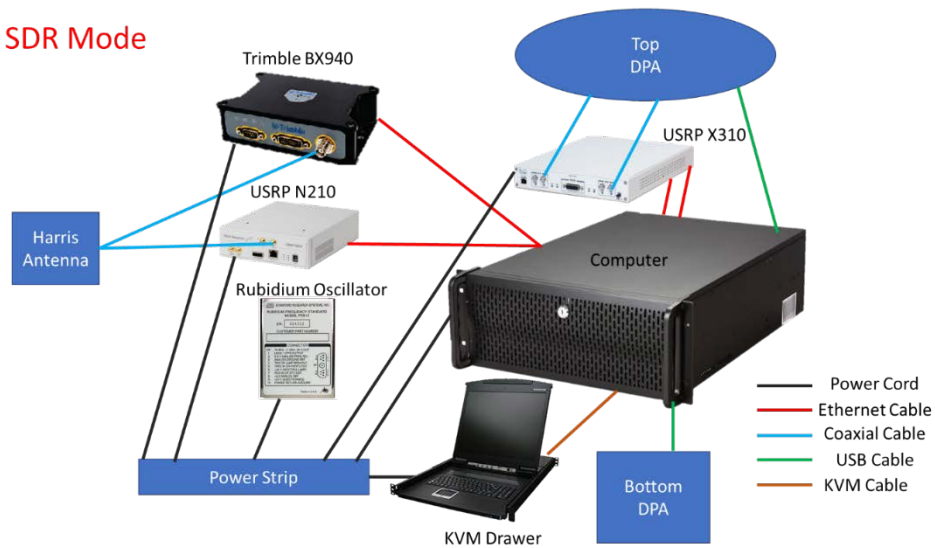


Figure 7. DPA SDR Mode Configuration

## **OVERALL TEST OBJECTIVE**

The overall test objective was to investigate ARAIM and DPA's capability for improving airborne GNSS system robustness. The overall test objective was met. Specific Test Objectives for this program included:

1. Determine ARAIM performance during benign maneuvering.
2. Determine ARAIM performance during limited tactical maneuvering.
3. Demonstrate ARAIM performance in a GPS-jammed environment.
4. Characterize DPA azimuth direction of arrival accuracy.

## **CONSTRAINTS**

- Incomplete software on the Stanford rack prevented real-time switching of the DPA mode from SDR to uBlox. Therefore, only a single mode was able to be tested during each flight. The late customer request to test both modes in all phases, and limited scheduling availability for the overwater flight meant that the SDR configuration was not flown overwater.

## TEST AND EVALUATION

After installing two DPA antennas and Harris multi-frequency antenna on the test aircraft, the test team flew eight sorties over 17.6 hours with all antennas collecting satellite and DOA data. Flight conditions were varied to expose the antennae to diverse environments and assess their response to each. The purpose of the test was to investigate ARAIM and DPA's capability for improving airborne GNSS system robustness. The test investigated ARAIM in a variety of conditions, including in benign maneuvering, limited tactical maneuvering, and in a GPS jammed environment, with a goal of assess whether ARAIM has the capacity for improving on traditional RAIM systems. While DPA had less stringent success criteria, since the system was installed on the aircraft DPA produced data in all of the same environments. The primary goal was to characterize DPA's ability to determine a signal's direction of arrival. All specific FTTs are documented in Appendix G.

Overall, the ARAIM algorithm was satisfactory, and the test produced sufficient data to characterize the DPA system. ARAIM HPL provided a significant improvement over RAIM HPL for all test points, ARAIM was able to provide relevant VPLs, and error never approached the protection levels. In both jamming and limited tactical maneuvering, ARAIM occasionally degraded but, in almost all cases, outperformed RAIM. Most importantly, ARAIM was able to provide HPLs and VPLs in regions where RAIM was unable to even provide a navigation solution. In tactical maneuvering, steep bank angles resulted in a loss of sufficient satellites to determine HPL and VPL, and caused RAIM and ARAIM drop-outs. Additionally, as the bank angle increased, horizontal and vertical axes interchange from the perspective of the antenna reference frame. The test was not scoped to investigate the precise bank angles that induced ARAIM loss, but the phenomenon was not observed during 30° angle-of-bank shallow turns. **Conduct steady bank angle testing at 10 degree AOB intervals. (R1)**

While DPA demonstrated rather large variance in DOA determination, error was bound fairly well in most circumstances. DPA demonstrated an average pointing error of 30° in azimuth, but contrary to expectations, demonstrated no significant elevation angle dependency until satellites were within 8° of zenith. Error also didn't appear to exhibit a dependency on any specific FTT's. In mild GPS jamming, the top-mounted DPA antenna was still able to maintain an average 30° error in azimuth, likely as it was more protected by the aircraft body from the jamming effects. The bottom-mounted antenna was saturated and demonstrated reduced accuracy in DOA determination. This test generated significant data for further analysis that will be conducted by Stanford University, with the intention of improving the system for tactical applications, including multi-path resilience and jamming source geolocation. **Continue further investigation into DPA performance. (R2)**

## GENERAL METHODOLOGY

### TEST SETUP

Both ARAIM and DPA systems were powered on and recording was initiated when aircraft power was applied on each sortie. Each system and tested system configuration was checked and verified to be properly functioning prior to each take-off. Proper setup for the DPA system was verified, and both the SDR and uBlox configurations displayed no abnormalities prior to takeoff. Data points were collected and recorded for every point, and local clock times were used to distinguish between different maneuvers and phases of flight. Since collecting multiple data points in the same maneuver with ARAIM may not have produced independent data points, the data were subjected to a serial autocorrelation test. If the test determined that the data points were not independent, the sample set was decimated. That process continued until the data set were confirmed independent. A detailed description of the data analysis is available in Appendix C.

## ARAIM IN BENIGN MANEUVERING

### TEST METHODS AND CONDITIONS

Flights were conducted in a stable manner to replicate typical benign civil and military flight conditions to include straight and level flight, shallow turns less than 30 degrees angle of bank, and 500 ft/min climbs and descents. The aircraft was flown at a full range of speeds and at altitudes ranging from 5,000 feet mean sea level (MSL) to 21,500 feet MSL and Final Approach Speed (FAS) to 175 KIAS. The autopilot system was used extensively to improve maneuver accomplishment and repeatability. A consolidated Flight Test Technique (FTT) matrix outlined in Appendix G, Table G2 describes the number of FTTs flown for all benign phases of flight, as well as how many independent data points were derived from the accomplishment of all FTTs. Table G1 outlines the specific methodology and techniques used to fly each FTT for consistency and repeatability.

### ARAIM VERTICAL PROTECTION LEVEL ACCURACY

VPL accuracy was characterized by comparing error between the UHARS truth source and ARAIM-generated position solution. Specific procedures for data tabulation are available in Appendix C. Of note, ARAIM and UHARS both provided the same refresh rate, and thus were already time-aligned. Throughout the entire range of benign maneuvering techniques, error never exceeded the reported VPL value. In any benign technique, the average error observed was 20 meters, while the minimum VPL produced was 71 meters, as presented in Table 3. ARAIM VPL was expected to always be conservative. As expected, ARAIM produced small errors that were well bounded by the VPL. A 71 meter (232 feet) VPL would be sufficient to maintain 1,000 foot spacing between two aircraft, which was a typical requirement for Reduced Vertical Separation Minimums (RVSM) airspace. Figure 8 presents the data in a box-and-whisker plot, with the whiskers representing the 99.3 percentile.

Table 3. ARAIM Vertical Protection Level Accuracy in Benign Maneuvering

			Error			Protection Level			
Maneuver	FTT Count	Sample Count	Mean (m)	$\sigma$ (m)	Max (m)	Mean (m)	$\sigma$ (m)	Min PL (m)	% Bounded
Racetrack	4	48	13	11	32	85	3	78	100%
Shallow Turns <30° AOB	11	864	23	16	82	105	11	81	100%
Spiral Climb 500 ft/min	5	320	21	16	59	104	10	78	100%
Spiral Descent 500 ft/min	10	1181	26	19	100	93	15	71	100%
Climb 500 ft/min	7	97	20	9	64	105	44	76	100%
Descent 500 ft/min	11	850	33	24	100	105	28	72	100%
Straight / Level	13	327	22	12	63	108	20	75	100%
Instrument Approach	4	88	5	6	20	85	4	81	100%
Takeoff	4	192	16	8	33	86	12	76	100%

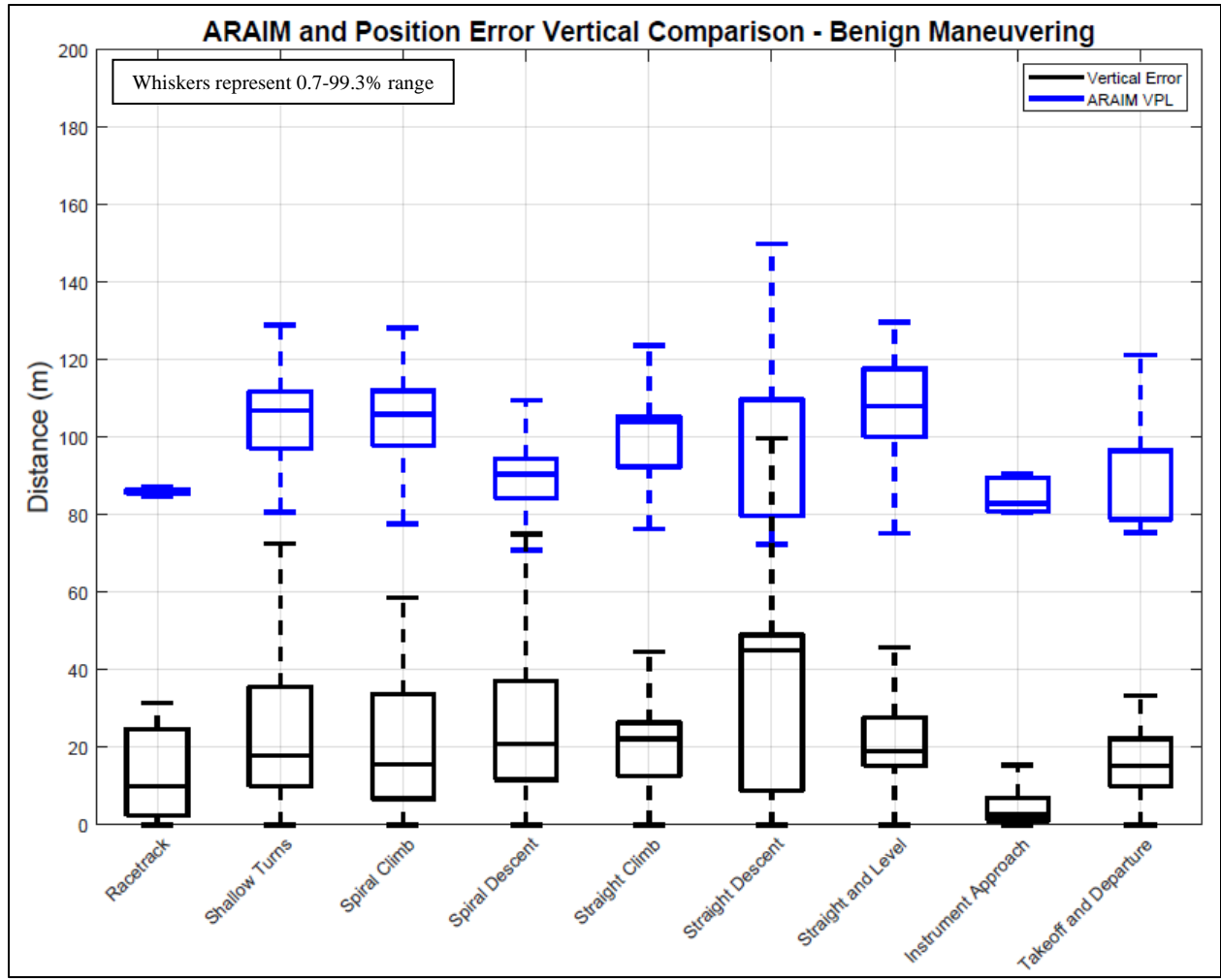


Figure 8. ARAIM and Position Error Vertical Comparison – Benign Maneuvering

### ARAIM HORIZONTAL PROTECTION LEVEL ACCURACY

Similar to VPL, the horizontal error never exceeded the reported HPL value. In any benign technique, the maximum error observed was 50.0 meters, while the minimum HPL produced was 49 meters, as presented in Table 4. HPL bounded every single data point for all benign maneuvers. Most horizontal errors were approximately one-third the magnitude of their associated HPL, and all HPL's were consistently 60 meters. The only abnormal data point presented in Table 4, and encapsulated on Figure 9, is error performance in the straight descent. While most other maneuvers saw average error around 15 meters, the straight descent recorded 29 meters of average error. During one straight descent maneuver, the UHARS operator observed unattributed interference, which may have contributed to the abnormal readings. Generally, the protection levels were excellent, and provided great operational utility.

Table 4. ARAIM Horizontal Protection Level Accuracy in Benign Maneuvering

			Error			Protection Level			
Maneuver	FTT Count	Sample Count	Mean (m)	$\sigma$ (m)	Max (m)	Mean (m)	$\sigma$ (m)	Min PL (m)	% Bounded
Racetrack	4	48	15	4	21	60	1	58	100%
Shallow Turns <30° AOB	11	864	13	6	42	59	3	54	100%
Spiral Climb 500 ft/min	5	320	14	6	27	57	2	51	100%
Spiral Descent 500 ft/min	10	1181	17	10	50	56	4	49	100%
Climb 500 ft/min	7	97	16	8	44	60	15	51	100%
Descent 500 ft/min	11	850	29	13	47	59	6	51	100%
Straight / Level	13	327	16	7	35	57	8	51	100%
Instrument Approach	4	88	14	8	25	56	3	49	100%
Takeoff	4	192	13	4	22	60	5	57	100%

**DIFFERENCE BETWEEN ARAIM AND RAIM HORIZONTAL PROTECTION LEVEL**

The difference in HPL between RAIM and ARAIM was measured and compared, with an expectation that ARAIM HPL would be lower than RAIM HPL. The mean ARAIM HPL across all benign maneuvering test points was 57 meters, and the mean RAIM HPL was 110 meters (see Table 5). One notable outlier existed in the 500 ft/min descent test point where the mean RAIM HPL (410 meters) was significantly higher than the other maneuvers. Potential interference on the GPS signal may have played a role in dramatically increasing the RAIM HPL, while having little effect on the ARAIM HPL. Overall, the ARAIM HPL provided a significant improvement over RAIM HPL for all benign maneuvering test points, typically achieving a 30% improvement in HPL value. The potential interference degraded RAIM performance, but did not degrade ARAIM, providing evidence that ARAIM can still function in environments where RAIM would falter.

Table 5. Difference between ARAIM and RAIM in Benign Maneuvering

Maneuver	FTT Count	Sample Count	RAIM Mean HPL (m) ( $\bar{x}_{RAIM}$ )	ARAIM Mean HPL (m) ( $\bar{x}_{ARAIM}$ )	Percent Improvement (%) $\left(\frac{\bar{x}_{RAIM} - \bar{x}_{ARAIM}}{\bar{x}_{RAIM}}\right)$
Racetrack	4	48	93	60	35%
Shallow Turns <30° AOB	11	864	94	59	37%
Spiral Climb 500 ft/min	5	320	78	57	27%
Spiral Descent 500 ft/min	10	1181	80	56	30%
Climb 500 ft/min	7	97	75	60	20%
Descent 500 ft/min	11	850	410	59	86%
Straight / Level	13	327	94	57	39%
Instrument Approach	4	88	77	56	27%
Takeoff	4	192	86	60	30%

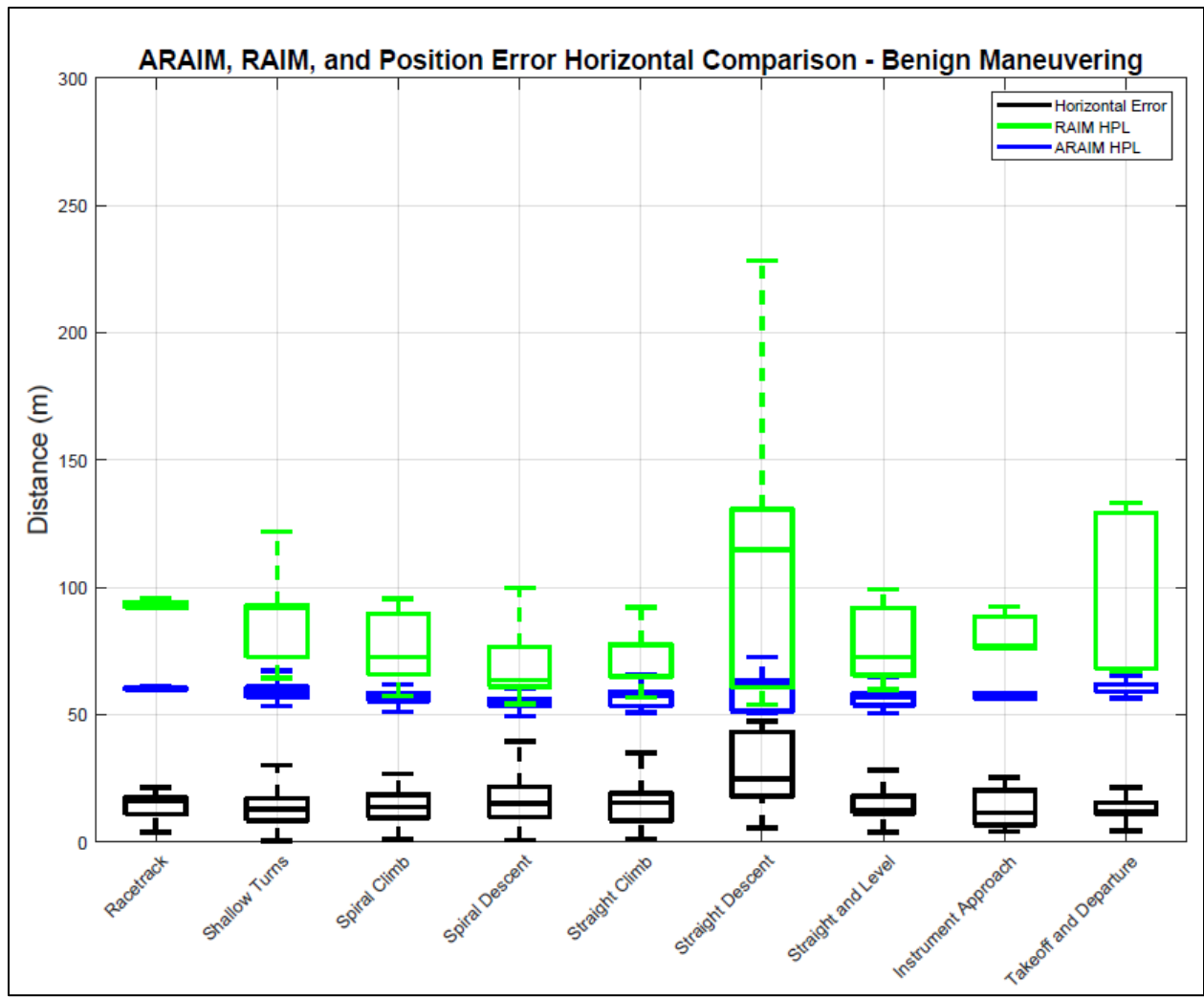


Figure 9. ARAIM, RAIM, and Position Error Horizontal Comparison – Benign Maneuvering

### ARAIM IN LIMITED TACTICAL MANEUVERING

In addition to benign maneuvering, a set of limited tactical maneuvers were performed in order to observe ARAIM performance in flight environments germane to military operations. A detailed description of the specific maneuvers and FTTs performed are summarized in Table G1. The data on ARAIM in limited tactical maneuvering VPL and HPLs, and the difference between RAIM and ARAIM Protection Level can be found in the Appendix E Section titled “ARAIM in Limited Tactical Maneuvering.”

### TEST METHODS AND CONDITIONS

Flights were conducted to replicate tactical flight profiles typical to military flight phases. Steep left and right turns up to 60 degrees angle of bank, bank to bank rolls from 60 to 60 degrees angle of bank, 1,000 ft/min climbs and descents and spiraling 1,000 ft/min climbs and descents were flown to replicate aggressive tactical flight profiles. Furthermore, these maneuvers were flown in a variety of geographic and topographical locations, including below adjacent mountainous terrain and over open water, in order to encompass a broad spectrum of operating environments. The ARAIM system performance was observed through the execution of maneuvers in low level flat terrain, low level mountainous terrain, and low level

overwater environments. The maneuvers were flown at a full range of flight conditions ranging from 200 feet above ground level (AGL) to 21,500 feet MSL and Final Approach Speed to 175 KIAS. Appendix G test matrices, including Table G3 and G4, present the FTTs flown for all tactical maneuvering phases of flight, as well as how many independent data points were derived from each maneuvering. Table G1 outlines the specific methodology and techniques used to fly each FTT.

### ARAIM VERTICAL PROTECTION LEVEL ACCURACY

In limited tactical maneuvering profiles, all maneuvers produced error that was well below the reported VPL. These results are outlined in Table E1. Throughout the range of maneuvers, position error never exceeded the reported ARAIM VPL values; the average error observed was approximately 10 meters, while the minimum VPL produced was 71 meters. ARAIM again demonstrated very small position errors that were well bounded by the conservative VPL values for all limited tactical maneuvering flight techniques. A 71 meter VPL (233 feet) may not provide an adequate value for flying a modified contour solely off GPS; however, the VPL error and VPL value characterizations reveal consistency and validity throughout the envelope of tactical maneuvers performed. Generally, the VPL's were small enough to be useful for navigation, while consistently bounding observed error, as shown in Figures 10 and 11.

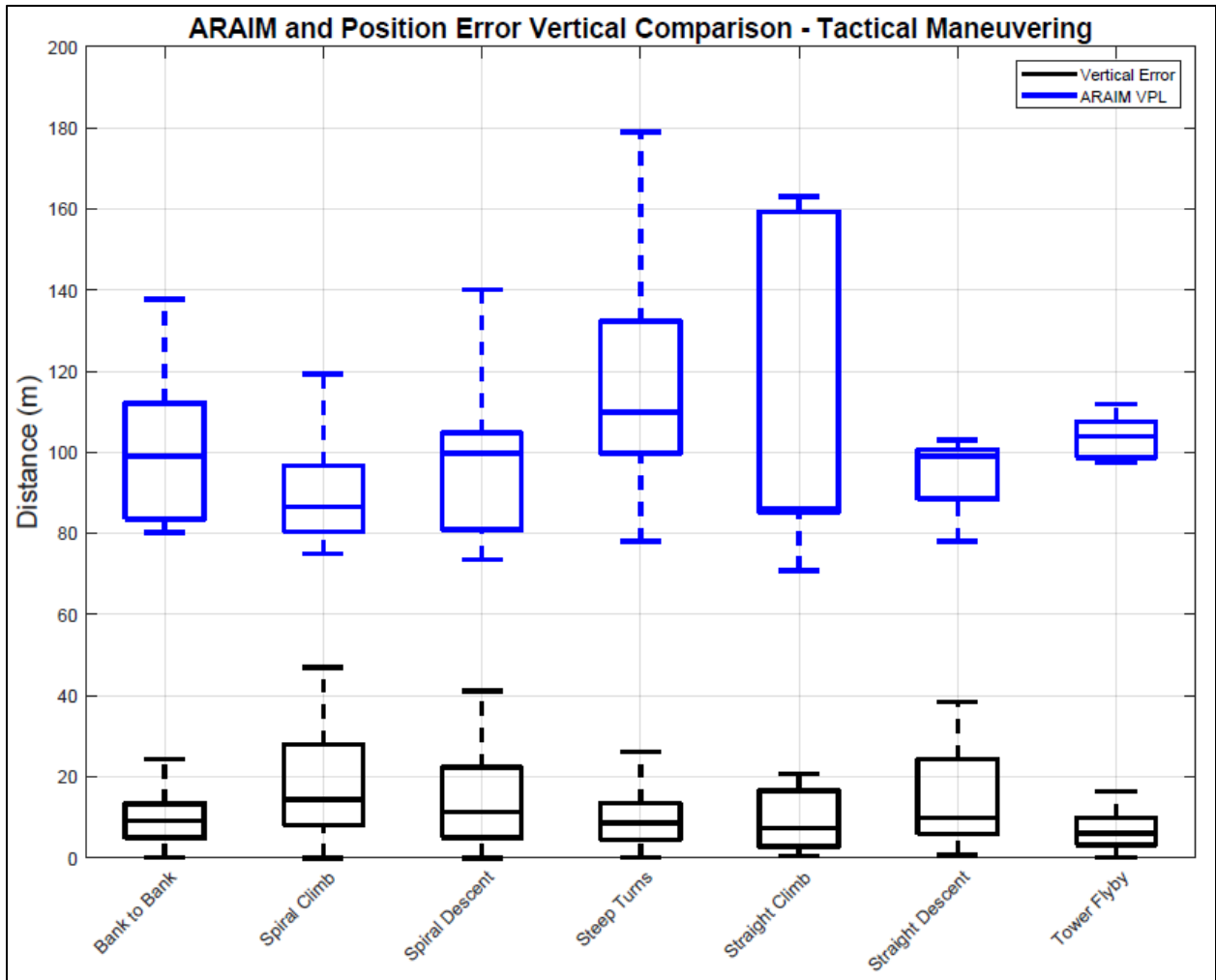


Figure 10. ARAIM and Position Error Vertical Comparison – Tactical Maneuvering

Steep turns, at 60° angle of bank, provided the largest challenge for ARAIM in producing usable VPLs. The ARAIM operator would often see satellites dropping off throughout the maneuver, and ARAIM had limited time during the turn to stabilize on any particular satellites. Steep turns in the low-level environment were even more degrading to ARAIM VPL performance, but were only able to bring the average VPL to 120 meters. Despite the high turn rate, ARAIM was still able to bound vertical error with reasonable VPL values.

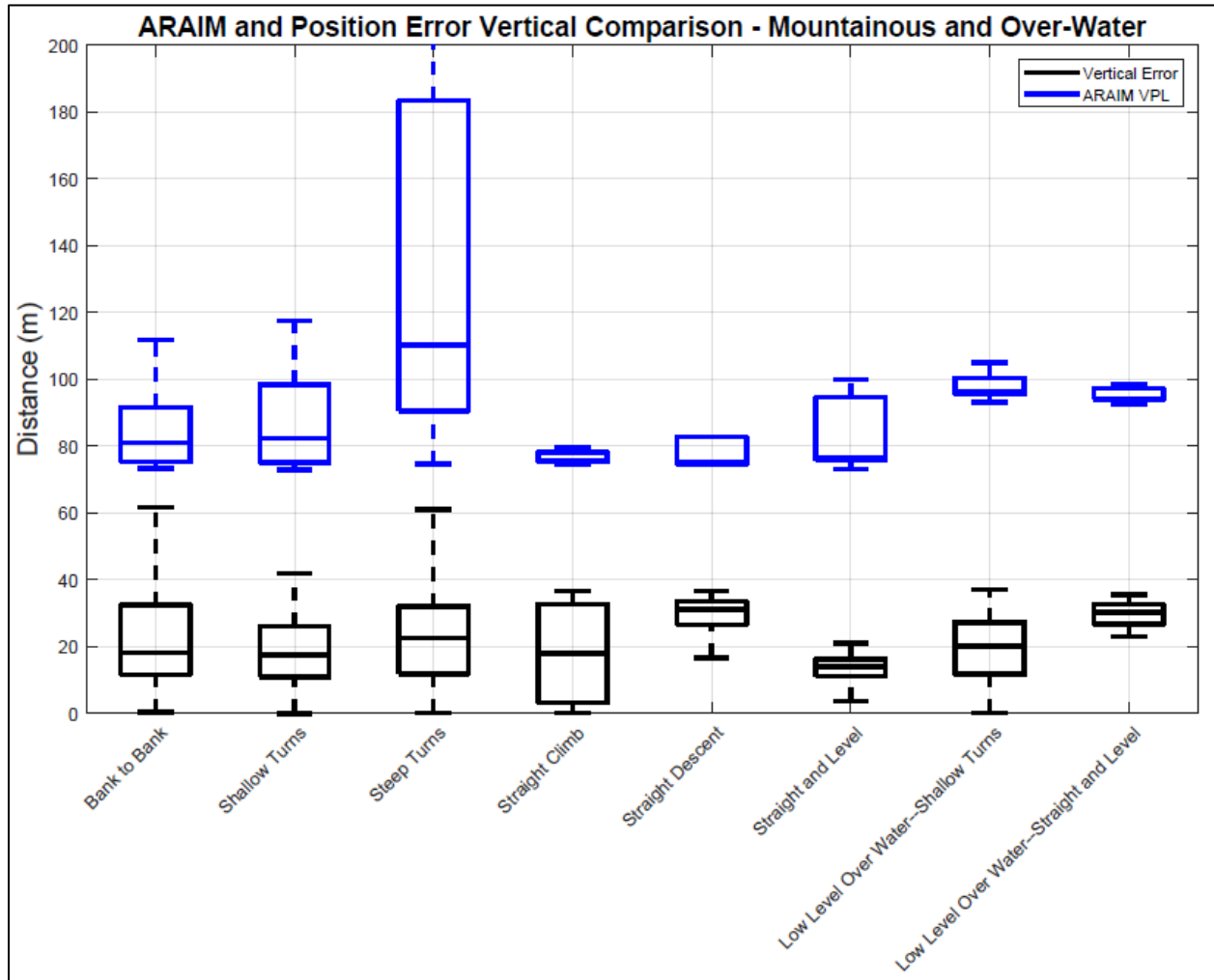


Figure 11. ARAIM and Position Error Vertical Comparison – Mountainous and Over-Water

### ARAIM HORIZONTAL PROTECTION LEVEL ACCURACY

For the limited tactical maneuvering profiles, all maneuvers produced error that was well below the reported HPL. These results are outlined in Table E2. Throughout the range of maneuvers, ARAIM error never exceeded the reported ARAIM HPL values; the average error observed in tactical maneuvering was 26 meters, while the average HPL produced was 63 meters. ARAIM again demonstrated small position errors that were well bounded by the conservative HPL values for all limited tactical maneuvering flight techniques. A 63 meter HPL (206 feet) may not be quite sufficient to fly close formation, or to provide protection while navigating through a steep valley; however, the HPL error and HPL value characterizations reveal consistency and validity throughout the envelope of tactical maneuvers performed, and the values are quite excellent. Just as with VPL, HPL performance suffered while in steep turns, especially at low-

level conditions. The maximum error observed was significantly higher at 115 meters, but the HPL average (121 meters) expanded to encompass the high error value.

### DIFFERENCE BETWEEN ARAIM AND RAIM HORIZONTAL PROTECTION LEVEL

The difference in HPL between RAIM and ARAIM was measured and compared, with an expectation that ARAIM HPL would be lower than RAIM HPL. The mean ARAIM HPL across all tactical maneuvering test points was 67 meters, and the mean RAIM HPL was 160 meters, as shown in Figure 12 and 13, and Table E3. Steep turns were again, notably, the cause of degradation in both RAIM and ARAIM performance. However, ARAIM appeared to be able maintain a more usable HPL value. With more satellites available from other constellations, ARAIM was likely able to see enough satellites with more reliability, causing the strong split in steep turn performance. Additionally, in the steep turn FTT, RAIM failed to provide a protection level for 28 data samples, while ARAIM only failed for 1 sample. For low-level steep turns, RAIM failed to provide a protection level for 22 samples, while ARAIM was successful for all points. Overall, the ARAIM HPL provided a significant improvement over RAIM HPL for all tactical maneuvering test points, offering improved performance and more availability.

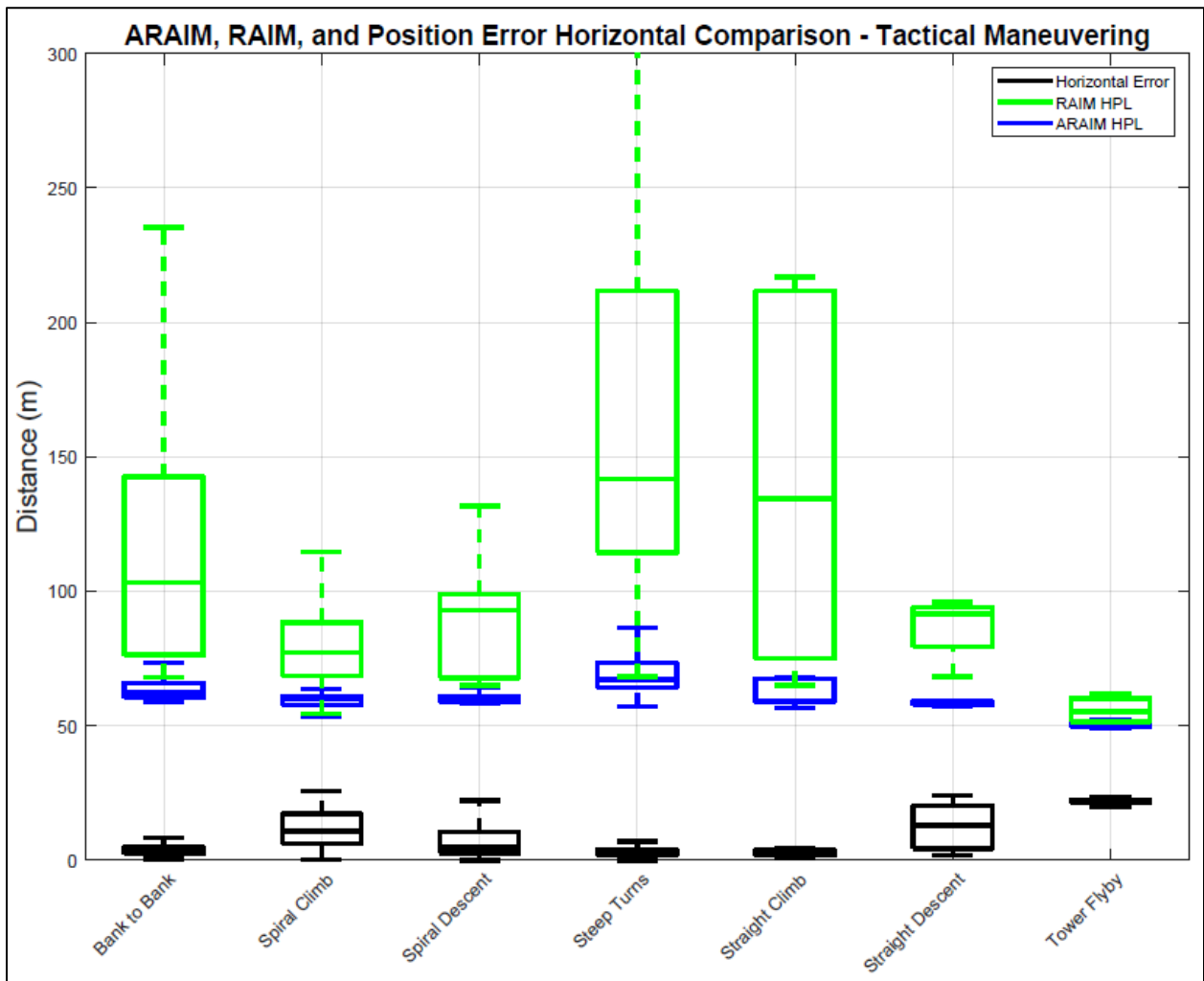


Figure 12. ARAIM, RAIM, and Position Error Horizontal Comparison – Tactical Maneuvering

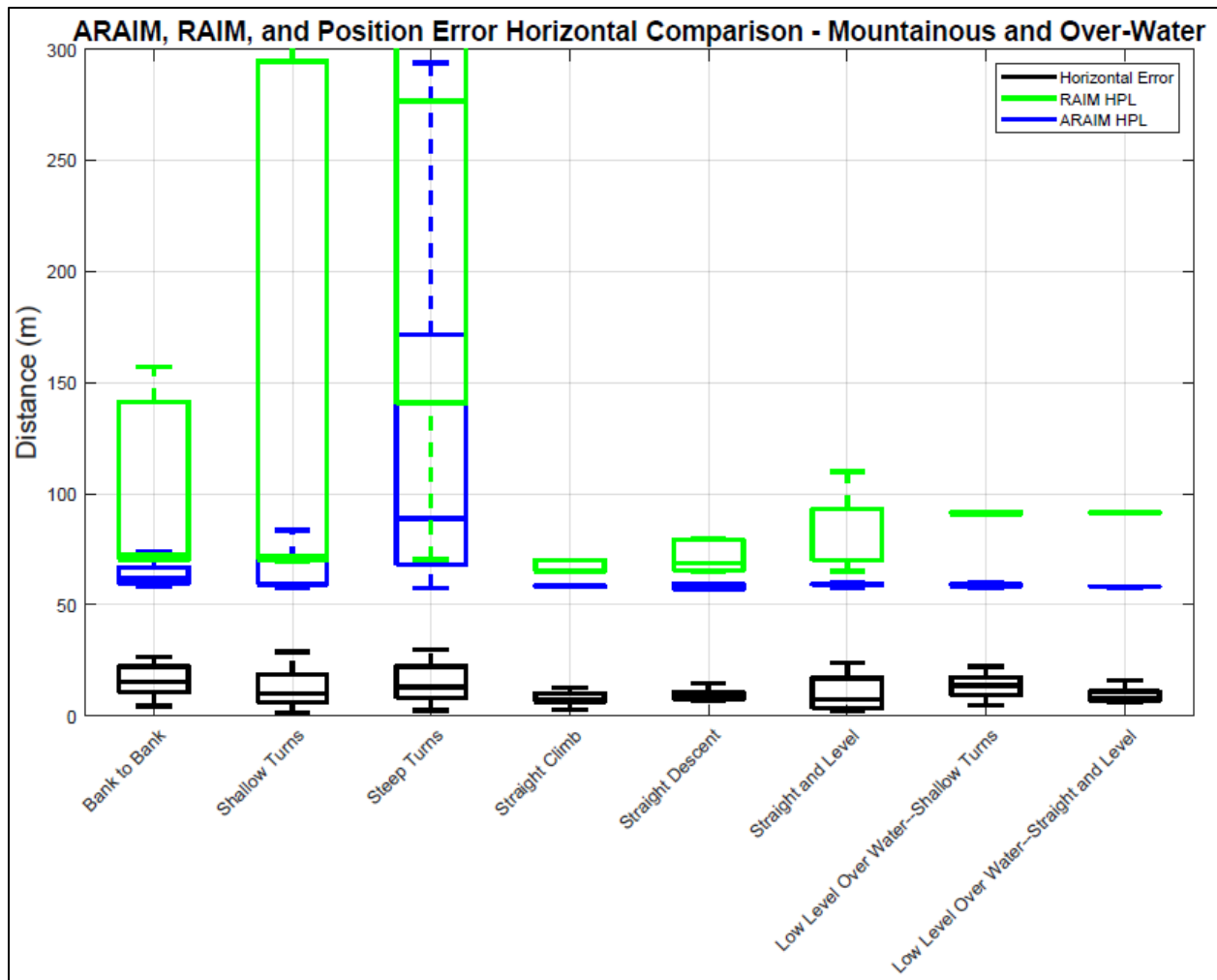


Figure 13. ARAIM, RAIM, and Position Error Horizontal Comparison – Mountainous and Over-Water

### ARAIM IN GPS JAMMED ENVIRONMENT

To expose the ARAIM system to GPS jamming, the test team participated in the exercise DT NAVFEST. During this event, jammers operated by the 746<sup>th</sup> FLTS flooded the Edwards test range with L1 and L2 jamming, as shown in Figure 14. The 746<sup>th</sup> FLTS controlled the jammer array pattern to attack the GPS L1 and L2 frequencies, while still leaving some GLONASS, Galileo, and Beidou frequencies exploitable. Figure 15 and 16 demonstrate the jammed frequency bands. Maximum open-air Carrier-to-Noise Ratios observed during the event climbed about 100 decibels. Of course, with a wide range of available jamming strengths and geometries, many data points were rendered unusable, even in the context of multi-constellation operations. Data presented in this section discounted unusable data points in which a navigation solution was not possible, but quantity of invalid data points is presented in Table 6.

### TEST METHODS AND CONDITIONS

Flights were conducted in night, GPS jammed environments in order to observe ARAIM performance in an environment germane to military operating environments, and both benign and tactical maneuvers were accomplished. FTTs were flown at different proximities to ground-based GPS jammers in order to experience two different levels of jamming designated as high (80dB open-air jamming-to-signal ratio) and

low (45dB open-air jamming-to-signal ratio). 8 ground-based portable box jammers (PBJ) with an effective radiated power (ERP) of 1.3 kW, and 6 high powered jammers (HPJ) with an ERP of 165 kW were utilized to provide jamming signals during flight test conduct. During the jamming events, the 14 GPS jamming systems combined their effects to overlay GPS jamming in a small geographic area, producing greater than 90 dB of open air jamming-to-signal ratio at 20,000 feet. The GPS jammers were active on both the GPS L1 and GPS L2 frequency, with no more than 25 MHz of bandwidth. Furthermore, jamming bandwidth was varied throughout all jamming events in order to meet requirements for multiple military users. Figure 14 reveals the GPS jamming laydown, and Figures 15 and 16 demonstrate the frequency spectrum with the largest range of jamming bandwidth, as well as the signals affected by the GPS jamming. Of note, the GLONASS L1 frequency was not jammed as part of the evaluation.

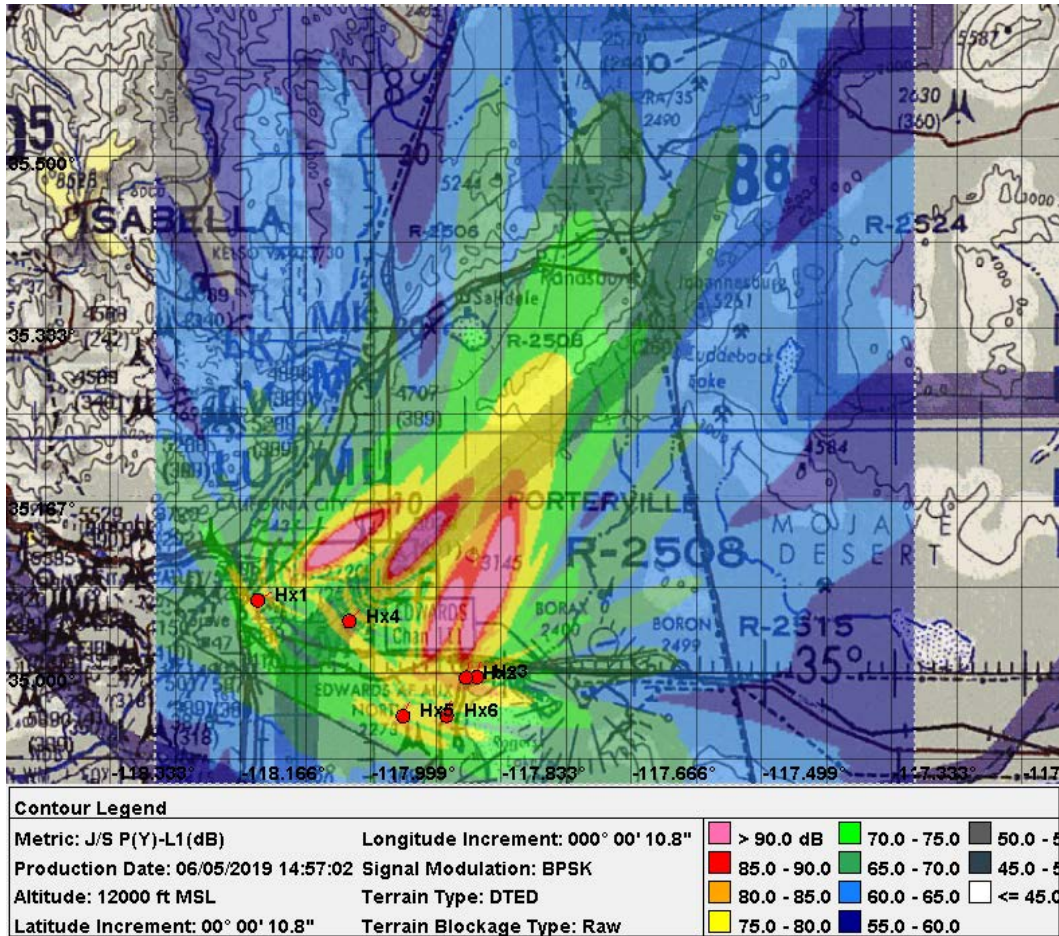


Figure 14. NAVFEST Jamming Projection at 12,000 feet Mean Sea Level

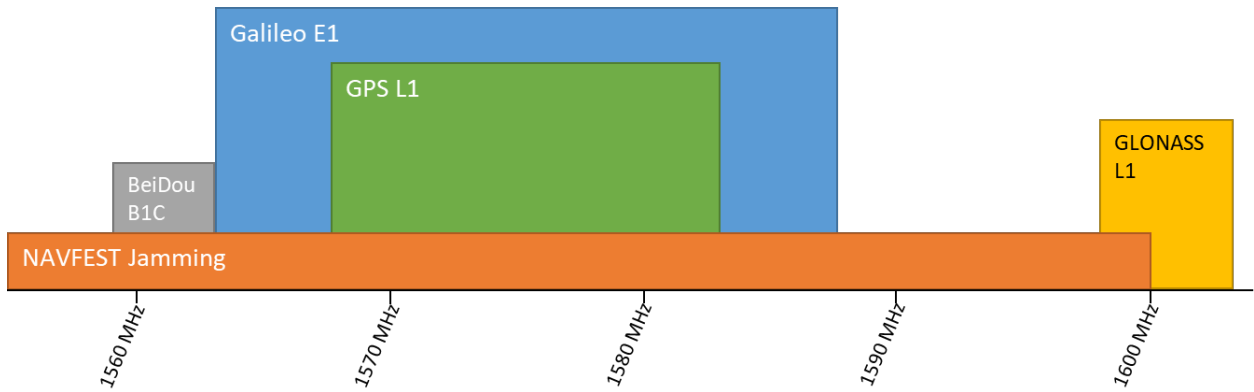


Figure 15. GNSS L1 Band and Intended Jamming Profile

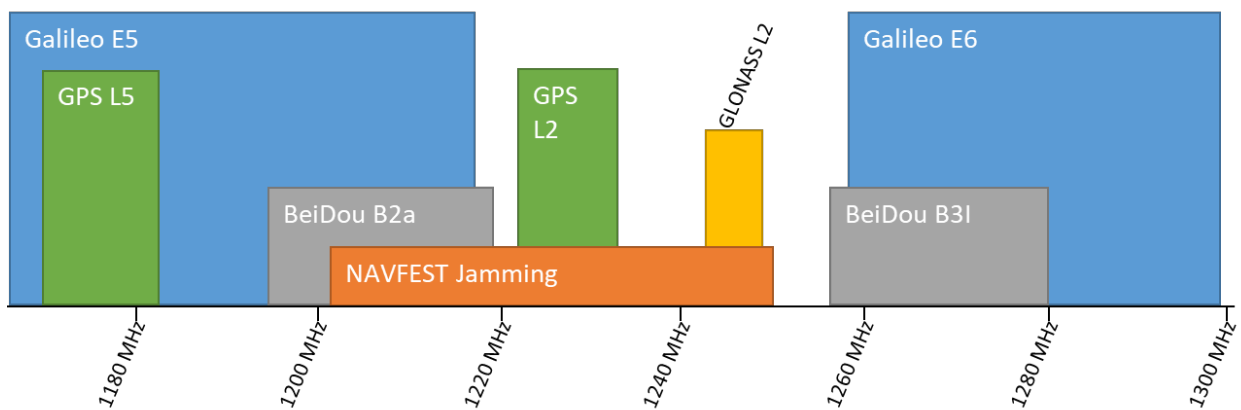


Figure 16. GNSS L2 Band and Intended Jamming Profile

The maneuvers that were accomplished in the GPS jammed environment included benign straight and level flight, shallow turns less than 30 degrees angle of bank, racetrack patterns, 500 ft/min climbs and descents, and spiraling 500 ft/min climbs and descents. Tactical maneuvers that were accomplished included steep left and right turns up to 60 degrees angle of bank, bank to bank rolls from 60 to 60 degrees angle of bank, 1,000 ft/min climbs and descents and spiraling 1,000 ft/min climbs and descents. Instrument approaches and landings were also accomplished in the GPS jammed environment. Both benign and tactical maneuvers accomplished in the GPS jammed environment were flown at a full range of altitudes and speeds ranging from surface to 24,500 feet MSL and Final Approach Speed (FAS) to 175 KIAS. The consolidated test point matrix in Appendix G, Table G5 describes the number of FTTs flown for all tactical maneuvering phases of flight, as well as how many independent data points were derived from the accomplishment of all tactical maneuvering FTTs for the ARAIM system. Table G1 outlines the specific methodology and techniques used to fly each FTT in the GPS jammed environment.

### ARAIM VERTICAL PROTECTION LEVEL ACCURACY

Throughout the entire range of GPS jamming maneuvers, including both benign and limited tactical maneuvering, error never exceeded the reported VPL value. The maximum error observed across maneuvers was 50 meters, while the minimum VPL produced was 72 meters, as presented in Table E4 and displayed in Figures 17 and 18. While ARAIM VPL was expected to always be conservative, ARAIM

produced very small errors that were well bounded by the VPL. The position error and VPL error were similar to those with no GPS jamming, with the VPL actually being lower than the minimum VPL without jamming. However, the truth source for this test, UHARS, also degraded during this test, with a certifiable accuracy of only 20 meters. Error values for all maneuvers often fell within the certification criteria, and thus could not be validated further.

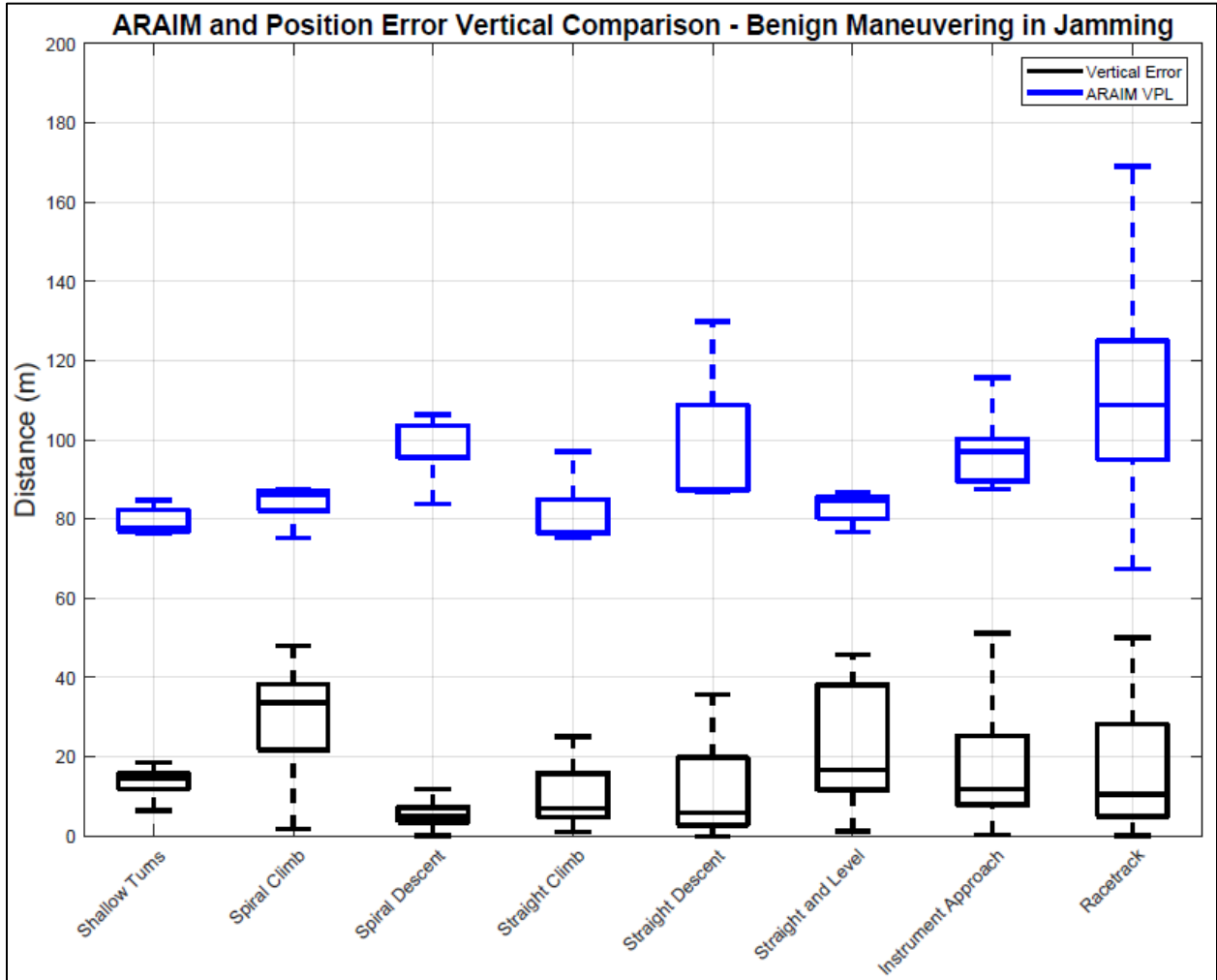


Figure 17. ARAIM and Position Error Vertical Comparison – Benign Maneuvering in Jamming

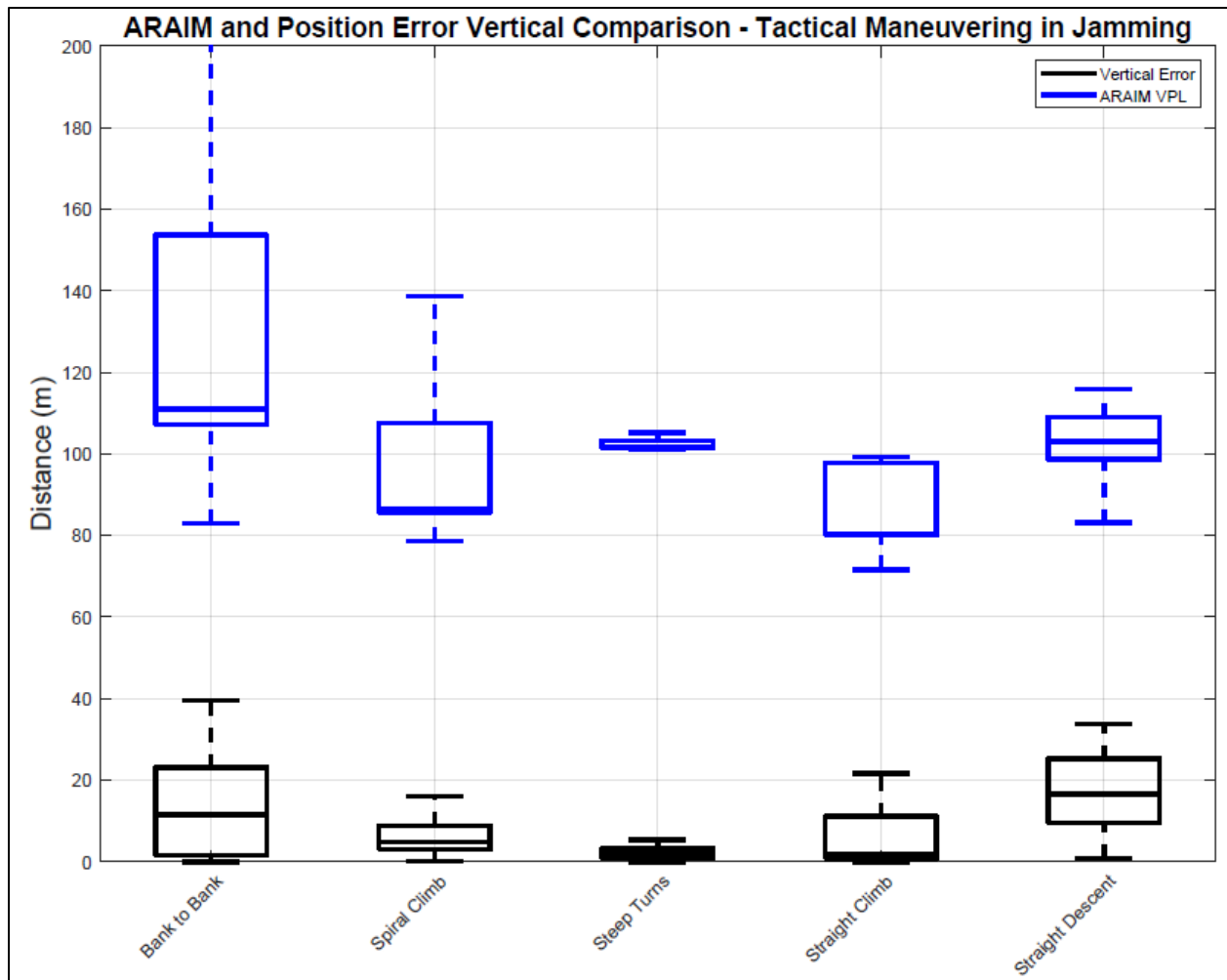


Figure 18. ARAIM and Position Error Vertical Comparison – Tactical Maneuvering in Jamming

### ARAIM HORIZONTAL PROTECTION LEVEL ACCURACY

For the GPS jammed environment profiles that were flown, all maneuvers and flight techniques exhibited error that was below the reported HPL and were bounded in all scenarios. These results are outlined in Table E5. Throughout the range of maneuvers, ARAIM error never exceeded or approached the reported ARAIM HPL values; the maximum error observed was 14.9 meters, while the minimum VPL produced was 54.2 meters. ARAIM again demonstrated small position errors that were well bounded by the conservative HPL values for all GPS jammed environment maneuver profiles. These results exhibit strong consistency of the ARAIM HPL values and their ability to bound error across the entire spectrum of maneuvers conducted in GPS jammed environments.

### DIFFERENCE BETWEEN ARAIM AND RAIM HORIZONTAL PROTECTION LEVEL

The difference in HPL between RAIM and ARAIM was measured and compared, with an expectation that ARAIM HPL would be lower than RAIM HPL. The mean ARAIM HPL across all GPS Jammed test points was 80 meters, and the mean RAIM HPL was 180 meters. Notable outliers existed in the Steep Turns, 60° Bank-to-Bank, and Racetrack test points where the respective mean RAIM HPLs (268.7, 435.0, & 549.2 meters) were significantly higher than the other maneuvers (see Figure 19 and 20). Individual

maneuvers with mean RAIM and ARAIM HPL are depicted in Table E6. ARAIM typically provided improved availability, as well, as RAIM would encounter successful jamming and fail to produce a protection level. In the spiral descent, straight descent, instrument approach, and in steep turns, ARAIM had much fewer losses of service over RAIM, providing more robust navigational solutions. Interestingly, in the straight climb and racetrack, RAIM reported protection levels when ARAIM did not. The straight climb had limited opportunity for execution, with only two straight climbs attempted in jamming. In the racetrack pattern, however, seven full racetracks were flown over two sorties, for 760 independent data points. RAIM reported significantly less outages, but RAIM also report a magnitude of 8 higher values for protection level. In the observed case of RAIM providing PLs when ARAIM was unable to, RAIM produced significantly degraded HPLs that were on the scale of thousands of feet large. With access to more constellations, ARAIM may have failed to provide protection level's in strong jamming conditions because known and observed error reduced confidence in the position solution. Overall, the ARAIM HPL provided a significant improvement over RAIM HPL when both provided solutions. When only ARAIM provided a solution, the error was still well bounded, and the HPLs were typically reasonable values. When only RAIM provided a solution, the HPLs were typically too large to be useful.

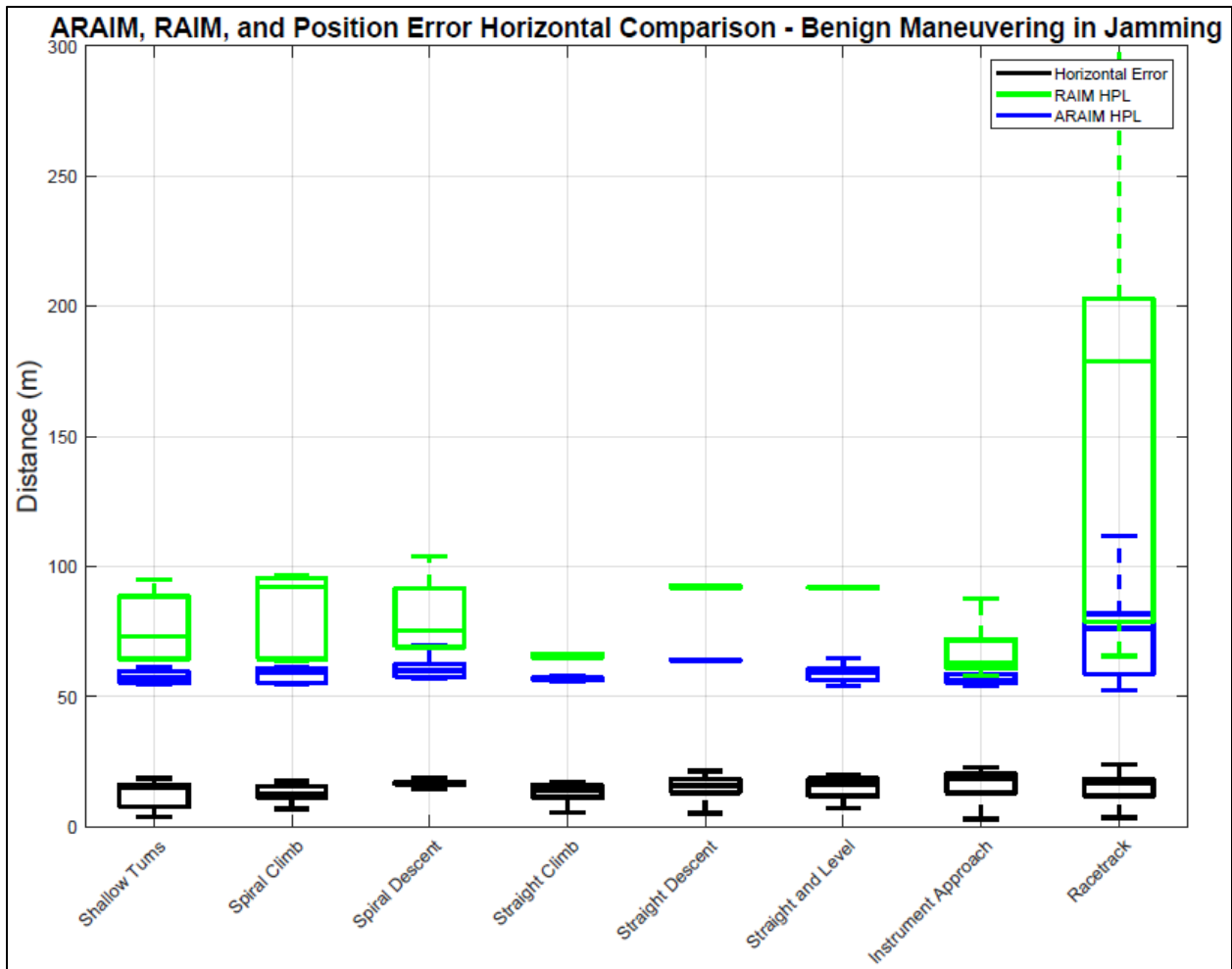


Figure 19. ARAIM, RAIM, and Position Error Horizontal Comparison – Benign Maneuvering in Jamming

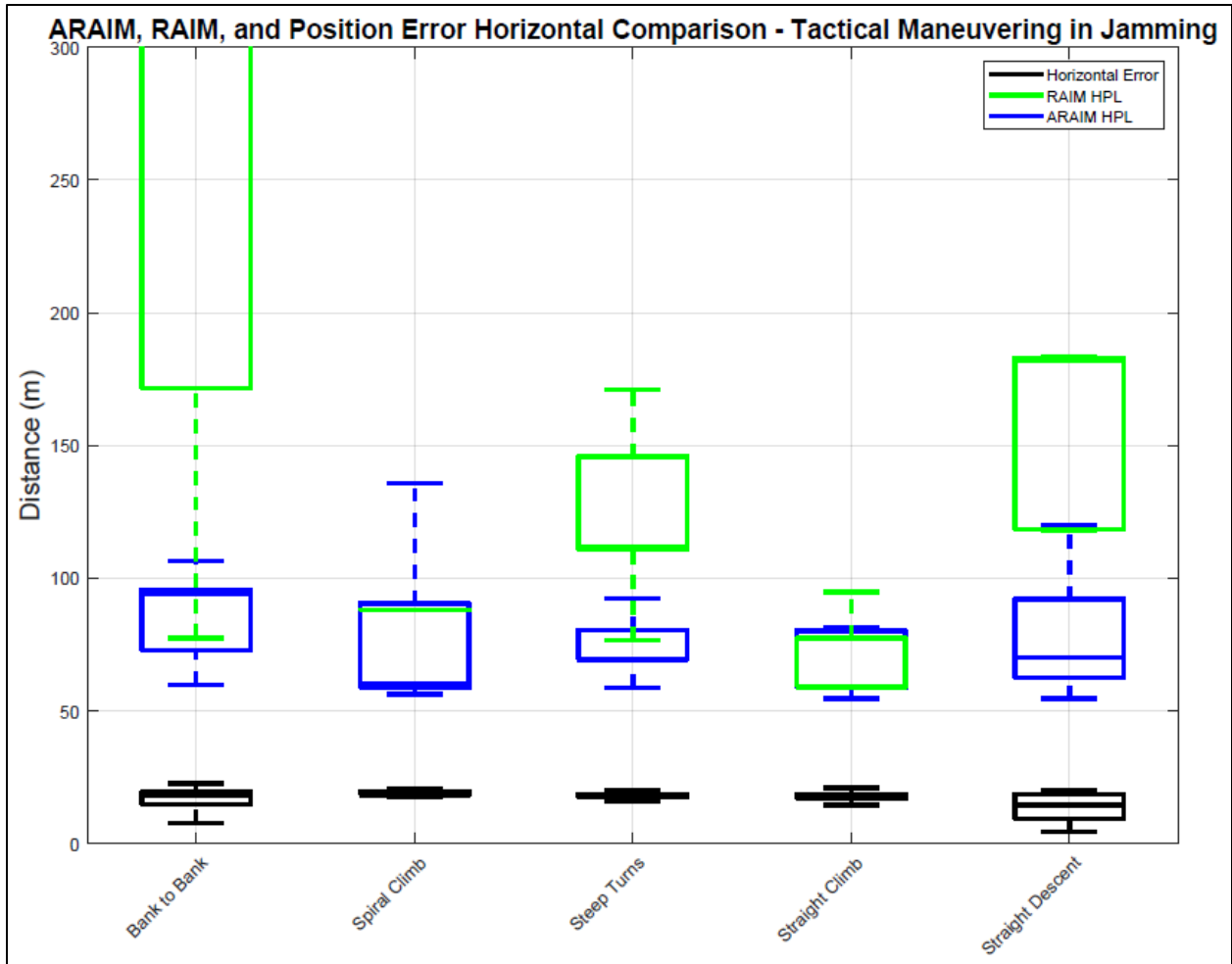


Figure 20. ARAIM, RAIM, and Position Error Horizontal Comparison – Tactical Maneuvering in Jamming

## DPA DIRECTION OF ARRIVAL ACCURACY

### TEST METHODS AND CONDITIONS

DPA data were collected in all phases of flight, operating environments, and maneuvering regimes encompassing the entirety of the test program. DPA data were collected in benign flight regimes including straight and level flight, shallow turns less than 30 degrees angle of bank, 500 ft/min climbs and descents, and spiraling 500 ft/min climbs and descents. DPA data were also collected in tactical flight regimes including steep left and right turns up to 60 degrees angle of bank, bank to bank rolls from 60 to 60 degrees angle of bank, 1,000 ft/min climbs and descents and spiraling 1,000 ft/min climbs and descents. Furthermore, these maneuvers were flown in a variety of geographic and topographical locations in order to encompass a broad spectrum of operating environments. The DPA system performance was observed through the execution of maneuvers in low level flat terrain, low level mountainous terrain, and low level overwater environments. Instrument approaches and landings down to the surface were also accomplished, along with all benign and tactical maneuvers in the night GPS jammed environment. Test points were accomplished at a broad range of altitudes and speeds ranging from surface to 21,500 feet MSL and Final Approach Speed (FAS) to 175 KIAS. Appendix G outlines the total number of FTTs flown in benign,

tactical, and GPS jammed flight phases, as well as the number of independent data points derived from each flown FTT in both the SDR and uBlox configurations.

### DPA AZIMUTH DIRECTION OF ARRIVAL ERROR

The azimuth DOA error was classified as any difference in the DPA determined-direction of arrival and the actual satellite position. Since the system was incapable of distinguishing between a correct DOA and a 180° offset solution, results below are only considered within the hemisphere centered on the target satellite. The DPA system demonstrated a tendency to track a target satellite, but had significant variance throughout each sortie. While observed error would occasionally be accurate, it could also diverge significantly. Figure 21 presents the entire compendium of data collected on all un-jammed sorties in a box-and-whiskers plot. The boxes contain the standard 25% and 75% quartiles, while the whiskers contain the 5<sup>th</sup> and 95<sup>th</sup> percentile. For all satellites, independent of elevation angle, the worst 25% of the DPA solutions were further than 55° from the target satellite, but the best 25% of the solutions were within 16°. Average error for low-, medium-, and high-elevation satellites all tended to 30°, with only a slight degradation for high-elevation satellites. Strong correlation between satellite elevation angle and error was predicted, but not observed, when separated in 30° bins. Figure 22 expands the observed error into 10° elevation increments. DPA performed consistently (approximately 30° of error) for all satellite elevation angles less than 80°. DPA only degraded at extremely high angles, and barely out-performed a random data set. That is, a random guess for satellite azimuth was only slightly worse than DPA performance at greater than 80° elevation angle.

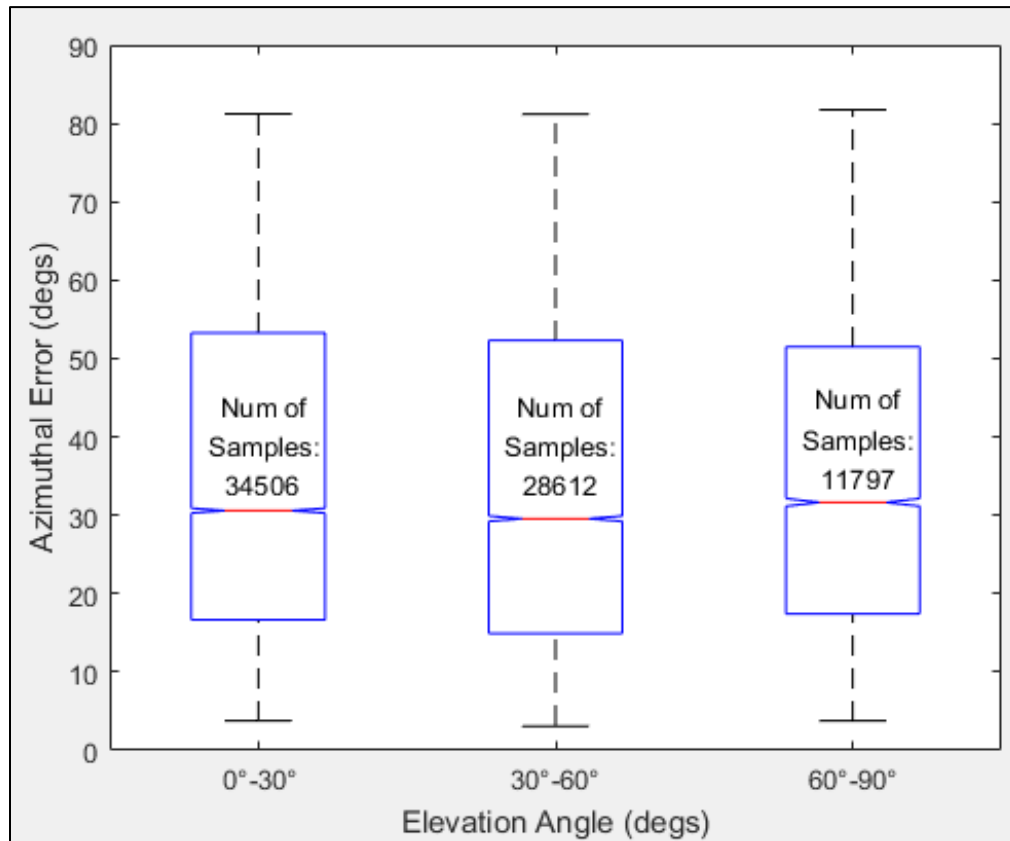


Figure 21. DPA DOA Azimuthal Error (Uncontested GPS Environment, 30° Increments)

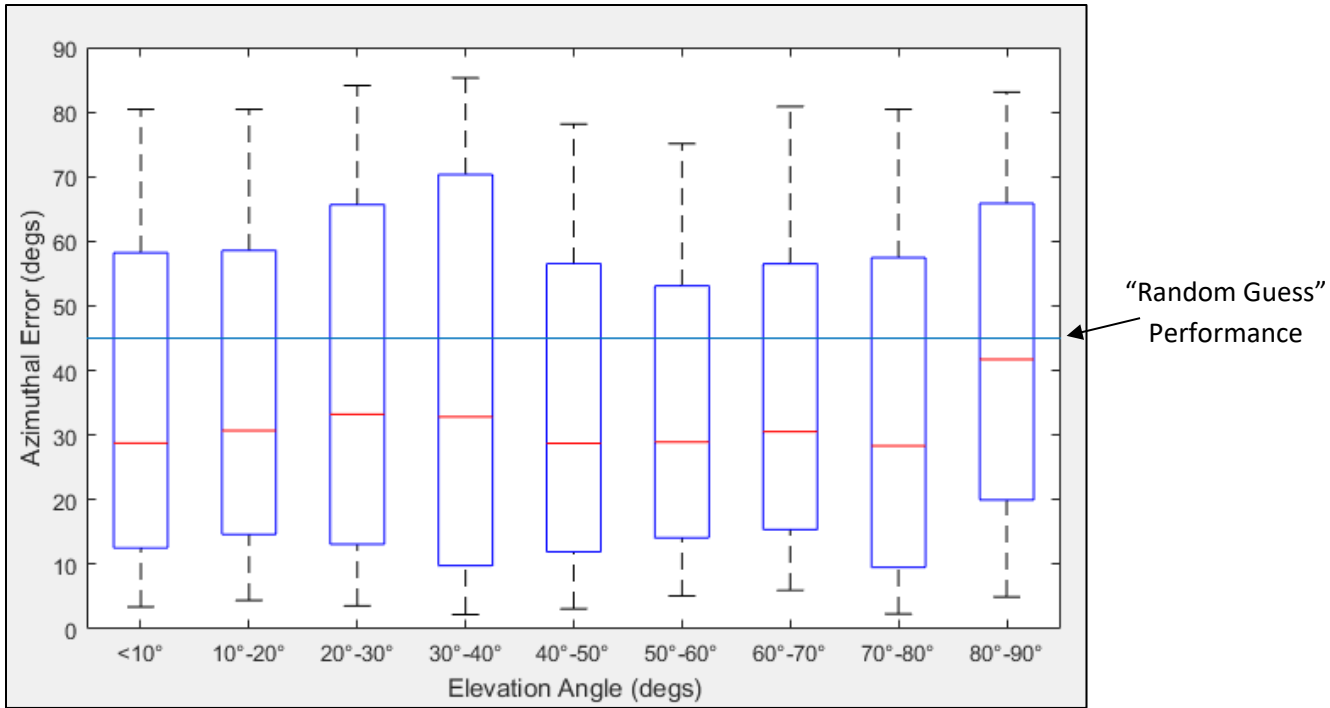


Figure 22. DPA DOA Azimuthal Error (Uncontested GPS Environment, 10° Increments)

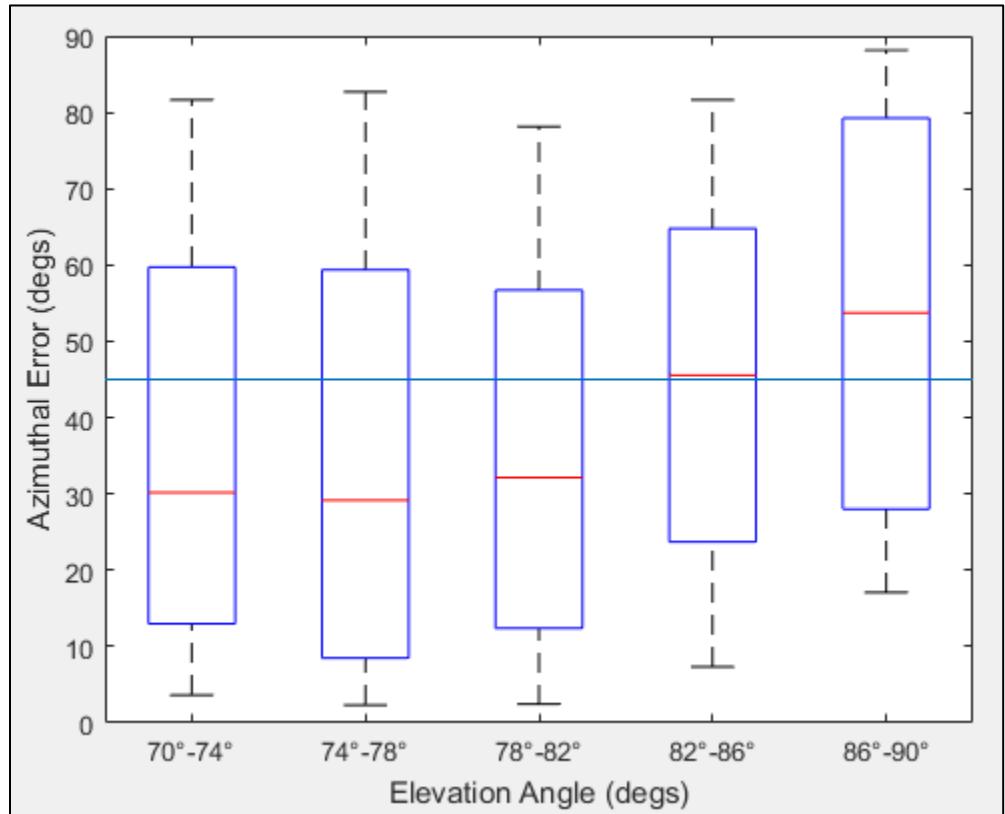


Figure 23. DPA DOA Azimuthal Error, High-Elevation Satellites (Uncontested, 4° Increments)

Figure 23 provides a narrower observation of the error observed for high-elevation satellites. Data review revealed that any elevations above  $82^\circ$  result in a sharp degradation in azimuthal accuracy. Below  $82^\circ$  satellite elevation, DPA produced consistent results, with a mean performance of  $30^\circ$  error. Also worth noting, DPA performed worse than a random guess for satellites above  $86^\circ$ . The graph implies that any satellites in the zenith cone of the antenna will experience significant azimuth error.

Figure 24 demonstrates the characteristic performance identified above in Figures 21 and 22. DPA tracking satellite PRN 28 on the seventh test flight is depicted. Throughout the entirety of the mission, the DPA system was able to generally track the satellite location, but produced large variance in its tracking accuracy. Despite some outliers at the beginning and end of the sortie, the error rate centers around  $30^\circ$  for the entirety of the sortie. PRN28 satellite elevation angle does climb throughout the sortie, but does not appear to increase the observed error. To assess the influence of FTT's on DPA performance, Figure 25 organizes the observed error for five different tracked satellites throughout the entirety of the seventh test flight. Direct comparison of each satellite at the same time provided implications about error dependence upon particular maneuvering. Error trends similarly across all five tracks, such as at the 3000 second mark when error climbed dramatically. However, many of the oscillations occur at times that are unexpected. For example, the steep climb in error at 4500 seconds was coincident with a period of straight-and-level flight. The aircraft is as stable as it could have been. Conversely, around 2000 seconds, DPA satellite tracking experiences a relative improvement, while the test team was accomplishing an aggressive spiral climb. Error is likely more about the environmental conditions, than about particular aircraft maneuvering.

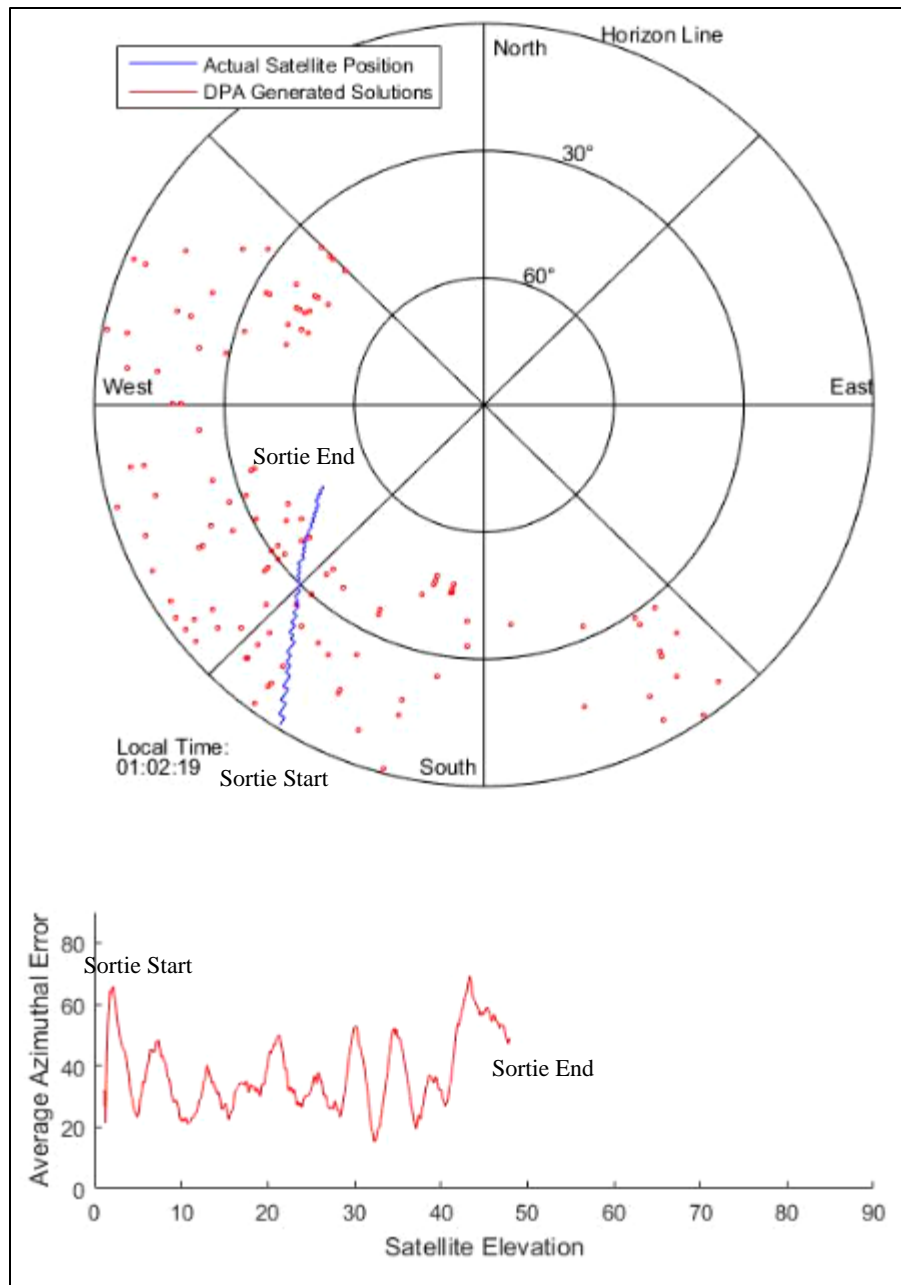


Figure 24. DPA Performance in Tracking PRN 28 on Flight 7, 17 and 18 September 2019

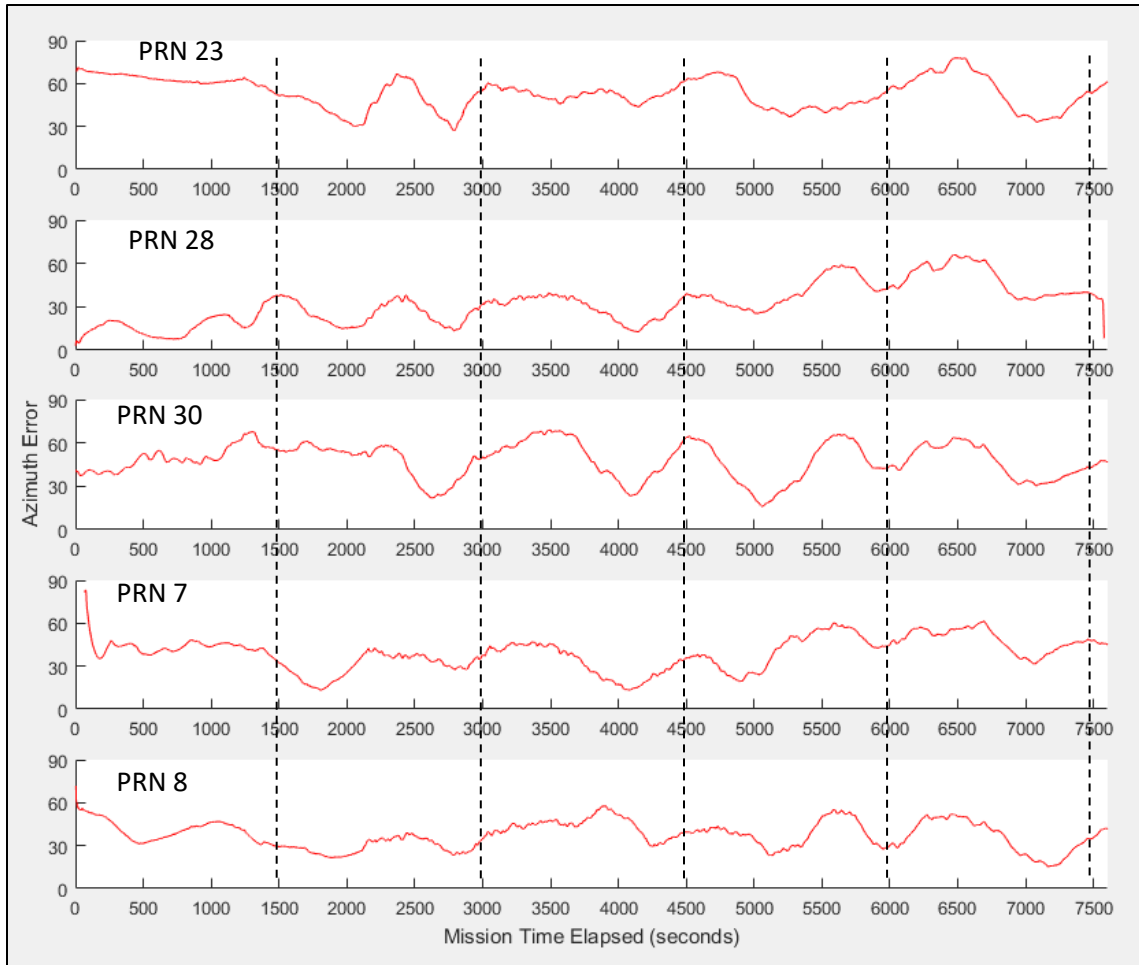


Figure 25. DPA Performance on Flight 7, 17 and 18 September 2019

Finally, DPA performance in a contested environment is presented below in Figure 26. During sortie execution, the DPA processing equipment reported significant degradation on the system. Interestingly, the results were much more promising. DPA was still able to achieve an average error of 30° throughout the entire sortie. One contribution to the DPA effectiveness during GPS jamming was the antenna configuration. The DPA antenna that was top-mounted had little problem tracking satellites, while the lower antenna was unreliable. Figure 27 compares the top-mounted antenna (left side) with the bottom-mounted antenna (right side). The top antenna demonstrated normal DPA tracking throughout the sortie, oscillating around 30°. Note that the satellite initially climbed in elevation, but then began to descend. The bottom-mounted antenna experienced significantly more error, and averaged 45° error throughout the jamming portion of the flight.

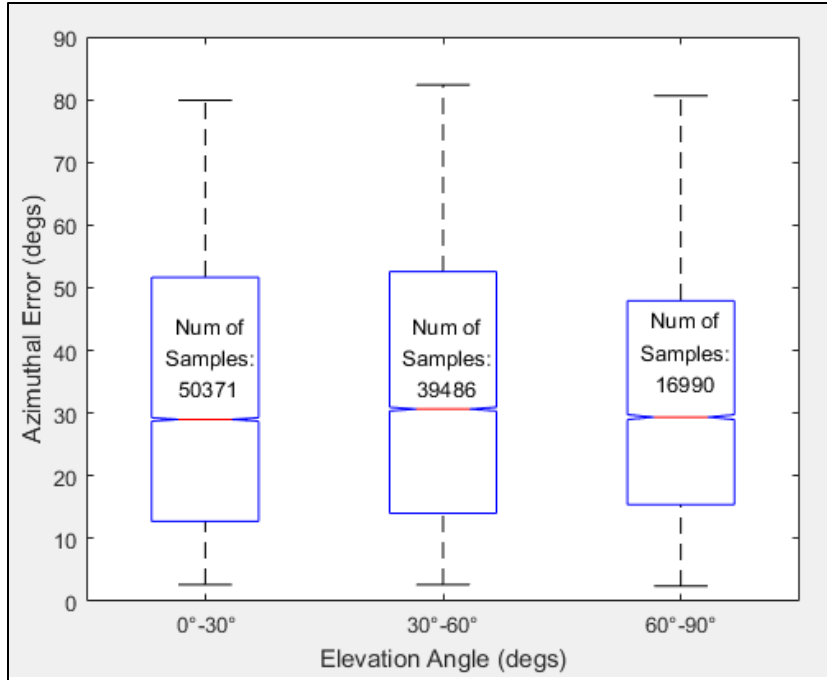


Figure 26. DPA DOA Azimuthal Error (Contested GPS Environment, 30° Increments)

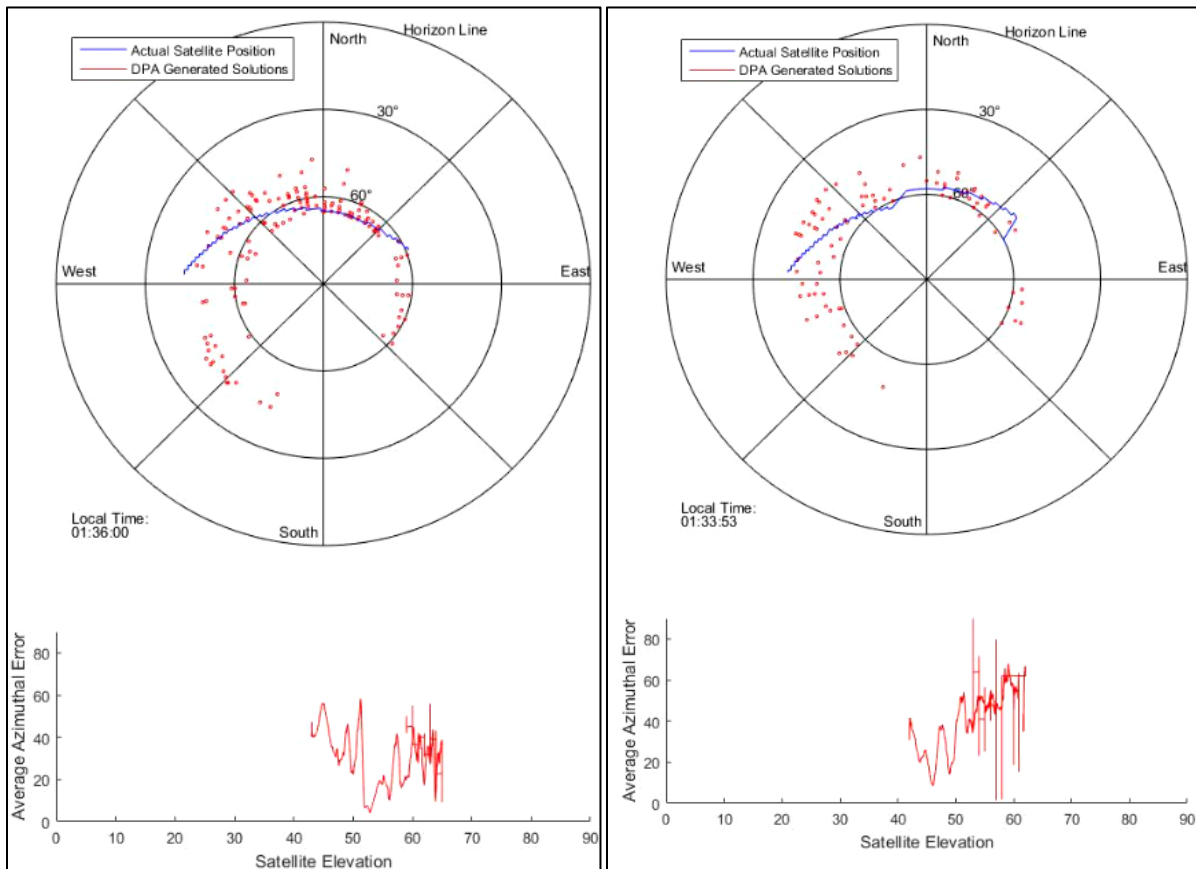


Figure 27. DPA Error, GPS Contested (Left: Top-Mounted DPA, Right: Bottom-Mounted DPA)

DPA performed better than expected. DPA was able to consistently track and report satellite azimuth, with an average of 30° error across virtually all flight regimes, including in tactical maneuvering and in high-powered GPS jamming. The lone exception was for elevation angles above 82°, upon which the system accuracy would degrade.

## TEST RESULTS SUMMARY

Overall, ARAIM performed very well. ARAIM provided sufficient protection to bound the error from exceeding protection values for all test points, and correctly indicated poorer protection levels in flight regimes that seemed likely to endanger GNSS accuracy, such as aggressive maneuvering, low level operations, and in jamming. ARAIM protection levels improved significantly over RAIM and showed increased consistency. ARAIM would often produce a navigation solution and associated protection level when RAIM did not have enough satellites to calculate an HPL. However, RAIM occasionally provided a navigation solution when ARAIM was unable to, but invariably had large and unusable protection level values when it did. In steep turns PL values would climb for both RAIM and ARAIM. GPS jamming produced similar results, with effective jamming causing significant degradation in protection levels, but error values remained small.

Table 6 summarizes the RAIM and ARAIM drop-out conditions. Table 7 presents ARAIM test results. Between maneuvering execution and successful data collection, all test objectives were evaluated successfully. Additionally, ARAIM performed satisfactorily, and DPA may demonstrate future utility for low-elevation satellites.

Table 6. RAIM and ARAIM Data Point Drop-Outs

Maneuver	RAIM Drop-Outs	ARAIM Drop-Outs
Low Level: Steep Turns	28	1
Limited Tactical: Steep Turns	22	0
GPS Jamming: Spiral Descent	38	20
GPS Jamming: Straight Descent	53	39
GPS Jamming: Instrument Approach	77	34
GPS Jamming: Racetrack	236	307
GPS Jamming: Bank-to-Bank	4	0
GPS Jamming: Steep Turns	2	8
GPS Jamming: Straight Climb	20	105

Table 7. ARAIM Test Results

Title	Descriptor	Ratings
<b>Overall Have DRAGON Test Results</b>		
ARAIM in Benign Maneuvering		Satisfactory
ARAIM Vertical Protection Level Accuracy	Good	
ARAIM Horizontal Protection Level Accuracy	Good	
Difference Between ARAIM and RAIM Horizontal Protection Level	Good	
ARAIM in Limited Tactical Maneuvering		Satisfactory
ARAIM Vertical Protection Level Accuracy	Good	
ARAIM Horizontal Protection Level Accuracy	Good	
Difference Between ARAIM and RAIM Horizontal Protection Level	Good	
ARAIM in GPS Jammed Environment		Satisfactory
ARAIM Vertical Protection Level Accuracy	Good	
ARAIM Horizontal Protection Level Accuracy	Good	
Difference Between ARAIM and RAIM Horizontal Protection Level	Good	

DPA performed well. Unexpectedly, error did not appear to trend with elevation angle, and the system was able to determine the DOA with an average error of 30° in azimuth. DPA began to fail at predicting DOA when the satellite was within 8° of the vertical. Large variances were not necessarily a function of the FTTs performed, but likely were more dependent on the specific geometry and environment of the test aircraft. Despite real-time indications otherwise, the DPA was able to track satellites in GPS jamming with very little degradation off the top antenna. The lower antenna was saturated quickly, and saw much higher error rates.



This page was intentionally left blank.

## REFERENCES

1. British Broadcasting Company. (2019, June 27). *Russia Denies Role in Israeli Airport GPS Jamming*. Retrieved from <https://www.bbc.com/news/technology-48787085>
2. Bellamy, W. (2017, January 31). *Are GPS Jamming Incidents a Growing Problem for Aviation?* Retrieved from aviationtoday.com: <https://www.aviationtoday.com/2017/01/31/are-gps-jamming-incidents-a-growing-problem-for-aviation/>
3. Inside GNSS. (2019, July 13). *Galileo Service Degraded on All Satellites Until Further Notice*. Retrieved from insidegnss.com: <https://insidegnss.com/update-galileo-service-degraded-on-all-satellites-precise-timing-facility-problems-cited/>
4. Lo, Sherman. Chen, Yu Hsuan. Jain, Hridayangam. Enge, Per. Stanford University. *Robust GNSS Spoof Detection using Direction of Arrival: Methods and Practice*. ONGNSS. June 2018.
5. Chen, Yu Hsuan. Lo, Sherman. Perkins, Adrien. Rothmaier, Fabian. Stanford University. Akos, Dennis. University of Colorado at Boulder. Enge, Per. Stanford University. *Demonstrating Single Element Null Steering Antenna Direction Finding for Interference Detection*. IONITM. January 2018.
6. Struck, Corey. Lee, Chiawei. Mitchell, Rebecca. Hughes, Brett. Knauss, James. Weed, Ryan. Zartman, Anthony. United States Air Force Test Pilot School. *Ultra High Accuracy Reference System Position Data Acquisition Without GPS*. October 2018.
7. Phelts, R. Eric. Blanch, Juan. Chen, Yu-Hsuan. Enge, Per. Stanford University. Riley, Stuart. Trimble Navigation Limited. *ARAIM in Flight Using GPS and GLONASS: Initial Results from a Real-Time Implementation*. IONGNSS. April 2016.
8. Chen, Yu-Hsuan. Rothmaier, Fabian. Stanford University. Akos, Dennis. University of Colorado at Boulder. Lo, Sherman. Enge, Per. Stanford University. *Towards a Practical Single Element Null Steering Antenna*. IONITM. January 2017.
9. Williams, George P. *DT NAVFEST 2017 Test Support Plan (TSP)*. July 2017.
10. 746<sup>th</sup> Test Squadron, *Central Inertial and Global Positioning System (GPS) Test Facility (CIGTF) Ultra-High Accuracy Reference System (UHARS) Increment-0 (Inc-0) Positioning Compendium Report*. Test Report, 704<sup>th</sup> Test Group, Holloman AFB NM, June 2018
11. *Navigation Programs Strategy (Version 1.0)*. Federal Aviation Administration, Washington, D.C. 20591, January 2018.

This page was intentionally left blank

# APPENDIX A – DETAILED TEST ITEM DESCRIPTION

## DUAL POLARIZED ANTENNA

The DPA used for testing measured 7.62 cm x 7.62 cm to conform to the maximum size of the C-12J antenna ports shown in Figure 5. Furthermore, antenna size was limited to fit in a form factor housing equivalent to a standard aircraft antenna. Aeronautical Radio, Incorporated (ARINC) Standard 743 suggested the largest size of a form-factor aviation antenna was 11.938 cm x 7.62 cm x 1.854 cm.

Figure A1 outlines the architecture and major components of the DPA. The antenna design utilized two individual PCBs. The top PCB included the dual feed patch antenna located on the top layer coincident with a largely metal top layer to create a completed ground plane. The second layer housed the hybrid coupler components. The dual feed patch antenna detected signals in both the x and y axes while the hybrid coupler served to transform the x and y signal components into LHCP and RHCP signals. The second PCB consisted of a four layer architecture. Notably, the second layer hosted the power supply and the third provided a ground for the transmission lines. All other components were placed on the fourth layer. The low noise amplifiers (LNA) utilized 20 dB gain to increase the power of the received signal. All radio frequency (RF) components were connected via 50 ohm transmission lines. Notably, the transmission line length for both feeds into the antenna were identical to ensure equal electrical phase delay between both signals.

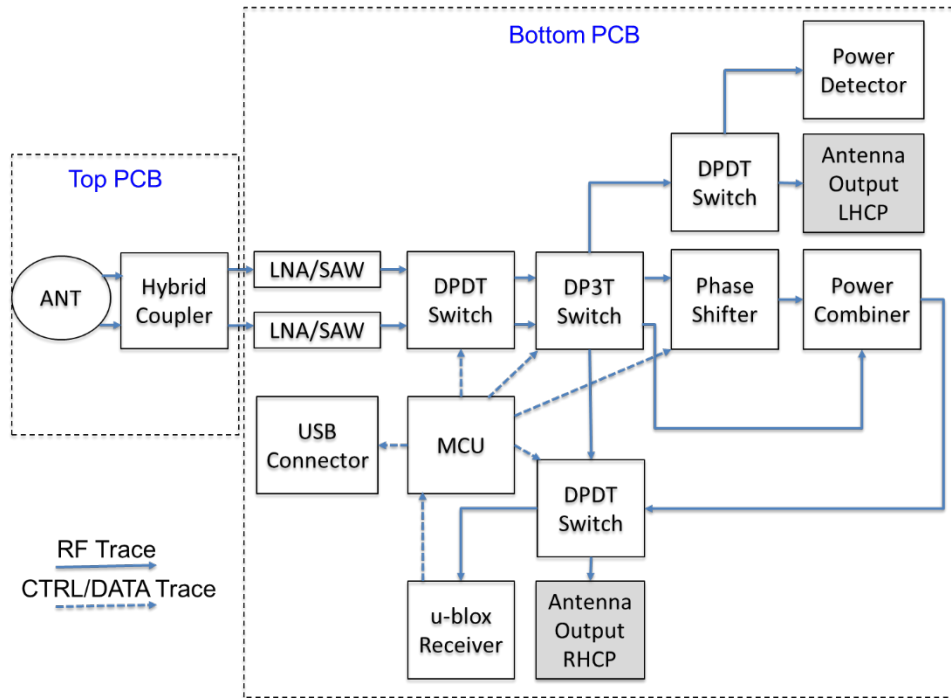


Figure A1. Major Components of the DPA

The primary purpose of the DPA was to provide azimuth DOA of the received signal. The DOA was determined by the phase shift between the RHCP and LHCP signals. The phase shifter discussed in Figure A1 rotates the RHCP signal through all phase shifts,  $\Psi$ . A combined signal was then generated using the equation below.

$$\textit{combined signal } (\Psi) = \textit{LHCP} - \textit{phase shifted } (\Psi)\textit{RHCP}$$

The phase shift angle required for best cancellation or minimum satellite C/No dictated the DOA of the incoming signal. All DOA determinations were made via post-processing versus real-time data. Notably, the DOA was aligned relative to the orientation of the antenna and was therefore heading dependent. The derived DOA was compared to time aligned truth data containing ephemeris satellite position data. The truth data permitted determination of true heading in addition to satellite azimuth and elevation from the antenna to calculate DPA errors with regards to these parameters. Full data analysis details are contained in Appendix C – Data Analysis.

## APPENDIX B – RATING CRITERIA

Table B1. 412<sup>th</sup> 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 C – DATA ANALYSIS

### ARAIM DATA ANALYSIS

Data analysis consisted of three comparisons depicted in Figure C1. Two of the assessments compared the ARAIM vertical and horizontal protection levels with the position error calculated using UHARS as the “truth” source. Additionally, a comparison between ARAIM and RAIM HPLs was investigated to identify any improvements gained using the new algorithm. Data for ARAIM analysis was provided via a Trimble GPS receiver and the 586 FLTS UHARS systems. Using the Trimble data, the ARAIM algorithm provided aircraft time, position solution, VPL, and HPL. The UHARS GPS receiver recorded actual aircraft position which was time-aligned to the ARAIM data file during analysis. For the ARAIM to RAIM comparison, the non-NAVSTAR GPS GNSS satellites were removed from Trimble-generated data file prior to processing using the RAIM algorithm. The RAIM algorithm used US-only satellites and computed PLs in the horizontal plane only. The HPL of the RAIM file were compared to those generated by ARAIM to determine capability differences between the two algorithms.

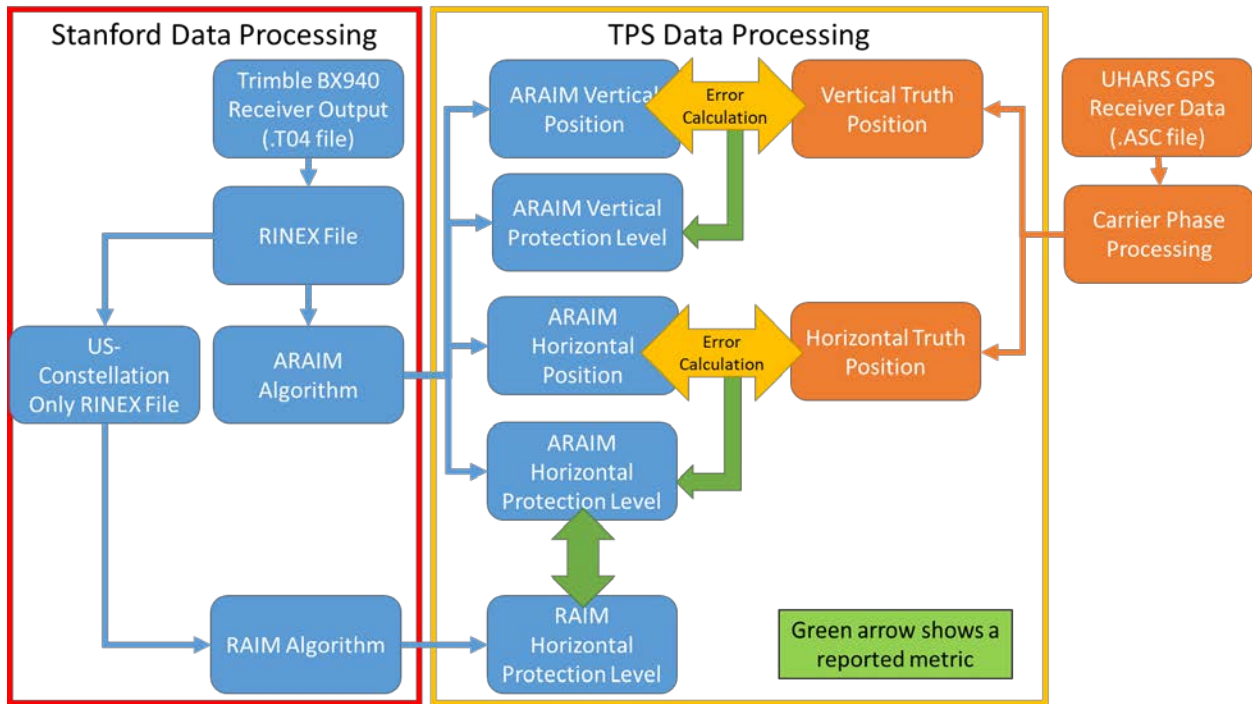


Figure C1. ARAIM Processing Flow Chart

### ARAIM FILE PROCESSING

During flight testing, the Trimble BX940 GPS receiver generated a .T04 file. Due to a proprietary Trimble software, the .T04 file was sent to Stanford for conversion to a RINEX file for analysis using the ARAIM algorithm. Using the Trimble file, Stanford provided a *2019-09-XX\_combined.T04* and *2019-09-XX\_combined\_Obs.mat* files for each sortie where XX was the date of the flight. To prepare the ARAIM algorithm for processing, a folder titled *run\_all\_ARAIM\_slo\_v2a\_preprocessed* was copied to a directory created for each sortie. This folder contained subfolders including *Obs\_matFiles*, *Obs\_TrimbleTxtFiles*, *processedT04*, and *T04Files* in addition to MatLab scripts for operation. After deleting all content in the subfolders (leave *view.dat* in *processedT04*), the aforementioned Stanford-generated files were copied to

folders titled *Obs.TrimbleTxtFiles/T04Files* and *Obs.matFiles*, respectively. Once all files were arranged, using *run\_all\_ARAIM\_slo.m* script initiated the ARAIM processing.

## ARAIM PARAMETER OUTPUTS AND SEGMENTATION

The ARAIM processed data file provided time, latitude ( $\varphi_1$ ), longitude ( $\lambda_1$ ), altitude (as a height above ellipsoid in meters) ( $h_1$ ), VPL, and HPL. Once processed, the ARAIM file was segmented FTT based on the specific FTT start and stop times recorded during the flight. For the truth source, the UHARS carrier phase processed data file provided time, latitude ( $\varphi_2$ ), longitude ( $\lambda_2$ ), altitude ( $h_2$ ). UHARS and ARAIM provided position solutions based on identical time scales, allowing for direct point-to-point comparison. The UHARS file was segmented based on the same intervals as the ARAIM file.

## INDEPENDENT POINT CALCULATION

A serial correlation (auto-correlation) algorithm was applied to the ARAIM data file to ensure data point independence. During the assessment, if the data set was found to exhibit serial correlation, the data set was decimated until correlation less than 20% was achieved. The described process was accomplished using the MatLab autocorr() and decimate() functions, respectively. If decimation does not yield multiple independent data points within an FTT interval, the FTT will be counted as a single data point.

## VERTICAL AND HORIZONTAL ERROR LEVEL CALCULATION

For each FTT-segment utilizing the ARAIM measured latitude ( $\varphi_{ARAIM}$ ), longitude ( $\lambda_{ARAIM}$ ), altitude ( $h_{ARAIM}$ ), the aircraft position was converted into Cartesian coordinates for comparison with the following formulas:

$$u_{ARAIM} = (N_{ARAIM} + h_{ARAIM}) \cos(\varphi_{ARAIM}) \cos(\lambda_{ARAIM})$$

$$v_{ARAIM} = (N_{ARAIM} + h_{ARAIM}) \cos(\varphi_{ARAIM}) \sin(\lambda_{ARAIM})$$

$$w_{ARAIM} = (N_{ARAIM}(1 - e^2) + h_{ARAIM}) \cos(\varphi_{ARAIM})$$

where  $a$ ,  $e^2$ , and  $N_{ARAIM}$  were ellipsoid Earth model parameters defined as,

$$a = 20925646.32546 \text{ ft}$$

$$e^2 = 0.0066943799$$

$$N_{ARAIM} = \frac{a}{\sqrt{1 - e^2 \sin^2(\varphi_{ARAIM})}}$$

Utilizing the UHARS measured latitude ( $\varphi_{UHARS}$ ), longitude ( $\lambda_{UHARS}$ ), and altitude ( $h_{UHARS}$ ), the aircraft position was converted into Cartesian coordinates for comparison with the following formulas:

$$u_{UHARS} = (N_{UHARS} + h_{UHARS}) \cos(\varphi_{UHARS}) \cos(\lambda_{UHARS})$$

$$v_{UHARS} = (N_{UHARS} + h_{UHARS}) \cos(\varphi_{UHARS}) \sin(\lambda_{UHARS})$$

$$w_{UHARS} = (N_{UHARS}(1 - e^2) + h_{UHARS}) \cos(\varphi_{UHARS})$$

where  $a$ ,  $e^2$ , and  $N_{UHARS}$  were ellipsoid Earth model parameters defined as,

$$a = 20925646.32546 \text{ ft}$$

$$e^2 = 0.0066943799$$

$$N_{UHARS} = \frac{a}{\sqrt{1 - e^2 \sin^2(\varphi_{UHARS})}}$$

Because ARAIM and UHARS utilized the same antenna, no lever-arm correction was required. The Cartesian error vectors were calculated using the following equations.

$$\Delta u = u_{f\_ARAIM} - u_{UHARS}$$

$$\Delta v = v_{f\_ARAIM} - v_{UHARS}$$

$$\Delta w = w_{f\_ARAIM} - w_{UHARS}$$

The Cartesian error was converted into a north ( $n_{error}$ ), east ( $e_{error}$ ), and height ( $h_{error}$ ) errors at the UHARS latitude ( $\varphi_{UHARS}$ ), longitude ( $\lambda_{UHARS}$ ) via the following formulas.

$$n_{error} = -\sin(\varphi_{UHARS}) \cos(\lambda_{UHARS}) \Delta u - \sin(\varphi_{UHARS}) \sin(\lambda_{UHARS}) \Delta v + \cos(\varphi_{UHARS}) \Delta w$$

$$e_{error} = -\sin(\lambda_{UHARS}) \Delta u + \cos(\lambda_{UHARS}) \Delta v$$

$$h_{error} = \cos(\varphi_{UHARS}) \cos(\lambda_{UHARS}) \Delta u + \cos(\varphi_{UHARS}) \sin(\lambda_{UHARS}) \Delta v + \sin(\varphi_{UHARS}) \Delta w$$

Finally, the radial error was calculated.

$$r_{error} = \sqrt{(n_{error})^2 + (e_{error})^2}$$

The radial error,  $r_{error}$ , and the ARAIM HPL will be averaged independently over the same FTT time samples. The average radial error will be output into a table of FTT, PL, and data confidence level. Likewise, the height error,  $h_{error}$ , and the ARAIM VPL will be averaged independently over the same FTT time sample. The average height error will be demonstrated to be below the average ARAIM vertical protection for the specific FTT and output into a table of FTT, PL, and data confidence level. An example of a FTT output table is figured below.

Table C1. Example FTT Output Table

Test Point Number	FTT Description		Vertical Protection Level	Range of Observed Error	Max Observed Error
			(m)	(m)	(m)
1	Takeoff	Surface - 400 ft AGL			
2	Departure	400 ft AGL - 5,000 ft MSL			
3	Straight and Level Flight, Shallow Turns <30° AOB	5,000 ft MSL / 4,000 - 6,000 ft			
4	Straight and Level Flight, Shallow Turns <30° AOB	10,000 ft MSL / 9,000 - 11,000 ft			
5	Straight and Level Flight, Shallow Turns <30° AOB	15,000 ft MSL / 14,000 - 16,000 ft			
6	Straight and Level Flight, Shallow Turns <30° AOB	20,000 ft MSL / 19,000 - 21,000 ft			
7	500 ft/min Rate of Climb Check	5,000 ft MSL - 20,000 ft MSL			
8	500 ft/min Rate of Descent Check	20,000 ft MSL - 5,000 ft MSL			
9	500 ft/min Spiraling Climb	10,000 ft MSL - 15,000 ft MSL			
10	500 ft/min Spiraling Descent	15,000 ft MSL - 10,000 ft MSL			
11	Landing	400 ft AGL - Surface			
12	Shallow turns and descents IAW approach procedures	IAW DoD FLIP approach plate			

**ARAIM TO RAIM HORIZONTAL PROTECTION LEVEL**

For the ARAIM to RAIM comparison, the same initial RINEX file was processed two separate ways. First, the RINEX file was processed using the ARAIM algorithm described above to produce an ARAIM solution. Second, the RINEX file was manipulated to remove any non-US GNSS satellite constellations. This altered RINEX file was re-run through the ARAIM algorithm, but with the other satellite constellations removed it effectively provided a traditional RAIM solution. Both the ARAIM and RAIM outputs were assessed for serial correlation. Serial correlation greater than 20% triggered a decimation. The correlation and decimation process continued until serial correlation was satisfactory. Once the bounds were validated, remaining data points were considered independent. Percent improvement was determined by calculating the difference in ARAIM HPL and RAIM HPL, and then dividing by the value of the RAIM HPL for each data point.

Table C2. Example RAIM and ARAIM Comparison Table

Test Point Number	FTT Description		ARAIM Horizontal Protection Level	RAIM Horizontal Protection Level	Percentage Improvement ARAIM over RAIM
			(m)	(m)	%
1	Takeoff	Surface - 400 ft AGL			
2	Departure	400 ft AGL - 5,000 ft MSL			
3	Straight and Level Flight, Shallow Turns <30° AOB	5,000 ft MSL / 4,000 - 6,000 ft			
4	Straight and Level Flight, Shallow Turns <30° AOB	10,000 ft MSL / 9,000 - 11,000 ft			
5	Straight and Level Flight, Shallow Turns <30° AOB	15,000 ft MSL / 14,000 - 16,000 ft			
6	Straight and Level Flight, Shallow Turns <30° AOB	20,000 ft MSL / 19,000 - 21,000 ft			
7	500 ft/min Rate of Climb Check	5,000 ft MSL - 20,000 ft MSL			
8	500 ft/min Rate of Descent Check	20,000 ft MSL - 5,000 ft MSL			
9	500 ft/min Spiraling Climb	10,000 ft MSL - 15,000 ft MSL			
10	500 ft/min Spiraling Descent	15,000 ft MSL - 10,000 ft MSL			
11	Landing	400 ft AGL - Surface			
12	Shallow turns and descents IAW approach procedures	IAW DoD FLIP approach plate			

## DPA DATA ANALYSIS

Overall, the DPA uBlox receiver output a DPA RINEX file. The DPA RINEX file was processed with the Stanford provided software. The output contained azimuth solutions per satellite and were compared to the satellite ephemeris data location using the UHARS-generated and aircraft attitude as the “truth” data. Satellite ephemeris data were provided by the National Geospatial Agency (NGA)’s GPS Precise Ephemeris division. The UHARS output in combination with the constellation ephemeris data were used as the truth source. Figure C2 provides a flowchart summary of this process.

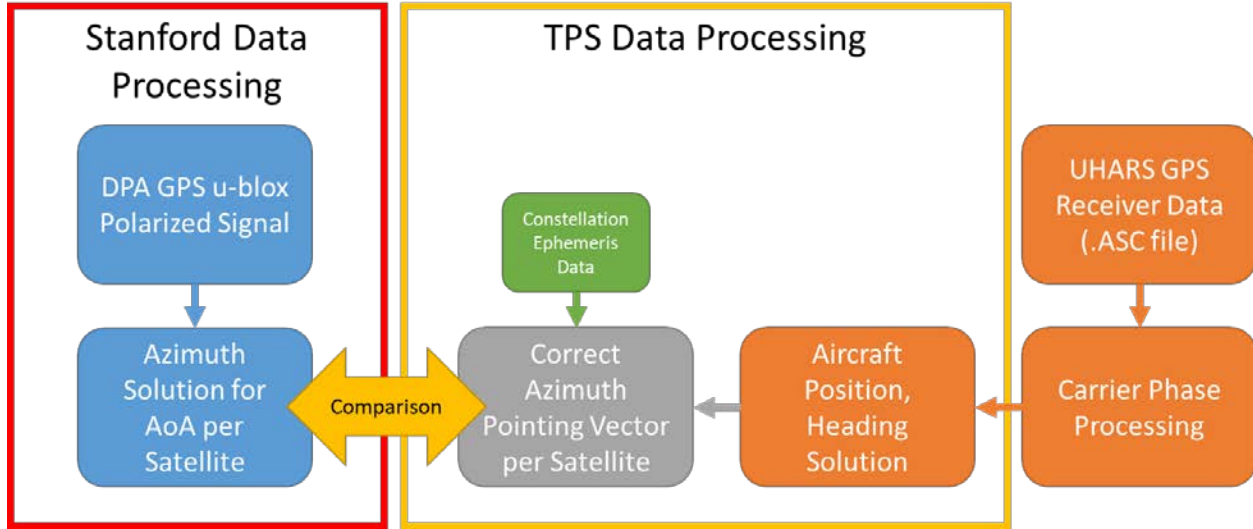


Figure C2. DPA Processing Flow Chart

## DPA PARAMETER OUTPUTS AND SEGMENTATION

The DPA RINEX file output was stored in the uBlox receiver and output in a RINEX file format. The DPA RINEX file was processed through the Stanford provided MatLab code and time, satellite ID, and horizontal and vertical satellite signal DOA were provided. Stanford GPS Labs codes converted the satellite signal DOAs from the DPA antenna reference frame to an East-North-Up (ENU) reference frame. The DPA file was segmented per FTT based on the specific FTT start and stop times recorded during the flight. For the truth source, the UHARS carrier phase processed data file provided time, latitude, longitude, altitude, heading, and velocity. The UHARS file was segmented per FTT based on the specific FTT start and stop times during the flight and for the same interval as the DPA start and stop times.

## DPA ROTATION AND TRANSLATION MATRICES

The DPA RINEX file required two separate translations and rotations. The first translation and rotation accounted for the physical distance and rotation between the DPA antenna and the UHARS antenna. The UHARS antenna was then translated into the DPA coordinate frame with a direction cosine matrix:

$$\begin{bmatrix} u_{r\_DPA} \\ v_{r\_DPA} \\ w_{r\_DPA} \end{bmatrix}_{Rotation} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\Phi_{DPA}) & \sin(\Phi_{DPA}) \\ 0 & -\sin(\Phi_{DPA}) & \cos(\Phi_{DPA}) \end{bmatrix} \begin{bmatrix} \cos(\Theta_{DPA}) & 0 & -\sin(\Theta_{DPA}) \\ 0 & 1 & 0 \\ \sin(\Theta_{DPA}) & 0 & \cos(\Theta_{DPA}) \end{bmatrix} \begin{bmatrix} \cos(\Psi_{DPA}) & \sin(\Psi_{DPA}) & 0 \\ -\sin(\Psi_{DPA}) & \cos(\Psi_{DPA}) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_{DPA} \\ v_{DPA} \\ w_{DPA} \end{bmatrix}$$

where  $\Phi_{DPA}$ ,  $\Theta_{DPA}$ , and  $\Psi_{DPA}$  are measured rotation angles. At this point, the UHARS truth data were in the DPA reference frame. The DPA data provided from Stanford was then translated into a North-East-Up reference frame.

## UHARS AZIMUTH POINTING VECTOR

The TPS student TMP team calculated the UHARS azimuth pointing vector for the test satellites. The truth source for signal DOA was calculated from the UHARS data set corrected for straight and level flight by finding the azimuth angle from the UHARS coordinate frame to the satellite. In order to accomplish this, the satellite ephemeris data and UHARS data were converted to fixed earth centered reference frame. Utilizing the UHARS measured latitude ( $\varphi_{UHARS}$ ), longitude ( $\lambda_{UHARS}$ ), altitude ( $h_{UHARS}$ ), the aircraft position will be converted into Cartesian coordinates for comparison with the following formulas:

$$u_{UHARS} = (N_{UHARS} + h_{UHARS}) \cos(\varphi_{UHARS}) \cos(\lambda_{UHARS})$$

$$v_{UHARS} = (N_{UHARS} + h_{UHARS}) \cos(\varphi_{UHARS}) \sin(\lambda_{UHARS})$$

$$w_{UHARS} = (N_{UHARS}(1 - e^2) + h_{UHARS}) \sin(\varphi_{UHARS})$$

where  $a$ ,  $e^2$ , and  $N_{UHARS}$  are ellipsoid Earth model parameters defined as,

$$a = 20925646.32546 \text{ ft}$$

$$e^2 = 0.0066943799$$

$$N_{UHARS} = \frac{a}{\sqrt{1 - e^2 \sin^2(\varphi_{UHARS})}}$$

The satellite ephemeris data were converted in a similar manner from latitude, longitude, and height into the earth fixed coordinate from  $u_{ephemeris}$ ,  $v_{ephemeris}$ , and  $w_{ephemeris}$  vector. A directional pointing vector will be calculated as the difference between the UHARS and ephemeris data.

$$\vec{\Delta E} = \vec{E}_{ephemeris} - \vec{E}_{UHARS} = \begin{bmatrix} u_{ephemeris} - u_{UHARS} \\ v_{ephemeris} - v_{UHARS} \\ w_{ephemeris} - w_{UHARS} \end{bmatrix}$$

The UHARS antenna coordinate plane was calculated by rotating the fixed earth centered  $u_{UHARS}$ ,  $v_{UHARS}$ , and  $w_{UHARS}$  by the roll, pitch, and yaw of the aircraft. Aircraft roll, pitch, and yaw will be retrieved from the UHARS dataset.

$$\vec{E}_{UHARS} = \begin{bmatrix} u_{SL\_UHARS} \\ v_{SL\_UHARS} \\ w_{SL\_UHARS} \end{bmatrix}_{Rotation} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\Phi_{SL}) & \sin(\Phi_{SL}) \\ 0 & -\sin(\Phi_{SL}) & \cos(\Phi_{SL}) \end{bmatrix} \begin{bmatrix} \cos(\Theta_{SL}) & 0 & -\sin(\Theta_{SL}) \\ 0 & 1 & 0 \\ \sin(\Theta_{SL}) & 0 & \cos(\Theta_{SL}) \end{bmatrix} \begin{bmatrix} \cos(\Psi_{SL}) & \sin(\Psi_{SL}) & 0 \\ -\sin(\Psi_{SL}) & \cos(\Psi_{SL}) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_{UHARS} \\ v_{UHARS} \\ w_{UHARS} \end{bmatrix}$$

Next, divide by the magnitude to create a unit vector of the plane.

$$\vec{E}_{UHARS\_NORM} = \vec{E}_{UHARS} / |\vec{E}_{UHARS}|$$

Finally, project the difference vector onto the UHARS antenna coordinate plane using the dot product and multiply by the  $E_{UHARS\_NORM}$  vector to restore direction.

$$\vec{E}_{projection} = (\overline{\Delta E} \cdot \vec{E}_{UHARS\_NORM}) * \vec{E}_{UHARS} / |\vec{E}_{UHARS}| = \begin{bmatrix} x_{projection} \\ y_{projection} \\ z_{projection} \end{bmatrix}$$

The value of  $z_{project}$  should become zero upon this projection. The angle between the latitude and longitude coordinates of UHARS and ephemeris satellite data will be computed using the inverse tangent of the difference of the latitude and longitude plus the aircraft true heading in the formula below:

$$\theta_{truth} = \cos^{-1} (x_{projection} / y_{projection})$$

$$\langle x_{projection}, y_{projection} \rangle$$

Reference Figure C3 for a visualization of the satellite projection onto the UHARS aircraft plane.

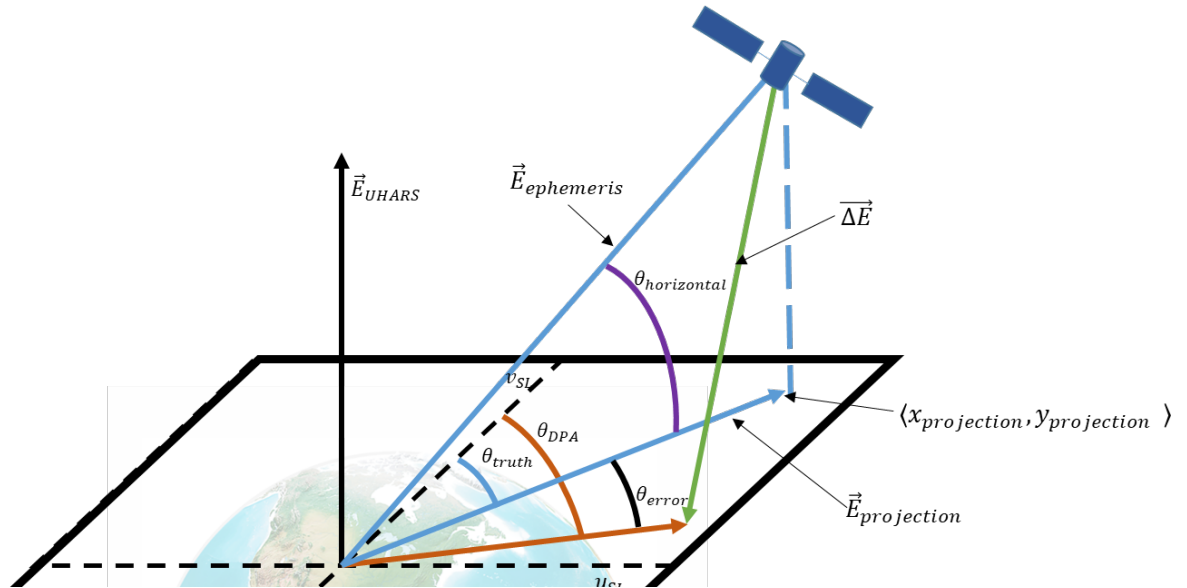


Figure C3. 3-D Projection of Satellite Ephemeris Data onto the DPA Antenna Reference Frame

### DPA AZIMUTH SOLUTION PER DOA COMPARISON

The TPS student TMP team determined the DOA for the test satellites in the DPA RINEX file and calculate the difference between the UHARS DOA ( $\theta_{truth}$ ) and the DPA DOA ( $\theta_{DPA}$ ) shown in the equation below and Figure C4.

$$\theta_{error} = |\theta_{truth} - \theta_{DPA}|$$

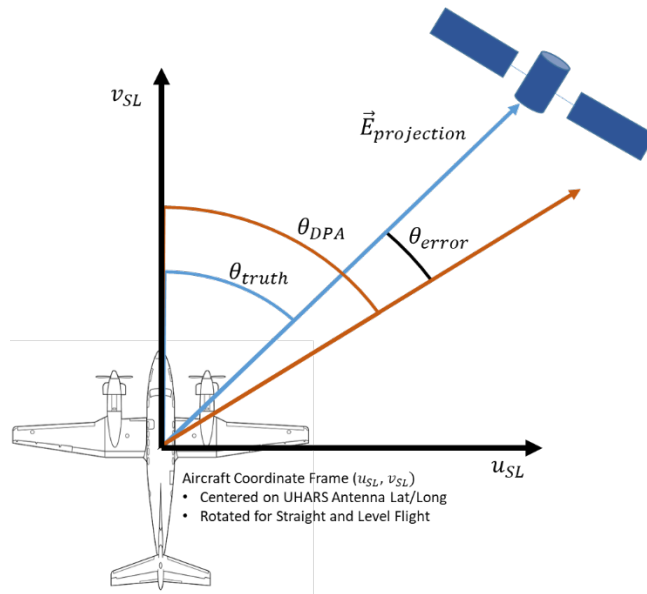


Figure C4. 2-D Satellite Ephemeris Projection onto the DPA Reference Frame

Five satellites were identified during post analysis for comparison per Figure C4. For each satellite, the azimuth solution error  $\theta_{error}$  was averaged over the span of the flight.

$$\theta_{error\_Average} = \frac{1}{n} \sum_{i=1}^n \theta_{error}$$

Finally, the average error,  $\theta_{error\_Average}$  in degrees were output per satellite.

# APPENDIX D – DAILY FLIGHT REPORTS

## HAVE DRAGON FLIGHT 1 – 9 SEPTEMBER 2019

Sortie Length: 2.3  
Total Hours: 2.3/18.0

### Sortie Summary:

Crew accomplished Flight #1 of the Have DRAGON investigation. The DPA/ARAIM console lost power on take-off, and the FTE couldn't restore DPA functionality. ARAIM appeared valid for the flight. The crew accomplished much of the intended benign maneuvering phases, including straight/level flight, shallow (28° AOB) turns, gentle climbs and descents (500 fpm), and spiraling climbs and descents (500 fpm, 30° AOB).

### Lessons Learned:

#### **Briefing/Test Cards:**

- Start the briefing with identifying the brief classification. For this mission, of course, the brief and sortie will be UNCLASSIFIED, but especially working with folks that can bounce between different environments, setting the briefing classification will help prevent security issues.
- Due to overlap with the Boeing Testbed, we're expecting to change callsigns for follow-on sorties. 1,000 lbs is a good estimate for Bingo fuel.
- 12.0 is a good estimate for Zero Fuel Weight, with 15.0 a good estimate for Takeoff weight. We don't use flaps for takeoff, resulting in V1: 110 kts, V2: 120 kts, Vyse: 125 kts
- I briefed the Motherhood. Bulldog briefed ground egress procedures as the EPOD. Use the electronic checklist when briefing another EPOD, rather than bringing the checklist from the aircraft. Watch out for the 25 knot x-wind limit. Winds are expected to be stronger tomorrow.

#### **Sortie Execution:**

- Bulldog did a great job of executing ground ops. He's pretty efficient on powering the mission instrumentation; engineers, listen carefully for Bulldog saying instrumentation is on. You can start powering-on your rack as soon as mission instrumentation has power.
- On takeoff, the DPA/ARAIM console lost power momentarily. Power returned quickly, and the system restarted, but following the power-on procedure was not able to activate the DPA system, even with multiple reset attempts. DPA was out-of-service for this mission. ARAIM data has been pulled and provided to Stanford already.
- The autopilot functions very similarly to the TPS' C-12's, and was very helpful in executing the required maneuvers today with precision. The only exception was climbs, which the autopilot wasn't able to maintain a constant VVI, and fluctuated on the edge of our (rather generous) tolerances. Most climbs were executed by the pilot flying instead. Understanding that the autopilot can't accomplish some of the tactical maneuvering data points, keep the system in mind for your comfort and ease of execution.
- The FTE doesn't really have much aircraft instrumentation available. He's relying on the crew to let him know he's on conditions. Be proactive in set up to save time!

#### **Engineering Notes:**

- Benign maneuvering almost complete, unless we want to go back for some DPA data.
  - Low priority but we should work that in later in the week if able.
- Yu-Hsuan is converting the ARAIM files from proprietary to a useable format tonight and hopefully we will have the data tomorrow.
- UHARS will take longer.
- Everything shakes in the aircraft. Don't be surprised if we get another computer reset before the end of the TMP. But overall:
  - We think today's incident will be rare. All the wires have been checked and double-checked.
  - The DPA wires on the roof remain secure.
  - If DPA doesn't connect, the DPA USB connection is now labeled, disconnect and reconnect.
- HAVE DRAGON fix-it bag now available
  - Includes keyboard, mouse, tape, small zip ties, start-up checklist
  - It's my helmet bag. Please don't lose it. It is at my desk, grab it anytime.
- Keyboard mouse issues shouldn't be a problem in the future.
  - There is a USB to a splitter connected to old school PS2 keyboard/mouse connectors. Move the usb the keyboard/mouse do not response again.
  - If that doesn't work, in the HAVE DRAGON fix-it bag is a keyboard and mouse. Both work when plugged into the computer.
- FTT Start time – Local time is perfect. Don't overcomplicate it.
- Ensure the cards are streamlined.
  - The profile was streamlined, but due to how are cards were built and approved, the top card and moving through cards wasn't as streamlined. Bottom line. Keep in simple and straight forward.

**Flight Date:** 9-Sep  
**Crew:** Jarvis / Coal  
**Sortie Duration:** 2.3  
**Notes:** All times are local

Card	Phase	Maneuver	Start Time	Stop Time	Altitude	Airspeed	Climbs/Descents		Notes
							Start Altitude	Stop Altitude	
1	Takeoff	Takeoff_and_Departure							
2b	Benign	Straight_and_Level	10:41:22	10:44:22	7500	166	----	----	
2b	Benign	Shallow_Turns	10:44:50	10:47:51	7520	165	----	----	
2a	Benign	Straight_Climb	10:52:00	10:55:00	----	159	8000	9060	
2b	Benign	Shallow_Turns	10:57:01	11:00:01	9720	161	----	----	
2b	Benign	Straight_and_Level	11:03:40	11:06:40	10000	165	----	----	
2a	Benign	Spiral_Climb	11:09:56	11:12:56	----	168	10500	12160	
2b	Benign	Straight_and_Level	11:15:41	11:18:41	12500	161	----	----	
2b	Benign	Shallow_Turns	11:19:15	11:22:15	12500	161	----	----	
2a	Benign	Straight_Climb	11:23:52	11:26:56	----	153	13000	14590	
2b	Benign	Straight_and_Level	11:28:23	11:31:23	15000	158	----	----	
2b	Benign	Shallow_Turns	11:32:58	11:35:59	15000	160	----	----	
2a	Benign	Spiral_Climb	11:36:34	11:39:36	----	160	15500	16870	
2b	Benign	Straight_and_Level	11:41:41	11:44:43	17500	161	----	----	
2b	Benign	Shallow_Turns	11:45:27	11:48:27	17520	159	----	----	
2a	Benign	Straight_Climb	11:49:50	11:52:50	----	158	15500	19740	
2b	Benign	Straight_and_Level	11:54:38	11:57:38	20000	164	----	----	
2b	Benign	Shallow_Turns	11:58:23	12:01:23	20000	157	----	----	
2c	Benign	Straight_Descent	12:04:05	12:07:05	----	159	19500	18000	
2c	Benign	Spiral_Descent	12:09:01	12:12:01	----	161	17000	15380	Turbulence
2c	Benign	Straight_Descent	12:13:29	12:16:29	----	161	14500	13220	
2c	Benign	Spiral_Descent	12:18:41	12:21:41	----	155	12000	10280	
2c	Benign	Straight_Descent	12:23:32	12:26:32	----	161	9500	8140	

Figure D1. Flight 1 FTTs Accomplished

## HAVE DRAGON FLIGHT 2 – 10 SEPTEMBER 2019

Takeoff: 0826  
Land: 1008  
Sortie Length: 1.7  
Total Hours: 4.0/18.0

### Sortie Summary:

Crew accomplished Flight #2 of the Have DRAGON investigation. Two full shutdown/startup cycles were required during ground ops to initialize the ARAIM/DPA system. The DPA Utility GUI lost its connection just prior to takeoff and was not re-established during the flight. However the DPA GUI appeared to update and collect data throughout the sortie. ARAIM appeared valid for the flight. The crew accomplished most of the intended tactical maneuvering (steep turns and 60-to-60 bank turns), low level (mountainous), and a TACAN instrument approach.

### Lessons Learned:

#### **Briefing/Test Cards:**

- NSTR
- A PDF version of the cards is saved to enable printing of kneeboard sized cards for the pilots.

#### **Sortie Execution:**

- Able to maintain 1,000 ft/min climb straight and level at 160 KIAS all the way up to 18k ft. Could only manage 1,000 ft/min spiral climb @ 160 KIAS up to 15k ft.
- Had to slightly descend during constant 60<sup>O</sup> Bank turns at 18k ft to maintain 160-165 KIAS. Started at 18k and ended at 17.6k after 3 minutes of turning.
- Executed the TACAN approach using the autopilot.
- Black Mountain area works well for the low level environment providing room to perform all maneuvers and still achieving terrain masking using the ridgeline.
- Data being downloaded to TPS hard drive and by Stanford post-flight

#### **Engineering Notes:**

- Limited tactical maneuvering almost complete.
  - Recommend investigating with uBlox configuration
- ARAIM/DPA rack required two full power cycles to initialize
- DPA Utility connected prior to taxi, but stopped just prior to takeoff
  - The DPA GUI updated throughout the flight (Doppler changes). Yu-Hsuan indicated this should mean data were collected but TBD
- If Ethernet (eno1) is not available and Stanford 940 will not load, remove and replace center power pack cable (green light but ref. Trouble shooting section of checklist)
  - Ensure both red and black Ethernet ports are blinking/have lights on the back of the computer
- When using Skyplot to monitor satellite tracking, satellites would drop in many of the 60 degree bank maneuvers
  - Noted for data analysis

**Flight Date:** 10-Sep  
**Crew:** Gator / Hack  
**Sortie Duration:** 1.7  
**Notes:** All times are local. DPA configuration = SDR

Card	Phase	Maneuver	Start Time	Stop Time	Altitude	Airspeed	Climbs/Descents		Notes
							Start Altitude	Stop Altitude	
1	Takeoff	Takeoff_and_Departure	8:26:20	8:28:00					
3b	Tactical	Steep_Turns	8:34:30	8:37:30	6000	174			Left turn
3b	Tactical	Bank_to_Bank	8:39:14	8:39:45	6000	174			L-->R
3b	Tactical	Bank_to_Bank	8:39:50	8:40:10	6000	174			R-->L
3a	Tactical	Straight_Climb	8:41:49	8:44:49		158	6000	9060	5-6 deg climb angle
3b	Tactical	Steep_Turns	8:48:30	8:51:30	9000	174			Right turn
3b	Tactical	Bank_to_Bank	8:53:36	8:53:56	9000	171			L-->R
3b	Tactical	Bank_to_Bank	8:53:28	8:53:47	9000	171			R-->L
3a	Tactical	Spiral_Climb	8:55:45	8:58:45		164	9100	12000	Right turn during climb
3b	Tactical	Steep_Turns	9:00:20	9:03:20	12000	174			Left turn
3b	Tactical	Bank_to_Bank	9:04:56	9:05:13	11600	173			L-->R
3b	Tactical	Bank_to_Bank	9:05:33	9:05:52	11600	173			R-->L
3a	Tactical	Straight_Climb	9:07:18	9:10:18		154	12000	14950	
3b	Tactical	Steep_Turns	9:11:25	9:14:25	15000	167			
3b	Tactical	Bank_to_Bank	9:15:15	9:15:33	15000	175			L-->R
3b	Tactical	Bank_to_Bank	9:15:58	9:16:13	15000	175			R-->L
3a	Tactical	Straight_Climb	9:17:30	9:20:30		163	15000	18000	
3b	Tactical	Steep_Turns	9:21:57	9:24:57	18000	172			
3b	Tactical	Bank_to_Bank	9:25:42	9:26:00	18000	163			L-->R
3b	Tactical	Bank_to_Bank	9:26:13	9:26:30	18000	163			R-->L
3c	Tactical	Spiral_Descent	9:27:55	9:30:55		160	18000	15000	
3c	Tactical	Straight_Descent	9:31:15	9:34:15		160	14900	12100	
3c	Tactical	Spiral_Descent	9:34:25	9:37:25		166	12000	9100	Left turn
3c	Tactical	Straight_Descent	9:37:38	9:40:38		152	9000	6100	
3c	Tactical	Spiral_Descent	9:40:47	9:43:30		172	6000	500 AGL	Right turn
5a	Low_Level_Mountainous	Straight_and_Level	9:43:30	9:44:37					
5a	Low_Level_Mountainous	Shallow_Turns	9:44:37	9:45:01					
5a	Low_Level_Mountainous	Straight_and_Level	9:45:01	9:46:01					
5a	Low_Level_Mountainous	Shallow_Turns	9:46:01	9:47:01					
5a	Low_Level_Mountainous	Straight_and_Level	9:47:01	9:52:20					
8	Landing	Instrument_Approach	9:56:20	10:03:30					

Figure D2. Flight 2 FTTs Accomplished

## **HAVE DRAGON FLIGHT 3 – 11 SEPTEMBER 2019**

Takeoff: 0925L  
Land: 1120L  
Sortie Length: 2.0  
Total Hours: 6.0/18.0

### **Sortie Summary:**

Crew accomplished Flight #3 of the Have DRAGON investigation. After engine start, the FTE was unable to successfully power-on the rack. After trouble-shooting with Stanford reps with no hope of resolution, aircraft was shut down. Crew Chief applied ground power to the aircraft, and the engineering team accomplished additional troubleshooting, developing a work-around. Aircraft was restarted and continued the mission. DPA and ARAIM appeared valid for the flight. The crew re-accomplished benign maneuvering and tower flybys in the u-Blox configuration. Around 1000L, during the sortie, the civilian after-market GARMIN GPS system used for navigation and an EFB with the Foreflight application both began losing navigation solutions. UHARS signal indications looked abnormal on both the L1 and L2 GPS frequencies. No interference was expected.

### **Lessons Learned:**

#### **Sortie Execution:**

- 2524 was crowded this morning, so we accepted the PIRA for airspace. It was a little more compact, and interference from traffic caused a reset and early transition. Overall, time was saved in the PIRA vice traveling out to Isabella.
- Heavier aircraft nearly maxed ITT (around 735°) in spiral climb at 20k' to 21.5k'. No issue accomplishing maneuver.
- Better to establish early on Tower Flyby line to provide more time in stable configuration
- Autopilot continues to be outstanding for maneuver execution in benign maneuvers (with exception of the 500 fpm stabilized climb)

#### **Engineering Notes:**

- KVA and ARAIM/DPA rack initialized on first start.
- Computer Case initialized on first start. After reset (required to rectify Ethernet (eno1) the computer case failed to send video input to the KVA. Several resets failed to rectify the issue and an aircraft shutdown was recommended.
- Additional step to be added to the checklist: *“If video input signal unavailable – cycle computer case”*
- Ublox data is saved to a SD card located within the antenna. Data analysis not possible without removing the antenna to gain access to the SD card.

#### **UHARS Notes:**

- Saw indications of L2 signals on UHARS oscilloscope display. L1 signal pulsed 3 or 4 times as well.
- Likely an indication of GPS interference.

**Flight Date:** 11-Sep  
**Crew:** Jarvis / Hover  
**Sortie Duration:** 2.0  
**Notes:** All times are local  
 DPA Configuration = uBlox

Card	Phase	Maneuver	Start Time	Stop Time	Altitude	Airspeed	Climbs/Descents		Notes
							Start Altitude	Stop Altitude	
2b	Benign	Shallow_Turns	9:30:10	9:33:10	7500	164	----	----	
2b	Benign	Straight_and_Level	9:33:30	9:36:10	7520	160	----	----	
2a	Benign	Straight_Climb	9:39:10	0:42:10	----	158	8000	9600	
2a	Benign	Spiral_Climb	9:43:00	9:46:00	----	160	10000	11520	
2b	Benign	Shallow_Turns	9:48:50	9:51:50	12500	159	----	----	
2b	Benign	Straight_and_Level	9:53:35	9:56:35	12500	160	----	----	
2a	Benign	Straight_Climb	9:58:00	10:01:00	----	158	13000	14800	
2a	Benign	Spiral_Climb	10:02:30	10:05:30	----	157	15500	17700	
2b	Benign	Shallow_Turns	10:07:35	10:10:35	17550	159	----	----	
2b	Benign	Straight_and_Level	10:12:35	10:15:35	17550	----	----	----	
2a	Benign	Straight_Climb	10:17:40	10:20:40	----	157	18400	19750	
2a	Benign	Spiral_Climb	10:21:20	10:24:20	----	158	20000	21300	
2c	Benign	Straight_Descent	10:27:00	10:30:00	----	162	20500	19160	
2c	Benign	Spiral_Descent	10:31:30	10:34:30	----	162	18300	16650	
2c	Benign	Straight_Descent	10:35:50	10:38:50	----	159	16000	14820	
2c	Benign	Spiral_Descent	10:40:30	10:43:30	----	162	14000	12400	
2c	Benign	Straight_Descent	----	----	----	----	----	----	Terminated due traffic
2c	Benign	Spiral_Descent	10:46:45	10:49:45	----	164	11000	9600	
2c	Benign	Straight_Descent	10:50:40	10:53:40	----	164	9300	7800	
6	Tower_Flyby	Tower_Flyby	11:01:15	11:02:51	----	160	2490	2400	
6	Tower_Flyby	Tower_Flyby	11:09:40	11:10:44	----	168	2520	2420	
6	Tower_Flyby	Tower_Flyby	11:16:50	11:17:50	----	165	2420	2420	

Figure D3. Flight 3 FTTs Accomplished

## HAVE DRAGON FLIGHT 4 – 12 SEPTEMBER 2019

Takeoff: 0716L  
Land: 0900L  
Sortie Length: 1.7  
Total Hours: 7.7/18.0

### Sortie Summary:

Crew accomplished Flight #4 of the Have DRAGON investigation. All rack power up procedures were executed IAW Stanford checklists and no anomalies were noted through the entire start up process. Ground ops were uneventful. The primary emphasis of the airborne mission was the low-level mountainous terrain flight regime, and the sortie was conducted in the Isabella, Koehn Lake, Cuddeback Lake, and Black Mountain areas from 500 ft AGL to 9,000 ft MSL. All maneuvers were executed in the u-Blox configuration. Around 0800L, the commercial Garmin and Foreflight GPS solutions experienced interference from an unknown source for approximately 10 minutes, then subsequently regained normal performance. DPA and ARAIM appeared valid throughout the duration of the flight.

### Lessons Learned:

#### **Sortie Execution:**

- Ensure the 586 FLTS flight crew are aware of brief times the day prior to execution. If brief times are changed with scheduling, ensure all flight crew are aware of changed brief times; the 586 FLTS does not receive the daily TPS flying schedule. (Option to forward Lt Spaulding the flight schedule)
- Early takeoffs are ideal for low level flying due to calm winds and smooth atmospheric conditions. Low level turbulence was not a factor during the early morning hours.

#### **Engineering Notes:**

- When operating in the u-blox configuration, only 1 device is detected with *uhd\_find\_devices* command (see attached \_070707)
- When running *./run-usrpn210*, the following was displayed seeming to indicate degraded performance. However, this is consistent with the display from previous u-blox flight (see attached \_070721)
- *./runme* will not function (No GUI available) when operating in u-blox

Sortie Duration: 1.7

Notes: All times are local

Card	Phase	Maneuver	Start Time	Stop Time	Altitude	Climbs/Descents			Notes
						Airspeed	Start Altitude	Stop Altitude	
1	Takeoff	Takeoff_and_Departure	7:20:00	7:22:00					
5c	Low_Level_Mountainous	Straight_Descent	7:27:20	7:30:50		164	6205	500 AGL	1100 fpm descent headed towards Mns.
5a	Low_Level_Mountainous	Straight_and_Level	7:30:50	7:33:50	500 AGL	164			Ref heading 050 to 045
5a	Low_Level_Mountainous	Shallow_Turns	7:34:30	7:37:31	500 AGL	161-171			
5a	Low_Level_Mountainous	Straight_and_Level	7:39:25	7:42:25	500 AGL	158-165			Ref heading 210
5b	Low_Level_Mountainous	Steep_Turns	7:45:00	7:46:43	500 AGL				
5b	Low_Level_Mountainous	Bank_to_Bank	7:48:06	7:49:06					
5b	Low_Level_Mountainous	Bank_to_Bank	7:50:36	7:51:32					L-->R then R-->L
5a	Low_Level_Mountainous	Shallow_Turns	7:52:15	7:55:35	750-800 AGL	162-167			
5b	Low_Level_Mountainous	Bank_to_Bank	7:57:11	7:58:45	Down to 400 AGL				L-->R then R-->L
5a	Low_Level_Mountainous	Straight_and_Level	8:00:00	8:03:00	580-630 AGL	160-163			Ref heading 210 to 216
5a	Low_Level_Mountainous	Straight_and_Level	8:04:30	8:07:30	500 AGL	165			Ref heading 030
5b	Low_Level_Mountainous	Steep_Turns	8:07:45	8:09:03	500 AGL				
5a	Low_Level_Mountainous	Shallow_Turns	8:09:18	8:12:37	570 AGL	164-171			Left turn at 30 AOB. Ref heading 300
5b	Low_Level_Mountainous	Steep_Turns	8:13:46	8:15:06					Right turn. Ref heading 360
5c	Low_Level_Mountainous	Straight_Climb	8:16:28	8:19:39		160-163	500 AGL	6000 MSL	
3a	Tactical	Spiral_Climb	8:24:16	8:27:16		162	6000	9000	Right turn
3c	Tactical	Straight_Descent	8:28:30	8:31:30		160-162	8500	5400	
3c	Tactical	Spiral_Descent	8:31:30	8:34:00		164	5400	500 AGL	Left turn. Terminated 30 sec early for terrain
5a	Low_Level_Mountainous	Straight_and_Level	8:36:48	8:38:48	500 AGL	163			
5c	Low_Level_Mountainous	Straight_Climb	8:39:00	8:40:20			500 AGL	1100 AGL	1000 fpm climbing right turn
5c	Low_Level_Mountainous	Straight_Descent	8:40:20	8:41:00			1100 AGL	500 AGL	On south side of Blk Mtn
5c	Low_Level_Mountainous	Straight_Climb	8:41:30	8:42:15			600 AGL	1200 AGL	Straight climb at 1000 fpm
5c	Low_Level_Mountainous	Straight_Descent	8:42:15	8:43:00			1200 AGL	500 AGL	
5a	Low_Level_Mountainous	Straight_and_Level	8:45:20	8:48:00					N. side of Blk Mtn with Mtns to the right of the a/c
8	Landing	Instrument_Approach	8:51:00	8:58:30					

Figure D4. Flight 4 FTTs Accomplished

## **HAVE DRAGON FLIGHT 5 – 13 SEPTEMBER 2019**

Takeoff: 0855L  
Land: 1146L  
Sortie Length: 2.9  
Total Hours: 10.6/18.0

### **Sortie Summary:**

Crew accomplished Flight #5 of the Have DRAGON investigation. All rack power up procedures were executed IAW Stanford checklists, with minor and previously encountered anomalies through the entire start up process (refer to Engineering Notes). Ground ops were uneventful. The primary emphasis of the airborne mission was the low-level overwater flight regime, and the sortie was conducted in W-289E and W-289W from 500 ft AGL to 16,000 ft MSL. All maneuvers were executed in the SDR configuration. DPA and ARAIM appeared valid through most of the flight, with DPA experiencing occasional airborne interruptions.

### **Sortie Execution:**

- Make sure to include the accessory fuel in TOLD calculations for Monday. On the other hand, for a general rule of thumb, we were just finishing the accessory fuel and moving on to normal takeoff fuel when we were finishing up our maneuvers over the water. The aircraft can LOITER.
- We submitted the DD175 to base ops. The Sport Call acted as clearance delivery, and then we intended to pick up IFR with Joshua after exiting the complex. Joshua could find our filed flight plan, and they were pretty heavily trafficked so we continued VFR with Flight Following.
- An un-forecast low marine deck hung over the water throughout the majority of the work areas. The only clear area was right by the islands, which we couldn't overfly lower than 1,000 ft AGL. Luckily, the cloud deck was just barely over the water, and we could operate clear at 500 ft AGL. All overwater maneuvers, and almost all benign and limited tactical test points are complete.

### **Engineering Notes:**

- The orange DPA data light failed to illuminate. Removing/replacing the DPA cable failed to rectify the issue. Rack was hard cycled via the rack power switch. Second start-up attempt resulted in DPA data light illumination.

**Flight Date:** 13-Sep  
**Crew:** Jarvis / Hover  
**Sortie Duration:**  
**Notes:** All times are local

Card	Phase	Manuver	Start Time	Stop Time	Altitude	Airspeed	Climbs/Descents		Notes
							Start Altitude	Stop Altitude	
1	Takeoff	Takeoff_and_Departure	8:55:40	8:56:20	----	----	----	----	
2	Benign	Straight_Climb	9:05:20	9:08:20		155-158	10000	11700	
3	Benign	Straight_and_Level	9:14:30	9:17:30	12500	158	----	----	
4	Tactical	Straight_Descent	9:21:30	9:24:30	----	167	11600	86900	Over Water
6a	Low_Level_Over_Water	Straight_and_Level	9:30:10	9:33:10	540	167	----	----	RADALT, Over Water
6a	Low_Level_Over_Water	Shallow_Turns	9:33:40	9:36:40	560	167	----	----	RADALT, Over Water, Left Turn
6a	Low_Level_Over_Water	Straight_and_Level	9:37:30	9:40:30	550	169	----	----	RADALT, Over Water
6a	Low_Level_Over_Water	Shallow_Turns	9:41:00	9:44:00	540	168	----	----	RADALT, Over Water, Left Turn
6a	Low_Level_Over_Water	Straight_and_Level	9:45:25	9:48:25	560	166	----	----	RADALT, Over Water
6a	Low_Level_Over_Water	Shallow_Turns	9:49:15	9:52:15	570	164	----	----	RADALT, Over Water, Left Turn
A1	Tactical	Spiral_Climb	9:58:30	10:01:30	----	153-167	2740	5460	Over Water, Left Turn
5	Benign	Straight_Descent	10:02:00	10:05:00	----	162	5120	3700	Over Water
5	Benign	Spiral_Descent	10:05:35	10:08:35	----	164	3320	1450	Over Water, Left Turn
A1	Tactical	Spiral_Climb	10:11:30	10:14:30	----	163	3600	5950	Over Water, Left Turn
5	Benign	Spiral_Descent	10:16:25	10:19:25	----	160	5230	3700	Over Water, Left Turn
5	Benign	Straight_Descent	10:19:55	10:22:55	----	161	3480	2200	Over Water
5	Benign	Spiral_Descent	10:32:40	10:35:40	----	163	5720	3980	Over Water, Left Turn
5	Benign	Straight_Descent	10:36:45	10:39:45	----	161	3320	1900	Over Water
3	Benign	Straight_and_Level	10:55:55	10:58:55	15000	158	----	----	
3	Benign	Straight_and_Level	11:02:45	11:05:45	11500	159	----	----	
7	Tower_Flyby	Tower_Flyby	11:20:30	11:21:35	210	170	----	----	RADALT
7	Tower_Flyby	Tower_Flyby	11:26:56	11:28:15	200	167	----	----	RADALT
7	Tower_Flyby	Tower_Flyby	11:33:25	11:34:40	200	168	----	----	RADALT
8	Landing	Instrument_Approach	11:42:25	11:45:00	----	----	----	----	Flew the ILS after establishing at the TACAN. Flew for approach to 22R.

Figure D5. Flight 5 FTTs Accomplished

## **HAVE DRAGON FLIGHT 6 – 16 / 17 SEPTEMBER 2019**

Takeoff: 2324L  
Landing: 0156L  
Sortie Length: 2.5  
Total Hours: 13.1/18

### **Sortie Summary:**

Crew accomplished flight #6 of the Have DRAGON plan w/ GPS jamming. No anomalies with startup. ARAIM and DPA in SDR mode monitored for the entire sortie and data collection was noted for the entire sortie. Accomplished 45 minutes of Have DRAGON FTTs, then accomplished GPS jamming characterization, then accomplished 3 more Have DRAGON FTTs during RTB. ARAIM work well. GPS was degraded or lost due to jamming throughout the sortie. Other constellations held solid as expected. Anticipate good ARAIM data at the “edges” of its capabilities to aid characterization throughout jamming. DPA did not work well and likely became degraded as soon as jamming was initiated. No locks were seen throughout the sortie. May be some DPA data at the edges of jamming but will require post-processing to determine.

### **Lessons Learned:**

- No significant INS drift or FMS/Falconview tablet GPS waypoint degradation existed for basic airspace navigation and route adherence during jamming.
- Ensure the NAVFEST/Orange Flag altitude blocks/callsigns/aircraft de-confliction game plan is briefed and available in the aircraft for SA enhancement, especially as the airspace becomes more congested with outside entities.
- Thoroughly brief communication plan and exercise frequencies. NAVFEST UHF common worked well for primary exercise communication; Joshua Approach monitors NAVFEST common.

### **Sortie Execution:**

- NAVFEST initially reported a 30 minute delay for jamming initiation, which subsequently only became a 5 minute delay. Otherwise, execution went smoothly. A transition at 45 minutes of flight time to J/S characterization was executed as planned. Initial 45 minutes of flight time were devoted to Have DRAGON, next 1 hour 15 minutes to J/S characterization, and the final 25 minutes were devoted to Have DRAGON.

### **Engineering Notes:**

- ./runme failed once to pull up the DPA screen. The screen would close on its own. After 2 more attempts, it held for the remainder of the sortie.

**Flight Date:** 16-Sep  
**Crew:** Penny / Coal  
**Sortie Duration:**  
**Notes:** All times are local

Phase	Manuver	Start Time	Stop Time	Altitude	Airspeed	Climbs/Descents		Heading	Notes
						Start Altit	Stop Altitude		
Takeoff	Takeoff_and_Departure	23:24:03	23:29:01	----	----				
Jamming_Benign	Straight_Climb	23:36:16	23:39:22	----	163	6500	8000		
Jamming_Benign	Spiral_Climb	23:39:40	23:42:40	----	162	8200	10000		Right Bank
Jamming_Benign	Straight_and_Level	23:44:44	23:37:40	9900	160				Mines to Harpers
Jamming_Benign	Shallow_Turns	23:48:23	23:51:23	9900	157	----	----		
Jamming_Benign	Straight_Climb	23:52:40	23:55:40	----	----	10500	12000		
Jamming_Benign	Spiral_Climb	23:56:20	23:59:20	----	----	12000	13600		Right Bank
Jamming_Benign	Straight_and_Level	00:01:16	00:04:16	13300	154	----	----		Harpers to Mines
Jamming_Tactical	Straight_Climb	00:07:30	00:10:30	----	159	15500	18500		Switched due to timing
Jamming_Tactical	Spiral_Climb	00:11:10	00:14:10	----	154	19200	21500		Over mines
Jamming_Racetac	Racetrack	00:26:10	00:29:10	24500	159	----	----	291	
Jamming_Racetac	Racetrack	00:32:40	00:35:40	24500	159	----	----	124	
Jamming_Racetac	Racetrack	00:37:40	00:40:40	24500	159	----	----	284	
Jamming_Racetac	Racetrack	00:43:22	00:46:22	24500	159	----	----	130	
Jamming_Racetac	Racetrack	00:47:30	00:50:30	24500	160	----	----	287	
Jamming_Benign	Straight_Descent	01:32:25	01:35:25	----	----	18700	16400		
Jamming_Benign	Spiral_Descent	01:38:45	01:38:45	----	----				
Jamming_Landing	Instrument_Approach	01:44:59	01:56:53	----	----	----	----		

Figure D6. Flight 6 FTTs Accomplished

## HAVE DRAGON FLIGHT 7 – 17/18 SEPTEMBER 2019

Takeoff: 2241L  
 Landing: 0035L  
 Sortie Length: 1.9  
 Total Hours: 15.0/18

### Sortie Summary:

Crew accomplished flight #7. Orange Flag GPS Jamming was cancelled due to POTUS support aircraft operating IVO Edwards AFB. Same profile as flight #6 was accomplished with the addition of steep turns and 60-60 bank to bank rolls.

### Lessons Learned:

- Don't fly FTTs in the final approach path while other aircraft are attempting to RTB.

### Engineering Notes:

- Earthnet powerpack required recycling
- Benign shallow turns were flown using alternating turns instead of a constant left or right turn.

Phase	Maneuver	Start Time	Stop Time	Altitude	Airspeed	Climbs/Descents		Heading	Notes
						Start Altitude	Stop Altitude		
Takeoff	Takeoff_and_Departure	22:41:00	22:43:00	----	----				
Benign	Straight_Climb	22:50:25	22:53:25	----	161	6800	8300		
Benign	Straight_Climb	23:06:55	23:09:55	----	161	10200	11800		
Benign	Spiral_Climb	22:54:45	22:57:45	----	161	8500	10130		
Benign	Spiral_Climb	23:10:40	23:13:40	----	160	12100	13740		
Benign	Straight_and_Level	23:02:55	23:05:55	10000	158	----	----		
Benign	Straight_and_Level	23:14:35	23:17:35	14000	160	----	----		
Benign	Straight_and_Level	23:33:10	23:36:10	10000	159	----	----		
Benign	Shallow_Turns	22:58:40	23:01:40	10000	160	----	----		Right to left alternating bank turns
Benign	Shallow_Turns	23:18:15	23:21:15	14000	161	----	----		Right to left alternating bank turns
Benign	Shallow_Turns	23:36:40	23:39:40	10000	162	----	----		Right to left alternating bank turns
Benign	Straight_Descent	23:25:00	23:28:00	----	----	13700	12200		
Benign	Straight_Descent	00:08:55	00:11:55	----	----	10080	8800		
Benign	Spiral_Descent	23:28:50	23:31:50	----	----	11820	10340		
Benign	Spiral_Descent	0:12:35	00:15:35	----	----	8500	7000		
Benign	Racetrack	23:40:35	23:43:35	10000	157	----	----	257	
Benign	Racetrack	23:50:20	23:53:20	10000	160	----	----	77	
Benign	Racetrack	23:45:30	23:48:30	10000	158	----	----	257	
Benign	Racetrack	23:55:00	23:58:00	10000	160	----	----	77	
Tactical	Steep_Turns	00:02:45	00:05:45	10020	165	----	----		
Tactical	Bank_to_Bank	00:06:50	00:07:05	10000	160	----	----		
Landing	Instrument_Approach	00:24:30	00:25:30	----	----				Go-around due traffic on runway

Figure D7. Flight 7 FTTs Accomplished

## HAVE DRAGON FLIGHT 8 – 18 / 19 SEPTEMBER 2019

Takeoff: 2231L  
 Landing: 0105L  
 Sortie Length: 2.6  
 Total Hours: 17.6/18

### Sortie Summary:

Crew accomplished flight #8. Jamming was operational starting at 2312 after initial check outs. Same profile as flight #6/7 was accomplished with the addition of multiple steep turns and 60-60 bank to bank rolls. Notably, during climb out and initial setup prior to the start of jamming intermittent dropouts of the satellites were seen on the Trimble Skyplot.

### Lessons Learned:

### Engineering Notes:

- Intermittent dropouts of the satellites were noted on the skyplot from approximately 2245-2300L during climb out and while flying straight and level at 6.5K.
- C-12J-1 stall speeds are limited to aircraft GW of 12,500lbs. Fuel load during sortie put starting weight at 16.3; airspeed used for all steep turns and bank-to-banks was 170KIAS with min airspeed of 160 KIAS

Flight Date:		18-Sep							
Crew:		Penny / Hack							
Sortie Duration:									
Notes:		All times are local							
Card	Phase	Maneuver	Start Time	Stop Time	Altitude	Airspeed	Climbs/Descents		Notes
							Start Altitude	Stop Altitude	
2	Takeoff	Takeoff_and_Departure	22:31:00	22:33:00					Did note intermittent satellite dropout on the Skyplot during climb out
3	Jamming_Benign	Straight_Climb	23:13:00	23:16:00		160	6500	8200	Jamming starting at 23:12:15 with sys checks from 2300-2305
4	Jamming_Benign	Spiral_Climb	23:16:28	23:19:28		155-160	8500	9800	L turn over 4 corners
5	Jamming_Benign	Straight_and_Level	23:20:20	23:23:20	9900	159			240 ref heading
6	Jamming_Benign	Shallow_Turns	23:24:01	23:27:01	10000	154-161			200 ref heading. E. of the mines near approach end of rwy 22
7	Jamming_Benign	Straight_Climb	23:28:40	23:31:40		159-165	10000	11500	080 ref heading. Abeam 4 corners
8	Jamming_Benign	Spiral_Climb	23:31:58	23:34:58		160-166	11700	13000	L turn, E of 4 corners
9	Jamming_Benign	Straight_and_Level	23:35:57	23:38:57	13000	160			250 ref heading. E. of 4 corners
10	Jamming_Benign	Shallow_Turns	23:39:40	23:42:40	13000	157-159			220 ref heading. L turn overhead the mines
11	Jamming_Benign	Straight_Descent	23:43:46	23:46:46		160-165	13000	11400	090 ref heading. Descent started approx halfway between pt A and B
12	Jamming_Benign	Spiral_Descent	23:47:10	23:50:19		159	11200	9300	070 ref heading. L turn near pt B
13	Jamming_Benign	Straight_and_Level	23:51:13	23:54:13	9000	157			250 ref heading. Near pt B
14	Jamming_Benign	Shallow_Turns	23:54:35	23:57:35	9000	165			240 ref heading. L turn near 4 corners
15	Jamming_Tactical	Steep_Turns	23:58:30	00:00:00	9000	170-175			150 ref heading. L turn. 15.2 GW
16	Jamming_Tactical	Bank_to_Bank	00:00:56	00:01:28	9000	170			L->R->wings level. Near pt A
17	Jamming_Racetack	Racetack	00:02:50	00:11:17	8900	153			
18	Jamming_Tactical	Straight_Climb	00:11:42	00:14:42		157-161	9000	12000	255 ref heading
19	Jamming_Tactical	Steep_Turns	00:15:46	00:16:17	12000	170			150 ref heading. L turn
20	Jamming_Tactical	Bank_to_Bank	00:18:00	00:18:45	11900	170			L->R->wings level. Halfway between pt A and B
21	Jamming_Racetack	Racetack	00:21:13	00:30:28	12000	165			
22	Jamming_Tactical	Straight_Descent	00:31:20	00:34:20		165	12000	9200	260 ref heading, starting at pt B
23	Jamming_Tactical	Steep_Turns	00:35:09	00:36:37	9000	175			210 ref heading. L turn. Started between pt A and B
24	Jamming_Tactical	Bank_to_Bank	00:36:50	00:37:30	9000	170			L->R->wings level, between pt A and B
25	Jamming_Benign	Straight_Descent	00:38:53	00:41:53		158-165	9000	7000	250 ref heading. Started at pt B heading W
26	Jamming_Benign	Spiral_Descent	00:42:10	00:45:10		160	6900	5500	L turn near 4 corners area
27	Jamming_Landing	Instrument_Approach	00:50:00	00:59:45					Started 12NM from the TACAN. Land time was 01:05:00

Figure D8. Flight 8 FTTs Accomplished

## APPENDIX E – TEST POINT SUMMARY

### ARAIM IN BENIGN MANEUVERING

ARAIM in benign maneuvering VPL and HPL accuracy, and the difference between RAIM and ARAIM Protection Level can be found in the Test and Evaluation Section titled “ARAIM in Benign Maneuvering.”

### ARAIM IN LIMITED TACTICAL MANEUVERING

#### ARAIM VERTICAL PROTECTION LEVEL ACCURACY

Table E1. ARAIM Vertical Protection Level Accuracy in Limited Tactical Maneuvering

			Error			Vertical Protection Level			
Maneuver	FTT Count	Sample Count	Mean (m)	$\sigma$ (m)	Max (m)	Mean (m)	$\sigma$ (m)	Min PL (m)	% Bounded
Bank-to-Bank Turns 60°-60°	11	42	10	8	50	104	25	80	100%
Spiral Climb 1000 ft/min	4	454	18	12	67	90	12	75	100%
Spiral Descent 1000 ft/min	4	415	14	11	41	97	19	74	100%
Steep Turns 60° AOB	6	905	10	8	115	124	42	78	100%
Climb 1000 ft/min	3	93	9	7	21	108	36	71	100%
Descent 1000 ft/min	4	4	15	11	38	95	10	78	100%
Tower Fly-By	6	201	7	5	30	104	5	97	100%
Low Level Bank-to-Bank 60°-60°	3	213	21	13	123	88	20	73	100%
Low Level Shallow Turns <30° AOB	5	639	18	10	42	93	41	73	100%
Low Level Steep Turns 60° AOB	3	262	23	15	158	175	132	75	100%
Low Level Climb 1000 ft/min	3	175	17	13	37	77	2	75	100%
Low Level Descent 1000 ft/min	3	29	29	5	37	77	4	74	100%
Low Level Straight/Level	9	390	14	7	39	83	10	73	100%
Low Level Overwater Shallow Turns <30° AOB	3	452	19	9	37	99	6	93	100%
Low Level Overwater Straight/Level	3	92	30	3	35	96	3	93	100%

## ARAIM HORIZONTAL PROTECTION LEVEL ACCURACY

Table E2. ARAIM Horizontal Protection Level Accuracy in Limited Tactical Maneuvering

Maneuver	FTT Count	Sample Count	Error			Horizontal Protection Level			
			Mean (m)	$\sigma$ (m)	Max (m)	Mean (m)	$\sigma$ (m)	Min PL (m)	% Bounded
Bank-to-Bank Turns 60°-60°	11	42	5	5	23	64	4	59	100%
Spiral Climb 1000 ft/min	4	454	11	7	26	60	6	50	100%
Spiral Descent 1000 ft/min	4	415	8	7	26	60	2	58	100%
Steep Turns 60° AOB	6	905	4	4	30	70	9	57	100%
Climb 1000 ft/min	3	93	3	1	4	62	4	57	100%
Descent 1000 ft/min	4	4	13	8	24	58	1	58	100%
Tower Fly-By	6	201	21	2	24	51	1	49	100%
Low Level Bank-to-Bank 60°-60°	3	213	16	6	27	67	13	58	100%
Low Level Shallow Turns <30° AOB	5	639	12	8	29	68	21	58	100%
Low Level Steep Turns 60° AOB	3	262	15	10	115	121	65	58	100%
Low Level Climb 1000 ft/min	3	175	8	2	13	59	1	58	100%
Low Level Descent 1000 ft/min	3	29	10	4	19	58	1	57	100%
Low Level Straight/Level	9	390	9	7	24	59	1	57	100%
Low Level Overwater Shallow Turns <30° AOB	3	452	13	5	22	59	1	57	100%
Low Level Overwater Straight/Level	3	92	9	3	18	58	1	57	100%

## DIFFERENCE BETWEEN ARAIM AND RAIM HORIZONTAL PROTECTION LEVEL

Table E3. Difference between ARAIM and RAIM HPLs in Limited Tactical Maneuvering

Maneuver	FTT Count	Sample Count	RAIM Mean HPL (m)	ARAIM Mean HPL (m)	Percent Improvement (%)
Bank-to-Bank Turns 60°-60°	11	42	127	64	50%
Spiral Climb 1000 ft/min	4	454	85	60	30%
Spiral Descent 1000 ft/min	4	415	88	60	32%
Steep Turns 60° AOB	6	905	194	70	64%
Climb 1000 ft/min	3	93	146	62	57%
Descent 1000 ft/min	4	4	87	58	33%
Tower Fly-By	6	201	56	51	9%
Low Level Bank-to-Bank 60°-60°	3	213	205	67	67%
Low Level Shallow Turns <30° AOB	5	639	185	68	63%
Low Level Steep Turns 60° AOB	3	262	821	121	85%
Low Level Climb 1000 ft/min	3	175	67	59	13%
Low Level Descent 1000 ft/min	3	29	71	58	18%
Low Level Straight/Level	9	390	78	59	24%
Low Level Overwater Shallow Turns <30° AOB	3	452	92	59	36%
Low Level Overwater Straight/Level	3	92	91	58	37%

## ARAIM IN GPS JAMMED ENVIRONMENT

### ARAIM VERTICAL PROTECTION LEVEL ACCURACY

Table E4. ARAIM Vertical Protection Level Accuracy in the GPS Jammed Environment

			Error			Vertical Protection Level			
Maneuver	FTT Count	Sample Count	Mean (m)	$\sigma$ (m)	Max (m)	Mean (m)	$\sigma$ (m)	Min PL (m)	% Bounded
Shallow Turns <30° AOB	3	48	14	2	19	79	3	77	100%
Spiral Climb 500 ft/min	3	48	30	12	48	85	3	74	100%
Spiral Descent 500 ft/min	3	162	8	8	41	103	30	84	100%
Climb 500 ft/min	2	122	10	7	25	80	6	75	100%
Descent 500 ft/min	3	323	11	11	46	106	38	87	100%
Straight/Level	4	49	21	14	46	83	3	77	100%
Instrument Approach	2	552	17	13	54	101	18	88	100%
Racetrack 30° AOB Turns	7	760	16	13	50	131	70	67	100%
Bank-to-Bank Turns 60°-60°	3	120	14	12	40	121	24	83	100%
Spiral Climb 1000 ft/min	1	46	8	7	24	97	21	79	100%
Steep Turns 60° AOB	2	113	3	3	17	106	23	88	100%
Climb 1000 ft/min	2	47	14	27	166	85	9	72	100%
Descent 1000 ft/min	1	46	17	10	34	105	13	82	100%

## ARAIM HORIZONTAL PROTECTION LEVEL ACCURACY

Table E5. ARAIM Horizontal Protection Level Accuracy in the GPS Jammed Environment

			Error			Horizontal Protection Level			
Maneuver	FTT Count	Sample Count	Mean (m)	$\sigma$ (m)	Max (m)	Mean (m)	$\sigma$ (m)	Min PL (m)	% Bounded
Shallow Turns <30° AOB	3	48	12	5	19	57	2	55	100%
Spiral Climb 500 ft/min	3	48	13	3	17	59	2	55	100%
Spiral Descent 500 ft/min	3	162	16	2	20	62	10	57	100%
Climb 500 ft/min	2	122	13	3	17	57	1	56	100%
Descent 500 ft/min	3	323	15	4	21	66	7	58	100%
Straight/Level	4	49	15	4	20	59	3	54	100%
Instrument Approach	2	552	16	5	23	61	14	54	100%
Racetrack 30° AOB Turns	7	760	15	4	24	82	32	53	100%
Bank-to-Bank Turns 60°-60°	3	120	-6	17	17	121	24	83	100%
Spiral Climb 1000 ft/min	1	46	-5	9	16	97	21	79	100%
Steep Turns 60° AOB	2	113	0	4	12	106	23	88	100%
Climb 1000 ft/min	2	47	-11	28	19	85	9	72	100%
Descent 1000 ft/min	1	46	-1	20	27	105	13	82	100%

## DIFFERENCE BETWEEN ARAIM AND RAIM HORIZONTAL PROTECTION LEVEL

Table E6. Difference between ARAIM and RAIM HPLs in the GPS Jammed Environment

Maneuver	FTT Count	Sample Count	RAIM Mean HPL (m)	ARAIM Mean HPL (m)	Percent Improvement (%)
Shallow Turns <30° AOB	3	48	76	57	25%
Spiral Climb 500 ft/min	3	48	84	59	30%
Spiral Descent 500 ft/min	3	162	134	62	54%
Climb 500 ft/min	2	122	65	57	13%
Descent 500 ft/min	3	323	122	66	46%
Straight/Level	4	49	87	59	32%
Instrument Approach	2	552	101	61	39%
Racetrack 30° AOB Turns	7	760	653	82	88%
Bank-to-Bank Turns 60°-60°	3	120	414	86	79%
Spiral Climb 1000 ft/min	1	46	86	72	16%
Steep Turns 60° AOB	2	113	206	74	64%
Climb 1000 ft/min	2	47	71	65	9%
Descent 1000 ft/min	1	46	179	78	57%

## **APPENDIX F – LESSONS LEARNED**

The successful execution of Have DRAGON testing hinged on the cooperation of multiple organizations including USAF TPS, the 586 FLTS, and Stanford University. Despite relatively smooth execution, lessons learned focus on the planning and reporting aspects of the test and associated interactions with these participating organizations.

### **Schedule and Utilize Ground Testing to Ensure Test Item Readiness**

Prior to flight testing, Stanford University demonstrated both the ARAIM software operation and DPA technologies in laboratory environments. However once integrated into the aircraft, the consolidation to the rack setup and vibrations inherent in flight operations caused unforeseen issues. Additionally, the test team was unfamiliar with test item operation until it was loaded on the aircraft just days before testing began. Ground testing proved critical for verifying operation of the Stanford created rack and for flushing out hardware and software issues that arose from the integration into the aircraft. These issues included discovery that a GPS amplifier was required for ARAIM operation and determining that DPA software limitations prevented switching configurations during flight.

As previously mentioned, ground testing provided the test team necessary time for test item familiarization. During this time the test team generated checklists required for test item operation and developed avenues for troubleshooting during follow-on testing. Without ground testing, the ability to maximize flight time and generate successful sorties throughout the fly window would have been significantly degraded.

### **Communicate Constantly About Configuration Changes and Requirements**

The Have DRAGON test team originally wrote the test plan assuming the DPA system was a set configuration. During ground testing, Stanford personnel notified the test team that DPA included two different configurations. The desire to execute all planned test points in each configuration would effectively double the planned flight time. This drove the test team to determine the highest priority system for data collection and clarify the requirements and desires of Stanford for data analysis. This change also required the test team to track DPA configurations flown during each sortie and develop guidance to dictate which DPA configuration would be flown for specific test points.

### **System Expert Presence Beneficial for Analysis and Troubleshooting**

Stanford personnel joined the test team for the entirety of ground testing. Their participation proved critical for troubleshooting test item issues stemming from integration with the test aircraft. Additionally, they were able to provide the test team with test item training that allowed the test team to create checklists for operation and identify when the system was not functioning as designed.

Stanford University GPS Labs software does already correct the DPA signal into azimuth and elevation in an East-North-Up reference system, providing very convenient data processing. The test team was not expecting to receive the level of support Stanford provided, and worked harder by not relying on the GPS Lab team as much as the team could have during data analysis.

**Double Check Assumptions. Different Model Aircraft Are Not the Same.**

During planning, the test team generated products and flight cards based on propeller RPM and power settings. These settings for the C-12J were assumed to be the same as those for the C-12C. However, the actual settings were different between the two airframes. Table F1 presents major observed differences between the two aircraft. Employment tactics are slightly different as well, as the 586<sup>th</sup> FLTS typically prefers a zero-flap take-off. Additionally, stall margins were determined for all steep turn maneuvers based on the C-12J-1 and aircraft gross weight. However, the aircraft empty weight violated the weights provided in the charts and required an additional buffer to be added to calculations. All configuration settings should be verified with operators early in planning to avoid last minute changes to test point conditions.

Table F1. Major Operations Limitations Differences between the C-12C and C-12J

Limitation:	C-12C	C-12J
Gear Retraction	163 KIAS	180 KIAS
Gear Extension	181 KIAS	180 KIAS
V <sub>MO</sub>	259 KIAS	247 KIAS
M <sub>MO</sub>	0.52 M	0.48 M
Flaps 40%	200 KIAS	168 KIAS
Flaps 100%	146 KIAS	153 KIAS
Flaps T/O	N/A	198 KIAS
Engine Temperature:	ITT (°C):	TGT (°C):
T/O	750	820
Continuous	725	810
Cruise	N/A	750
Prop RPM:	RPM	RPM
T/O	2000	1700
Continuous	2000	1700
Cruise	N/A	1550
Torque	100%	3400 ft-lbs

**The 586 FLTS is an Effective Test Organization. They're Very Efficient at Completing the T-2 Modification Process and Re-Focusing Efforts on the Test Articles.**

Modifications and hardware integration were handled entirely by the 586 FLTS. They implement a policy that enables signing off low risk modifications at the squadron commander level. This permits rapid approval and streamlines the modification process. This process enabled the test team to focus efforts on execution and data analysis preparation while having assurances of test aircraft and test item readiness.

**Organizations are Often Unaware of TPS Timelines.**

For Have DRAGON, data pre- and post-processing was conducted by outside organizations. The 746<sup>th</sup> prepared UHARS data while Stanford provided ARAIM and DPA data files. In both cases, these organizations were required to pre-process the data based on proprietary software and data formats. In most cases, these organizations were expeditious in providing data to the test team. However, the compressed timeline dictated by TPS requirements was often unknown to these organizations. This necessitated numerous follow-ups and requests from the test team to obtain data in a timely fashion to support their timeline.

**Rapid T-2 Modification Process does mean accepting some additional risk.**

During the first flight on takeoff, the computer rack housing the processing software for both DPA and ARAIM lost power. Weak cable connections came loose due to vibrations from the engine, and the sharp rotation. Once in the air, the cables were reconnected in flight, and the system powered back on successfully. The rack reported that DPA was not powered, but the team was happy to discover that DPA was still collecting data. Still, a complete and unexpected loss of power may have jeopardized system operation and could potentially damage the systems. Testing the system more diligently on the ground, prior to first launch, may have prevented the incident entirely. For a small-scope mission, such as this one, the rapid execution timeline was appropriate, but may induced problems or errors due to the expeditious preparation for execution.

This page was intentionally left blank.

# APPENDIX G – FTT MATRIX AND INDEPENDENT DATA POINTS

**Table G1. FTT Maneuver Matrix**

FTT	Configuration	Airspeed Band	Altitude Band	Tolerances	Limits	Procedure	Data Responsibilities
Straight and Level	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / FAS - 180 KIAS	5,000 ft MSL - 20,000 ft MSL	± 200 feet ± 15 KIAS	BAL	Set power as required Stabilize within databand for 3 mins	PF: Advise when on condition TC: Record maneuver start and stop time
Shallow Turn >30 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / FAS - 180 KIAS	5,000 ft MSL - 20,000 ft MSL	± 200 feet ± 15 KIAS ± 5° AOB	BAL	Set power as required Stabilize within databand for 3 mins	PF: Advise when on condition TC: Record maneuver start and stop time
500 ft/min Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	5,000 ft MSL - 20,000 ft MSL	500 ±250 feet/min ROC ± 5° AOB	BAL	Set power to establish 500 ft/min at 160 KIAS Pitch to establish and maintain 500 ft/min climb Stabilize within databand for 3 mins	PF: Advise when on condition TC: Record maneuver start and stop time
500 ft/min Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	20,000 ft MSL - 5,000 ft MSL	500 ±250 feet/min ROD ± 5° AOB	BAL	Set power to maintain 500 ft/min at 160 KIAS Pitch to establish and maintain 500 ft/min descent Stabilize within databand for 3 mins	PF: Advise when on condition TC: Record maneuver start and stop time
500 ft/min Spiraling Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 15,000 ft MSL	500 ±250 feet/min ROC 30± 5° AOB	BAL	Set power to establish 500 ft/min at 160 KIAS Simultaneously pitch up and roll to establish a 500 ft/min climb at 30° AOB Stabilize within databand for 3 mins	PF: Advise when on condition TC: Record maneuver start and stop time
500 ft/min Spiraling Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	15,000 ft MSL - 10,000 ft MSL	500 ±250 feet/min ROD 30± 5° AOB	BAL	Simultaneously pitch down and roll to establish a 500 ft/min climb at 30° AOB Stabilize within databand for 3 mins	PF: Advise when on condition TC: Record maneuver start and stop time
Sleep turn >60 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	5,000 ft MSL - 20,000 ft MSL	± 200 feet ± 15 KIAS ± 15° AOB	BAL	Set power to maintain 160 KIAS Simultaneously roll to 60 AOB whilst increasing back sick pressure to maintain level Stabilize within databand for 720° of heading change	PF: Advise when on condition TC: Record maneuver start and stop time
Bank to Bank Rolls 60 - 60 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	5,000 ft MSL - 20,000 ft MSL	± 200 feet ± 15 KIAS 60-5° AOB	BAL	Set power as required Trim for level flight Establish 60° left bank, <i>smoothly</i> (≥ 3 sec yoke reversal) reverse roll to 60° right bank Return to level flight Establish 60° right bank, <i>smoothly</i> (≥ 3 sec yoke reversal) reverse roll to 60° left bank Return to level flight	PF: Advise when on condition TC: Record maneuver start and stop time
1,000 ft/min Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 20,000 ft MSL	± 500 feet/min ± 15 KIAS	BAL	Set power to maintain 1,000 ft/min at 160 KIAS Pitch to establish and maintain maximum rate of climb Stabilize within databand for 3 mins	PF: Advise when on condition TC: Record maneuver start and stop time
1,000 ft/min Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	20,000 ft MSL - 10,000 ft MSL	± 500 feet/min ± 15 KIAS	BAL	Set power to maintain 1,000 ft/min at 160 KIAS Pitch to establish and maintain 1,000 ft/min rate of descent Stabilize within databand for 3 mins	PF: Advise when on condition TC: Record maneuver start and stop time
1,000 ft/min Spiraling Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 20,000 ft MSL	± 500 feet ± 15 KIAS 60-5° AOB	BAL	Set power to maintain 1,000 ft/min at 160 KIAS Simultaneously pitch up and roll to establish a maximum rate of climb at 30° AOB Stabilize within databand for 3 mins	PF: Advise when on condition TC: Record maneuver start and stop time
1,000 ft/min Spiraling Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	20,000 ft MSL - 10,000 ft MSL	± 500 feet ± 15 KIAS 60-5° AOB	BAL	Simultaneously pitch down and roll to establish a 1,000 ft/min climb at 30° AOB Stabilize within databand for 3 mins	PF: Advise when on condition TC: Record maneuver start and stop time
Tower Fly By	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	150 ft AGL - 250 ft AGL	± 50 feet ± 5 KIAS	BAL	Establish on downwind at 3500 and call "Downwind, Flyby, Airspeed" Remain above 500' AGL over Hwy 58 and above 400' AGL at final Descend to 100/200' AGL, establish on the line by mid takeoff Fly 3 minute leg on nominated heading Set cruise power and trim for straight, level flight	PF: Advise when on condition TC: Record maneuver start and stop time
Race Track	Prop RPM - 1550 Flaps - Up Gear - Up	Refer to Test Condition Matrix	10,000 ft MSL - 20,000 ft MSL	± 200 feet ± 15 KIAS 30±5° AOB	BAL	Roll left establish and maintain an instrument standard rate turn Fly 3 minute leg on reciprocal heading Roll left establish and maintain an instrument standard rate turn Roll out on original heading	PF: Advise when on condition TC: Record maneuver start and stop time

Table G2. Benign FTT Independent Data Points

Phase	FTT	Configuration	Airspeed Band	Altitude Band	FTTs Flown	Total Independent Data Points Flown		
						ARAIM	DPA - SDR	DPA - uBloX
Benign	Straight and Level	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / FAS - 180 KIAS	5,000 ft MSL - 20,000 ft MSL	15	15	9	6
Benign	Shallow Turn <30 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / FAS - 180 KIAS	5,000 ft MSL - 20,000 ft MSL	12	12	6	6
Benign	500 ft/min Rate of Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	5,000 ft MSL - 20,000 ft MSL	9	9	4	5
Benign	500 ft/min Rate of Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	20,000 ft MSL - 5,000 ft MSL	11	11	6	5
Benign	500 ft/min Spiraling Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 15,000 ft MSL	7	7	2	5
Benign	500 ft/min Spiraling Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	15,000 ft MSL - 10,000 ft MSL	10	10	5	5

Table G3. Limited Tactical FTT Independent Data Points

Phase	FTT	Configuration	Airspeed Band	Altitude Band	FTTs Flown	Total Independent Data Points Flown		
						ARAIM	DPA - SDR	DPA - uBloX
Tactical	Steep turn <60 AOB	Prop RPM - 1550 Flaps - Up	160 KIAS / 140 - 180 KIAS	5,000 ft MSL - 20,000 ft MSL	6	6	5	1
Tactical	Bank to Bank Rolls 60 - 60 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	5,000 ft MSL - 20,000 ft MSL	11	11	10	1
Tactical	1,000 ft/min of Climb Check	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 20,000 ft MSL	3	3	3	0
Tactical	1,000 ft/min Rate of Descent Check	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	20,000 ft MSL - 10,000 ft MSL	4	4	3	1
Tactical	1,000 ft/min Spiraling Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 20,000 ft MSL	4	4	3	1
Tactical	1,000 ft/min Spiraling Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	20,000 ft MSL - 10,000 ft MSL	4	4	3	1

Table G4. Low-Level FTT Independent Data Points

Phase	FTT	Configuration	Airspeed Band	Altitude Band	FTTs Flown	Total Independent Data Points Flown		
						ARAIM	DPA - SDR	DPA - uBlox
Tower Fly By	Tower Fly By	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	150- 250 ft AGL	6	6	3	3
Landing	Instrument Approach & Landings	Shallow turns & descents IAW approach procedures ILS and TACAN approach	FAS	IAW DoD FLIP approach plate	6	6	3	3
Low Level Operations in Mountainous Terrain	Straight and Level	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	>500 ft AGL	9	9	3	6
Low Level Operations in Mountainous Terrain	Shallow Turn <30 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	>500 ft AGL	5	5	2	3
Low Level Operations in Mountainous Terrain	Steep turn <60 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	>500 ft AGL	3	3	0	3
Low Level Operations in Mountainous Terrain	Bank to Bank Rolls 60 - 60 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	>500 ft AGL	3	3	0	3
Low Level Operations in Mountainous Terrain	Steep Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	>500 ft AGL	3	3	0	3
Low Level Operations in Mountainous Terrain	Steep Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	>500 ft AGL	3	3	0	3
Low Level Operations Overwater	Straight and Level	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	>500 ft AGL	3	3	3	0
Low Level Operations Overwater	Shallow Turn <30 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	>500 ft AGL	3	3	3	0

Table G5. GPS Jamming FTT Independent Data Points

Phase	FTT	Configuration	Airspeed Band	Altitude Band	FTTs Flown	Total Independent Data Points Flown		
						ARAIM	DPA - SDR	DPA - uBlox
Jamming	Straight and Level	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / FAS - 180 KIAS	5,000 ft MSL - 24,500 ft MSL	5	5	2	3
Jamming	Shallow Turn >30 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / FAS - 180 KIAS	5,000 ft MSL - 24,500 ft MSL	4	4	1	3
Jamming	500 ft/min Rate of Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	5,000 ft MSL - 24,500 ft MSL	4	4	2	2
Jamming	500 ft/min Rate of Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	24,500 ft MSL - 5,000 ft MSL	3	3	1	2
Jamming	500 ft/min Spiraling Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 15,000 ft MSL	4	4	2	2
Jamming	500 ft/min Spiraling Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	15,000 ft MSL - 10,000 ft MSL	3	3	1	2
Jamming	Steep turn <60 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	5,000 ft MSL - 24,500 ft MSL	3	3	0	3
Jamming	Bank to Bank Rolls 60 - 60 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	5,000 ft MSL - 24,500 ft MSL	3	3	0	3
Jamming	1,000 ft/min of Climb Check	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 24,500 ft MSL	2	2	1	1
Jamming	1,000 ft/min Rate of Descent Check	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	24,500 ft MSL - 10,000 ft MSL	2	2	1	1
Jamming	1,000 ft/min Spiraling Climb	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 24,500 ft MSL	0	0	0	0
Jamming	1,000 ft/min Spiraling Descent	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	24,500 ft MSL - 10,000 ft MSL	0	0	0	0
Jamming	Racetrack - Straight and Level	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 24,500 ft MSL	11	11	5	6
Jamming	Racetrack - Shallow Turn <30 AOB	Prop RPM - 1550 Flaps - Up Gear - Up	160 KIAS / 140 - 180 KIAS	10,000 ft MSL - 24,500 ft MSL	11	11	5	6

## APPENDIX H – ABBREVIATIONS, ACRONYMS, AND SYMBOLS

<u>Abbreviation</u>	<u>Definition</u>	<u>Units</u>
AFB	Air Force Base	---
AFTC	Air Force Test Center	---
AOB	Angle of Bank	---
ARAIM	Advanced Receiver Autonomous Integrity Monitoring	---
ARINC	Aeronautical Radio, Incorporated	---
CFIT	Controlled Flight Into Terrain	---
COTS	Commercial-Off the Shelf	---
DAF	Department of the Air Force	---
DRAGON	Detect, Recognize and Adapt to GPS Overt Noise	---
DOA	Direction of Arrival	degrees
DOP	Dilution of Precision	---
DPA	Dual Polarized Antenna	---
EGT	Exhaust Gas Temperature	---
ENU	East-North-Up	---
EU	European Union	---
FAA	Federal Aviation Administration	---
FAS	Final Approach Speed	knots
FLTS	Flight Test Squadron	---
FTT	Flight Test Technique	---
GLONASS	Global Navigation Satellite System (Russian)	---
GNSS	Global Navigation Satellite System	---
GPS	Global Positioning System	---
HPJ	High Powered Jammer	---
HPL	Horizontal Protection Level	meters
IAW	in accordance with	---
ID	Identification	---
INS	Inertial Navigation System	---
ITT	Inlet Turbine Temperature	---
JON	Job Order Number	---
LDTO	Lead Developmental Test Organization	---
LHCP	Left-Hand Circular Polarized	---
LT	Lieutenant	---

KIAS	Knots Indicated Airspeed	knots
KTAS	Knots True Airspeed	knots
LNA	Low Noise Amplifiers	---
MAAST	MatLab Algorithm Availability Simulation Tool	---
MatLab	Matrix Laboratory	---
MSL	Mean Sea Level	ft
NAVFEST	Navigation Festival	---
NAVSTAR	Navigation Signal Timing and Ranging	---
NDB	Non-Directional Beacons	---
NGA	National Geospatial Agency	---
OI	Operating Instructions	---
PBJ	Portable Box Jammer	---
PCB	Printed Circuit Board	---
PDU	Power Distribution Unit	---
PL	Protection Level	meters
PSN	Pseudo-Random Noise	---
RAAF	Royal Australian Air Force	---
RAIM	Receiver Autonomous Integrity Monitoring	---
RF	Radio Frequency	---
RHCP	Right-Hand Circular Polarized	---
RINEX	Receiver Independent Exchange Format	---
RPA	Remote Piloted Aircraft	---
RVSM	Restricted Vertical Separation Minimums	---
SDR	Software-Defined Radio	---
S/N	Serial Number	---
TIM	Technical Information Memorandum	---
TMP	Test Management Project	---
T.O.	Technical Order	---
T/O	Take-off	---
TPS	Test Pilot School	---
TSPI	Time Space & Position Information	---
UHARS	Ultra-High Accuracy Receiver System	---
US	United States	---
USAF	United States Air Force	---
USN	United States Navy	---

VHF	Very-High Frequency	---
VPL	Vertical Protection Level	meters
VOR	VHF Omnidirectional Range	---
WAAS	Wide Area Augmentation System	---

This page was intentionally left blank.

## APPENDIX I – DISTRIBUTION LIST

	<u>Number of Copies</u>		
	<u>E-mail</u>	<u>Digital</u>	<u>Paper</u>
<u>Onsite</u>			
Test Pilot School Attn: Mr. David Vanhoy 220 Wolfe Ave, Edwards AFB CA 93524 Email: <a href="mailto:david.vanhoy@us.af.mil">david.vanhoy@us.af.mil</a>	1	0	0
Edwards AFB Technical Research Library Attn: Darrell Shiplett 307 E Popson Ave Edwards AFB CA 93524	0	0	2
AFTC/HO Attn: AF Test Center/HO Mailbox 305 E Popson Ave Edwards AFB CA 93524	1	0	0
<u>Offsite</u>			
Test Pilot School Attn: Captain Christopher Fulton 3601 Fairgreen Lane Palmdale CA 93551 Email: <a href="mailto:christopher.fulton.6@us.af.mil">christopher.fulton.6@us.af.mil</a>	1	0	0
Defense Technical Information Center Submit per DTIC procedures Attn: DTIC-O 8725 John J. Kingman Rd, Ste 0944 Ft Belvoir VA 22060 Email: <a href="mailto:aq@dtic.mil">aq@dtic.mil</a>	1	0	0
Stanford GPS Laboratory, Aeronautics & Astronautics Department Attn: Sherman Lo 496 Lomita Mall Stanford, CA 94305 Email: <a href="mailto:daedalus@stanford.edu">daedalus@stanford.edu</a>	1	0	0
Total	4	0	2