



**DESIGN AND DEVELOPEMENT OF A UNIQUE TWO-WAY FIELD PROBE
SYSTEM USING A SHIELDED OCTOCOPTER**

THESIS

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AFIT-ENG-MS-17-M-042

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THESIS

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Andrew J. Knisely, B.S.E.E

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THESIS

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Abstract

Accurate Radar Cross Section (RCS) measurements are most reliable if the uncertainty of these measurements can be quantified. The particular contributor to uncertainty examined in this research occurs when an electromagnetic (EM) wave transmitted from the radar deviates from its planar form as it traverses towards a target. The cause of this deviation results from interference within the test volume or medium between the radar and target. The method to quantify this uncertainty involves using a shielded octocopter as a unique two-way field probe.

A canonical shield is required to encapsulate the octocopter, as it provides a predictable RCS profile used to quantify the test volume's effect on an EM wave. The shield designs to consider are canonical shapes drafted in CUBIT and measured in SENTRI software to simulate and assess backscatter RCS. A squat-cylinder shield is fabricated as a result of these simulations. High frequency RCS measurements (2 - 18GHz) of the shield reveal that a frequency less than 2.8 GHz effectively conceals the octocopter's RCS profile.

Position and pose measurements acquired from the octocopter's u-blox GPS, Piksi DGPS, and INS modules are characterized to determine the uncertainty of the drone's navigation scheme as this can affect the accuracy of magnitude and phase measurements acquired when probing a test volume. The most effective position solution is acquired from the Piksi DGPS, accurate to 2.8cm. The shielded octocopter developed in this research demonstrates that it is possible to use this system as a two-way field probe.

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Andrew J. Knisely

Table of Contents

	Page
Abstract	iv
Acknowledgements	v
Table of Contents	vi
List of Figures	ix
List of Tables	xii
List of Acronyms	xiii
I. Introduction	1
1.1 Background	2
1.2 Problem Description	3
1.3 Research Focus	4
1.4 Investigative Questions	5
1.5 Methodology Overview	6
1.6 Assumptions	7
1.7 Research Significance	7
1.8 Preview	8
II. Literature Review	9
2.1 Radar Cross Section	9
2.2 Field Probe	11
2.2.1 Standard Field Probes	12
2.2.2 Unique Two-Way Field Probe Concept	13
2.3 Navigation Fundamentals	18
2.3.1 Global Positioning System	18
2.3.2 Differential GPS	20
2.3.3 Inertial Navigation System	21
2.3.4 Waypoint Navigtion	23
2.4 Uncertainty Analysis	25
2.5 Octocopter	26

2.6 Summary	27
III. Methodology	28
3.1 GPS Characterization.....	28
3.1.1 Piksi DGPS Characterization Trials.....	32
3.1.2 u-blox Characterization Trials.....	34
3.2 INS Characterization.....	36
3.2.1 Pitch and Roll Characterizations	37
3.2.2 Yaw Characterizations	39
3.3 Position-Pose Time Differential Characterization	40
3.4 Pixhawk-Piksi Integration	45
3.5 Field Probe Shield Design and Development.....	47
3.6 Field Probe Shield Construction and Integrtrion	49
3.6.1 Squat Cylinder Design, Construction, and Integration.....	50
3.6.2 Geodesic Sphere Design, Construction, and Integration.....	52
3.7 Shield RCS Measurements.....	54
3.7.1 AFIT ACER Radar Calibration.....	54
3.7.2 ACER High Frequency RCS Measurements.....	55
3.7.3 Outdoor RCS Range Preparation.....	58
3.8 Field Probe Measurement Procedure	61
3.9Summary.....	64
IV. Results.....	65
4.1 Piksi Module Characterization	65
4.1.1 Piksi Static Trials.....	65
4.1.2 Piksi Dynamic Trials	68
4.2 u-blox LEA-6 GPS Characterization.....	71
4.3 INS Characterization	76
4.4 Position-Pose Characterization Summary	82
4.5 Shield Design RCS Prediction Analysis	83
4.6 Solid Shield Design RCS Prediction Analysis.....	92
4.7 Field Probe Flight Testing and RCS Characterization.....	98

4.7.1 Solid-Shielded Octcopter Flight Performance	98
4.7.2 High Frequency RCS Characterizations (Squat Cylinder).....	103
4.8 Summary.....	112
V. Conclusions and Recommendations.....	114
5.1 Conclusions.....	114
5.2 Significance.....	119
5.3 Research Recommendations.....	120
5.4 Summary.....	122
Bibliography.....	123

List of Figures

	Page
1. Polar Plots of Corner Reflector and Sphere RCS Profiles	10
2. Incident EM Plane Wave Deviation	12
3. Standard Field Probe Configurations.....	13
4. Unique Two-Way Field Probe Concept.....	14
5: Geodesic Sphere Shielding A Tihedral.....	15
6. Indoor Field Probe	17
7. Basic GPS Geolocation Scheme	19
8. DGPS Scheme.....	20
9. Mechanical Accelerometer and Gyroscope	22
10. Mission Planner Flight Plan.....	24
11. 3DR X8 Octocopter	26
12a. Piksi-NovAtel Base Station System Architecture	29
12b. Piksi-NovAtel Rover System Architecture.....	30
13. NovAtel and Piksi Characterization Apparatus	31
14. Piksi Console Display of SPP Solutions.....	32
15. Pitch and Roll Tilt Table Apparatus	38
16. Yaw Characterization - Turn Table Apparatus	40
17. Position-Pose Alignment System Architecture.....	42
18. UDP Data Stream Set-up between Mission Planer and C++ Program	44
19. 3DR Pixhawk and Piksi Serial 4/5 Connection	46
20. CUBIT Meshes of Squat Cylinder, T-B Sphere, and Torus Ring	48

21.	SENTRI Backscatter RCS cuts, Waterline Scan and Vertical Scan	49
22.	X8 Octocopter Frame Modifications with L channel extensions	50
23.	Squat Cylinder Shield and Frame Extensions.....	51
24.	Shielded Octocopter Positioning and Communication Components.....	52
25.	Geodesic Sphere Cage Design	53
26.	ACER Facility, Shielded Octopter mounted on Cylinder Foam Column.....	57
27.	Target Items, Actual and Theoretical.....	57
28.	Ground Control Station Set-up	58
29.	Outdoor RCS Range with AFIT RNR and GCS Layout	60
30.	Radar Van and Field Probe	60
31.	Piksi RTK vs. NovAtel RTK Static Trial 1	66
32.	Piksi Position Solutions vs. NovAtel Truth Position (Trial 1)	68
33.	Piksi Position Solutions vs. NovAtel Truth Position.....	69
34.	u-blox vs. NovAtel GPS Solution Static Trial	72
35.	u-blox - NovAtel Data Alignment	73
36.	NovAtel and u-blox Lap Extraction.....	74
37.	Extracted Pitch Samples	76
38.	Extracted Roll Samples.....	78
39.	Extracted Yaw Samples	80
40.	C++ Time Stamp Samples Overlaid with Mission Planner Samples	84
41.	Time Stamped and Aligned Position and Pose (Field Probe Flight)	85
42.	Live and Replay Data Sets for Trials 9 and 10	86
43.	Inaugural Square Path Flight Program, Position-Pose Time Difference	87

44.	GPS-Triggered Radar Pulses	89
45.	Time Difference Between Each Successive Pulse.....	89
46.	Waterline Scan Global RCS, Squat Cylinder	92
47.	Vertical Scan Global RCS, Squat Cylinder	92
48.	Waterline Scan Global RCS, T-B Sphere	94
49.	Vertical Scan Global RCS, T-B Sphere	94
50.	Waterline RCS Scans [300, 500, 700 MHz]	96
51.	10° Horizontal Slant RCS Scans [300, 500, 700 MHz]	97
52.	Initial Flight Test Satellite Count (u-blox LEA-6 GPS)	99
53.	Piksi Altitude Samples vs. Acquired Satellite Samples.....	100
54.	u-blox Satellite Count, Battery Voltage Level, and Throttle Percent	101
55.	Global RCS Plots (0° Elevation "Waterline")	103
56.	Global RCS Plots, Shielded Octocopter (Varied Elevation Angles)	104
57.	Composite ISAR (All Targets)	105
58.	Shielded Octocopter RCS Sector Averages (4 cuts).....	106
59.	Sector Averages (2-4 GHz).....	107
60.	Shielded - Only RCS Sector Averages (20 cuts)	108
61.	Shielded Octocopter RCS Sector Averages (20 cuts).....	108

List of Tables

	Page
1. Pitch and Roll Test Angles	37
2. Yaw Test Angles.....	39
3. Piksi Base Station and Rover Software Settings.....	45
4. Mission Planner Configuration Settings for Pixhawk	46
5. ACER High Frequency Test Matrix	56
6. Piksi Static Trials, RTK Fix Statistics	67
7. Piksi Dynamic Trials, RTK Statistics	70
8. Piksi Altitude Statistics	71
9. u-blox Static Trial Statistics.....	73
10. u-blox Dynamic Trial Statistics	75
11. Pitch Statistics.....	77
12. Roll Statistics	79
13. Yaw Statistics.....	81
14. Position and Pose Accuracy Characterization	82
15. Flight Program Time Difference Mean and Standard Deviations	87
16. Pulse Time Differential for Position/Pose Acquired from C++ Program.....	90
17. Position\Pose Telemetry Rate Characterization.....	116

List of Acronyms

ACER - AFIT Advanced Compact Electromagnetic Range

AFIT - Air Force Institute of Technology

ANT - Autonomous Navigation Technology

CEM - Computational-Electromagnetic

COTS - Commercial Off The Shelf

DGPS - Differential Global Positioning System

DRMS - Distance Root Mean Square

EM - Electromagnetics

FEM - Finite Element Method

GCS - Ground Control Station

GPS - Global Positioning System

HH - Horizontal Horizontal

IAR - Integer Ambiguity Resolution

INS - Inertial Navigation System

IMU - Inertial Measurement Unit

LLA - Latitude - Longitude - Altitude

MAVLINK - Micro Air Vehicle Communication Protocol

MEMs - Micro Electro Mechanical System

MRSE - Mean Radial Spherical Error

NED - North - East - Down

NRTF - National Radar Test Facility

PP - Phi Phi

RAM - Radar Absorbent Material

RCS - Radar Cross Section

RNR - Random Noise Radar

RTK - Real Time Kinematic

SPP - Single Point Precision

T-B - Topless-Bottomless

TCP - Transmission Control Protocol

TT - Theta Theta

UDP - User Datagram Protocol

VV - Vertical Vertical

DESIGN AND DEVELOPMENT OF A UNIQUE TWO-WAY FIELD PROBE SYSTEM USING A SHIELDED OCTOCOPTER

I. Introduction

Since the 1980's, stealth technology has become an integral feature of the modern warfighter. Stealth technology allows the user to counter radar systems by avoiding detection while in adversary air space. As a result of this technology, new requirements for improving radar cross section (RCS) measurements have been issued to make airframes meet criteria for low radar cross-section [8]. RCS measurements are conducted in indoor and outdoor test ranges, each with unique advantages and disadvantages. The indoor compact range allows for a controlled environment in which radar absorbing material (RAM) is used to minimize reflected electromagnetic (EM) wave interference while measuring a target's RCS. Maintaining an indoor compact range can be costly. The size of the test facility is a limitation to the size of the target under test. As a result, an outdoor range is desirable for measuring the RCS of a large object such as aircraft. However, an outdoor RCS range is subject to interference from ground clutter and other possible sources such as rain, humidity, temperature, insects, and animals [21]. In either case, the overall size of outdoor and indoor ranges are dependent on the far-field requirements for RCS measurements coupled with the frequency of the operation and target size anticipated [17]. It is desired to obtain accurate magnitude and phase measurements of an incident EM wave on the target to accurately measure and characterize the target's RCS profile.

1.1 Background

RCS measurement programs must consider the objectives of the experiment and the operational applications such as far-field, polarization, instrumentation sensitivity, and range facility requirements as a part of program planning [17]. RCS is an important parameter for the design of modern aircraft, missiles, helicopters, military ground vehicles, launchers, airport buildings, and other important strategic installations; however, it can be difficult to consider all possible phenomena that occur during an RCS measurement [23]. A method of documenting and reporting measurement uncertainties must be employed at range facilities to assess the various individual errors that contribute to the overall uncertainty in an RCS measurement [4].

Understanding the effects on an EM wave that traverses a test volume during an RCS measurement requires the use of a field probe. A field probe is a tool that quantifies sources of error and uncertainty in RCS measurements by measuring the deviation of the illuminating field from the ideal plane wave. In the case of a two-way field probe, radar is used to transmit uniform EM waves towards a target and then receive reflected EM waves that scatter away from the target. A magnitude and phase comparison is assessed between the ideal (calibrated) RCS measurements and the RCS measurements taken at different locations within the test volume. It is desired that the target takes the form of a canonical shape in order to properly characterize the behavior of the EM field. A canonical shape such as a sphere or a cylinder consists of known scattering phenomenology that can be predicted analytically and computationally. The difference between the measured RCS throughout the test volume and the calibrated (truth) RCS determines the perturbations of the incident plane wave, thus provides an indication of the test volume's effect on the EM wave behavior.

1.2 Problem Description

Current field probes used in practice require timely set-up using support structures at various locations within the test volume to obtain a collection of RCS measurements. This repetitious process can introduce uncertainty and ambiguity in the probe's measurement of the EM wave. The ambiguity may arise from changes in the frequency, polarization, propagation direction, signal modulation, and orientation of the probe with respect to the direction of the electromagnetic field vector each time the probe is used [13]. Previous research conducted at the Air Force Institute of Technology (AFIT) has explored a unique two-way field probe concept involving a commercial off the shelf (COTS) quadcopter-drone encased in a geodesic sphere to measure the EM waves while traversing an indoor test volume [7, 10]. A drone offers an agile method of moving the probe throughout the test volume without the need of a support structure that could interfere with the probe measurement. The utilization of a drone for dynamic probe measurements requires a characterization of the uncertainty that occurs in its position defined by coordinate vectors; x , y , z , and pose defined by its angular rotations; pitch, roll, and yaw. This is necessary, as the magnitude and phase information acquired from the field probe's RCS are dependent on these quantities.

Indoor compact range testing involved the use of VICONTM Motion Capturing systems to report the position and pose of the drone as it navigated within a GPS denied environment. VICONTM measures the position and pose with high precision compared to the GPS and INS modules that are onboard the drone [10]. Aside from the inaccuracies of the drone's onboard positional systems, many factors in the outdoor environment may contribute to the position and pose errors, including GPS signal clutter from tall trees or buildings, weather conditions such as wind or rain, and signal disturbances in the communication link between the ground control

station and drone caused by neighboring frequency emitters. Inaccurate measurements of the field probe's position and pose will lead to an inaccurate RCS measurement.

1.3 Research Focus

The main focus of this research is to develop a unique two-way field probe system that is capable of quantifying RCS measurement uncertainty at an outdoor RCS range using a shielded octocopter. The octocopter relies on the global positioning system (GPS) and inertial navigation system (INS) to perform waypoint navigation. The accuracy of each system must be characterized as they contribute to the measured position and pose, respectively. The accuracy in the field probe's position and pose is a major contributor to the uncertainty of the field probe's RCS measurement, therefore, it is critical to identify its precise location and orientation when a measurement is conducted. Assuming an ideal EM plane wave incident on the field probe, the extracted magnitude and phase quantities received from the probe's RCS is a function of the position and pose relative to the incident EM plane wave. If the probe maintains orientation and changes position, the phase measurement will vary as a function of the probe position downrange from the radar. If the probe maintains position and changes orientation, the magnitude of the probe's RCS will vary as a function of the probe's pose. Differential GPS (DGPS) must be implemented on the octocopter to improve position accuracy. The position and pose measurements acquired from the octocopter must also be time-aligned to ensure these quantities can be paired with an RCS measurement of the field probe acquired from radar.

1.4 Investigative Questions

The following questions must be posed to explore the use of an octocopter as a two-way field probe to conduct electromagnetic field measurements at an outdoor RCS range:

- 1.) How accurate is the octocopter's position and pose? The outdoor operation of the octocopter requires use of the drone's onboard GPS and INS. Each system has an accuracy threshold that must be characterized.
- 2.) What is the time differential between the GPS and INS telemetry update rates? This difference must be characterized to interpret the time stamp alignment between position and pose data recorded from the octocopter's telemetry stream.
- 3.) What shield designs are ideal for this field probe technique? The shield must satisfy RCS requirements while avoiding inhibition of the drone's aerodynamic performance.
- 4.) How does the selected shield design effect the octocopter's communication link and positioning system? The shield may attenuate incoming and outgoing signals of the GPS and telemetry stream.
- 5.) How is the octocopter's flight performance affected by the shield during an outdoor demonstration? The octocopter must be able to navigate the desired waypoint pattern while encapsulated with the shield and subjected to weather conditions that may occur realistically at an outdoor RCS range.

1.5 Methodology Overview

A critical component of this thesis is to establish a ground control station that can operate the octocopter by means of autonomous waypoint navigation as well as a method for recording position and pose data from the octocopter's GPS and INS modules. This involves using Mission Planner, a commercially accessible software that is compatible with the octocopter's flight controller, 3DR Pixhawk 32-bit autopilot system. A Piksi differential GPS (DGPS) module is used to provide accurate real time kinematic (RTK) position solutions to the octocopter's flight controller. This system needs to be characterized to determine the accuracy and precision of the reported position values. The Piksi Console software monitors the DGPS module's satellite reception, signal strength, and reported locations relative to the ground control station.

A canonical conductive shield encompassing the octocopter is designed and measured using CUBIT and SENTRi software, respectively. The shield design is limited by the placement of the Piksi DGPS module and the octocopter's thrust to weight ratio. The Piksi rover module must be positioned on the shielded octocopter to enable the reception of adequate GPS satellite signal strength and to provide position telemetry to the Piksi base station connected to the ground control station. The octocopter's telemetry communication must also be unperturbed by the shield, as it provides the vehicle's status via 3DR 915MHz Wireless Radio antennae.

Flight testing will determine the shield's aerodynamic impact on the octocopter as it navigates and executes maneuvers to accomplish desired flight patterns. Satellite reception, throttle usage, and battery life will be monitored from the Mission Planner telemetry. Analysis of the octocopter's position and pose measurements acquired from these flight tests will be examined for time-stamp alignment to determine if a program is needed to align and record position and pose and ensure an equal quantity of time-stamped samples. Ultimately, a field

probe system capable of outdoor navigation and recording position and pose measurements is the final product of this research.

1.6 Assumptions

The following assumptions are made to limit the scope of this research project:

- 1.) The octocopter's shield design will be optimized for AFIT's Random Noise Radar (RNR) operable frequency range of 300MHz to 700MHz.
- 2.) The pitch and roll of the octocopter will not exceed $\pm 10^\circ$ for a given flight program.
Therefore, the shield will only be illuminated within $\pm 10^\circ$ from the radar.
- 3.) The iGaging Angle Cube, accurate to $\pm 0.2^\circ$, will be used as a truth source for characterizing the accuracy of the octocopter's inertial measurement unit.
- 4.) The AFIT ANT Center NovAtel GPS, accurate to ± 0.007 m, will provide truth position coordinates to compare with the Piksi DGPS module and the u-blox LEA6 GPS position coordinates to determine each system's accuracy.
- 5.) The communication link between the ground station and octocopter will not interfere with the RCS measurements recorded from the radar.

1.7 Research Significance

Sponsorship for this research is provided by the National RCS Test Facility (NRTF), Holloman Air Force Base, New Mexico. The NRTF has a large outdoor RCS test range for measuring the RCS of large objects. The operation and timeliness of field probe measurements

at a large outdoor test facility are crucial from a cost and efficiency perspective. Currently, the uses of dynamic field probes are experimental. Previous research conducted at AFIT has demonstrated proof of concept for utilizing this unique two-way field probe to measure EM waves traversing a test volume, only to yield inconclusive RCS measurements as a result of deformations in the probe's shielding mechanism. The current research effort aims to provide a system that demonstrates the effectiveness of this proposed field probing technique. Analysis will include the characterization of the octocopter's position and pose as well as shield design analysis that involves RCS measurements obtained from a Computational Electromagnetic (CEM) solver and AFIT's Advanced Compact Electromagnetic Range (ACER) facility.

The results of this research will provide the NRTF a system developed and designed to conduct two-way field probe measurements at an outdoor RCS range. Successful results will lead to a reformed field probing technique that will improve RCS measurement accuracy and simplify the probe measurement process.

1.8 Preview

This thesis is organized into five chapters. *Chapter II* provides the overview and explanation of literary concepts pertaining to radar measurements and the octocopter's navigation systems. The procedural guidelines for developing the octocopter's shield design, characterizing the octocopter's position and pose uncertainties, Piksi-Pixhawk Integration, and octocopter flight testing are discussed in *Chapter III*. The results obtained from testing are examined in *Chapter IV*. *Chapter V* concludes the research by summarizing the results and analysis obtained from the shielded octocopter flight tests to determine the direction of future work intended to expand this research.

II. Literature

This chapter describes the literary concepts and terminology associated with the unique two-way field probe concept such as radar cross section, navigation, and measurement uncertainty. The use of standard field probes and their limitations are discussed. Previous research related to the use of a drone as a two-way field probe is also presented to provide the foundation and direction of this current research effort presented in this thesis. The relationship between position and pose uncertainty and how it affects the probe's RCS measurements is also explained.

2.1 Radar Cross Section

"Radar Cross Section (RCS) is a key parameter used in radar design, target detection, and system benchmarks" [14]. It is typically defined to be a "far-field parameter that represents the effective target area as seen by the radar" [14]. EM waves transmitted from radar will excite the surface currents on the measured target, causing re-radiation of an EM wave. The shape of a perfectly electrical conductor (PEC) target will dictate the scattering phenomena that can occur under the presence of incident EM waves [13]. An EM wave will reflect towards the monostatic radar receiver if it is normally incident upon a relatively planar surface or scatter in all directions (diffract) if the EM wave is normally incident on corners, edges, or curved surfaces. A prominent RCS return is indicative of specular reflection, where most of the incident EM wave is reflected towards the radar's antenna receiver. Creeping waves occur as a form of diffraction in which the incident EM wave re-radiates after traveling around the back of a curved surface.

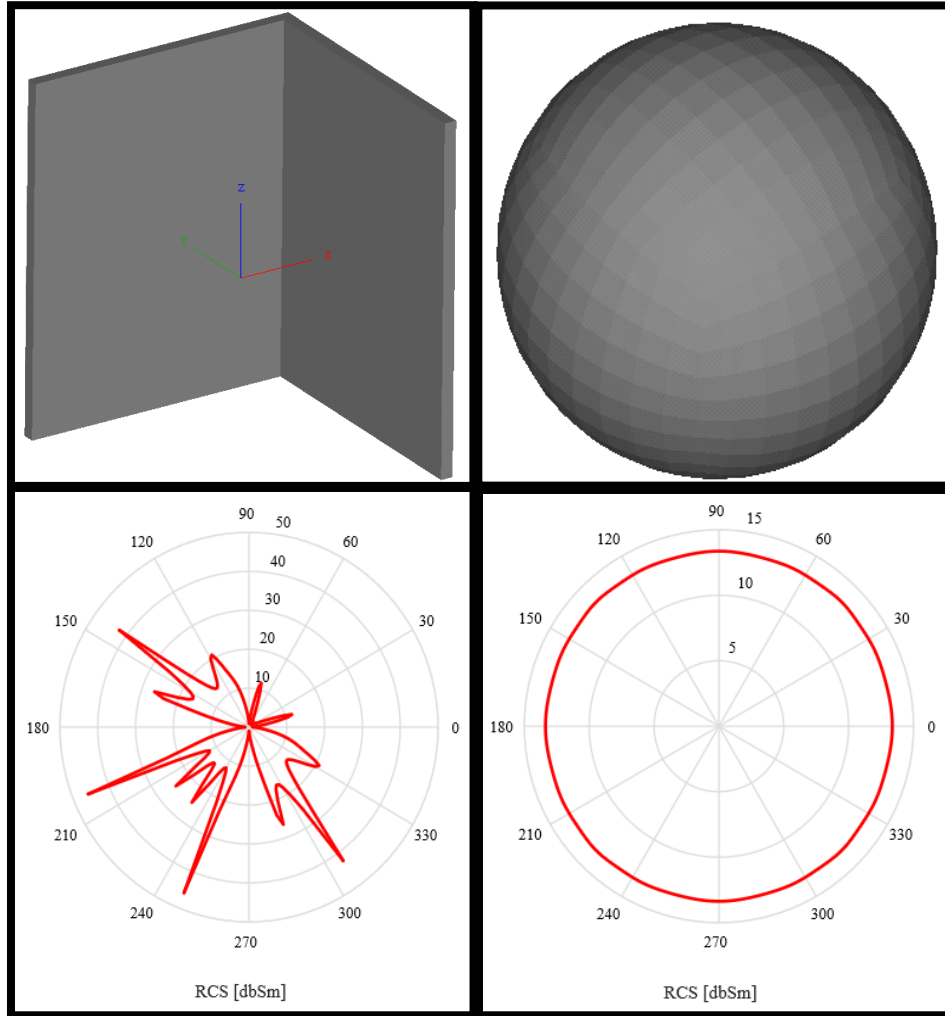


Figure 1. Polar Plots: Corner Reflector (Left) and Sphere (Right) RCS Profiles

Additionally, the material, size, and the incident wave's aspect as it traverses towards the measured target affects the scattering phenomena. The surface currents induced on the object are sensitive to the electric and magnetic properties of the material applied. A conductive material will radiate energy as its surface charges are accelerated by the interaction of the incoming EM wave. A material of weak conductivity has a low current density, meaning there are fewer free charges to excite per surface area of the target. Size of the target relative to the wavelength of the EM wave generated from the radar affects the amount of energy captured by the target and reflected towards the antenna receiver. More energy is captured if the size of the object is large

relative to the wavelength. Less energy is captured if the size of the object is small relative to the wavelength. The phase of the incoming EM waves are determined by the wavelength of their sinusoidal crests. Phase changes in the EM wave are sensitive to variance in the aspect angle. The phase of the incoming EM wave will influence the constructive and destructive interference occurring with the reflected EM waves. This interaction consequently varies the measured magnitude of the EM wave and contributes to the overall scattering profile of a target as observed over various aspect angles as seen in Figure 1 (previous page).

RCS is generally defined as follows:

$$\sigma = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{|E^s|^2}{|E^i|^2} \quad (1)$$

where E^i is the incident electric field, E^s is the scattered electric field, and R is the range between the EM wave source and the target. "The limit as R approaches infinity implies that the target is infinitely far away, where a plane wavefront is incident on the target" [3].

The scattering nature of a target is best understood if the uncertainty of the RCS measurement can be quantified. The particular contributor to uncertainty focused in this research is caused by the test volume where the RCS measurement is conducted. The following section presents information regarding the use of standard field probes as well as prior research conducted at AFIT on the unique two-way field probe concept.

2.2 Field Probe

The ideal plane wave is desired when assessing the scattering characteristics of a target. The simplicity of the plane wave allows for a straightforward comparison between the incident and reflected EM waves measured from a target. However, the region between the radar and

target, known as the test volume, may perturb the incident EM wave from its planar form before it reaches the target. The scattered EM wave is also affected by the test volume on its traversal back to the radar receiver when scattered from the target.

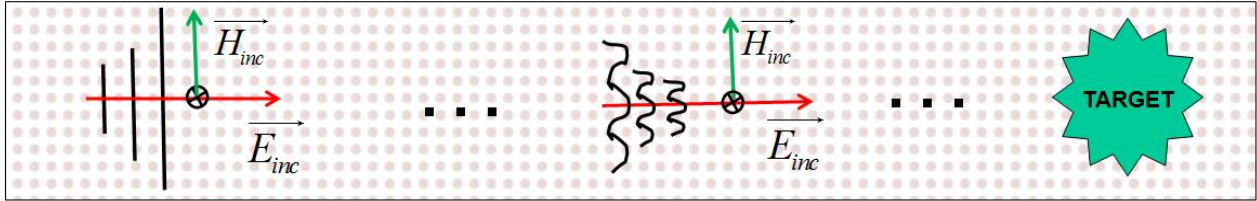


Figure 2. Incident EM Plane Wave Deviation

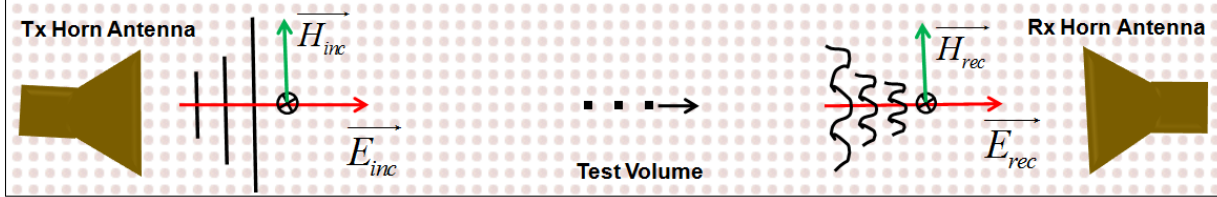
Deviations exhibited on an EM wave result in RCS measurements that are not accurately representative of the true scattering nature of the target. The intent of a field probe is to determine the uncertainty of the RCS measurement by measuring the deviations in the EM wave induced by the electromagnetic conditions of the test volume.

2.1.1 Standard Field Probes

There are two standard field probe configurations used to measure EM wave deviation. The one-way method uses an antenna to directly measure the plane EM wave transmitted from radar at the opposite end of the test volume in a bistatic configuration. A direct comparison made between the transmitted and received wave reveals if a deviation occurs within the region between the transmitter and receiver. The two-way method uses a monostatic configuration, relying on the predictable scattering nature of a canonical target placed at the opposite end of the test volume downrange from the radar transmitter. The RCS profile measured from the canonical target is compared to its ideal RCS solution to determine the variation in the EM wave induced by the test volume. It is important that a canonical target is used in the two-way field probe measurements. If the wave is reflected by an irregularly shaped target, a characterization

cannot be made about the accuracy of the field probe measurement due to the target's inconsistent and unpredictable EM scattering features.

One Way Configuration:



Two Way Configuration:

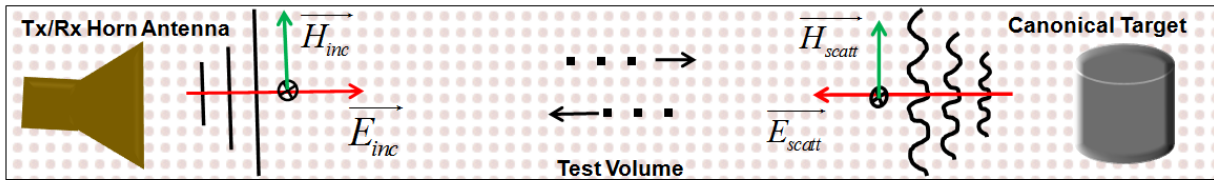


Figure 3. Standard Field Probe Configurations

The commonality between these standard probe methods is their reliability, accuracy, and timeliness to conduct RCS measurements. Each configuration relies on using a support structure to translate and scan the test volume when conducting a probe measurement. The set-up of such structures can be tedious and also contribute further interference with the probe measurement in addition to the test volume's interference. Obtaining a high resolution measurement of the test volume's effect on ideal EM plane waves requires multiple scans of the test volume, an expensive use of time at an RCS range. The alternative solution to these issues is to introduce a unique two-way field probe technique to reduce or eliminate the shortcomings of standard probes.

2.1.2 Unique Two-Way Field Probe Concept

The unique two-way field probe concept has been the main focus of current and previous research efforts conducted at AFIT. The unique aspect of this two-way field probe method is to

use a drone encapsulated in a canonical shield to scan and probe the test volume, eliminating the need of a support structure (see Figure 4).

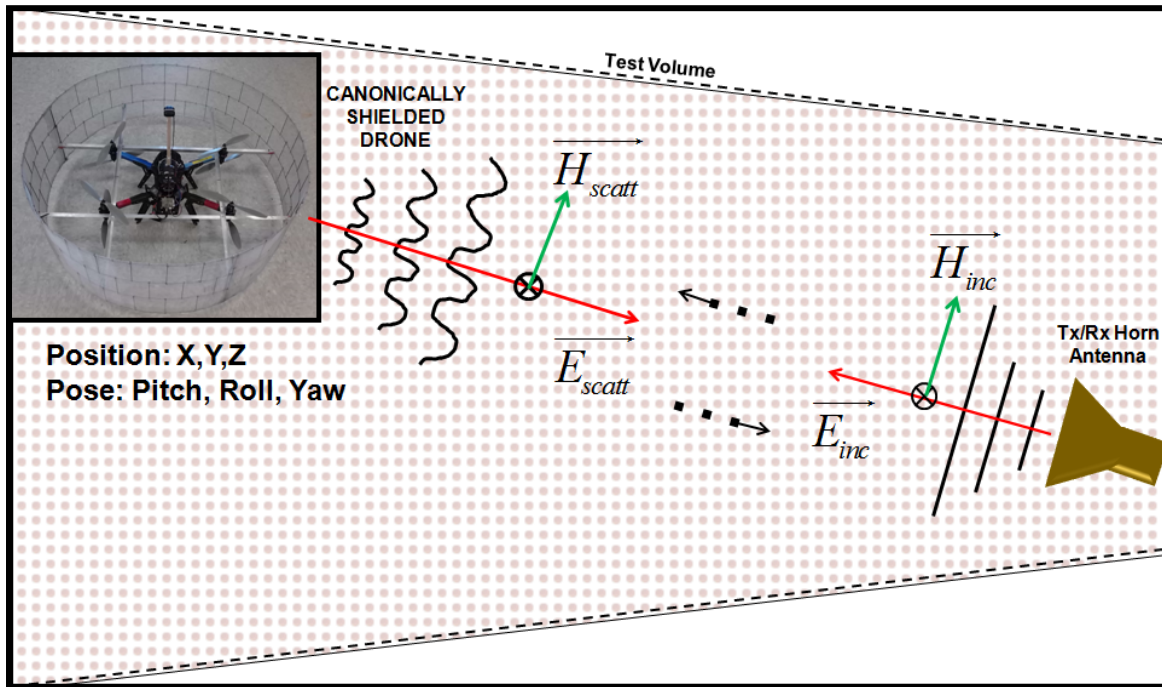


Figure 4. Unique Two-Way Field Probe Concept

The initial research effort conducted by Captain Travis Albee at AFIT explored the use of a geodesic sphere to shield an inner object's RCS profile from radar. The geodesic sphere's fabrication and shape is most ideal considering that it is impossible to construct a perfect sphere casing. The considerations of a drone's flight dynamics also influences this shield design, as it is impossible to operate the drone entirely encapsulated in a solid-cased shield. In order to examine the shielding characteristics of the geodesic sphere, traditional targets such as the flat plate and dihedral are placed inside the shield. These objects provide a recognizable RCS response if the geodesic sphere fails to shield at a particular frequency band. At lower frequencies (less than 2.5 GHz), the geodesic sphere produces a consistent RCS smear effect across its entire aspect. However, measuring the shield's RCS at frequencies exceeding the 2.5 GHz cut-off reveal that

the geodesic sphere cannot shield the inner object. Instead, the incident EM waves penetrate the cavities of the sphere and illuminate the interior target. The cavities of the geodesic sphere emulate waveguides that may be narrowed with fine wire to increase the operable frequency band to shield the inner object. The result of this effort proves that a 2v geodesic sphere cage is capable of shielding the RCS of an inner object up to a certain cut-off frequency that is dependent on the cage's cavity size [21].

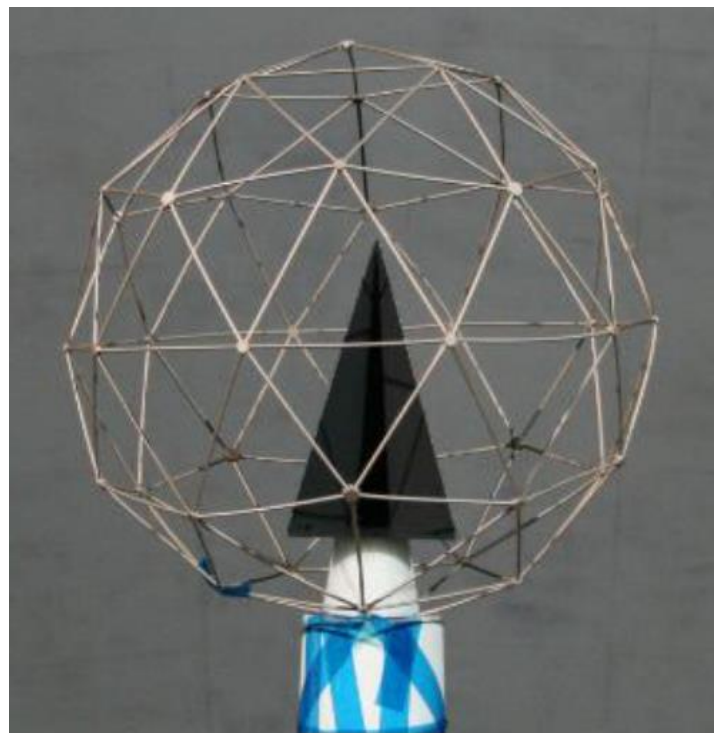


Figure 5. Geodesic Sphere Shielding A Tihedral [21]

The following research conducted at AFIT comprised of two concurrent efforts. Lt. Nathan Lett's research effort was to develop a system capable of conducting field probe measurements at an indoor RCS range. Captain James Dossett examined the drone's position and pose uncertainties effect on the field probe measurements conducted at an indoor RCS range. The indoor field probe's system architecture comprised of a LabVIEW™ control model to

navigate a shielded Parrot Bebop drone based on its position and pose measured from VICON Motion Capture cameras. The 2v geodesic sphere that encapsulated the Parrot Bebop had to be modified by removing the bottom, as the Bebop drone's flight controller relies on an ultra-sonic sensor to measure height above ground. The position and pose uncertainties of the Bebop drone's navigation systems and the VICON cameras were characterized to develop a Monte Carlo model relating the outdoor and indoor position and pose accuracies, respectively, to the RCS measurements of the field probe conducted at the indoor RCS range. A systematic approach to assess the uncertainty in deviated EM plane waves was employed as follows:

- 1.) Obtain RCS calibration measurements of the shielded drone placed on a pylon downrange from radar. This involves orienting the shielded drone at various pose angles and recording the corresponding RCS measurements along with the drone's position and pose measured from VICON.
- 2.) Use the drone's autonomous navigation system to scan the test volume while synchronously recording position, pose, and probe RCS measurements. This data collection represents the in-flight measurements of the field probe.
- 3.) In post-processing of the calibration and in-flight data sets, interpolate the pose of the drone recorded in-flight with its expected RCS value observed in the calibration measurements. This yields an interpolation data set consisting of in-flight pose values directly corresponding to calibration RCS values (truth data set).
- 4.) Subtract the in-flight RCS measurements with the interpolated RCS measurements to reveal the deviation in the incident EM wave caused by the test volume.

- 5.) Based on the accuracy of the drone's navigation system (VICON or GPS/INS), perform a Monte Carlo Uncertainty test to create data sets of possible position and pose measurements observed during the in-flight test.
- 6.) Repeat steps (3) and (4) using the Monte Carlo data sets to determine the uncertainty in the deviated incident EM wave.

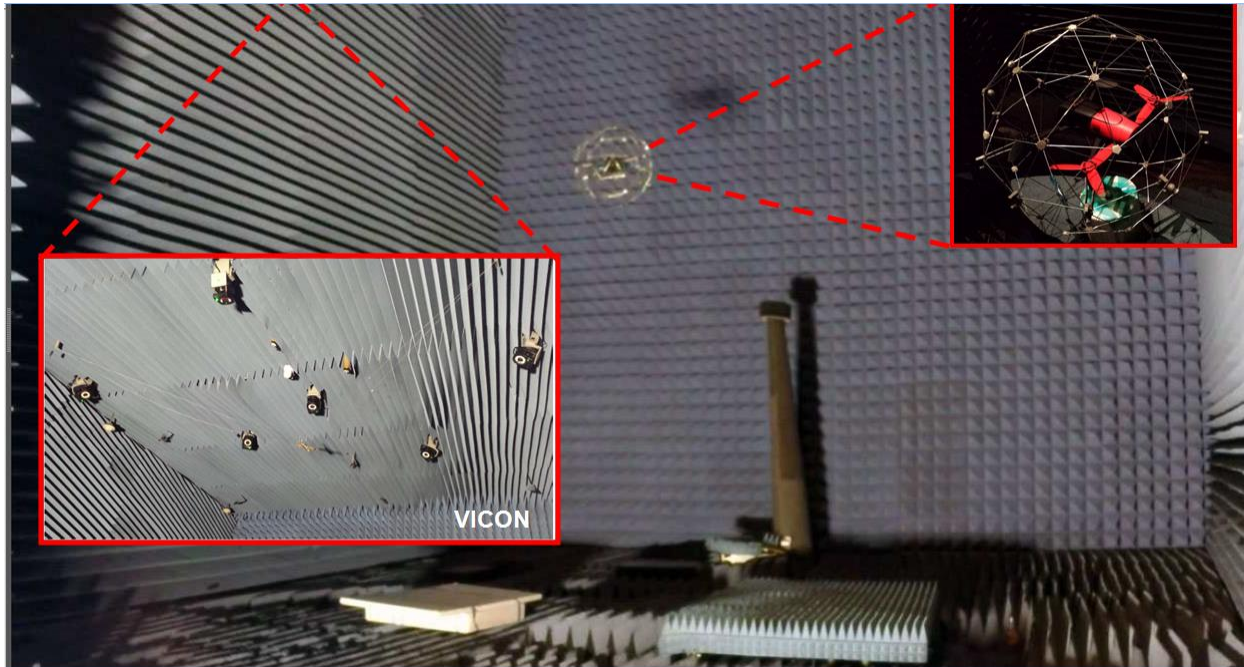


Figure 6. Indoor Field Probe [7,10]

The result of this research effort was inconclusive due to deformities in the shield caused by repeated collisions within the test volume. Each collision would effectively alter subsequent RCS measurements of the field probe. Also, the intent of yawing the drone to create a more traditional sphere-like RCS return from the geodesic sphere while scanning the test volume was unsuccessful due to the instability in the drone's flight control system while performing the necessary maneuvers. However, the limitations and short-comings identified in the previous

research effort provides significant guidance and insight for the research presented in this thesis, to develop a unique two-way field probe system capable of navigating the outdoor environment.

The challenge with this unique two-way field probe method is knowing accurately the position and pose of the shielded drone when acquiring the RCS measurement. The magnitude and phase quantities extracted from the RCS of the field probe are a direct function of the probe's position and pose. Therefore, uncertainty in the position and pose will also contribute to the uncertainty in the field probe measurement, aside from the test volume's effect on the incident EM wave measured by the probe. The following sections discuss the navigation mechanisms involved in this research to achieve outdoor flight of the shielded octocopter.

2.3 Navigation Fundamentals

The positional translation of the octocopter requires a two-fold system. The GPS and INS modules must function in tandem to track the current location and orientation of the aerial vehicle and transverse it towards the desired location. The accuracy of the position and pose measured from the octocopter is dependent on the accuracy of these systems.

2.3.1 Global Positioning System

The global positioning system(GPS) consists of three main components: a space segment, a control segment, and a user segment [1]. The space segment contains a constellation at least 24 operational satellites that orbit Earth in approximately 12 hour intervals. These satellites transmit modulated carrier signals that contain navigational messages used to determine distance between a user's current location and desired location as a function of the time it takes for the transmitted signal to reach the ground. The control segment consists of a network of ground

stations that monitors the satellite constellation and predicts the location of each satellite and the timing of each transmitted navigation message. The user segment is the application of the positional information, acquired by using a GPS receiver. The position solutions are reported in latitude and longitude coordinates, a reference to earth's geodetic surface [1].

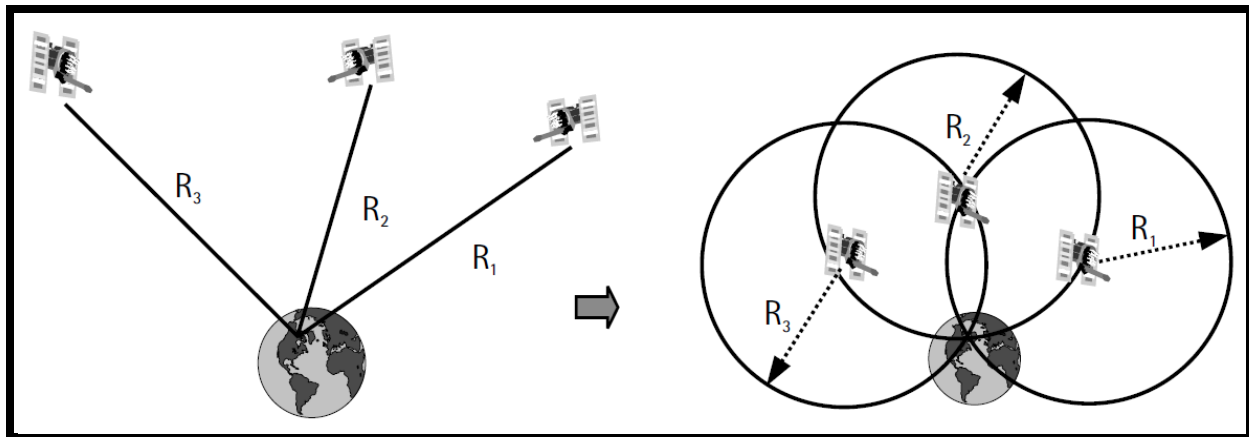


Figure 7. Basic GPS Geolocation Scheme [1]

The octocopter in this thesis uses a 3DR u-blox LEA-6 GPS to report its position coordinates to the user. The u-blox GPS contains 50 receiver channels to acquire signals transmitted from a satellite constellation[22]. The accuracy of the position solution provided by the GPS increases as more receiver channels acquire satellite signals. At minimum, 4 receiver channels are required to correlate the octocopter's 3-dimensional position coordinate (x, y, z) or 3 satellites to correlate its lateral (x, y) position (see Figure 7). A satellite's signal may not achieve correlation with the GPS receiver if there is interference on the signal. For instance, if the octocopter operates around heavy brush, tall trees, buildings, valleys, or canyons, the satellite's signal may become attenuated and diminish in strength before achieving a position fix on the GPS receiver. This concept relates to a particular concern in this thesis regarding the use of a shield to encapsulate the octocopter for the field probe design. An additional component of this research is to investigate the shield's effect on the GPS or communication link signals between

the octocopter and GCS. The shield may cause interference or obstruction to the octocopter's signal-dependent systems, possibly affecting the satellite correlation process on the u-blox GPS, and consequently, its reliability and accuracy.

Achieving accurate position measurements from the octocopter is a crucial component of the unique two-way field probe concept. The standalone GPS onboard the octocopter has limited accuracy based on its receiver channels' ability to acquire a large quantity and correlation of satellite signals. A system that is used to improve position accuracy of the standalone GPS is the differential GPS.

2.3.2 Differential GPS

The Differential GPS (DGPS) is a supplementary navigation method used to improve positional accuracy in real time [9]. According to [5], a differential receiver is placed at a base station where the exact coordinates are known.

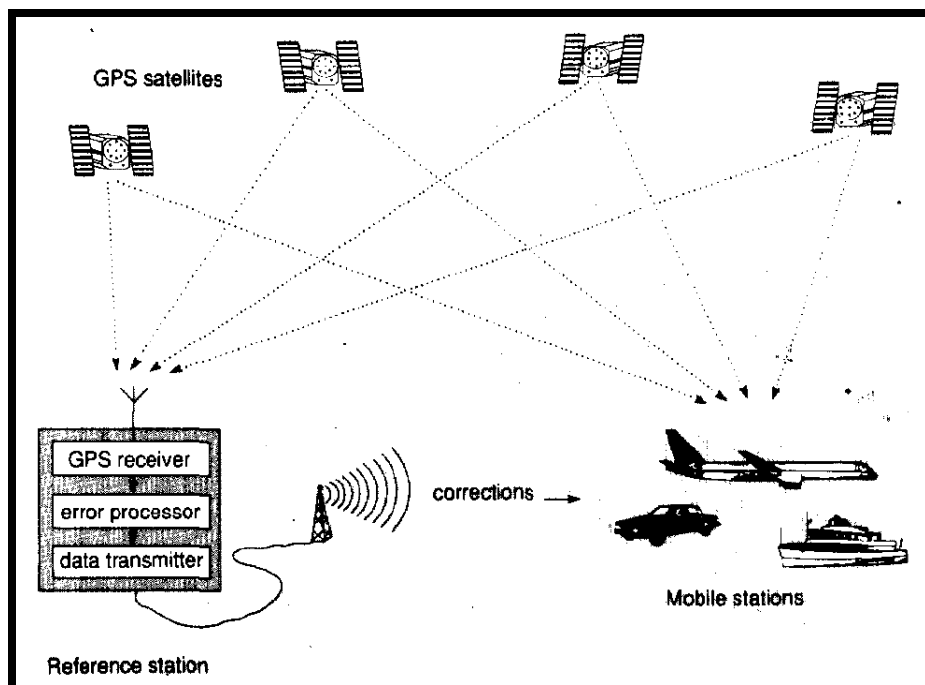


Figure 8. DGPS Scheme [9]

The base station receiver acquires the positioning signal transmitted by satellite continuously and compares the measured position coordinates with the known reference coordinates. The difference in this range represents the differential correction that is sent to the user [5].

This thesis will analyze the Piksi module from Swift Navigation, developed to provide DGPS data to the octocopter's flight controller. Piksi uses a real time kinematic (RTK) technique to improve the accuracy of the GPS, relying on carrier based positioning (measure the phase of GPS signal carrier wave) as opposed to code based positioning (decipher codes from 4 or more satellites). Piksi RTK solutions are reported at cm level positional accuracy [20]. In a differential configuration, Piksi will operate in a float mode or a fixed mode. The float solution is an inaccurate approximation in which the position algorithm cannot round its solution to a whole number as in the fix mode. Instead, a floating number represents the triangulated position approximated by the GPS receiver.

The octocopter's GPS is critical for identifying its current position. However, navigating the octocopter to a desired position requires a pitch, roll, and/or yaw maneuver. An Inertial Navigation System is required to accomplish this translation.

2.3.3 Inertial Navigation System

The Inertial Navigation Systems (INS) is used to track position and orientation of an object relative to a known starting point, orientation, and velocity [15]. This process involves using measurements provided by accelerometers and gyroscopes in an Inertial Measurement Unit (IMU) [15]. The IMU contains three orthogonal rate-gyroscopes to measure angular velocity and three orthogonal accelerometers to measure linear acceleration [15]. These inertial instruments may be mounted on a servo-driven gimbaled platform, or along axes attached to a

vehicle, known as the strapdown approach [11]. The INS module onboard the octocopter follows the strapdown approach. This approach uses computational stabilization as opposed to mechanical stabilization from gimbaled configurations [11].

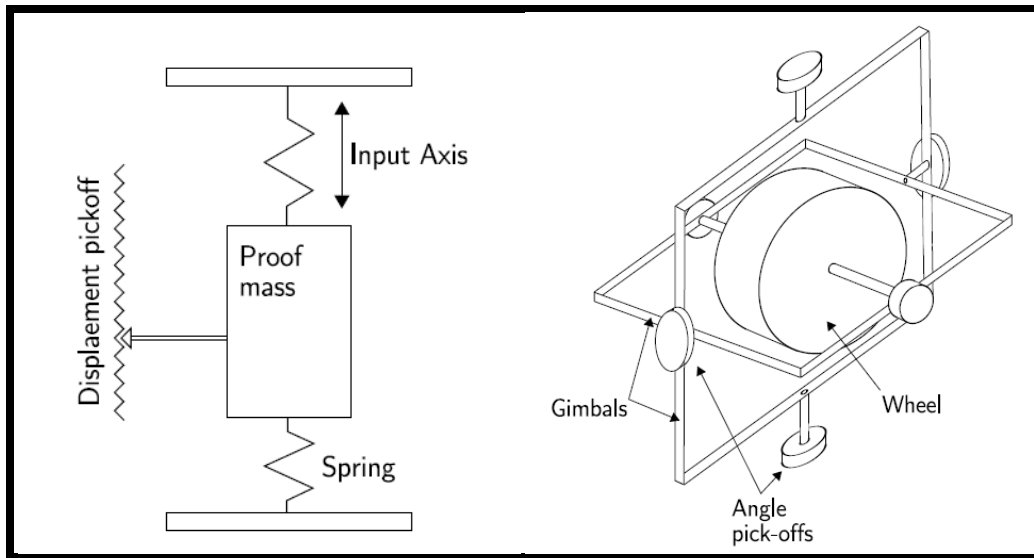


Figure 9. Mechanical Accelerometer (Left) and Gyroscope (Right) [15]

The octocopter uses the gyroscope to maintain proper pitch, roll, and yaw angles. An input command to the octocopter's flight controller may require a pitch, roll, or yaw maneuver to change the octocopter's location to a desired position. The accelerometer will enable the octocopter to maintain the required accelerations by monitoring changes in velocity throughout the flight. If the octocopter experiences external disturbances such as wind, the position and pose control and stability algorithms programmed in the flight controller will provide input commands to counter the disturbance with an opposing pose maneuver. The gyroscope and accelerometer will ensure the octocopter maintains the proper angular rotations and acceleration, regardless of these changes.

The INS is subject to measurement error as a bi-product of the gyroscope and accelerometer's calibration and sensitivity. Uncertainties are notable in micro-electromechanical

systems (MEMS) based sensors, similar to the octocopter's IMU module. For instance, the spinning wheel inside of a gyroscope could have a mass imbalance, effectively making the system more sensitive to line acceleration [6]. An increase of line acceleration will cause a decrease in the accuracy of the pose estimation. The summation of these errors over time leads to the phenomenon known as drift. For example, if the octocopter must establish a proper heading angle for navigation, the bearing angle must be calculated and compared to the current heading. If an inaccuracy develops in the IMU, the octocopter may rotate uncontrollably as it pursues the desired heading with an improper angle measurement.

The GPS and INS systems are important components of the octocopter's navigation scheme. These systems provide position and pose information to the octocopter's flight controller, determining the flight mode based on the relationship between actual and desired position and pose measurements. The application of this concept occurs in waypoint navigation.

2.3.4 Waypoint Navigation

The octocopter's flight plan requires identifying points of desired position coordinates on a geographic map. These coordinates are known as waypoints. A waypoint coordinate functions as point in which the octocopter changes action. Examples of flight modes include, take-off, loiter, land, or navigate to next waypoint. A flight plan includes a home point and a destination point. Intermediary points may be used between the home and destination points to influence the route and profile of the flight path. This research involves using Mission Planner to create flight plans for outdoor waypoint navigation as shown in Figure 10.

A connection between Mission Planner and the octocopter is established using either UDP or TCP communication protocols over a wireless telemetry link. The flight plan developed

in Mission Planner is sent to the octocopter's flight controller over this communication link.

Messages sent between Mission Planner and the octocopter are in the form of the MAVLINK protocol. MAVLINK is a message marshalling library for micro air vehicles that communicates telemetry and flight commands between the aerial vehicle and ground station [12].

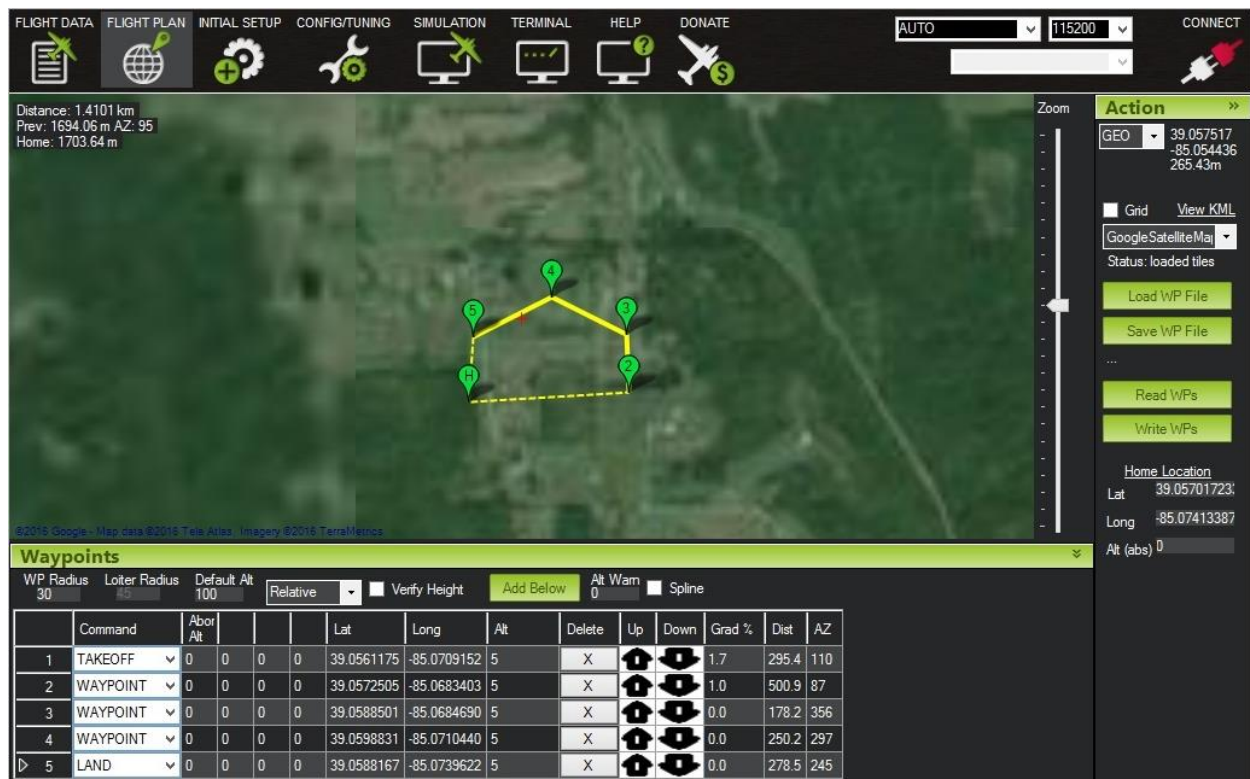


Figure 10. Mission Planner Flight Plan

The position and pose of the octocopter acquired during waypoint navigation has limited accuracy. If the shielded octocopter is to be used as a two-way field probe, an uncertainty analysis must be conducted to determine the accuracy of the systems responsible for measuring position and pose of the shielded octocopter. If accuracy is not quantified, a relationship cannot be drawn between the position and pose of the octocopter and uncertainty in the field probe measurement.

2.4 Uncertainty Analysis

The reported position and pose uncertainties of the octocopter's navigation system must be correlated to the RCS measurements when probing a test volume. "Measurement uncertainty is a quantitative indication of the quality of the measurement results without which they could not be compared between themselves, with specified reference values or to a standard" [16]. The purpose of evaluating and stating the uncertainty is to properly judge a measurement based on an interval or confidence level to quantify the doubt regarding the measurement result. An accurate estimate relies on numerous trials in which an average can be calculated to provide an estimation of the true value in a measurement. If the repeated measurements report different results, the spread or standard deviation will quantify the quality of the set of measurements to report the difference in the individual readings [18]. Uncertainty in this research may occur as a result of numerous internal and external factors that can affect the quality of the measurements. Internal factors that can contribute to uncertainty in the octocopter's navigation scheme may include calibration of the octocopter's IMU prior to flight and signal processing latency in the octocopter's flight controller. The external factors may include the operating conditions of the octocopter in the outdoor environment. Signal attenuations that can occur are between the ground station communication link to the octocopter and the satellite signals acquired by the u-blox and Piksi module receivers. Uncertainty is not limited to internal and external factors associated with the accuracy of GPS and INS modules onboard the drone. Another factor this research investigates is the octocopter's flight performance when encapsulated with a shield. The following section provides further detail on the octocopter's performance capabilities as a standalone aerial vehicle.

2.5 Octocopter

The drone model used in this research is the 3DR X8 octocopter. The communication link range of this octocopter from the launch point is 300m [19]. This characteristic is important to note, as achieving the appropriate far-field distance from radar measurements conducted at an outdoor RCS range will require strategic placement of the ground station relative to the octocopter's flight path. The X8 octocopter's payload capacity is 800g (1.7 lbs) [19]. This threshold should be sufficient for the shield design and materials considered for the field probe. Chapter III will discuss the X8 frame modifications required to integrate a shield intended for field probe measurements. The shield along with the frame modifications adds extra payload to the octocopter. Flight testing intends to determine the octocopter's overall endurance when a shield is fixed to its frame.



Figure 11. 3DR X8 Octocopter [18]

2.6 Summary

The accuracy of the two-way field probe will depend on the position and pose uncertainties measured from the octocopter. The Piksi module will provide DGPS data to supplement the octocopter's positioning system by correcting the positional coordinate errors of the octocopter's onboard GPS receiver. The octocopter's GPS and INS will also be characterized for position and pose accuracy. Mission planner will be used to create flight plans by establishing a set of waypoint coordinates for the octocopter to navigate. The following chapter describes the methodology to design and develop the unique two-way field probe system.

III. Methodology

The main objective is to develop a system that can acquire EM wave magnitude and phase as a function of the field probe's position and pose within a test volume. Truth sources are required to assess the accuracy of the octocopter's GPS and INS. The NovAtel GPS provides truth position measurements for comparing the positional accuracy of Piksi and u-blox LEA-6 position systems onboard the octocopter. The iGaging Angle cube provides truth angle measurements used to assess the pitch, roll, and yaw accuracies of the octocopter's accelerometers, gyroscopes, and compasses. Integration of a shield to encapsulate the octocopter requires an RCS characterization to determine its associated EM scattering phenomenology.

3.1 GPS Characterization

An accurate positioning system available on the consumer market to date is Swift Navigation's Piksi module. The intent is to provide accurate RTK position solutions directly to the Pixhawk flight controller, overriding the u-blox LEA-6 GPS module onboard the X8 octocopter. The advertised precision for Piksi is centimeter level accuracy but can vary based on geographic location and satellite signal reception. Therefore, the positional accuracy of the Piksi system used in this research must be examined statically and dynamically to determine the actual precision attainable for this research effort. All of the position accuracy characterizations in this thesis were conducted at AFIT's Autonomy and Navigation Technology (ANT) Center. The ANT Center houses an accurate NovAtel GPS system that can identify location reportedly within

± 0.007 m accuracy. This system provides the truth location for comparison to the Piksi and u-blox LEA-6 position solutions.

The Piksi and NovAtel systems each consist of a base station and rover. Each base station remains at a surveyed, stationary position to provide a known reference location to their counterpart rovers. Each rover is placed on the golf cart to track position relative to their base stations. The golf cart enhances the mobility of the rovers by allowing the NovAtel and Piksi equipment to remain fixed to the vehicle. The position of the rovers are dependent on the position of the golf cart for each static and dynamic test. The experimental set-up and execution for each characterization was performed with the assistance of Captain Blake McCollum [2]. Captain McCollum developed the system architecture (see Figure 12a and Figure 12b).

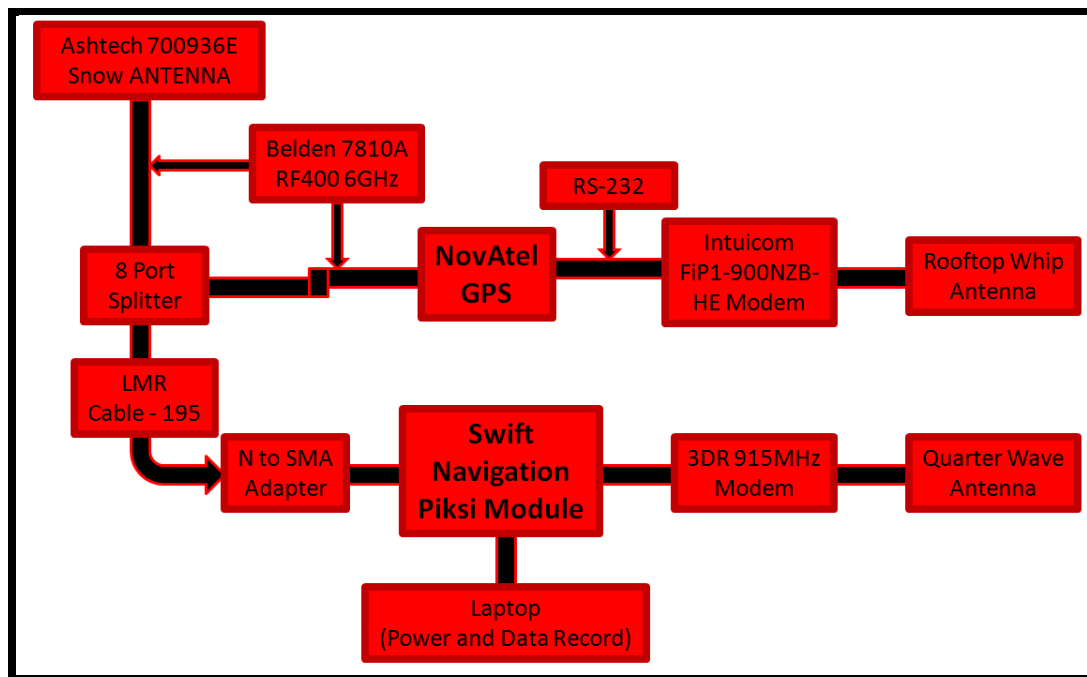


Figure 12a. Piksi-NovAtel Base Station System Architecture

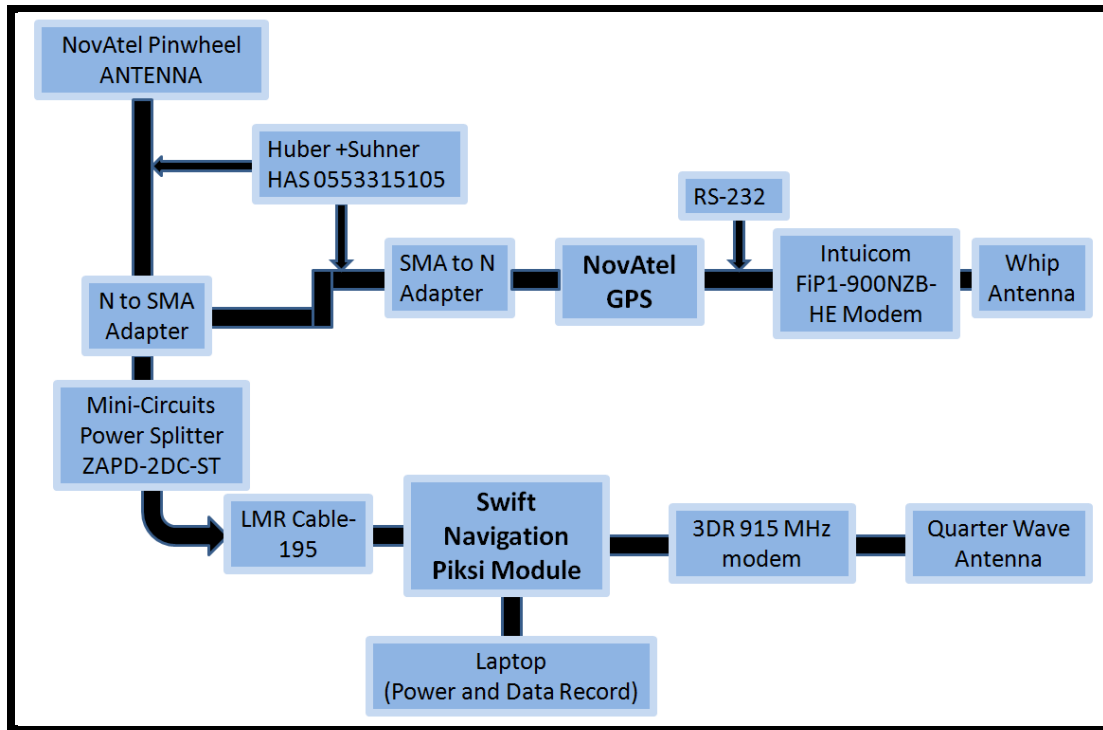


Figure 12b. Piksi-NovAtel Rover System Architecture

The Piksi and NovAtel base stations are routed to the same reference antenna, an Ashtech Snow Antenna via an 8-port splitter. The Piksi and NovAtel rovers share the same pinwheel antenna located on the golf cart. Utilizing the same antennae for each base station and rover eliminates the need to apply range offset between the Piksi and NovAtel systems during the post-processing of the position data. Three laptops are used in the characterization process. Each laptop provides power and acquires data for the Piksi base station, Piksi rover, and the NovAtel rover. The NovAtel base station is powered from inside the ANT Center. The NovAtel and Piksi laptops record position solutions at a rate of 5Hz. Figure 13 shows the test apparatus used for the static and dynamic characterizations.



Figure 13. NovAtel and Piksi Characterization Apparatus

Piksi Console software is used to monitor and record position data from the Piksi GPS modules. It is also used to upgrade the firmware of the hardware and to apply mode configurations such as frequency of data logging, communication link baud rate, antenna selection, or the observation accuracy of acquired satellites. The Piksi solution output can be calculated based on a "low latency" mode or "time-matched" mode. The time-matched mode is recommended for a dynamic rover and base station to provide the most accurate position solution. Each time stamp requires a corresponding set of correction observations. The alternate setting, "low latency" does not provide the most accurate solution but is reported to acquire RTK fix at a faster rate than "time-matched" mode using anticipated satellite observations to calculate the position solution. All tests performed on the Piksi used firmware version 0.26 in "time-matched" mode.

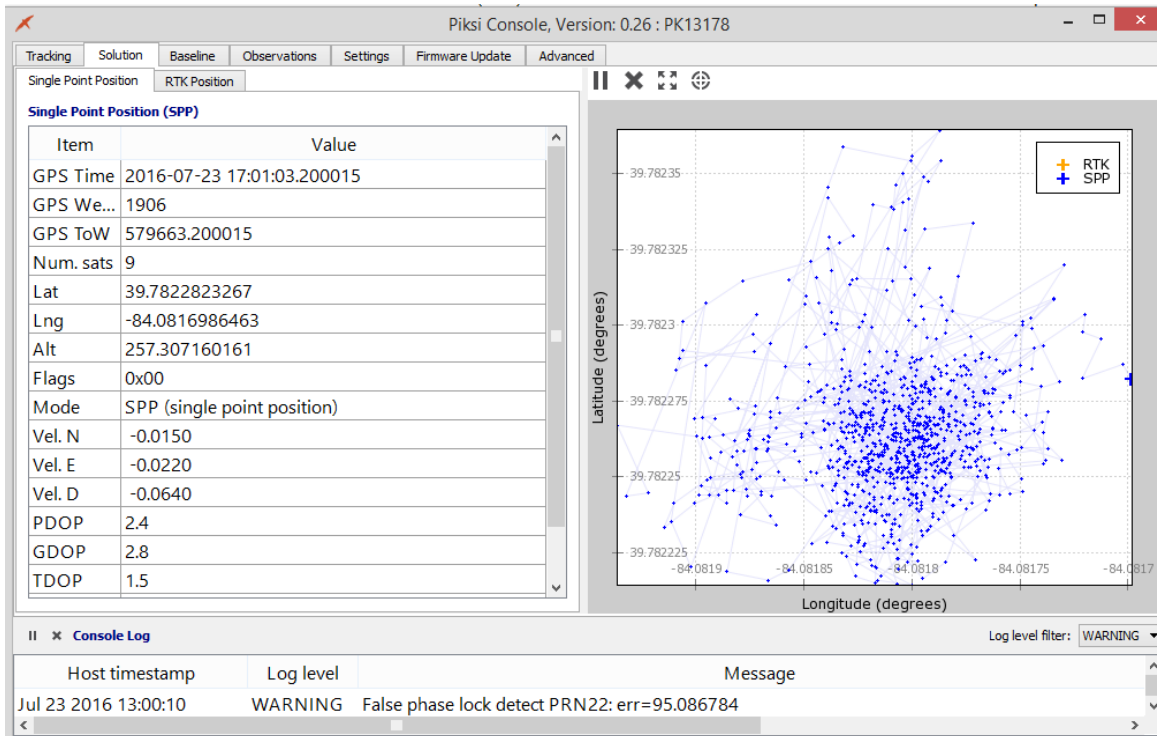


Figure 14. Piksi Console Display of SPP Solutions

The Piksi module position solutions are reported in three different modes: Single Point Precision (SPP), RTK Float, and RTK Fix. SPP is the normal GPS solution reported when only one Piksi module is operated. Two Piksi modules are required to calculate a differential solution. Float mode is achieved when a low correlation of satellite signals are used to calculate the position solution. If the same set of satellites (at least 5 or more) are acquired and correlated to triangulate the position, RTK fix is achievable. Throughout the Piksi trials, the RTK Fix and Float modes are assessed for accuracy to determine the possible scenario outcomes for the reported position solution.

3.1.1 Piksi DGPS Characterization Trials

The Piksi characterization involves two static and two dynamic trials. A static trial is assessed to determine the accuracy of Piksi when the range between the rovers and the base

stations remain constant. The static trials are accomplished with the ANT Center golf-cart remaining stationary in front of AFIT's East lot as position data is recorded from the NovAtel and Piksi systems. The stationary golf cart allows the position solutions to compile in the same relative location. Static trial 1 and 2 lasted approximately 18 minutes and 25 minutes, respectively. Post-processing the data involves importing the Piksi ".csv" and NovAtel's ".gps" files into MATLAB® to parse all data into an equal number of NovAtel and Piksi position solutions. The static trial assessment is a simple differential comparison between an equal number of time aligned Piksi and NovAtel position solution samples.

The dynamic trials involve driving the golf cart in a consistent circular path in front of AFIT's East lot for approximately 25 minutes. The motion of the golf cart varies the range between the rovers and base stations. The NovAtel and Piksi software interfaces are re-initialized to record position data for each subsequent trial. The dynamic trial assessment involves aligning the time stamps of the position data and parsing the recorded laps of the golf cart to observe any ambiguities in the samples. Such ambiguities may involve latency in a reported Piksi solution resulting in excessive NovAtel position solutions. The excess solutions are removed from the laps in order to maintain an equal number of samples while averaging the error differences between the NovAtel and Piksi systems.

The following equations are applied to characterize the accuracy of the Piksi Module:

$$DRMS = \sqrt{\frac{\sum_{i=1}^n [(p_e^i)^2 + (p_n^i)^2]}{n}} \quad (2)$$

$$MRSE = \sqrt{\frac{\sum_{i=1}^n [(p_e^i)^2 + (p_n^i)^2 + (p_d^i)^2]}{n}} \quad (3)$$

DRMS = distance root mean square, MRSE = Mean Radial Spherical Error

$p_n^i, p_e^i, p_d^i = i^{th}$ north, east, and down position, respectively, relative to the true solution (m)

The North, East, and Down (NED) errors are assessed independently for each reported NovAtel and Piksi position solution. Piksi reports position solutions in NED format, however, NovAtel reports position solutions in latitude-longitude-altitude (LLA) format. The MATLAB® command `geodetic2ned` is used to convert NovAtel's LLA coordinates to NED, enabling a direct coordinate comparison with Piksi. The difference between the NovAtel solution and Piksi NED solutions reveal the accuracy of Piksi. These errors contribute to the overall lateral position error calculated by the DRMS shown in equation (2). The MRSE shown in equation (3) is used to calculate the three dimensional error observed when accounting for the reported altitudes from Piksi and NovAtel.

Characterizing altitude involves placing the Piksi rover on top of a handcart that has a height adjustable platform. The truth height above ground is measured using a meter stick. Each measured elevation consists of 1000 samples acquired for averaging a reported altitude from the Piksi. The Piksi rover is measured over 20 varying height changes. The difference between the height reported from the Piksi rover and the height measured from the meter stick equates to the height error.

3.1.2 u-blox LEA6 GPS Characterization Trials

The u-blox LEA-6 is the default positioning system on the X8 octocopter. If the Piksi Module fails (i.e. low satellite acquisition or weak Tx-Rx communication link), the octocopter's Pixhawk flight controller will auto-default to the u-blox system. The accuracy of the u-blox GPS module must be characterized in the event of a Piksi Module failure. The uncertainty values

obtained from the u-blox GPS characterization will contribute to the positional uncertainty of the field probe if the flight data reflects that the Piksi Module was not functional at the time of the field probe tests.

The system architecture for characterizing the u-blox system is identical only for the NovAtel components from the Piksi characterization. The difference is that the octocopter is placed at a known offset range (31 inches) from the NovAtel rover antenna as opposed to connecting the u-blox GPS receiver directly to the NovAtel rover antenna. After mounting the octocopter to a pole on the back of the golf cart, the offset range, or range between the mounting pole and NovAtel pinwheel antenna is measured. The octocopter is connected to a laptop via a micro-usb cable. Mission Planner software is used on the laptop to establish serial communication with the octocopter to record the position solutions reported by the u-blox GPS in LLA format.

Performing a 1 hour continuous trial, the golf cart remained static for 30 minutes and dynamic for 30 minutes. The dynamic golf cart follows the same AFIT East Lot path as before with the Piksi trials. Post-processing the NovAtel and u-blox data requires using MATLAB® to import and merge the position data of both systems. The NovAtel and u-blox position data is converted from LLA to NED coordinates to enable the application of the same error formulas (2 and 3) used in the Piksi characterization. The offset range is subtracted from the u-blox position data to establish a direct comparison in the reported location between the NovAtel and u-blox systems. The static and dynamic data sets are parsed from the NovAtel and u-blox position data files. The static trial assessment is a straight forward comparison between an equal number of time aligned NovAtel and u-blox position solution samples compiled in the relatively same location. The dynamic trial assessment involves aligning the position data and parsing the

recorded laps of the golf cart to observe any ambiguities in the samples caused by latency in the u-blox or NovAtel data-logging frequency. The positional characterization is assessed based on the position errors calculated from equations (2) and (3). The characterization of the u-blox LEA 6 altitude accuracy is based on comparison to the NovAtel truth altitude reported during the static and dynamic golf cart trials. The difference in testing the height accuracy with the Piksi and u-blox is due to the sensitivity of each device. Piksi is more sensitive to centimeter level changes whereas u-blox is sensitive to meter level changes. The u-blox altitude reference matches NovAtel's altitude reference as distance above sea level, whereas Piksi references height differential above the ground or flat earth.

The analysis of the Piksi and u-blox GPS modules completes the position characterization of the octocopter. The next component to characterize is the octocopter's INS module. The following section details the process of determining the accuracy of this system.

3.2 INS Characterization

The inertial navigation system houses the IMU used to measure the pitch, roll, and yaw orientations observed on the octocopter. The accelerometers and gyroscopes must be calibrated before the INS characterization is performed to ensure that the most accurate pose measurements are provided for analysis. Mission Planner provides a set of calibration instructions that are performed as the octocopter's Pixhawk flight controller is connected to the laptop via a micro-usb cable. The procedure for calibrating the IMU is performed as two separate processes. The first involves the accelerometer calibration, in which the octocopter is tilted on all six sides: left, right, forward, backward, top, and bottom. The second process involves the magnetometer compass calibration. The magnetometer calculates the heading of the octocopter relative to true

north. The octocopter is rotated about each three dimensional axis while the top of Pixhawk flight controller faces true north. A map of the compass samples are created with each rotation and averaged to calculate the overall x, y, and z offsets exhibited by the magnetometer. The calibration of the accelerometer and magnetometer completes the preliminary set-up routine for INS testing. It is critical to calibrate the accelerometer and magnetometer compass before operating the octocopter to ensure that the proper orientation and heading angles are established relative to the vehicles take-off position.

3.2.1 Pitch and Roll Characterizations

The apparatus for characterizing pitch and roll involves using a makeshift tilt-table and the iGaging Angle Cube to provide the truth angle measurements. The octocopter is placed level on a flat tray platform and connected to the Mission Planner laptop via micro-usb cable. The octocopter must be level and centered in the flat tray to avoid any offset ambiguity in an angle measurement. The angle cube is placed on top of the octocopter just above the Pixhawk flight controller housing the IMU. A bubble level is used to verify that the octocopter and angle cube are flush with the resting surface, ensuring that there are no angle offsets at zero reference.

Table 1 shows the angles used in the pitch and roll characterizations.

Table 1. Pitch and Roll Test Angles

Small[°]	±2.25	±2.05	±1.85	±1.6	±1.35	±1	±0.8	±0.65	±0.3
Medium[°]	±9	±8	±7	±6	±5	±4	±3	±2	±1
Large[°]	±45	±40	±35	±30	±25	±20	±15	±10	±5

The focus is on small, medium, and large angle intervals to determine if there is any relationship between these transitions and the overall accuracy of the octocopter's inertial measurements. The

tilt table is elevated with a combination of books for medium to large angles and CD ROMs for the smaller angles as shown in Figure 15. Each angle is recorded for approximately 5 minutes before tilting the octocopter to the next angle. This ensures that at least 1000 steady state samples or samples in which the tilt table was undisturbed are recorded and averaged to obtain a concise angle measurement reported from the octocopter. Truth angles are recorded from the iGaging cube. An offset may occur if a desired angle cannot be achieved. For example, if 30° is the desired angle, the angle cube may only provide a reading of 30.05° . The 0.05° must be subtracted from the data recorded from Mission Planner during the post-processing.

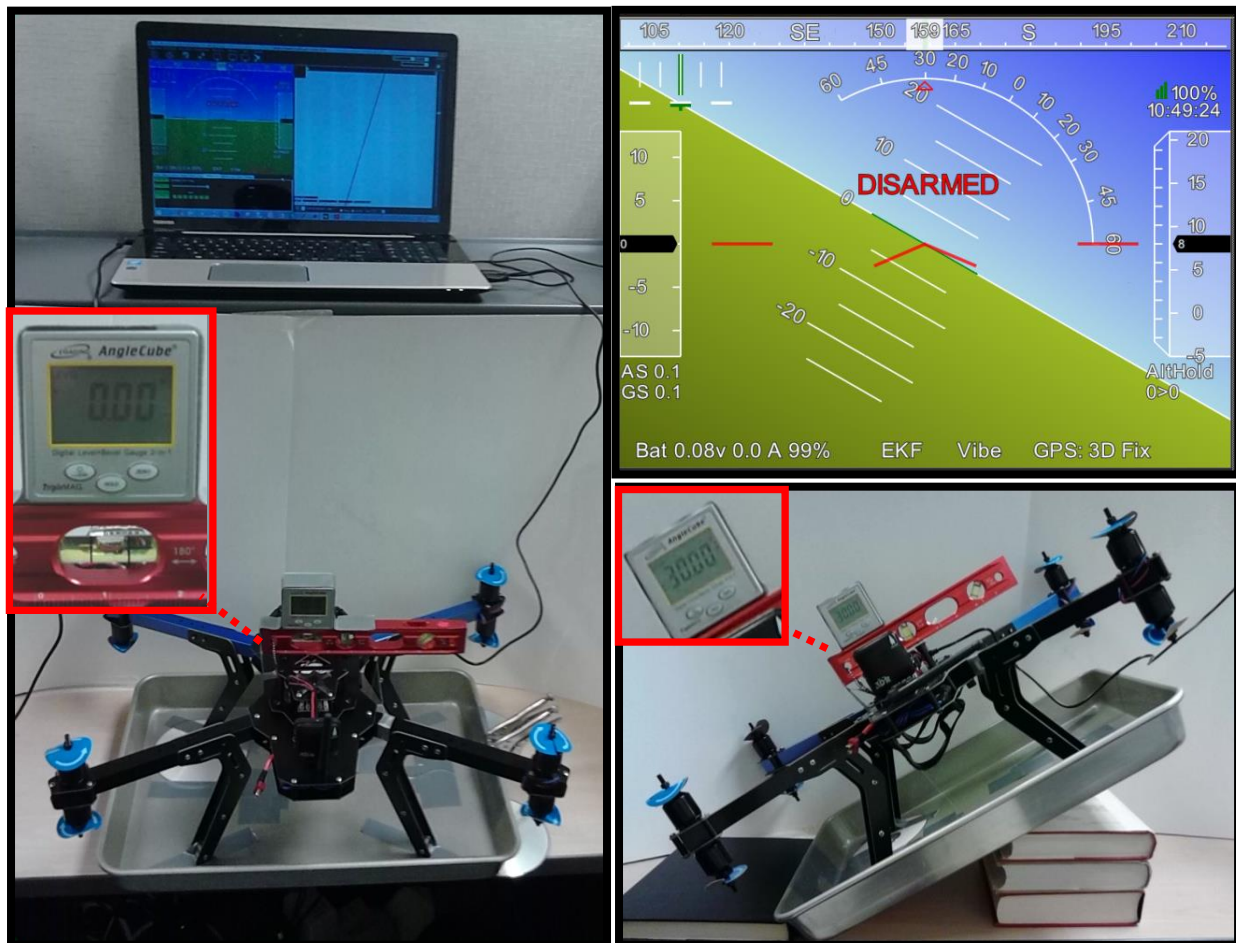


Figure 15. 0° Level (Left), 30° Tilt (Bottom Right) and Mission Planner (Top Right)

Mission planner records the inertial measurements from the octocopter. The telemetry data file (.tlog) is automatically generated when a connection is made to the octocopter from Mission Planner. The ".tlog" can be converted to a ".mat" file through Mission Planner's "Data Flash Logs" section. The ".mat" telemetry file is loaded into MATLAB's® workspace. The variable arrays "roll_mavlink_attitude_t" and "pitch_mavlink_attitude_t" are extracted from the ".mat" file contents. The angle error calculation is a difference between the octocopter's reported angles (including any offsets) and the iGaging Angle Cube reported angles.

3.2.2 Yaw Characterization

The X8 octocopter's yaw orientation is determined by the rotation of a compass that calculates the vehicle's bearing and heading angles relative to true north. The characterization involves placing the octocopter on a turntable and rotating it to a range of small, medium, and large angles as shown in Table 2:

Table 2. Yaw Test Angles

Small[°]	±9	±8	±7	±6	±5	±4	±3	±2	±1
Medium[°]	±45	±40	±35	±30	±25	±20	±15	±10	±5
Large[°]	±90	±80	±70	±60	±50	±40	±30	±20	±10

The X8 octocopter has a 3DR external compass and an interior compass within the Pixhawk flight controller that measure the rotation about the octocopter's vertical axis. The iGaging Angle Cube measures rotation based on its horizontal axis. Therefore, the turntable must be elevated to allow the angle cube and octocopter to measure rotation about a horizontal and vertical axis. CD ROMS are used to shim the turntable into a fixed position between rotations. The "zero position" is established where the turn table is flush with the resting surface as seen in Figure 16.

Each angle is recorded for approximately 5 minutes before rotating the octocopter to the next angle. As with pitch and roll, the yaw's raw data is parsed into 1000 steady state samples for each angle change. The error is measured from the difference between the angular changes or deltas reported from both the octocopter and the angle cube instead of actual angle measurements. This is due to the fact that the reported angle from the iGaging cube differs from the reported angle of the octocopter as a result of the turn-table incline. However, the octocopter and angle cube will experience the same angle changes based on the rotation of the turn-table.

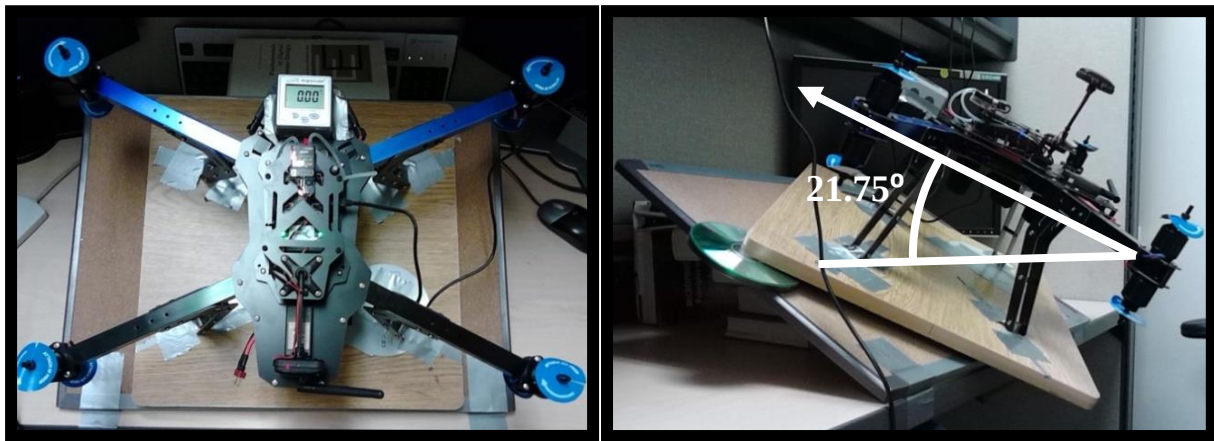


Figure 16. Yaw Characterization - Turn Table Apparatus

At this point, the GPS and INS characterizations of the octocopter are complete. The next step is to interface the Piksi DGPS with the octocopter's Pixhawk flight controller. The intention is to operate the drone while using the highly accurate positioning system and aligning the position data with the pose measurements received from the drone's telemetry link.

3.3 Position-Pose Time Differential Characterization

The position and pose time stamping and alignment is a critical factor in the overall analysis of the field probe's RCS measurements. This data must be aligned in order to determine the precise location and orientation of the probe as RCS measurements are acquired during the

flight program. The position and pose data discussed in this section involves the u-blox GPS and the INS modules onboard the octocopter. The Pixi DGPS module is not included in this characterization, as it relies on a position telemetry stream independent of the octocopter telemetry. The time stamp measurements of the u-blox GPS and INS modules are recorded onboard the Pixhawk flight controller prior to reception on the GCS. The issue of the position and pose time stamps is that a timing jitter occurs between position and pose measurements. This observation is seen in the position and pose data acquired from the telemetry logs that are output from Mission Planner. As a result, a program must be developed to capture the reported position and pose from the Mavlink telemetry stream as it is updated during the octocopter's flight.

The program developed to capture and time stamp position and pose values is written in Visual C++. The program uses a User Datagram Protocol (UDP) connection with the Mavlink telemetry stream. The Mavlink telemetry stream between Mission Planner and the octocopter is sent from Mission Planner (the client) across the UDP data stream, to the C++ program (the server). Communication between Mission Planner and the C++ program is established on IP address "127.0.0.1" and on port number "14550". The C++ program receives the telemetry data packet and decodes the Mavlink message into position and pose information. This information is written to a ".csv" file on the GCS desktop.

The following procedure is required to establish the UDP connection between Mission Planner and the C++ time stamp/align program:

- 1.) Compile the C++ program
- 2.) Click Mission Planner Interface and press "ctrl + f"

- 3.) Click "Mavlink" and select "UDP Client" in the drop down
- 4.) Select baud rate "57600"
- 5.) Click "Connect" and enter "127.0.0.1" for IP and "14550" for port number in the ensuing prompts
- 6.) The C++ program will show the position, pose, and GPS time stamp information streamed from Mavlink. Close the C++ program to end recording.



Figure 17. Position-Pose Alignment System Architecture

Figure 17 illustrates the procedure described in the above steps. The significance of the C++ program's ability to align the position and pose data is that their respective time stamps can be directly compared to determine their difference. The original intent of this C++ program is to use the Mavlink telemetry stream real-time, during a flight test. However, weather conditions limits the chances of executing this program with a live outdoor flight test. Alternatively, Mission Planner has the capability to replay a ".tlog" as if a flight program is occurring real-time. Before characterizing this difference, the appropriate log replay speed must be established when loading a ".tlog" into Mission Planner to review a completed flight plan. This ensures that as many samples as possible can be acquired from the telemetry replay, comparable to the real-time recorded data written in the original ".tlog". The replay speeds examined in succession are "10x", "5x", "2x", and "1x". The appropriate log replay speed is established by comparing the number of samples acquired from the original Mission Planner ".tlog" with the ".csv" file generated from the C++ program. After establishing the appropriate log replay speed, a verification is performed to ensure that the replay of the acquired position-pose samples is comparable to the live acquisition of these samples when using the C++ program. 10 trials are performed for the replay and the live data acquisition. For each trial, a serial usb connection is established with the octocopter from the GCS and the C++ program is executed to time-stamp/align and write position and pose data to file. The ".tlog" generated from Mission Planner for a specific trial is replayed, applying the same procedure as before to time-stamp/align the data. The mean and standard deviations are assessed and compared between the live and replay data for the difference in GPS and INS time stamps. Confirming that there is a relatively small difference between the live and replay data sets, the subsequent trials involve replaying 5 different flight programs, each with 10 trials. The difference between the GPS and INS aligned

time stamps are calculated for each trial. The mean and standard deviations are assessed for the overall time stamp differences in each trial. The combined averages for each of the 10 trials provides the overall mean error and standard deviation for a particular flight program. The overall mean error and standard deviation is approximated based on the average of the 5 flight programs combined.

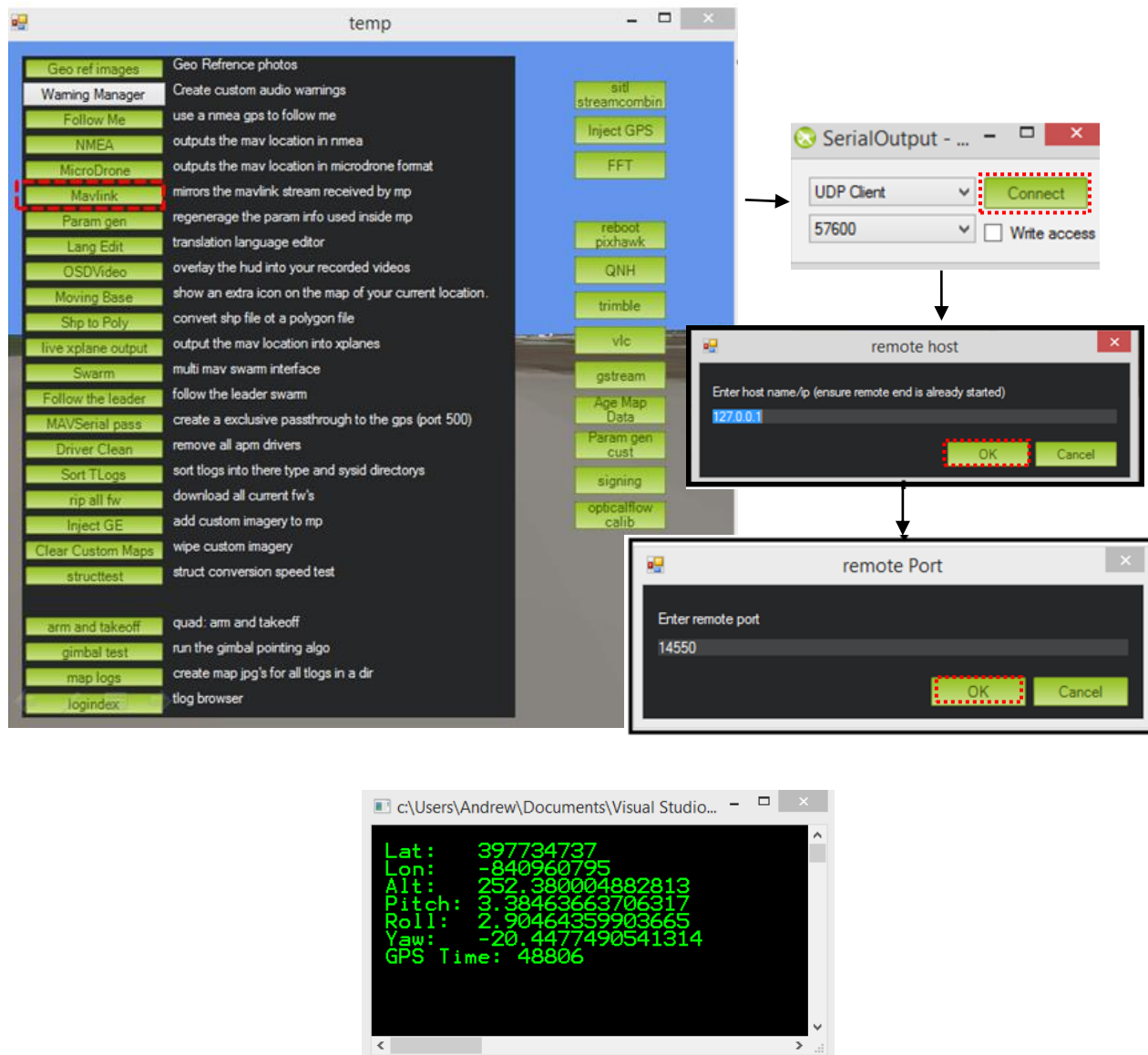


Figure 18. UDP Data Stream Set-up between Mission Planner and C++ Program

3.4 Pixhawk - Piksi Integration

The Piksi Console software is used to apply mode settings when the base station and rover are connected to the computer via a micro-usb adapter. Table 3 provides the settings that must be applied and saved to the Piksi base station and rover to enable their compatibility with the Pixhawk flight controller. The Piksi base station must be connected after establishing a surveyed (LLA) location. The simplest method to determine the truth location of the base station is to select the "solution tab" in Piksi Console and use the output LLA coordinates found under the "Single Point Precision" section of the console. These coordinates must be copied and applied to the "Survey Position" section (see "Base Station Settings", Table 3) to enable the Piksi-Pixhawk communication drivers. After saving the settings to flash, each Piksi module must be powered off to allow the changes to take effect.

Table 3. Piksi Base Station and Rover Software Settings

Piksi Base Station Settings		
Piksi Console Section	Setting	Value
Surveyed Position	latitude	base station location
Surveyed Position	longitude	base station location
Surveyed Position	altitude	base station location
Surveyed Position	Broadcast	TRUE
Solution	soln freq	5hz
Solution	output every n obs	1
sbp	obs message max size	102
UART A	baudrate	57600
Telemetry	Configuration string	AT&F,ATS1=57,ATS2=64,ATS3=50,ATS5=0,AT&W,ATZ
Piksi Rover Settings		
Piksi Console Section	Setting	Value
Solution	Soln freq	5hz
Solution	output every n obs	1
sbp	obs message max size	102
UART B	sbp message mask	65280
UART A	baudrate	57600
Telemetry	Configuration string	AT&F,ATS1=57,ATS2=64,ATS3=50,ATS5=0,AT&W,ATZ

Mission Planner is used to configure the Pixhawk flight controller's GPS settings in order to establish communication with Pixsi. Pixhawk is connected to the Mission Planner laptop via a micro-usb cable. In the "CONFIG/TUNING" tab, the "full-parameter list" is selected. Table 4 shows the settings that must be applied to enable a secondary GPS to function on the Pixhawk. After applying the settings, "Write Params" must be selected to save the changes.

Table 4. Mission Planner Configuration Settings for Pixhawk

Setting	Value
GPS_MIN_DGPS	100 "Acceptable RTK Solution to switch to DGPS"
GPS_NAVFILTER	8
GPS_TYPE	1 "GPS Standalone"
GPS_TYPE2	8 "Swift Nav"
SERIAL0_BAUD	115
SERIAL1_BAUD	57
SERIAL2_BAUD	115
SERIAL2_PROTOCOL	5

The octocopter's flight controller, Pixhawk, provides a Serial 4/5 input to power and transfer data from its internal processor to a connected device. The Pixsi module UART B port interfaces directly (using a 4/5 cable) to this Serial 4/5 port as shown in Figure 19. The Pixsi rover module must be connect to the Pixhawk before applying power to the octocopter.

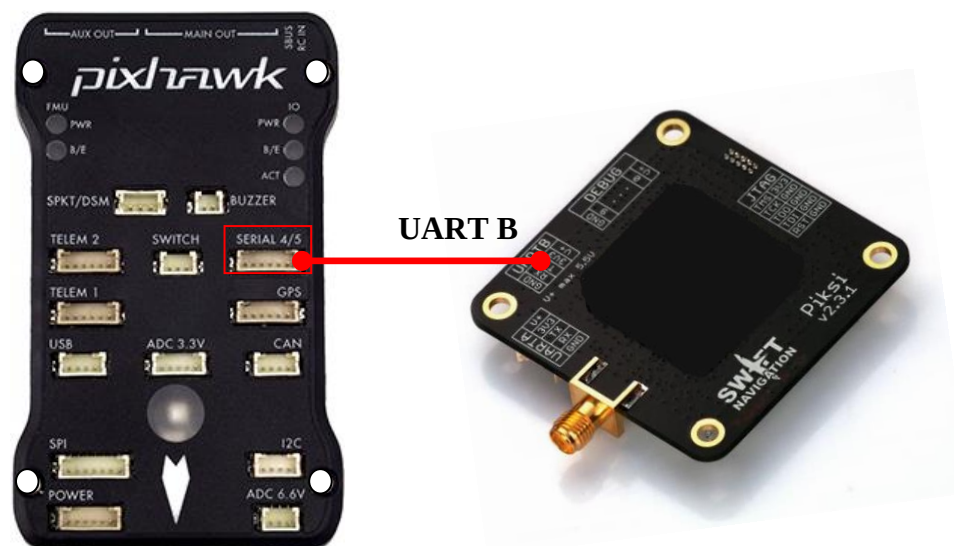


Figure 19. 3DR Pixhawk (Left) and Pixsi (Right) Serial 4/5 Connection

After a serial connection is established to the flight controller, the Pixsi base station is connected to the laptop via micro-usb cable. It is critical to power the octocopter (rover) before applying power to the base station. This allows the stationary Pixsi module to establish itself as the base station. Pixsi Console software is opened and a UDP broadcast is initiated. The UDP broadcast setting is found under the "Advanced" tab and selecting "Networking". The IP Address must be set to "127.0.0.1" with the port number "13320". After selecting "start", the base station will await a connection from the Pixsi rover. A wireless connection from Mission Planner is established with the octocopter. While Mission Planner is active, pressing laptop keys "ctrl-f" opens a custom settings console. "GPS Inject" followed by "UDP-Host" are selected from this interface. The port number of "13320" is entered into the prompt and "start" is selected to initiate the UDP communication stream of Pixsi solutions to the Pixhawk flight controller. Under the "Status" tab, "gpsstatus2" must output a number greater than "0" to assure that the differential GPS solutions are being read into Pixhawk. Pixsi "Float" mode will generate a value of 1 or 3. Pixsi "RTK Fixed" will generate a value of 4 or 5.

The following section examines the development of the shield to encapsulate the octocopter. The particular focus is on designing a solid-based shield that can provide desirable RCS characteristics when measuring the field probe using CEM techniques. The second design considered is the traditional 2v geodesic sphere that was explored in previous research efforts.

3.5 Field Probe Shield Design and Development

The field probe's shield design requires a canonical geometry such as a sphere or a cylinder to provide a known/predictable RCS profile required to probe an EM wave in a test volume. The solid (casing) geometries considered are the squat cylinder and the topless-

bottomless sphere. Each solid geometry must have an open top and bottom to avoid inhibiting the octocopter's aerodynamics. Also, the GPS receiver must have a full horizon exposure to the outdoor environment in order to receive satellite signals for triangulating position. Figure 20 shows the development of each shield design using Sandia National Laboratories' CUBIT Geometry and Mesh Generation Toolkit. It should be noted that the dimension of each shield is reminiscent of the radial and height values stated in the following section, "*Field Probe Shield Construction and Integration*".

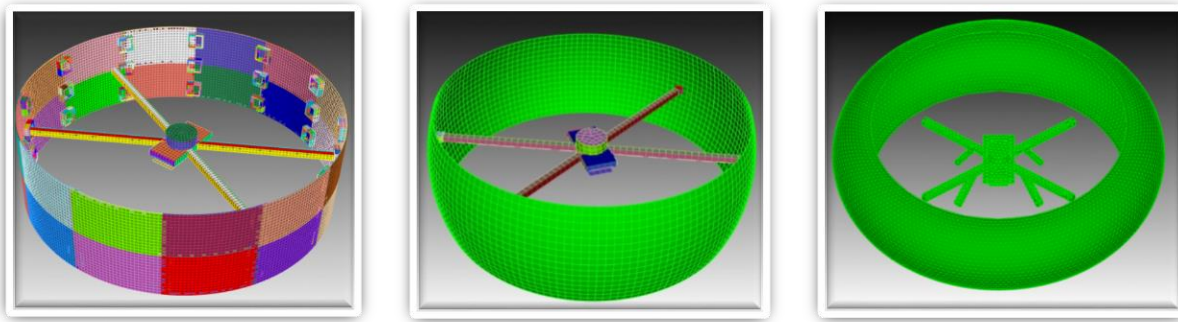


Figure 20. Squat Cylinder (Left), Topless-Bottomless(T-B) Sphere (Middle), and Torus Ring (Right)

A mesh convergence is assessed to determine if the appropriate number of mesh elements are used on each geometry. A mesh convergence is determined by applying a different number of mesh elements (ranging from coarser to finer) to the geometry and comparing an RCS cut at a particular polarization and frequency to each mesh type. If two mesh types are within a 1% difference in the predicted RCS measurement, the mesh is considered converged. A sufficient amount of mesh elements will yield a meaningful RCS prediction once the models are imported (as EXODUS II files) and measured in SENTRi, developed under the Department of Defense High Performance Modernization Program's Computational Research and Engineering Acquisition Tools and Environment (CREATE™) Project. SENTRi calculates the monostatic

RCS backscatter of the shield designs using Finite Element Methods (FEM). Figure 21 on the following page shows the RCS cut patterns conducted for each design in SENTRI.

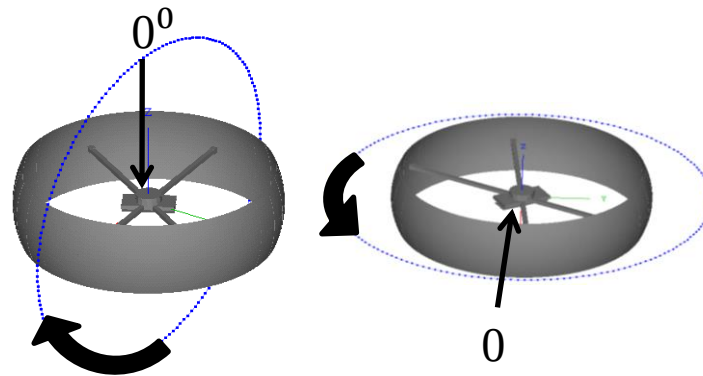


Figure 21. Waterline Scan (Left) and Vertical Scan (Right)

The RCS cut patterns are conducted over 10 discrete frequencies between 300MHz and 700MHz at PP (horizontal-horizontal) and TT (vertical-vertical) polarizations. Each data set acquired from the pattern cuts are combined to form a global RCS map relating the frequency, aspect angle, and RCS of the measured geometry for each polarization. The global RCS map is used to assess the scattering characteristics of the shielded octocopter for each incoming frequency/polarization variant EM wave.

3.6 Field Probe Shield Construction and Integration

The shield design for the field probe begins with modifying the frame of the octocopter to extend the arms past the length of the propellers. This ensures that the propellers are unobstructed by the shield encapsulating the octocopter. Extending the arms of the octocopter requires the use of Multipurpose 6061 Aluminum 90 Degree Angle, 0.040" Thick, 5/8" x 5/8" (width x height) at 2' in length. These L-channels are fixed to the outer sides of each arm frame using 18-8 Stainless Steel Button-Head Socket Cap screws (M3 x 0.5, 25mm length).



Figure 22. Modifying the X8 octocopter frame with L channel extensions

3.6.1 Squat Cylinder Design, Construction, and Integration

The squat cylinder shield design consists of a cage made from aluminum fence material (14 gauge wire) at a radius of 496mm and a height of 305mm. Encompassing the fence material is an aluminum screen mesh that intends to minimize the openings of the cage. The approximate weight of the shield is 3 lb. The addition of the aluminum L-channels for the frame extensions adds approximately 0.7 lb to the octocopter. The aluminum frame is arranged in a hash mark pattern to provide eight attachment points on the shield. The attachment points also provide reinforcement to the walls of the shield. Figure 23 shows the resulting shield and frame extension integration prior to mounting onto the octocopter.

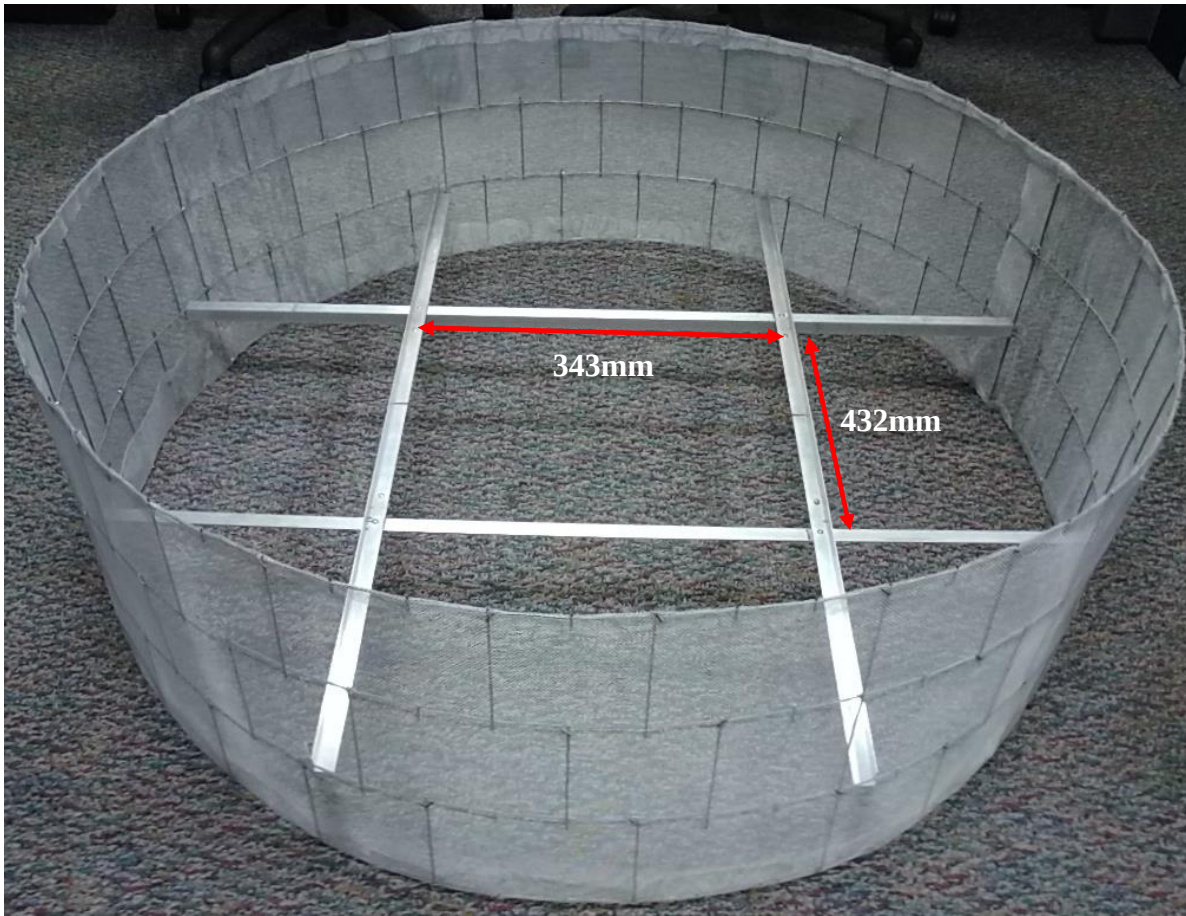


Figure 23. Squat Cylinder Shield and Frame Extensions

A preliminary test must be conducted to ensure that the shield does not cause an interference for the GPS and communication links needed to operate the octocopter. This test involves moving the vehicle at a range away from the GCS and at varying orientations to determine if the Piksi DGPS and u-blox systems is still capable of acquiring the desired number of satellites needed to obtain an RTK fix or at least a 3-dimensional position fix. Concurrently, the signal strength of the 3DR modem is monitored. Modifications to the shield or GPS and comm-link antennae placement are determined based on this test.

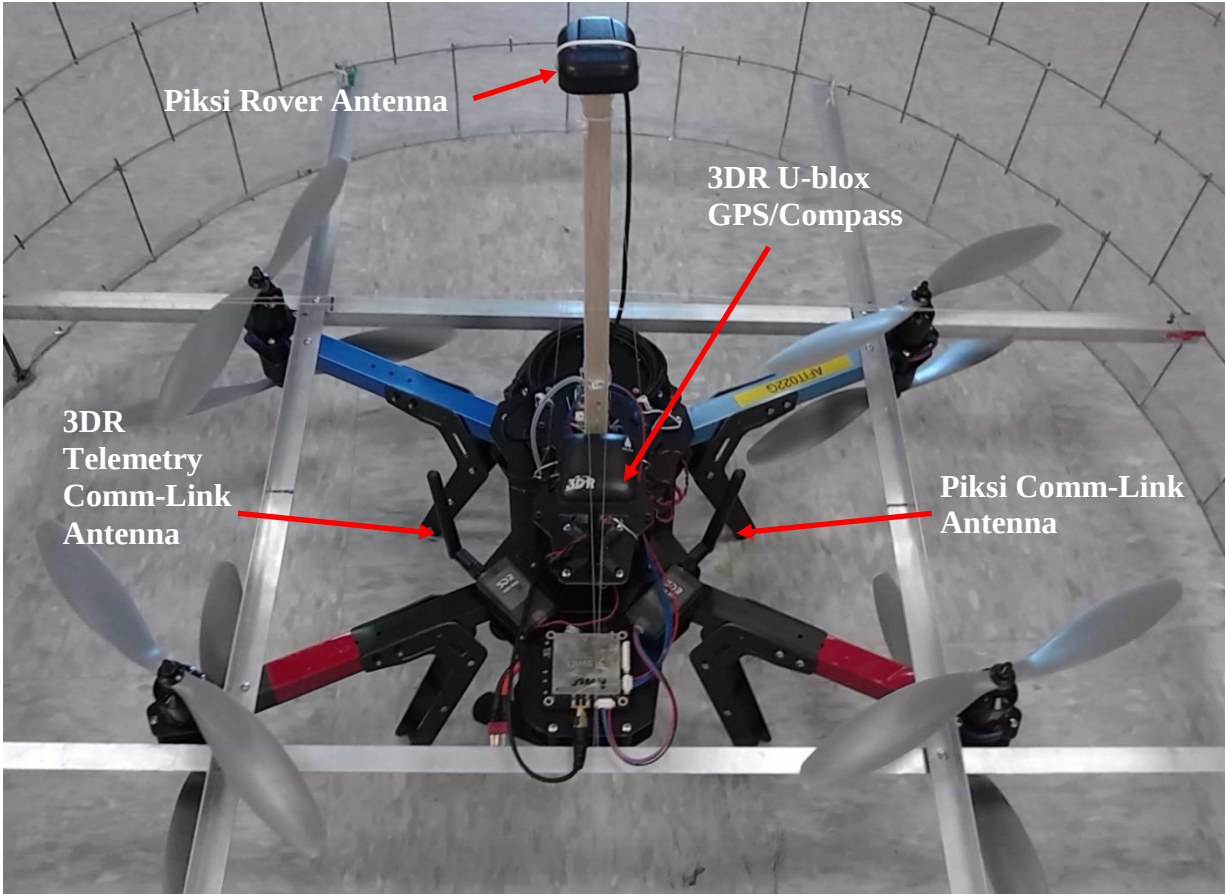


Figure 24. Shielded Octocopter Positioning and Communication Components

The RCS profile of the squat cylinder shield may not provide the most optimal results given a particular orientation and flight pattern. Therefore, a separate shielding mechanism is considered as an alternate. The following section describes the geodesic sphere construction and integration.

3.6.2 Geodesic Sphere Design, Construction, and Integration

The geodesic sphere design is based on the 2v frequency as shown in Figure 25. The cage is constructed from 3 mm diameter carbon fiber tubes containing aluminum rods and jointed together using 3D printed PLA material coupled with adhesive. The overall diameter of the cage is 1219.2 mm and the weight is approximately 1 lb. Using the geodesic sphere design

permits the legs to be removed from the octocopter. However, a separate mount must be constructed to provide a means of take-off (see Figure 25).



Figure 25. Geodesic Sphere Cage Design

The shield incorporated on the X8 octocopter completes one-third of the overall field probe system architecture. The other two components of the two-way field probe system are the GCS that monitors the octocopter telemetry and the AFIT RNR to measure the field probe's RCS.

3.7 RCS Measurements

The shielded X8 octocopter is configured to function as a two-way field probe for outdoor RCS measurements. The ability to execute these measurements requires extensive preparation and mission planning to ensure that the shielded octocopter is capable of probing a test volume. The following subsections provide the preparation and procedure for operating the two-way field probe at the outdoor RCS range.

3.7.1 AFIT ACER Radar Calibration

The AFIT ACER radar system used in this research must be calibrated to remove ambiguity from the RCS measurements conducted on the field probe. This involves calibrating the radar with a canonical shape such as a sphere or cylinder that has accurate or "known" RCS solutions. The following equation calculates the calibrated electric field (E_m) [23]:

$$E_m = \frac{E_t - E_{bt}}{E_c - E_{bc}} E_p \quad (4)$$

$$E_p = \frac{E_c}{E_{c(\text{theoretical})}} \quad (5)$$

- Measure the electric field of the target, including the noise and background (E_t)
- Measure the background electric field, including noise, *target mount*, (E_{bt})
- Measure the calibration target's electric field, noise, and background (E_c)
- Measure the background electric field, including noise, *calibration mount*, (E_{bc})
- Apply the numerical prediction of the electric field for the calibration target (E_p)

The calibration objects used are the 750 and 900 cal cylinders, placed at a distance of 10 meters downrange from the radar. Calibration verification is assessed by comparing the

difference of the cal target's actual RCS measurement to its theoretical (ideal) RCS measurement. The mean error and standard deviation of these measurements are examined using the ALPINE© toolbox developed by Dr. Peter Collins. The cal object exhibiting the least mean error compared to its theoretical measurement is selected for the post-process calibration of the target's RCS measurement.

3.7.2 ACER High Frequency RCS Measurements

The initial RCS measurements conducted on the shielded octocopter involve using AFIT's RCS indoor compact range, the ACER facility. This facility uses a LINTEK 2000 radar system that operates at a frequency band of 2 to 18GHz. The intent of the high frequency RCS measurements is to determine the threshold frequency in which the shield fails to inhibit the RCS profile of the octocopter. The high frequency characteristics of the shielded octocopter is also examined over various elevation angles to assess the shield's RCS profile if the octocopter is pitched or rolled within and outside the $\pm 10^\circ$ illumination field.

The process of conducting RCS measurements in ACER involves placing a target on a foam cylinder column that is fixed to a pylon. The targets must be centered and leveled so that the great circle cuts are uniform. The test begins with conducting calibration measurement on a 7.5in. and 9in. diameter squat cylinders. These canonical calibration targets provide a baseline RCS measurement to compare against a theoretical solution. A background measurement of the calibration mount and the target mount is taken so that it can be subtracted from the subsequent target measurements in post-processing. The targets examined are the shield, octocopter, and shielded octocopter. Each target is subjected to 0° , 5° , 10° , and 15° pitch angles. The testing concludes with a re-measure of the calibration targets to numerically assess the changes in the

test volume that occurred from before and after conducting the target measurements. Table 5 shows the complete test matrix conducted at the ACER facility. It should be noted that each data run involves saving the RCS measurement by a particular file extension, noted in column 1. Each data file acquired from the ACER facility is imported and processed using the ALPINE® toolbox.

Table 5. ACER High Frequency Test Matrix

Measurement	Target	Polarization	Frequency	Azimuth	Elevation
Cal Measurement.cal	750 Cyl	HH	2.0:0.1:18.0GHz	0°	0°
Cal Measurement.cal	900 Cyl	HH	2.0:0.1:18.0GHz	0°	0°
Cal Mount.cbk	Foam Cylinder Mount	HH	2.0:0.1:18.0GHz	0°	0°
Target Mount.bkg	Foam Cylinder Mount	HH	2.0:0.1:18.0GHz	0°	0°
Target.tar	Octocopter	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	0°
Target.tar	Octocopter	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	5°
Target.tar	Octocopter	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	10°
Target.tar	Octocopter	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	15°
Target.tar	Shielded Octocopter	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	0°
Target.tar	Shielded Octocopter	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	5°
Target.tar	Shielded Octocopter	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	10°
Target.tar	Shielded Octocopter	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	15°
Target Mount.bkg	Foam Cylinder Mount with Foam Sheet	HH	2.0:0.1:18.0GHz	0°	0°
Target.tar	Shield	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	0°
Target.tar	Shield	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	5°
Target.tar	Shield	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	10°
Target.tar	Shield	HH	2.0:0.1:18.0GHz	0.0:1.0:360.0°	15°
Cal Measurement.cal	750 Cyl	HH	2.0:0.1:18.0GHz	0°	0°
Cal Measurement.cal	900 Cyl	HH	2.0:0.1:18.0GHz	0°	0°



Figure 26. ACER Facility, Shielded Octocopter mounted on Cylinder Foam Column

The results obtained from the ACER facility are compared to theoretical RCS measurements conducted in SENTRI. Figure 27 shows the test objects comparison. The theoretical model is developed in CUBIT and saved as an Exodus II file to be imported into SENTRI. A select set of frequencies measured during the ACER tests are applied in the CEM analysis for comparison.

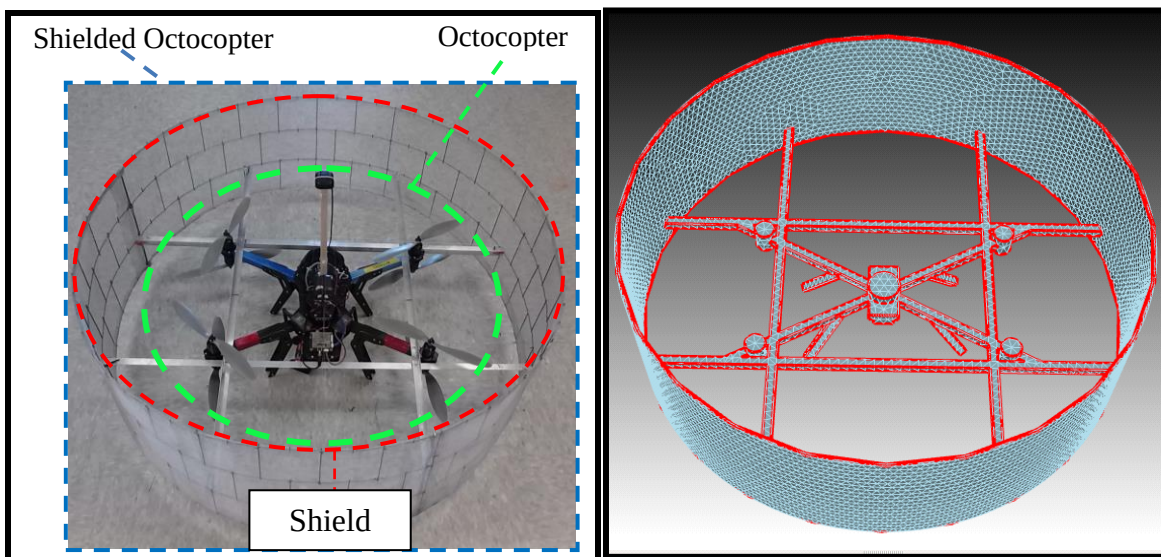


Figure 27. Target Items, Actual (Left) and Theoretical (Right)

3.7.4 Outdoor RCS Range Preparation

The outdoor RCS range must accommodate for the far-field distance between the AFIT RNR and the field probe. Determining the appropriate range for the field probe requires a test in which the shielded X8 octocopter is manually positioned in the direction of the noise radar transmit/receive antenna at an ambiguous downrange distance. The noise radar is monitored for detecting the return signature of the field probe as the probe is moved within range. A definitive return signature of the target is preferred for establishing the appropriate downrange distance from the noise radar. Once the downrange distance has been established, the accompanying region at that point is considered the field probe's quiet zone or the region in which the EM wave radiated from the noise radar is considered planar as it reaches the target.

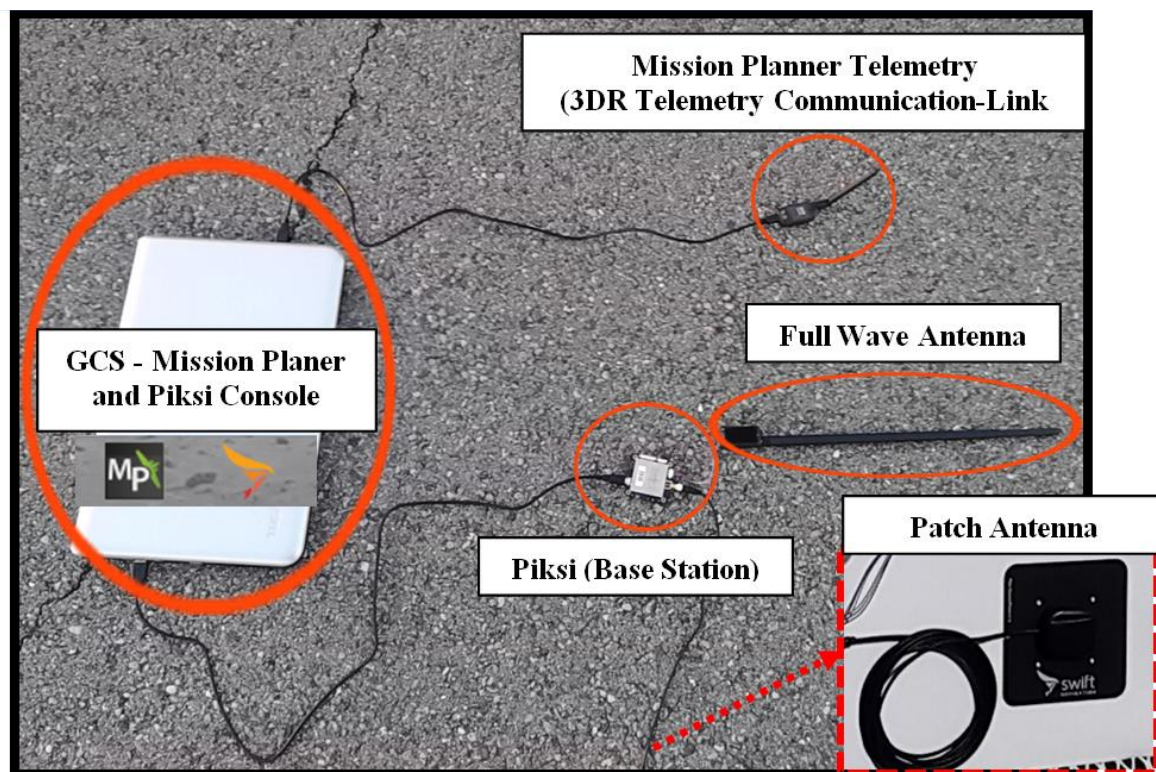


Figure 28. Ground Control Station Set-Up

The GCS layout is shown in Figure 28. The procedure for setting up the hardware and software is performed as follows:

- 1.) Ensure the Piksi base station and rover patch antennae have ground planes.
- 2.) Start the octocopter (rover) first and wait approximately 1 minute.
- 3.) Plug in the Piksi Base station usb into the laptop and open the Piksi Console software on the laptop
- 4.) Screen capture the base station SPP solution from Piksi Console (needed for post-processing as a reference "truth" location)
- 5.) Start Mission Planner and select "Auto" then "Connect"
- 6.) Refer to section 3.3, "Pixhawk - Piksi Integration", if desired to directly interface Piksi with the octocopter's Pixhawk flight controller.

The GCS is positioned to be within range of the octocopter's communication link (within 391 m as tested previously). The octocopter and GCS are equipped with 915MHz 3DR Antennae. This communication link enables the GCS to write waypoints over a wireless connection to the octocopter's flight controller and to receive telemetry data for data logging purposes. 3DR Antennae are also used for the Piksi communication link between the base station and rover. The telemetry link and Piksi link operate on different channels to avoid cross-interference. An assembled team consisting of a safety pilot, project safety manager, and a spotter are required for maintaining visual line-of-sight on the shielded octocopter during flight. The GCS requires two personnel to monitor the reported trajectory of the vehicle and flight performance characteristics reported from the telemetry data stream. The AFIT RNR is oriented to transmit thermal noise waves in a direction away from the personnel for safety precaution. A separate team is needed to operate and monitor the noise radar as it measures the RCS of the shielded octocopter.



Figure 29. Outdoor RCS Range with AFIT RNR and GCS layout



Figure 30. Radar Van (Left) and Field Probe (Right)

3.8 Field Probe Measurement Procedure

The shielded octocopter developed in this research is designed to provide field probe measurements conducted at an outdoor RCS range. The following steps describe the procedure for using this system and post-processing the data acquired from this system to determine deviations and uncertainty observed in the incident EM wave measured in the test volume (assuming the time stamps of RCS measurements acquired from radar are identical to the position/ pose timestamps):

1.) Acquire the field probe's truth-RCS "Calibration" data set:

Place the shielded octocopter at an established "zero-phase" location in the test volume. Use low frequency band radar system to perform azimuthal RCS scans (0° to 360°) of the probe at a select range of elevation angles between $\pm 20^{\circ}$. Between each elevation angle measurement, drag and drop the output of the radar's RCS measurement log, Mission Planner's ".tlog" and Piksi console's baseline ".csv" logs to a folder labeled with each of their associated elevation angle measurement. Repeat the section 3.7.4 procedure for each successive elevation angle adjustment before performing the azimuthal scans. This ensures that Mission Planner and Piksi Console outputs unique log files between each elevation angle measurement. When finished with all measurements, save each elevation angle folder to a master folder entitled "Truth RCS data".

2.) Scan the test volume using the shielded octocopter:

Refer to section 3.7.4 "*Outdoor RCS Range Preparation*" to prepare the octocopter and GCS telemetry before starting any RCS measurements. Place the shielded octocopter at an

established "zero-phase" location in the test volume. Use Mission Planner to write a desired waypoint flight program to the octocopter's flight controller (refer to Mission Planner documentation). Power on the low band radar system to transmit EM waves in the direction of the shielded octocopter. Using the octocopter's 3DR radio controller, apply throttle and navigate the shielded octocopter to a modest altitude (3 - 5 meters above ground level). Switch to "auto" mode on the 3DR radio controller. The shielded octocopter will navigate the pre-programmed waypoint flight program. As this flight program executes, the user can apply yaw from the 3DR radio controller to rotate the shielded octocopter. This is recommended when using the 2v geodesic sphere to provide a "smooth" RCS profile reminiscent of a perfect sphere. When the flight program has ended, use the 3DR radio control to switch back to "manual" mode and cautiously land the shielded octocopter. Turn off the radar and close Mission Planner and Piksi Console to stop logging telemetry data. Save the RCS log, Mission Planner ".tlog", and Piksi Console ".csv" logs to a folder entitled "Flight RCS data".

3.) Determine the deviation in the incident EM wave traversing the test volume:

At this point, all the data required to analyze the test volume's effect on EM waves has been collected. The next step is to post-process the data, starting with creating an RCS calibration matrix relating the elevation and azimuth angles of the shielded octocopter to the corresponding RCS measurements observed at those angles. For each elevation angle folder, import all RCS data logs into MATLAB one at a time from the "Truth RCS data" folder. The procedure for creating the calibration matrix is as follows:

- a.) Parse the calibration RCS data for each elevation angle, creating an array of size M by N, where length M is the number of elevation angles and length N is the number of corresponding calibration RCS values
- b.) Parse the azimuth angles and elevation angles, assigning unique variables to each.
- c.) Use "scatteredInterpolant" function and input the azimuth, elevation, and calibration RCS arrays. The output of this function is the calibration matrix. The calibration matrix is essentially used as a 2-dimensional function to look up an expected RCS value based on yaw and pitch observed during the field probe in-flight measurements.

The next step is to import the position, pose, and RCS data sets from the "Flight RCS data" folder into MATLAB. The in-flight yaw and pitch quantities are input into the calibration matrix created from the previous step. The output yields the expected RCS values observed during the probe's flight. Subtract this truth array from the array of in-flight RCS values. The resulting data set reveals the deviations exhibited in the incident EM wave in the test volume.

4.) Apply uncertainty to the field probe measurements:

Use the Monte Carlo approach to generate possible position and pose values observed from the shielded octocopter during the in-flight measurements. A random number is generated in each Monte Carlo trial for a given position and pose coordinate acquired during the in-flight measurements. Each random number generated is constrained to the absolute accuracy of the position and pose measurement (see table 14). Input the pitch and yaw data sets generated from the Monte Carlo trials into the calibration matrix found previously to

obtain the possible RCS measurements observed during the in-flight probe of the test volume.

3.9 Summary

The system architecture for the field probe involves interfacing the Piksi DPGS module with the Pixhawk flight controller and developing a shield capable of providing desirable RCS characteristics. Characterizations of the position-pose measurements involve determining the accuracy of the u-blox and Piksi modules, as well as the INS module onboard the octocopter. This is accomplished by comparing the GPS to AFIT's NovAtel system and comparing INS to the iGaging angle cube. The position and pose time stamping alignment involves developing a C++ program to synchronize and log the incoming telemetry data received over the 3DR communication link between the octocopter and GCS. Characterizations of the position, pose, and time differential between the GPS and INS time stamps completes the assessment of the field probe system's uncertainty. The following chapter examines the results of each characterization and RCS measurements to provide an assessment of the shielded octocopter's outdoor flight performance.

IV. Results

This chapter presents the results and analysis for developing the outdoor two-way field probe system. The results provided include the characterizations of the octocopter's GPS/INS modules, position/pose time stamp differential, and RCS measurements of the field probe. Sector averaging is applied to the high frequency RCS measurements in order to distinguish RCS phenomena occurring within a region of the target's aspect. The final assessment of the shielded octocopter developed in this research is based on the flight performance under realistic outdoor RCS range conditions.

4.1 Piksi Module Characterization

The analysis of static and dynamic golf cart trials involves comparing Piksi's reported RTK fix position solutions to the truth source, NovAtel. The expected result from these trials is for Piksi to provide centimeter level accuracy for its position relative to the NovAtel position when operating in RTK fix mode. The Piksi RTK float mode is not examined as the intent is to only use Piksi when it provides the most accurate position solutions to the octocopter's Pixhawk flight controller. The following subsections assess the position data acquired from Piksi and NovAtel to determine the 2D and 3D position accuracy of Piksi.

4.1.1 Piksi Static Trials

The reported static NED positions of the Piksi (RTK Fixed) and NovAtel rovers from trial 1 are shown in Figure 31. These samples acquired over a 25 minute duration in trial 1 followed by an 18 minute duration in trial 2 are averaged to determine the rovers' location. It is

observed that after approximately 2 minutes, the reported position from the Piksi changes instantaneously by approximately 0.3 meters. It is not known the cause of the position change, nor did it occur in subsequent trials. This ambiguity greatly affected the lateral accuracy calculated from the DRMS and was therefore removed from the analysis of the position uncertainty characterization.

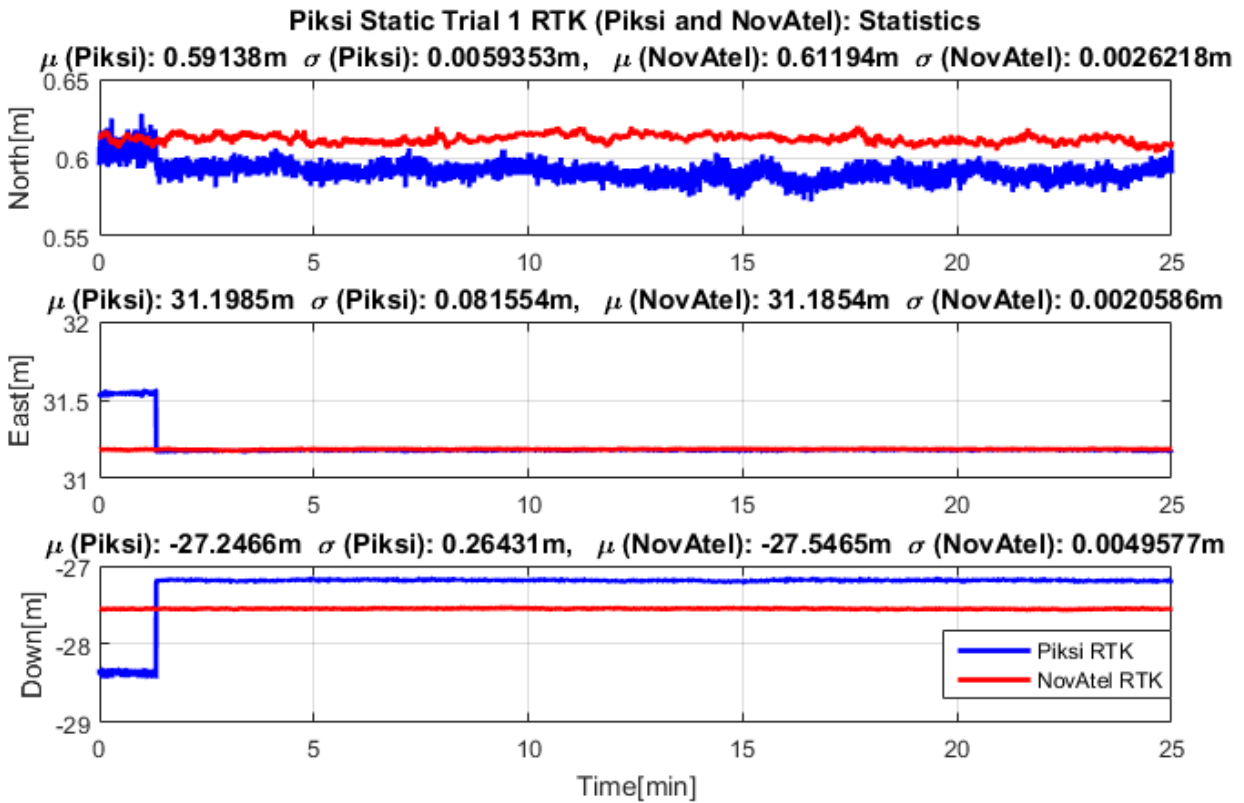


Figure 31. Piksi RTK vs. NovAtel RTK Static Trial 1

Table 6 shows the computed mean and standard deviation errors for each static trial. The RTK fix from static trial 1 yields a lateral position error of 2.32 cm followed by static trial 2 position error of 2.24 cm. The altitude error between NovAtel and Piksi averages approximately 36.25cm. The RTK float mode from static trial 1 yields a lateral accuracy of 33.1 cm followed by a static trial 2 position error of 2.10 cm. It should be noted that the Piksi Float mode accuracy

will directly vary as a function of the Integer Ambiguity Resolution (IAR) number. This quantity refers to the resolution of carrier-phase measurements based on the number of satellites observed by the Piksi rover. Assuming a static Piksi rover, a large IAR number indicates a float position solution is not consistent with its preceding position solutions. However, a small IAR number indicates less ambiguity between the position solutions generated from the rover, therefore having a strong correlation. It is believed that much of the static trial 2 characterization for float mode was performed with a low IAR number (possibly 1) considering the lateral accuracy is representative of RTK Fix precision.

Table 6. Piksi Static Trials, RTK Fix Statistics (4381 Samples)

	Trial 1		Trial 2		Total μ Error	Total σ Error	95% Confidence Intervals
	μ Error	σ Error	μ Error	σ Error			
North(m)	0.0211	0.0057	0.0204	0.0049	0.0208	0.0053	± 0.00015
East(m)	0.0064	0.0041	0.0069	0.004	0.0067	0.0405	± 0.00119
Down(m)	-0.3618	0.0116	-0.3631	0.0142	0.3625	0.0129	± 0.00038
DRMS(m)	0.0232	0.0989	0.0228	0.094	0.0230		
MRSE(m)	0.3628	0.1461	0.3641	0.1518	0.3635		

Piksi's Fixed RTK mode overall lateral accuracy, obtained from averaging both static trials is 2.08 cm. The Piksi Float mode lateral accuracy obtained from the static trials is 33.05cm. The overall 3-dimensional RTK Fix accuracy of 36.35cm is poor due to the GPS receiver's limited ability to approximate the height above the ground. The same is true for the float mode in which 34.10 cm accuracy is observed. Overcoming this limitation in altitude accuracy is further described in Chapter 5 "*Conclusions and Recommendations*" section.

4.1.2 Piksi Dynamic Trials:

The initial analysis of the dynamic golf cart tests intends to examine the various precisions obtained from the Piksi module. The SPP solutions are provided by each Piksi module as a standalone GPS solution. The baseline output from both Piksi modules provides a more accurate differential position solution acquired from RTK float and fixed modes. This concept is evident in Figure 32. Piksi's SPP position solutions are not as correlated relative to the path of the golf cart as the float and fixed RTK. The float RTK is more consistent relative to the path of the golf cart but appears to have a range offset from the NovAtel system. The RTK fixed mode obtains the most precise position that closely matches and overlaps the NovAtel's reported position.

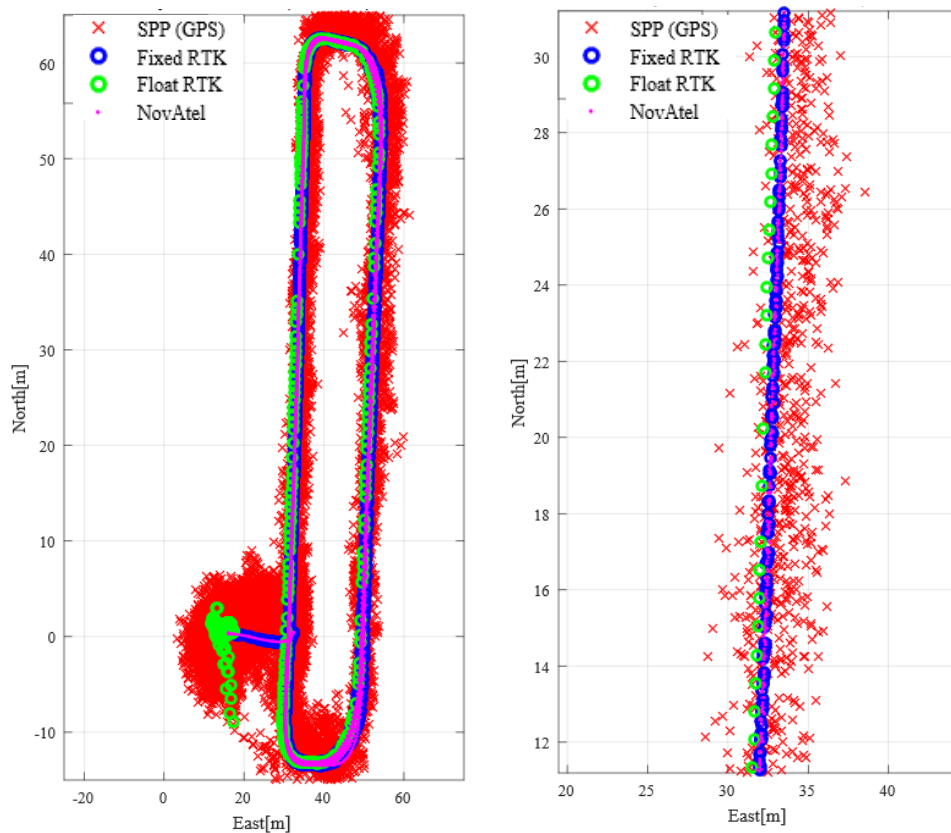


Figure 32. Piksi Position Solutions vs. NovAtel Truth Position (Trial 1 AFIT East Lot)

Figure 33 shows the NovAtel and Piksi position data aligned by the time stamps acquired from their ".gps" and ".csv" output files, respectively. The aligned data is parsed to determine the number of RTK fix samples acquired from Piksi for a given lap. In total, 11 laps were completed in the first dynamic trial. The second trial consisted of 7 parsed laps. Table 7 shows the summary of the NED errors determined for each lap and the overall error from combining both dynamic trials.

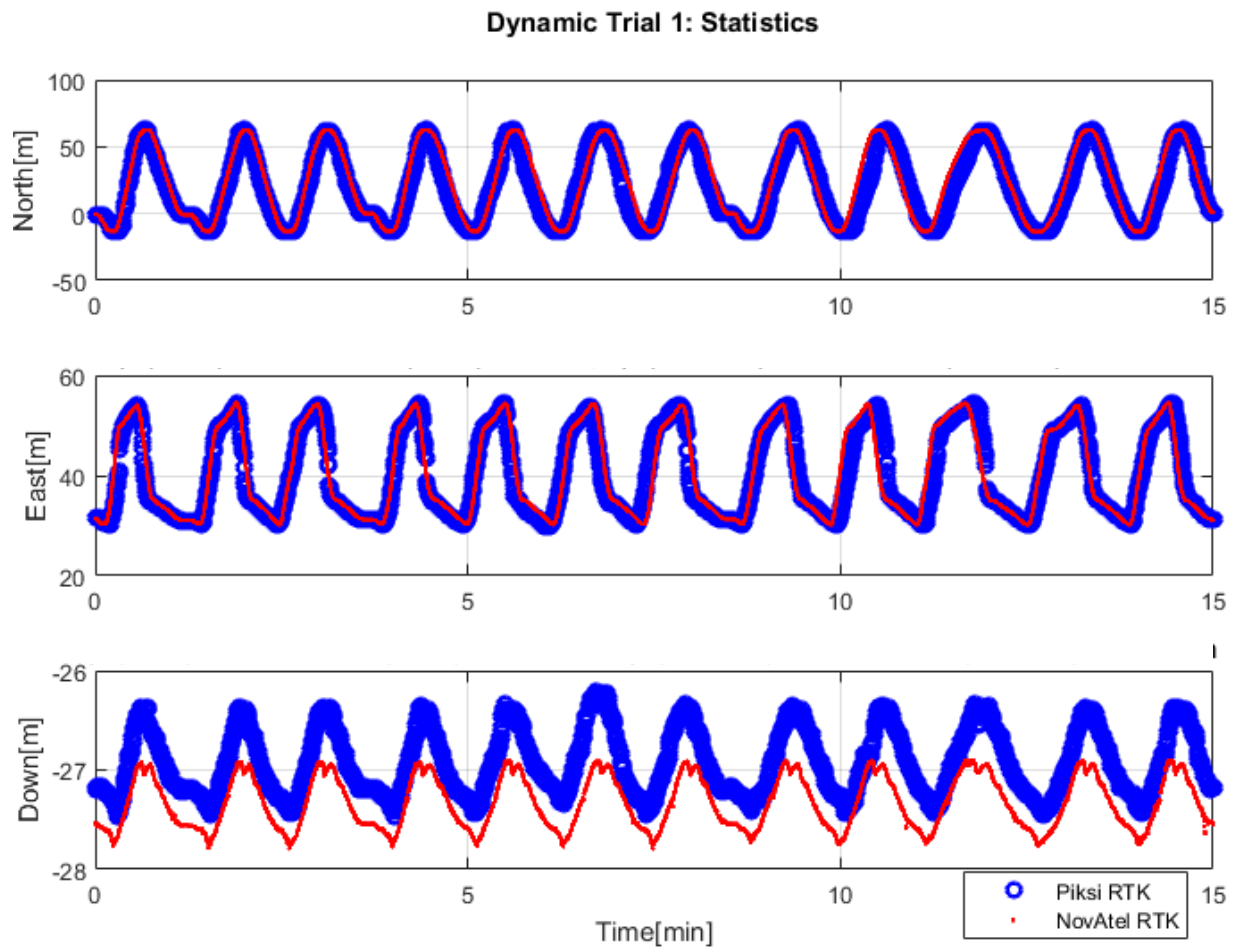


Figure 33. Piksi and NovAtel Aligned Position Solutions (Trial 1 AFIT East Lot)

Table 7. Piksi Dynamic Trials, RTK Statistics

Lap	Trial 1								Samp.
	North(m)		East(m)		Down(m)		DRMS(m)	MRSE(m)	
	μ Error	σ Error	μ Error	σ Error	μ Error	σ Error	μ Error	μ Error	
1	0.0251	0.0107	0.0079	0.008	-0.042	0.0759	0.0295	0.426	193
2	0.0284	0.0124	0.0133	0.0076	0.4226	0.0833	0.0345	0.423	183
3	0.0295	0.0118	0.0108	0.0072	0.4187	0.0833	0.0343	0.419	206
4	0.0283	0.0126	0.0141	0.0082	0.4187	0.0831	0.035	0.424	184
5	0.0288	0.0169	0.0118	0.0114	0.4196	0.0998	0.0371	0.42	128
6	0.6143	0.9797	0.2295	0.3606	19.9	0.1101	1.2306	19.056	222
7	0.0255	0.0143	0.011	0.0104	0.4183	0.0887	0.0329	0.418	222
8	0.0231	0.0315	0.0041	0.0104	0.426	0.0891	0.0414	0.426	231
9	0.0337	0.0169	0.0162	0.0179	-0.443	0.0826	0.0448	0.443	202
10	0.0279	0.0118	0.0117	0.0083	-0.438	0.0847	0.0335	0.438	241
11	0.0274	0.0103	0.0094	0.0075	-0.414	0.0772	0.316	0.414	234
Avg.	0.0278	0.0149	0.011	0.01	0.0814	0.0849	0.0316	0.425	2024
Lap	Trial 2								Samp.
	μ Error	σ Error	μ Error	σ Error	μ Error	σ Error	μ Error	μ Error	
1	0.0303	0.011	0.0131	0.0062	-0.421	0.0823	0.0353	0.421	201
2	0.0294	0.0117	0.0117	0.0062	0.4378	0.0899	0.0343	0.438	218
3	0.028	0.0106	0.0106	0.0062	0.4266	0.0798	0.0324	0.427	213
4	0.0275	0.0113	0.0103	0.0065	0.4264	0.0899	0.0321	0.426	203
5	0.0311	0.024	0.014	0.0164	0.4116	0.0883	0.0448	0.412	235
6	0.0263	0.0116	0.0123	0.0068	0.4123	0.0819	0.032	0.412	220
7	0.0288	0.0117	0.0128	0.007	-0.425	0.0846	0.0343	0.425	220
Avg.	0.0288	0.01402	0.01157	0.0089	0.1812	0.0852	0.35245	0.423	1275
Total:	0.02827	0.01402	0.01157	0.0089	0.1313	0.170123	0.035245	0.424	3299
		± 0.00048		± 0.0003		± 0.0098		← 95% Confidence Intervals	

The Table 7 results indicate that the number of sample sizes ranging from 128 to 241 RTK fixed positions are extracted from each lap. The speed and location of the golf cart relative to the recording frequency of the Piksi and NovAtel laptops contributes to the number of samples acquired for each lap. Piksi's float mode would occur periodically during the trial. In particular, lap 6 had to be removed from the overall averaging. Most of this lap was compromised by RTK float mode, leading to a lateral accuracy of 1.23 m. Dynamic trial 1 yields a lateral position error of 3.55 cm followed by static trial 2 position error of 3.50 cm. The height error differential between NovAtel and Piksi is consistently around 42 cm, a similar value to the static trials. Averaging both of the trials, the 2D position error is 3.5245 cm and the 3D position error is 42.4 cm. The relatively large error between the NovAtel and Piksi altitudes is contributing to the 3D result. As a result of the altitude difference between Piksi and NovAtel observed in the static and

dynamic trials, a separate test is conducted on the Piksi to further assess its differential height accuracy relative to ground level, as this solution is most meaningful when operating the field probe in its true test environment.

The varying Piksi rover heights acquired from the handcart lift are shown in Table 8. The varying height changes indicate that Piksi is capable of calculating a height difference within a 32 centimeter accuracy. The averaged error obtained from comparing the Piksi rover height to a meter stick is 26 cm.

Table 8. Piksi Altitude Statistics (1000 Samples per Height Δ)

Height Δ (m)	0	0.019	0.051	0.044	0.019	0.0191	0.044	0.0318	0.057	0.044	
μ Error (m)	-0.235	-0.220	-0.253	-0.26	-0.24	-0.226	-0.299	-0.257	-0.271	-0.25	
σ Error (m)	0.0093	0.0104	0.0152	0.0158	0.0158	0.0110	0.0238	0.0111	0.0149	0.0244	
	0.0572	0.019	0.019	0.019	0.019	0.0191	0.013	0.0318	0.038	0.032	Avg:
	-0.275	-0.26	0.049	-0.27	-0.38	-0.291	-0.337	-0.304	-0.308	-0.32	-0.26000
	0.0158	0.0120	0.0166	0.0144	0.0340	0.0186	0.0284	0.0182	0.0192	0.0108	0.016985

4.2 u-blox LEA-6 GPS Characterization

The u-blox GPS characterizations involve applying an offset distance to the u-blox position data to align its position values at the same location as the NovAtel receiver antenna. The offset distance magnitude of 0.86m measured from the u-blox antenna and the NovAtel rover antenna on the back of the golf cart. Figure 34 shows the NED position solutions acquired from the u-blox and NovAtel systems over a 30 minute static trial after applying the range offset to the data. The u-blox system's position varies much more than Piksi as seen in the previous static trials. This highlights the precision of differential position solutions in comparison to the standalone GPS solutions. The altitude determined by u-blox differs by approximately 1.41m from the NovAtel device compared to Piksi's altitude differential (~38 cm).

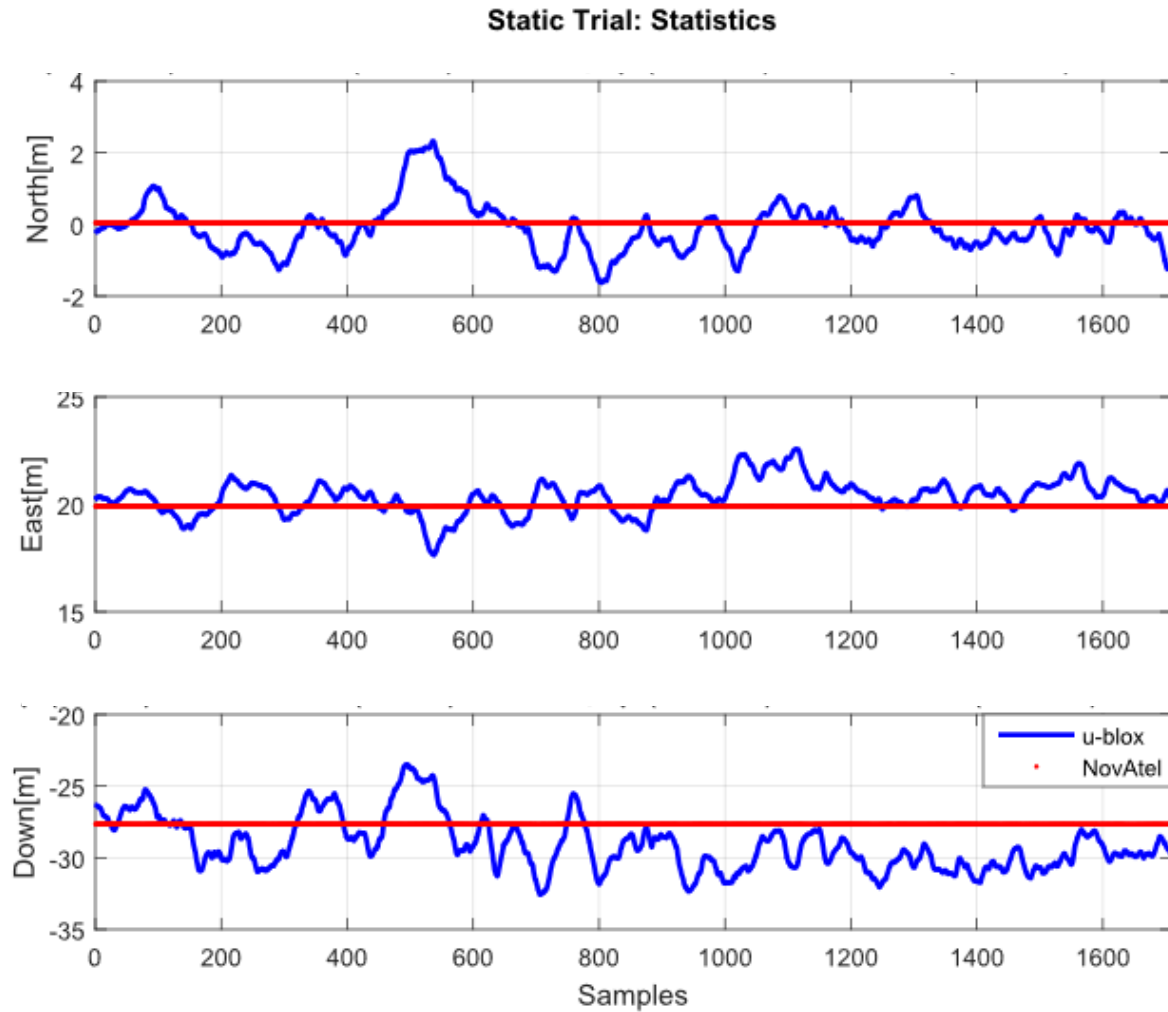


Figure 34. u-blox vs. NovAtel GPS Solution Static Trial

Table 9 lists the NED position errors after applying the range offset to the data. The 2D error is 1.1441 m and the 3D error is 2.5860 m. As expected, the lateral error is significantly worse in the u-blox system compared to the Piksi differential position solutions relative to the NovAtel solutions. The 3-dimensional error of the u-blox system is worse than the Piksi by approximately 0.786 m.

Table 9. u-blox Static Trial Statistics(1710 Samples)

	μ Error	σ Error	95% Confidence Intervals
North[m]	0.1365	0.6798	± 0.0322
East[m]	-0.4625	0.7842	± 0.0372
Down[m]	1.4113	1.8409	± 0.0873
DRMS[m]	1.1441		
MRSE[m]	2.5860		

The dynamic trial post-processing requires time aligning the NovAtel and u-blox position samples. As with the Piksi data, the process of synchronizing the time stamps of NovAtel's ".gps" file and u-blox's ".mat" file is applied to both data sets:

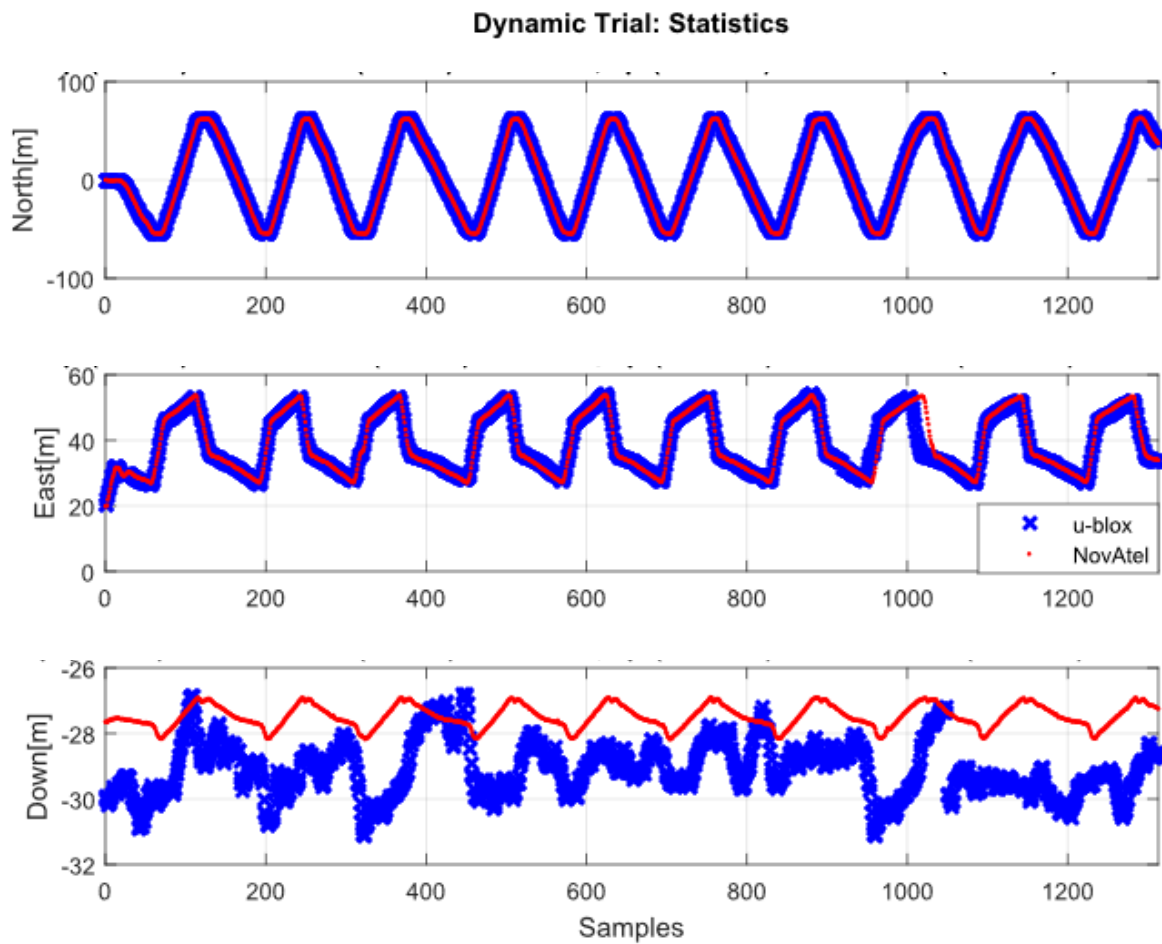


Figure 35. u-blox - NovAtel Data Alignment

After aligning the data, a lap by lap extraction is applied to determine the mean error statistics and number of samples acquired for each lap. Figure 36 shows a total of 10 laps completed in which 118 to 165 samples were recorded. The DRMS values indicate meter level of lateral precision is obtained from u-blox. The statistics for each lap are listed in Table 10.

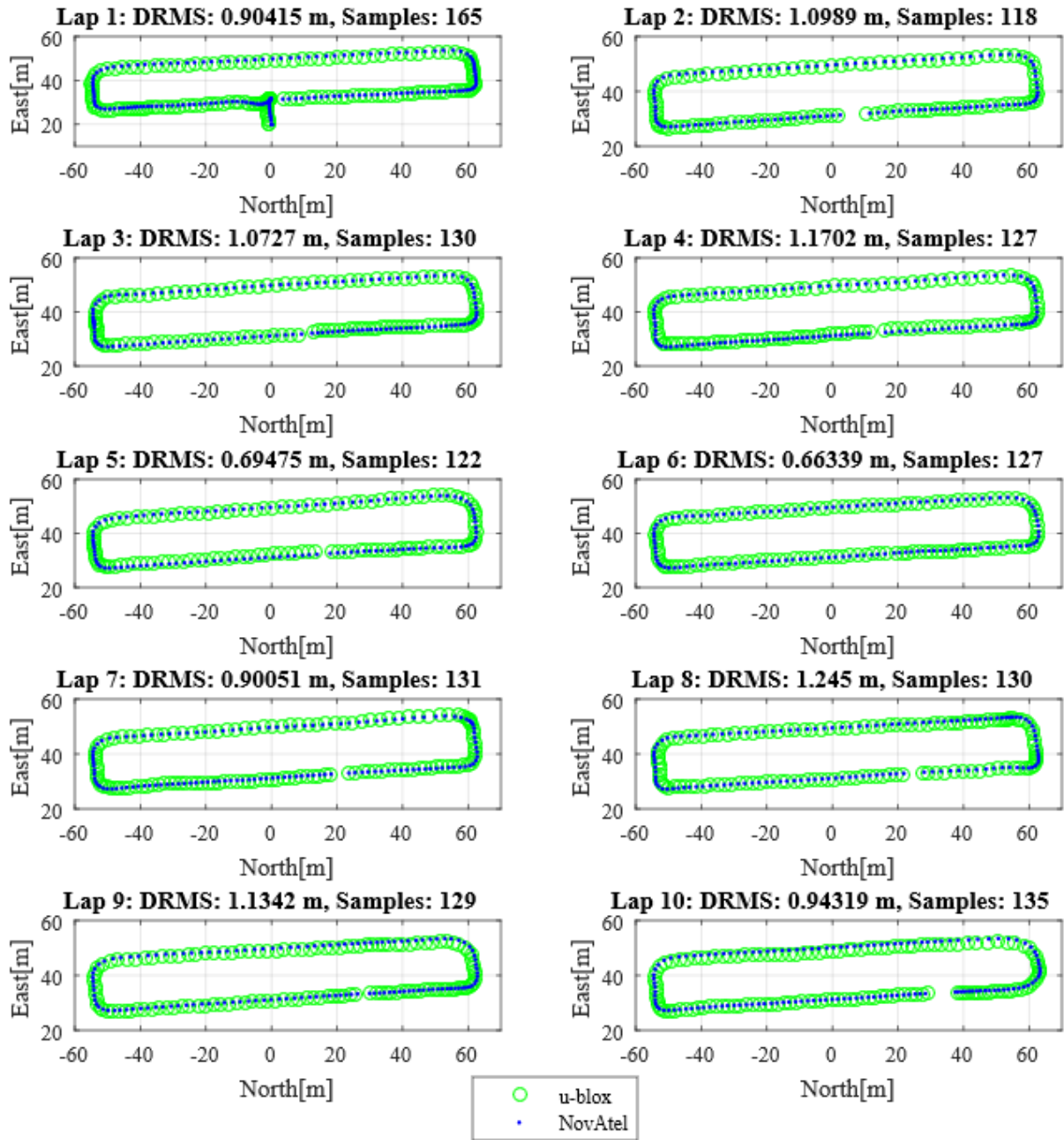


Figure 36. NovAtel and u-blox Lap Extraction

Table 10. u-blox Dynamic Trial Statistics

	North (m)		East (m)		Down (m)		DRMS (m)	MRSE (m)	
Lap	μ Error	σ Error	μ Error	σ Error	μ Error	σ Error	μ Error	μ Error	Samp.
1	0.1139	0.6374	0.3975	0.5925	1.6533	0.7526	0.9041	2.0282	165
2	-0.2046	1.0025	0.3231	0.3871	1.8833	0.4456	1.0989	2.2251	118
3	-0.6123	0.7963	-0.0772	-0.4783	1.6164	1.0277	1.0727	2.1935	130
4	-0.6639	0.8125	-0.1536	-0.3274	1.2373	0.6948	1.1702	2.0416	127
5	-0.3235	0.3276	-0.2118	-0.3122	1.5211	0.3305	0.6948	1.7043	122
6	-0.4170	0.4049	0.1203	0.4235	1.2721	0.3594	0.6634	1.4787	127
7	-0.5326	0.6450	-0.0563	-0.4221	1.2415	0.5894	0.9005	1.6422	131
8	-0.4976	1.0284	0.2668	0.3371	1.7163	0.4700	1.2450	2.1714	130
9	-0.1402	0.8724	0.5804	0.4723	2.0943	0.4713	1.1342	2.4275	129
10	-0.2185	0.4165	0.6522	0.3212	2.0906	0.6027	0.9432	2.3708	135
Avg.	-0.3496	0.69435	0.131904	0.40847	1.63262	0.5744	0.9827	2.02833	1314

According to Table 10, the overall 2D accuracy obtained from averaging the mean errors of the DRMS is 0.9827 m. This is 16.14 cm. more accurate result than the DRMS from the static trial. The 3D accuracy is 2.02833 m, also an improvement over the static trial by 55.76 cm. Compared to the Piksi, the lateral accuracy differs by an order of magnitude (1.09m statically and 0.9475m dynamically). This is expected, as u-blox position solutions are non-differential, meaning that they do not reference a surveyed reference location.

The following section provides the analysis of the octocopter's INS. The INS characterizations complete the uncertainty measurements by examining the pose accuracy at varying levels of precision (i.e. small, medium, and large angle changes). The application of these particular accuracies to the uncertainty model are determined based on the angular response of the octocopter's pose encountered along its flight path as the field probe is measured at the outdoor RCS range.

4.3 INS Characterization

The pitch, roll, and yaw measurements require extracting the steady state samples from the '.mat' files created from Mission Planners telemetry logs (".tlogs"). These samples are compared to the iGaging angle cube to determine the error. Figures 37, 38, and 39 show the extracted samples in addition to the mean error and standard deviations for each angle measurement. It should be noted that IMU drift is an observed phenomena based on the magnitude of the error observed in angle change occurring between each individual angle measurement (i.e. 5° to 10° vs. 0.1° to 0.2°). IMU drift is not quantified in these characterizations.

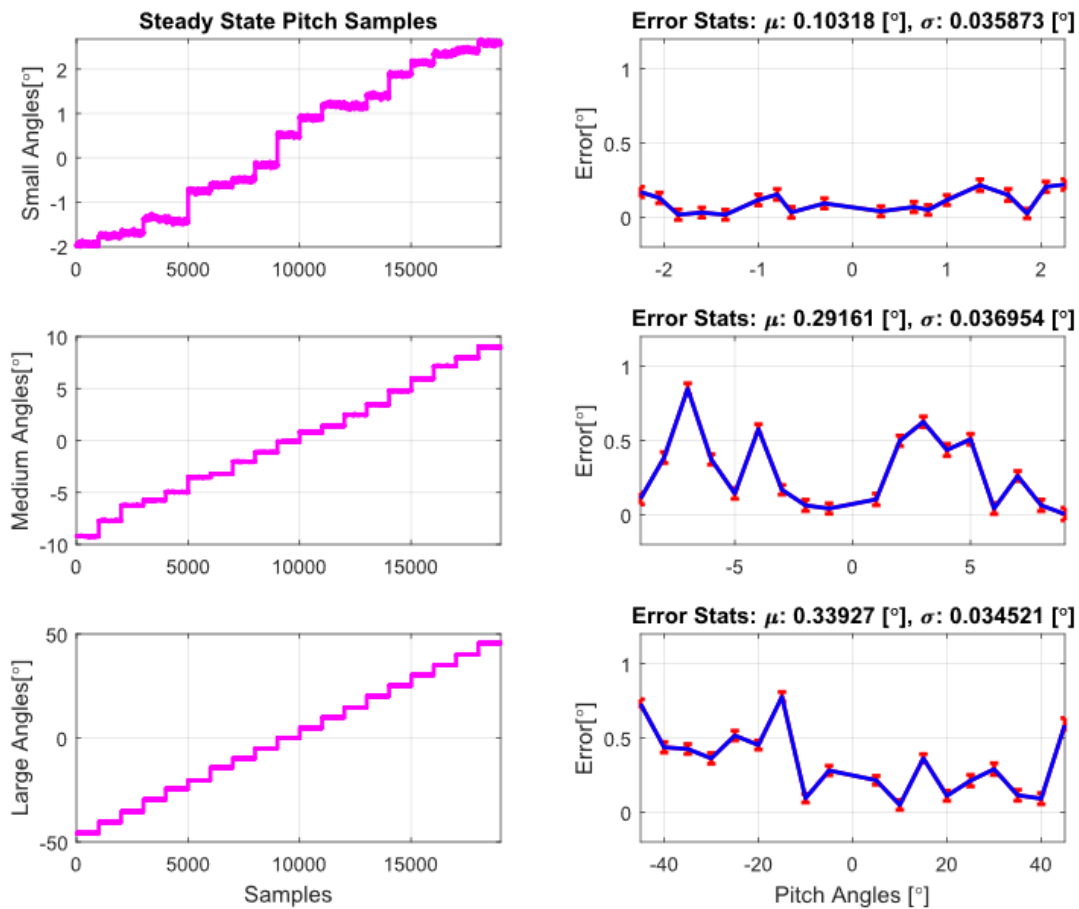


Figure 37. Extracted Pitch Samples

The pitch samples acquired from the tilt table test show an increasing error difference from the iGaging cube measurements by approximately 0.1° as the angle deviations increase from small to large. This is expected as the angle differences increase, IMU drift or summation of angle errors also increase. However, the standard deviation appears to remain consistent (approximately 0.03°) for each angle change. A consistent standard deviation indicates that the angle measurements from the IMU do not deviate or vary much with respect to each angle change; small, medium, or large.

Table 11 shows the pitch angle summary, providing the mean error and standard deviation error for each tested angle.

Table 11. Pitch Statistics (1000 samples per angle)

Pitch Statistics								
Large Angle Results			Medium Angle Results			Small Angle Results		
Angle	Mean Error	STD Error	Angle	Mean Error	STD Error	Angle	Mean Error	STD Error
45	0.5872	0.0468	9	0.0046	0.0425	2.25	0.2207	0.0365
40	0.0916	0.038	8	0.0634	0.0394	2.05	0.2053	0.0360
35	0.1141	0.0372	7	0.2607	0.0342	1.85	0.0257	0.033
30	0.2900	0.0398	6	0.0418	0.0374	1.6	0.1501	0.0412
25	0.2124	0.0393	5	0.5085	0.0368	1.35	0.2161	0.0401
20	0.1107	0.0345	4	0.436	0.0414	1	0.1160	0.0341
15	0.3627	0.0288	3	0.6257	0.0362	0.8	0.0495	0.0338
10	0.0489	0.0334	2	0.4977	0.0353	0.65	0.0694	0.0354
5	0.2150	0.0298	1	0.1034	0.0395	0.3	0.0404	0.0347
-5	0.2808	0.0324	-1	0.0418	0.0354	-0.3	0.0937	0.0348
-10	0.0941	0.0288	-2	0.0632	0.0383	-0.65	0.0331	0.0373
-15	0.7775	0.0326	-3	0.168	0.0323	-0.8	0.1536	0.0371
-20	0.452	0.0304	-4	0.5769	0.0328	-1	0.117	0.0367
-25	0.5161	0.0331	-5	0.1427	0.0359	-1.35	0.0171	0.0342
-30	0.3624	0.0361	-6	0.3724	0.0350	-1.6	0.0317	0.0341
-35	0.4256	0.0334	-7	0.8485	0.0369	-1.85	0.0175	0.0356
-40	0.4370	0.0355	-8	0.3852	0.037	-2.05	0.1305	0.0360
-45	0.7290	0.0314	-9	0.1085	0.0389	-2.25	0.1699	0.0352
Avg.	0.33927	0.034532		0.29161	0.036954		0.10318	0.035873

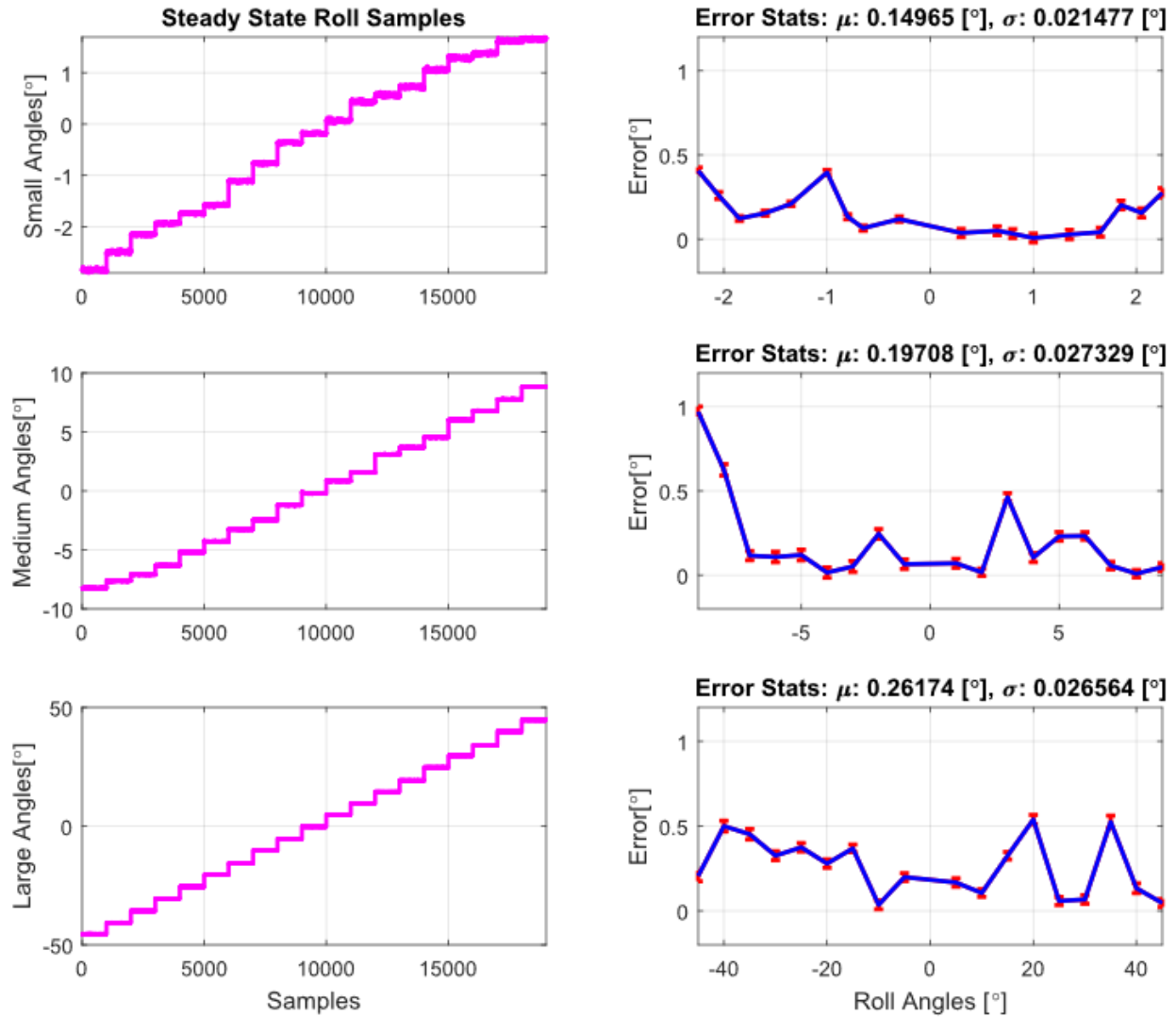


Figure 38. Extracted Roll Samples

The roll samples acquired from the tilt table test show an increasing error difference from the iGaging cube measurements as the angle differences increase from small to large by approximately 0.05° . This is expected as the angle differences increase, IMU drift errors also increase. However, as observed in pitch, the standard deviation appears to remain consistent for each angle change (approximately 0.02°). The accelerometers and gyroscopes are measuring the angular change of the octocopter at pitch and roll orientations. This test indicates that roll is

slightly more accurate than pitch for medium and large angle changes by approximately 0.09° . This notion is consistent with the difference in pitch and roll standard deviations. Roll has a standard deviation that is lower than pitch by approximately 0.01° . The result is a lower angle error difference with each change between small, medium, and large angles for the roll measurements. The roll maneuver may be slightly less susceptible to IMU drift compared to pitch. There is little difference between pitch and roll for the small angle changes, therefore, a conclusion cannot be made about their relationship to their respective standard deviations.

Table 12 shows the roll angle summary, providing the mean error and standard deviation error for each tested angle.

Table 12. Roll Statistics (1000 samples per angle)

Roll Statistics								
Large Angle Results			Medium Angle Results			Small Angle Results		
Angle	Mean Error	STD Error	Angle	Mean Error	STD Error	Angle	Mean Error	STD Error
45	0.0468	0.0235	9	0.0478	0.0234	2.25	0.2751	0.0279
40	0.1339	0.0288	8	0.0086	0.0222	2.05	0.1557	0.0273
35	0.5247	0.037	7	0.0569	0.0229	1.85	0.2028	0.026
30	0.0676	0.0253	6	0.2326	0.0227	1.6	0.0415	0.0263
25	0.0585	0.0239	5	0.2303	0.0259	1.35	0.0274	0.0281
20	0.5391	0.0272	4	0.1044	0.0268	1	0.007	0.0264
15	0.3253	0.0222	3	0.4629	0.0238	0.8	0.033	0.0266
10	0.1056	0.0229	2	0.0172	0.022	0.65	0.0496	0.0267
5	0.1678	0.025	1	0.0704	0.0264	0.3	0.0369	0.0248
-5	0.1994	0.0233	-1	0.0649	0.0283	-0.3	0.1191	0.0165
-10	0.0361	0.026	-2	0.245	0.029	-0.65	0.0654	0.0157
-15	0.3687	0.0223	-3	0.0516	0.0326	-0.8	0.1331	0.0153
-20	0.2791	0.0249	-4	0.0153	0.0307	-1	0.3956	0.0154
-25	0.3749	0.0251	-5	0.1198	0.0321	-1.35	0.2097	0.0137
-30	0.3258	0.0264	-6	0.1082	0.0312	-1.6	0.1541	0.0152
-35	0.4523	0.0312	-7	0.1161	0.0276	-1.85	0.1224	0.0146
-40	0.4999	0.032	-8	0.6249	0.0341	-2.05	0.2592	0.0208
-45	0.2059	0.0312	-9	0.9705	0.0304	-2.25	0.4064	0.0193
Avg.	0.26174	0.026564		0.19708	0.027329		0.14965	0.021477

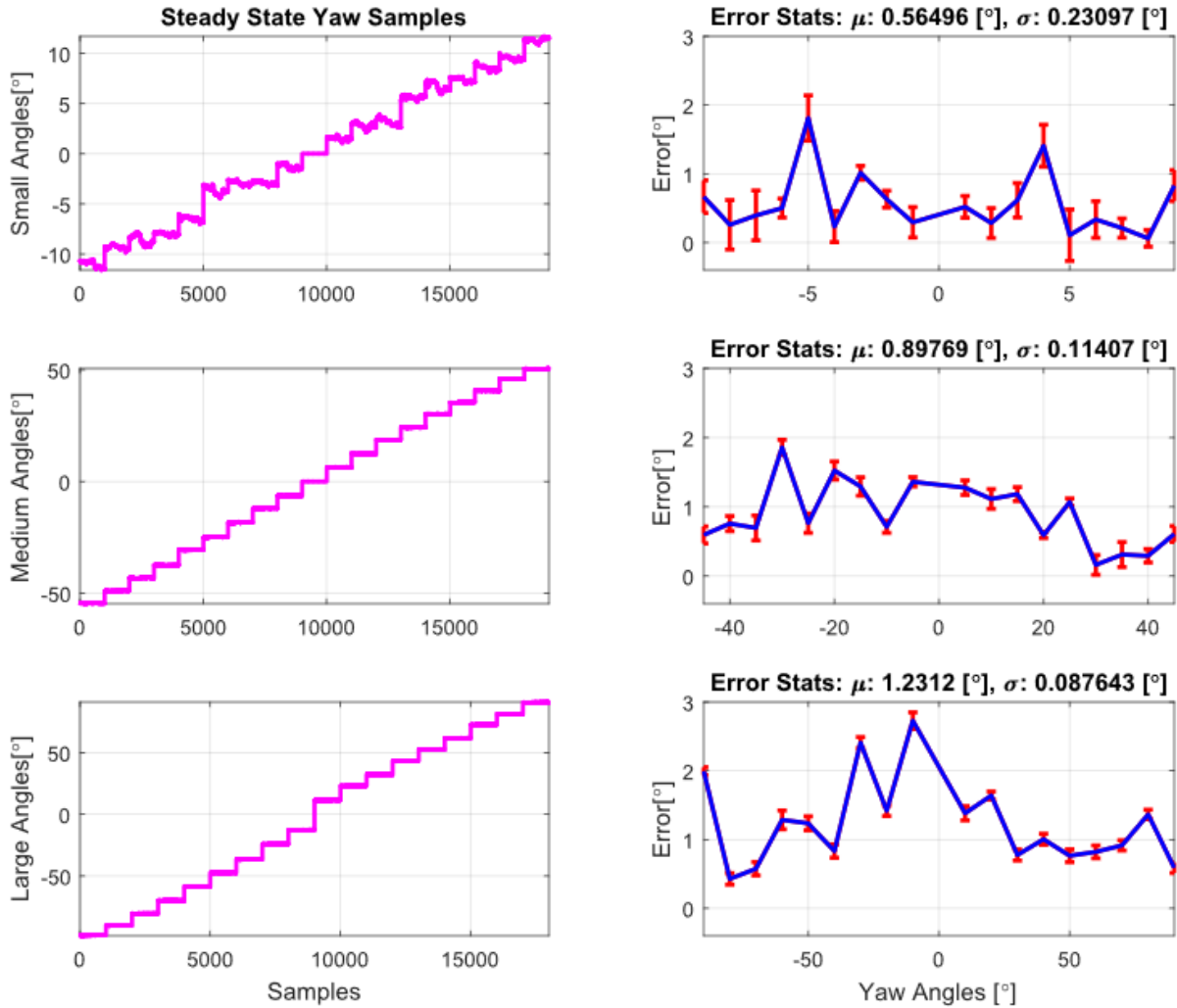


Figure 39. Extracted Yaw Samples

The yaw samples acquired from the turn table test show an increasing error difference from the iGaging cube measurements as the angle changes increase from small to large. This is expected, as angle increases, IMU drift or summation of angle errors will increase. The mean error is significantly greater compared to the pitch and roll data. The yaw measurement is acquired from internal and external compasses onboard the octocopter instead of the accelerometers and gyroscopes used to measure pitch and roll. The compass is clearly more sensitive to angle change, as seen with the standard deviations decreasing for every increasing

angle change; small, medium, and large. A greater angle change in the yaw is much more effective for the compass to approximate orientation as indicated by the decreasing standard deviation. It was determined that using the pitch and roll small angle changes for the yaw characterization is not possible due to the compass's sensitivity threshold, which appears to be no less than 1° of angle variation.

Table 13 shows the yaw angle summary, providing the mean error and standard deviation error for each tested angle.

Table 13. Yaw Statistics (1000 samples per angle)

Yaw Statistics								
Large Angle Results			Medium Angle Results			Small Angle Results		
Angle	Mean Error	STD Error	Angle	Mean Error	STD Error	Angle	Mean Error	STD Error
90	0.5892	0.0757	45	0.6074	0.114	9	0.8281	0.2252
80	1.3648	0.0685	40	0.2917	0.0971	8	0.0608	0.1214
70	0.9148	0.074	35	0.3097	0.1809	7	0.2102	0.1394
60	0.8201	0.0927	30	0.1603	0.1423	6	0.335	0.2668
50	0.7638	0.0925	25	1.0686	0.0525	5	0.1071	0.3739
40	1.0039	0.0807	20	0.5911	0.0422	4	1.4086	0.3054
30	0.7749	0.0803	15	1.1837	0.1005	3	0.6144	0.2507
20	1.6399	0.0583	10	1.113	0.142	2	0.2836	0.2171
10	1.3821	0.1034	5	1.2762	0.1054	1	0.5186	0.1591
-10	2.7289	0.1207	-5	1.3614	0.0668	-1	0.2941	0.221
-20	1.4191	0.0766	-10	0.7101	0.086	-2	0.6305	0.1226
-30	2.4088	0.0816	-15	1.2937	0.1326	-3	1.0149	0.1012
-40	0.8314	0.0976	-20	1.5242	0.1303	-4	0.2321	0.2261
-50	1.2357	0.1014	-25	0.7633	0.1395	-5	1.8107	0.3294
-60	1.2862	0.1362	-30	1.8587	0.1096	-6	0.5012	0.1383
-70	0.5753	0.0973	-35	0.6942	0.1804	-7	0.3942	0.3624
-80	0.427	0.0834	-40	0.7577	0.1084	-8	0.2581	0.3595
-90	1.9953	0.0566	-45	0.5935	0.1228	-9	0.6669	0.2379
Avg.	1.2312	0.087643		0.89769	0.11407		0.56496	0.23097

4.4 Position-Pose Characterization Summary

The characterization of the X8 octocopter includes the position driven by the u-blox LEA6 or the Swift Navigation Piksi module, and the pose measurements acquired from the INS. Table 14 displays these values acquired from the characterization tests, including 95% confidence intervals reported for the position and pose uncertainty.

Table 14. Position and Pose Accuracy Characterization

	X[m] North	Y[m] East	Z[m] Down
Piksi DGPS (RTK Fix)	0.024535 ±0.000315	0.009135 ±0.000745	0.26 ±0.0002
Piksi DGPS (RTK Float)	0.03617 ±0.002251	0.31950 ±0.0002348	-0.3386 ±0.002235
u-blox LEA 6 (Octocopter un-aided)	0.37615 ±0.02445	0.160902 ±0.0213	4.61911 ±0.04311
Inertial Navigation System	Pitch[°]	Roll[°]	Yaw[°]
	0.33927 ±0.00047	0.26172 ±0.00034	1.2312 ±0.0012

The Piksi RTK fix provides the most precise position solution for the octocopter. If the RTK fix is unattainable, the default u-blox GPS takes priority to provide position solutions to the octocopter. The pitch, roll, and yaw accuracies acquired from these characterizations are the worst case scenarios in which a large angle change occurs. These large angle changes have been observed in flight tests of the octocopter performing the raster flight path at the outdoor RCS range.

Overall, the accuracies of the GPS and INS will contribute to the uncertainty bounds of the Monte Carlo Analysis conducted on the position and pose of the field probe as it relates to the interpolated RCS measurement. The RCS measurement acquired from the field probe must be characterizable, meaning that the scattering phenomenology is predictable based on a canonical geometry.

4.5 Position-Pose Time-Differential Characterization

When examining position and pose data acquired from the Mission Planner ".tlogs", it is realized that these measurements are not synchronized with respect to each other, but rather have their own independent number of logged and time-stamped samples. An uneven number of samples requires using a C++ program to decode position and pose measurements from the Mavlink telemetry and logging each measurement as they are captured from the telemetry stream. This section examines the time-differential characterization between position and pose of the u-blox GPS and INS modules onboard the octocopter, beginning with the effect that the ".tlog" replay speed has on the number of samples acquired for time stamping and alignment.

In Figure 40, it is apparent that a faster replay speed results in fewer samples acquired from the Mavlink telemetry stream. Therefore, the most effective replay speed is real time (1x). Figure 40 shows the overlay of the C++ program's 1x replay (time aligned samples) with the Mission Planner data acquired from the real time telemetry stream.

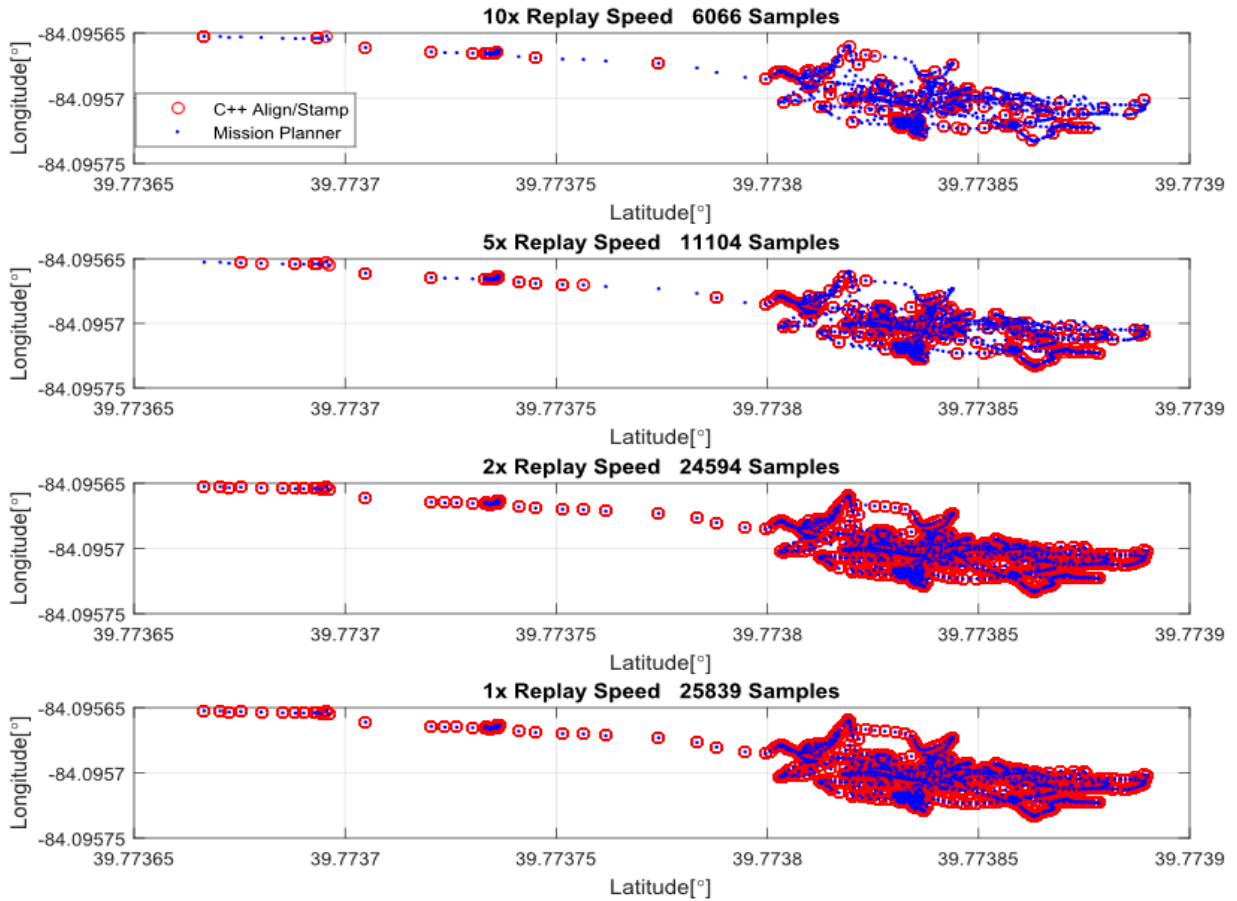


Figure 40. C++ time stamp samples overlaid with Mission Planner ".tlog" samples

Each of the 5 ".tlogs" from various flight programs are replayed at 1x speed to acquire the telemetry stream position/pose data and time alignment using the C++ program as shown in Figure 41. This data is extracted from the ".csv" logs generated by the C++ program and processed in MATLAB®. This technique is used whether or not the data is acquired live from the octocopter's telemetry or from a replayed telemetry log.

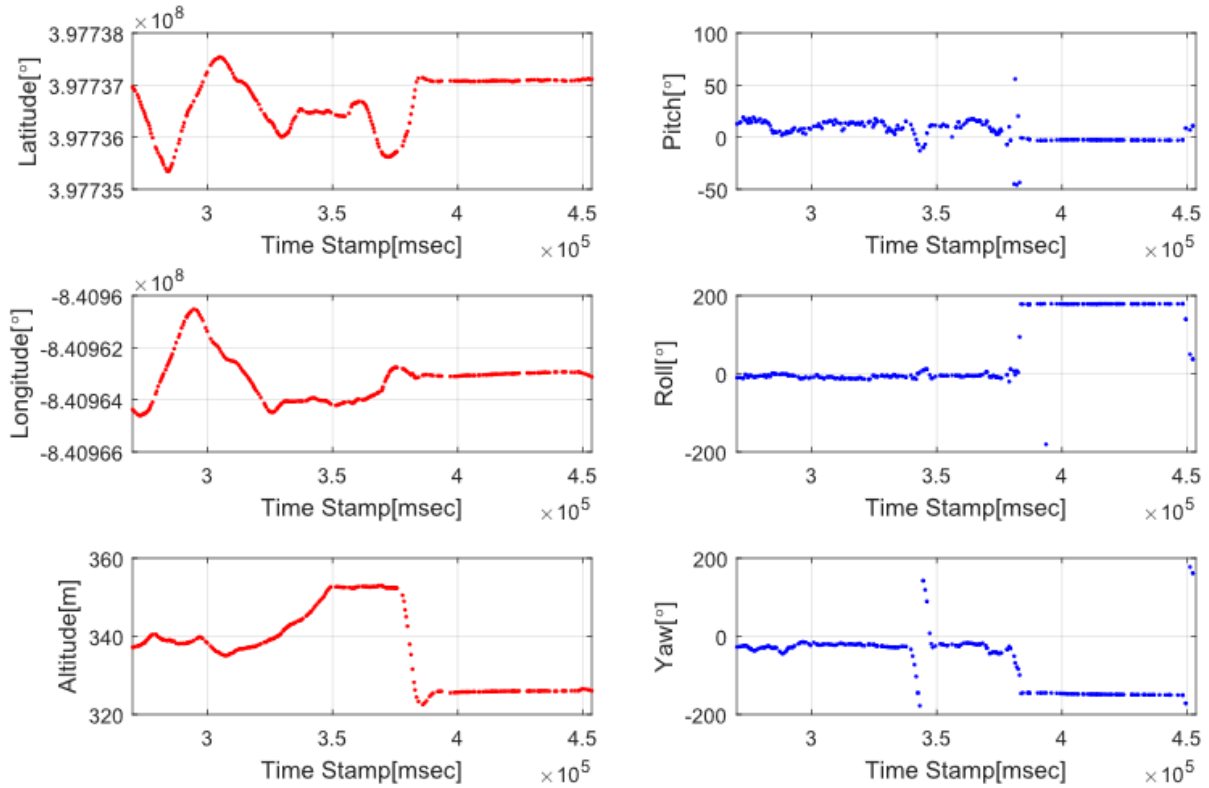


Figure 41. Time Stamped and Aligned Position and Pose (Field Probe Inaugural Flight)

The next test involved establishing a serial connection between the octocopter and the GCS and re-initiating for 10 trials. Each log generated from the trial was replayed to determine if there was significant difference between the mean GPS and INS time stamps generated from the live and replayed position/pose data. Figure 42 shows trials 10 and 9 live and replayed data sets. It is apparent in all 10 trials that the live and replay data sets exhibit very close GPS-INS time difference averages and standard deviations. The consistency in the position and pose time stamp differences between log replay versus acquiring the data real-time gives confidence to replay a pre-recorded telemetry log to perform the characterization of the time stamp differential between GPS and INS.

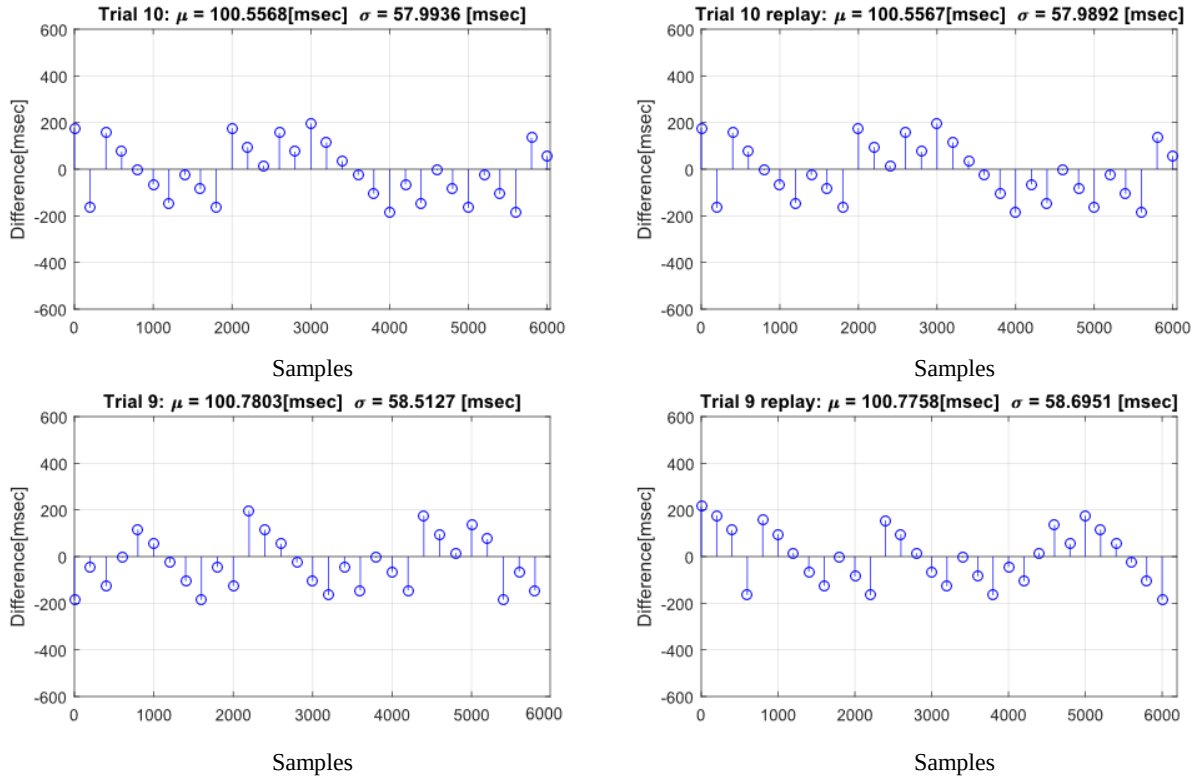


Figure 42. Live (Left) and Replay(Right) Data Sets for Trials 9 and 10, showing the difference (GPS Time Stamp - INS Time Stamp)

The following test results show the replay for 1 of 5 different flight program logs. Ten trials are processed to show the time difference between the position and pose stamps. The flight program is shown in Figure 43 from the inaugural flight test of the octocopter. It can be seen that each of the trials have a similar mean difference and standard deviation in the position-pose time differential. This occurrence is consistent among each of the flight programs tested as shown in Table 15.

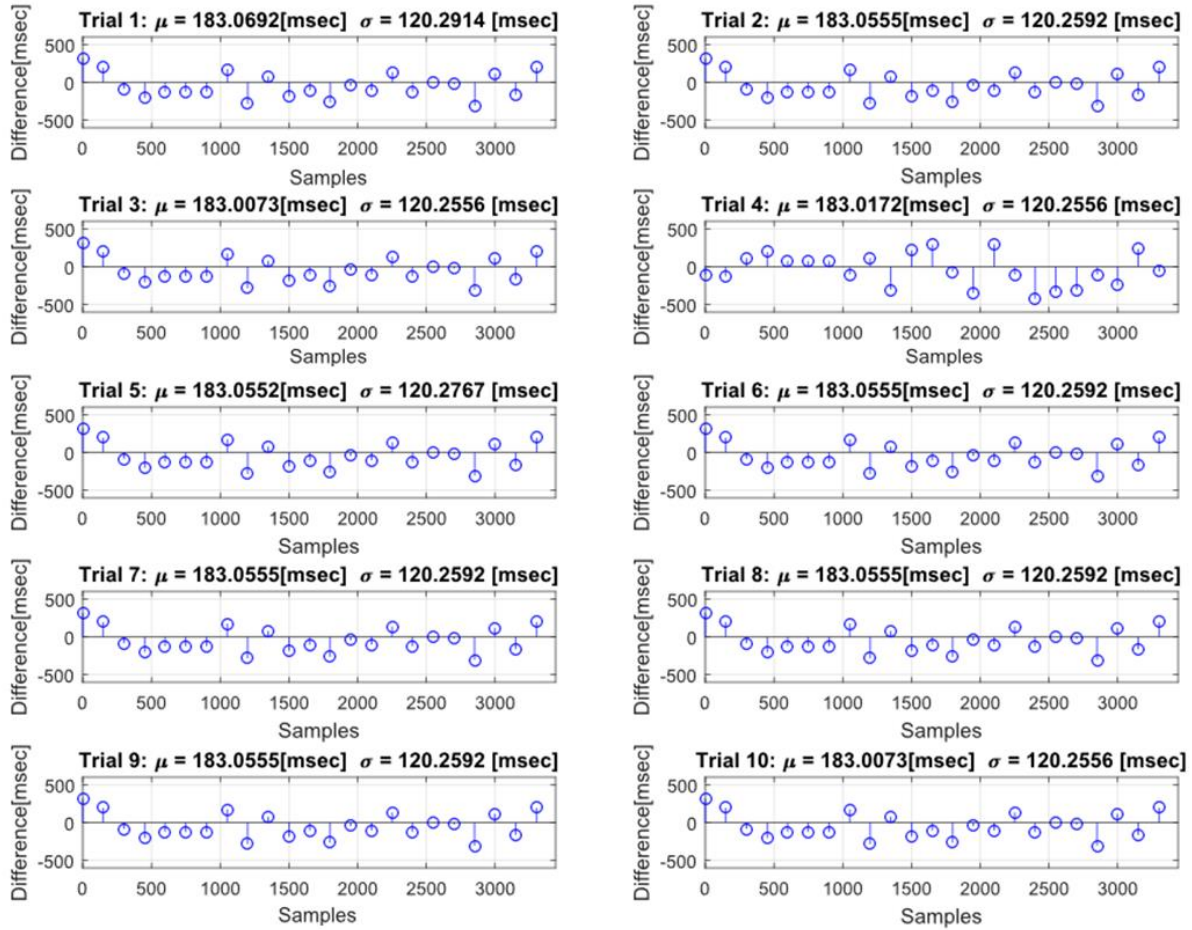


Figure 43. Inaugural Square Path Flight Program, Position-Pose Time Difference

Table 15. Flight Program Time Difference Mean and Standard Deviations

Flight Programs	μ [msec]	σ [msec]	Samples
Octocopter Checkout	264.5801	333.13736	31000
Inaugural Square	183.04337	120.26309	40000
Inaugural Raster	316.6955	346.83699	22000
Inaugural Field Probe	174.24663	227.590533	36000
Piksi Failed Test	294.95339	372.49172	16000
Total	246.703798	280.0639386	145000

The total average of all 5 flight programs position/pose time difference is approximately 246.70 milliseconds. The cause in variation in the average time differences between each flight program is relatively unknown. It should be noted that the usb serial connection between the

octocopter and the GCS yields an average mean error of approximately 100.77 milliseconds, a smaller difference compared to the 3DR wireless serial link. It is believed that the serial link allows for a more rapid and direct data transfer between the octocopter and GCS.

An additional focus related to the position/pose time difference characterization is the frequency update rate between each successive time stamp. The telemetry update rate for the time stamps is approximately 5Hz for a typical GPS module. Monitoring the GPS pulse trigger generated by the Mavlink telemetry received by the C++ program, it is apparent in Figure 44 that the pulse frequency is not representative of a consistent frequency. The lapse of acquiring telemetry data may occur as a result of the communication link between the GCS and the octocopter. As a result, a further characterization is required to determine the uncertainty between a pulse update. Applying the same technique as before, multiple trials for each flight program are conducted to determine the difference in elapsed time between each pulse. Figure 45 shows the difference between successive pulses for each trial executed for a particular flight program. Note that the first 110 (approx.) samples show very little error difference. During that period, the GPS had not acquired a satellite fix and therefore did not have any time-stamp position solutions to report. It also should be noted that the time differences between each trial are inconsistent as a ".tlog" is replayed and processed by the time stamp/align C++ program. Five trials are assessed for 4 separate flight programs as part of the elapsed time averaging. Table 16 shows the averages and standard deviations for each trial.

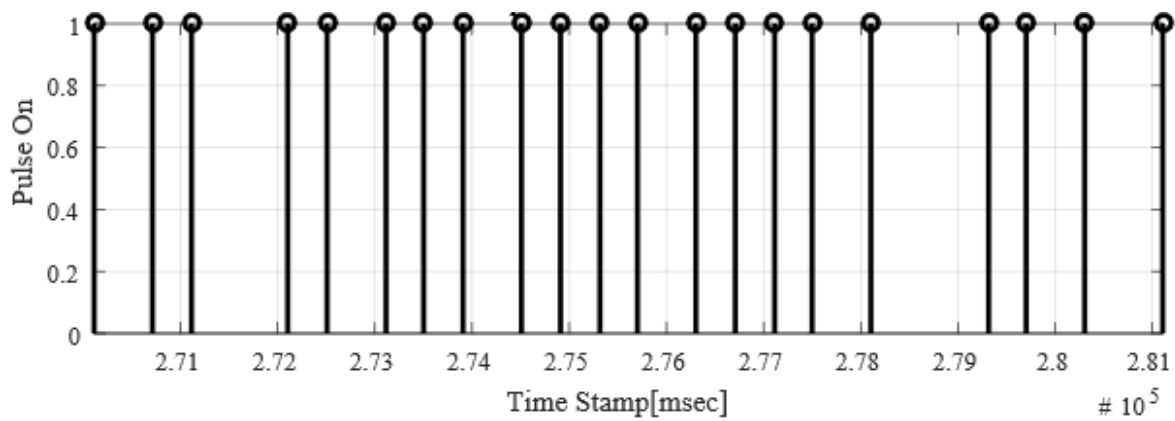


Figure 44. GPS-Triggered Pulses

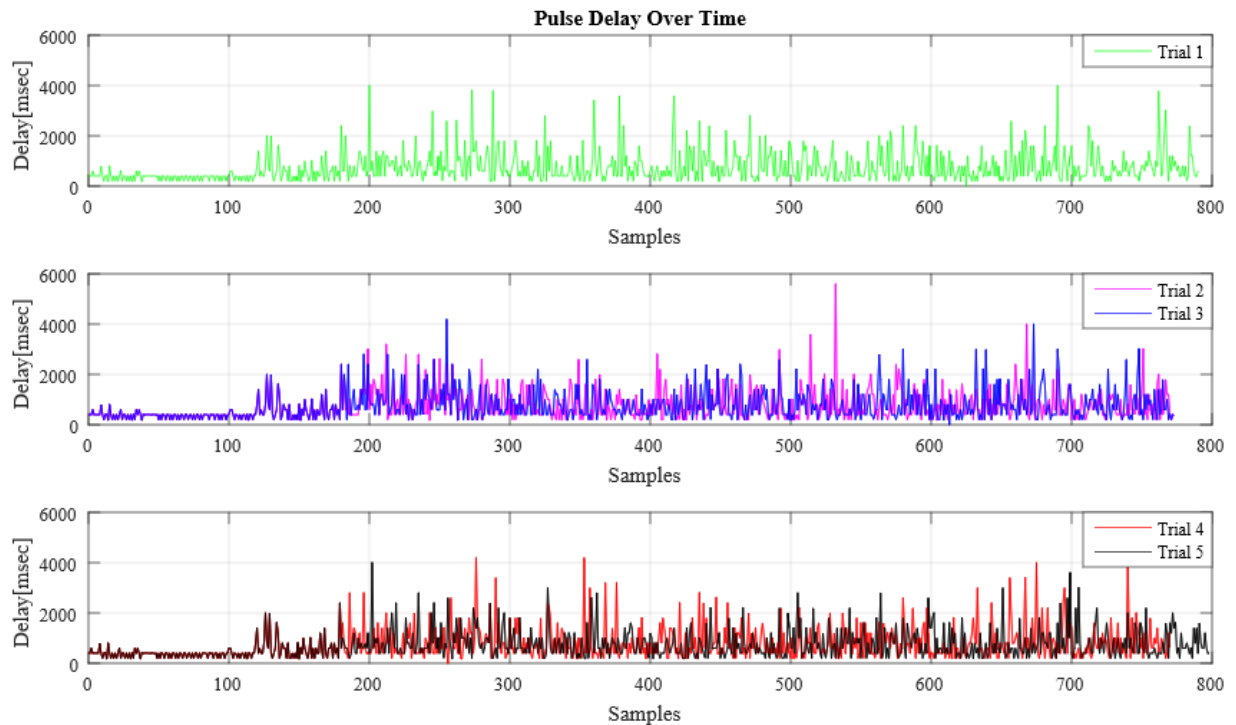


Figure 45. Time Difference Between Each Successive Pulse ("Piksi Failed Test" Program with Multiple Trials)

Table 16. Pulse Time Differential for Position/Pose acquired from C++ Time Stamp/Align Program

Inaugural Square				Inaugural Raster			
GPS	AVG[msec]	STD[msec]	Samples	GPS	AVG[msec]	STD[msec]	Samples
Trial 1	684.3134	427.8903	268	Trial 1	626.1929	262.0297	451
Trial 2	682.8607	420.0107	280	Trial 2	626.1929	262.0297	451
Trial 3	680.4306	421.2343	281	Trial 3	626.1929	262.0297	451
Trial 4	680.4306	421.2343	281	Trial 4	626.1929	262.0297	451
Trial 5	680.4306	421.2343	281	Trial 5	602.4234	238.4621	418
Total	681.6932	422.3208	1391	Total	621.439	257.3162	2222
Inaugural Square				Inaugural Raster			
INS	AVG[msec]	STD[msec]	Samples	INS	AVG[msec]	STD[msec]	Samples
Trial 1	686.3321	578.7959	268	Trial 1	625.4812	498.6512	451
Trial 2	684.6571	569.908	280	Trial 2	626.9069	497.3437	451
Trial 3	676.8826	581.8417	281	Trial 3	626.9069	485.1149	451
Trial 4	680.4928	580.2397	281	Trial 4	626.9069	489.4402	451
Trial 5	682.2206	581.9717	281	Trial 5	603.1531	424.0048	418
Total	682.117	578.5514	1391	Total	621.871	478.911	2222
Inaugural Field Probe				Piksi Failed Test			
GPS	AVG[msec]	STD[msec]	Samples	GPS	AVG[msec]	STD[msec]	Samples
Trial 1	538.5109	3131.203	413	Trial 1	735.0544	603.5328	791
Trial 2	404.5608	238.0481	526	Trial 2	750.3966	591.8673	774
Trial 3	431.6383	299.0852	575	Trial 3	750.3966	589..423	774
Trial 4	433.9021	309.4007	572	Trial 4	751.786	622.4394	771
Trial 5	438.5018	335.0467	566	Trial 5	726.4168	553.3553	799
Total	449.4228	862.5567	2652	Total	742.8101	592.7987	3909
Inaugural Field Probe				Piksi Failed Test			
INS	AVG[msec]	STD[msec]	Samples	INS	AVG[msec]	STD[msec]	Samples
Trial 1	1055.8	13291	413	Trial 1	735.129	786.28	791
Trial 2	404.327	392.2148	526	Trial 2	750.8618	775.1721	774
Trial 3	431.5287	415.4362	575	Trial 3	750.8618	814.4736	774
Trial 4	432.3934	424.6473	572	Trial 4	751.8898	808.3479	771
Trial 5	436.977	437.3254	566	Trial 5	725.5407	760.8427	799
Total	552.2052	2992.125	2652	Total	742.8566	789.0233	3909
Overall(GPS) AVG:623.841msec				STD:4043.00 msec			
Overall(INS) AVG:649.763msec				STD:1209.653msec			

The overall average of the elapsed time difference between each successive pulse trigger generated from the Mavlink telemetry stream is approximately 623.841 milliseconds for the u-blox GPS pulse and 649.763 milliseconds for the INS pulse. This error is substantial considering that the intended frequency rate for generating the pulses is 5 Hz or 200 millisecond of delay between each pulse for either system. However, the results indicate that the average time difference for each system (GPS and INS) are closely correlated. The considerable delays in time stamp updates may reveal that the GCS cannot keep pace with the telemetry stream acquired from the octocopter. The possible cause of this is that large quantities of measurements processed on the Pixhawk flight controller are overwhelming the ground station's ability to decode the Mavlink telemetry stream, organizing and parsing the large volume of data into a telemetry log. As a result of this issue, an external clock system may be required to establish a consistent pulse mechanism to time stamp position and pose coordinates and trigger radar pulses.

4.6 Solid Shield Design RCS Prediction Analysis

The SENTRi CEM simulations of the backscatter RCS for each solid shield design are discussed in this section. These results are intended to provide a means of predicting the scattering profiles of the squat cylinder and topless-bottomless sphere across varying aspect angles and frequencies examined at waterline and vertical cuts.

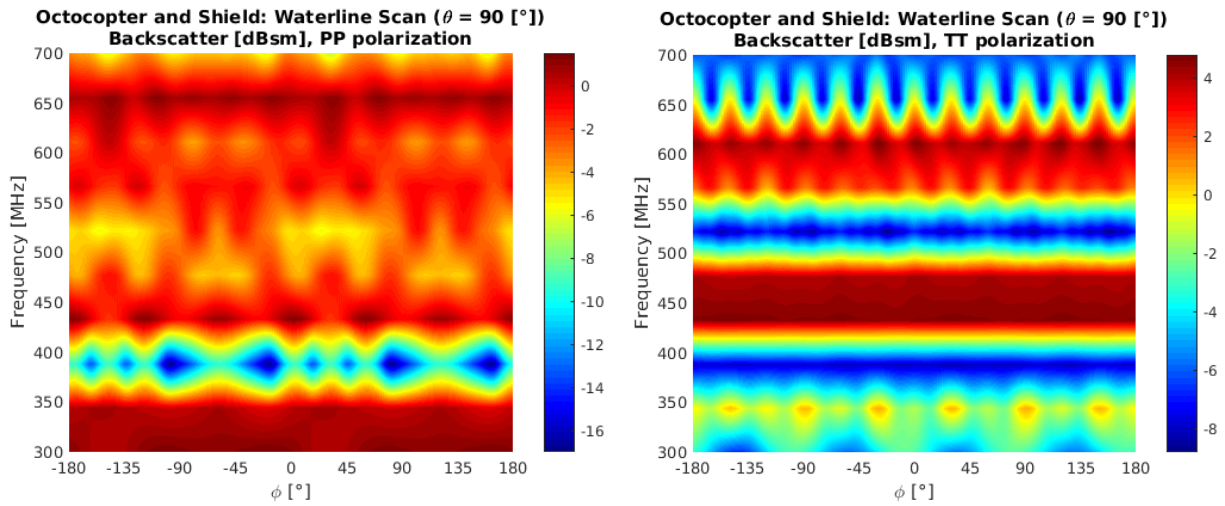


Figure 46. Waterline Scan Global RCS, Squat Cylinder

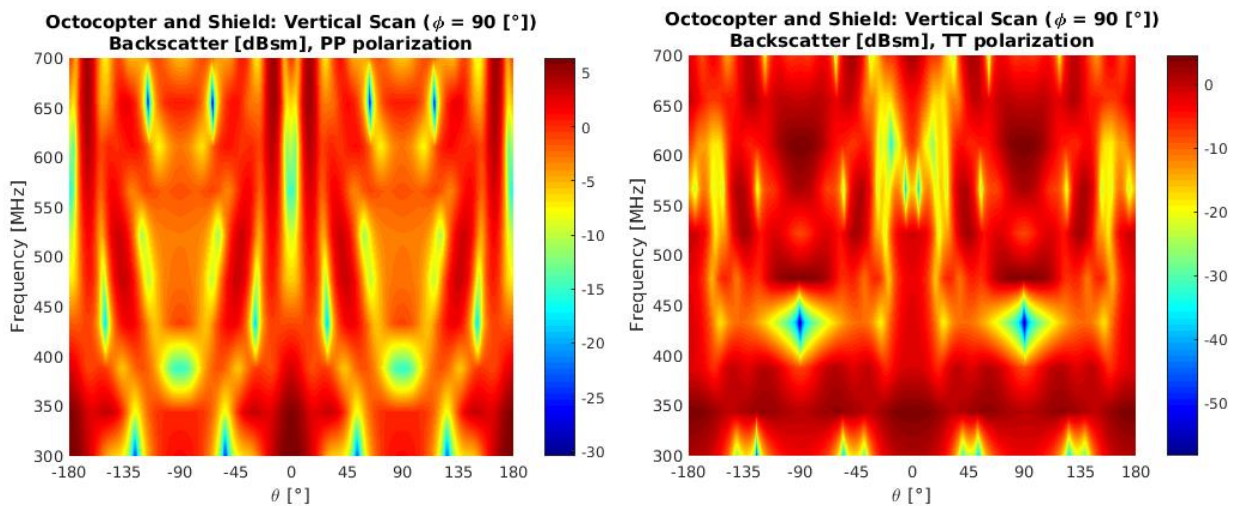


Figure 47. Vertical Scan Global RCS, Squat Cylinder

The waterline scans of the squat cylinder are intended to determine if the shield can minimize the variable scattering nature of the octocopter. The PP-polarization has a consistent RCS of approximately 2dB with a variance of 0.118 dB for 300MHz to 350MHz. The curvature of the squat cylinder surface is aligned with the horizontal orientation of the incoming EM wave. The result of this interaction is a creeping wave that contributes to interference between the incident and reflected EM waves, as frequency increases above 350MHz. A lobbing effect occurs, as seen with frequencies above 350MHz. This potentially is a result of the diffracted fields above and below the shield, illuminating the octocopter. Resonance is observed at approximately 653MHz, where there are a combination of discontinuities at that frequency create an echo, similar to the effect of an antenna. The electrical length of an EM wave at 350 MHz is approximately 0.459 meters. This is close to the dimension of the frame extension used to join the octocopter with the shield (0.5 meters). The TT-polarization reveals a consistent RCS of 5dB (variance of 2.148 dB) occurring between 410MHz to 490MHz. A resonant response occurs at approximately 610MHz. Based on these waterline scans, the RCS of the shielded octocopter remains uniform, concealing the variable scattering properties of the octocopter.

The vertical scans of the squat cylinder shield are intended to determine the angular bounds of the squat cylinder's shielding effect on the overall RCS of the octocopter. It should be noted that 0° is broadside to the top of the shielded octocopter (looking down). At this angle, there is a specular response, as the top of the octocopter appears flat, reflecting most of the incident EM wave. Outside these angular bounds are the diffractive properties of the shield edges and the corners of the octocopter arms and legs. The combination of the shield and octocopter generally contributes to a constructive and destructive interference between the various scattering mechanisms on the shielded octocopter. Resonant responses are observed at

broadside of the shielded octocopter. This occurs at 360MHz to 405MHz for PP-polarization and 400MHz to 450MHz for TT-polarization. As the RCS measurement continues down the side of the shield, it appears that the backscatter from the octocopter is obscured by $\pm 30^\circ$ broadside to the shield. This is sufficient shield coverage as the octocopter's pitch and roll maneuvers during flight are assumed to be within a $\pm 10^\circ$ range.

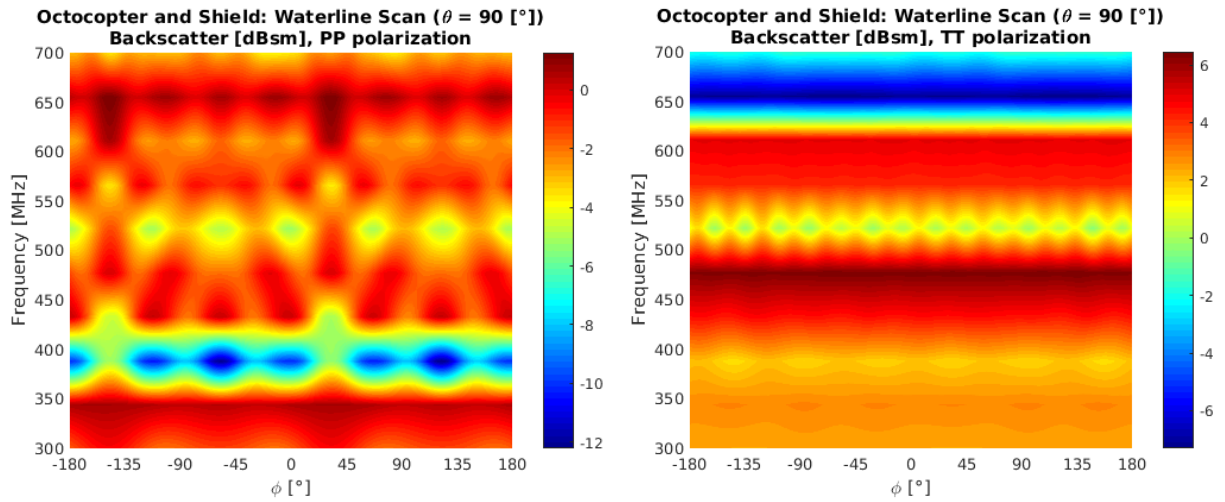


Figure 48. Waterline Scan Global RCS, T-B Sphere

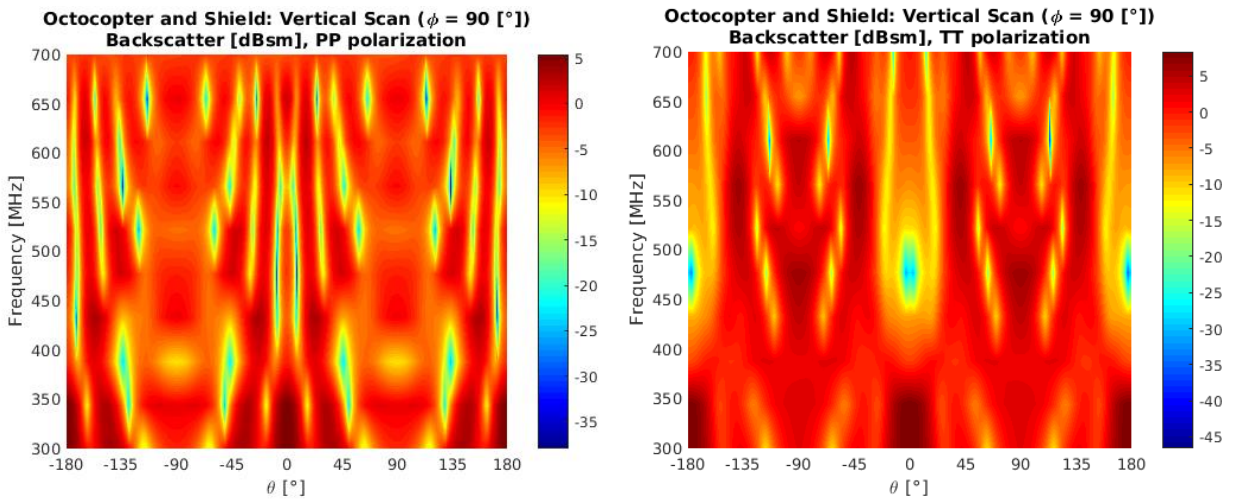


Figure 49. Vertical Scan Global RCS, T-B Sphere

The waterline PP-polarization of the T-B sphere exhibits minor lobbing across a majority of the tested frequency spectrum, with exception to 350MHz to 410MHz and 505MHz to 545MHz bands. These lobes are induced by the phase differences between the incident EM wave and the reflected EM waves that are causing constructive and destructive interference patterns. This occurs with the squat cylinder at the same frequency band. The octocopter is influencing the surface currents excited on the shield at that particular frequency band. A resonant response should be noted at 348MHz and again at 653MHz. Examining the waterline scans at TT-polarization, the T-B sphere has the most consistent backscatter RCS over the entire frequency spectrum compared to the squat cylinder, with exception to the 500MHz to 550MHz band. The vertical scan at PP-polarization appears to have similar response to the squat cylinder. The subtle differences occur at the edges and inner walls of the shield where the curvature is horizontal and vertical. Also, at broadside ($\pm 90^\circ$), the resonance seen before with the squat cylinder has strengthened in the T-B sphere by 8dB. The TT-polarization is also similar in overall RCS, with exception to the shield broadsides from 400MHz to 450MHz. The resonant response seen before in the squat cylinder does not exist with the T-B sphere at that frequency band. The T-B sphere provides a coverage of $\pm 45^\circ$, exceeding the squat cylinder's coverage by approximately $\pm 15^\circ$.

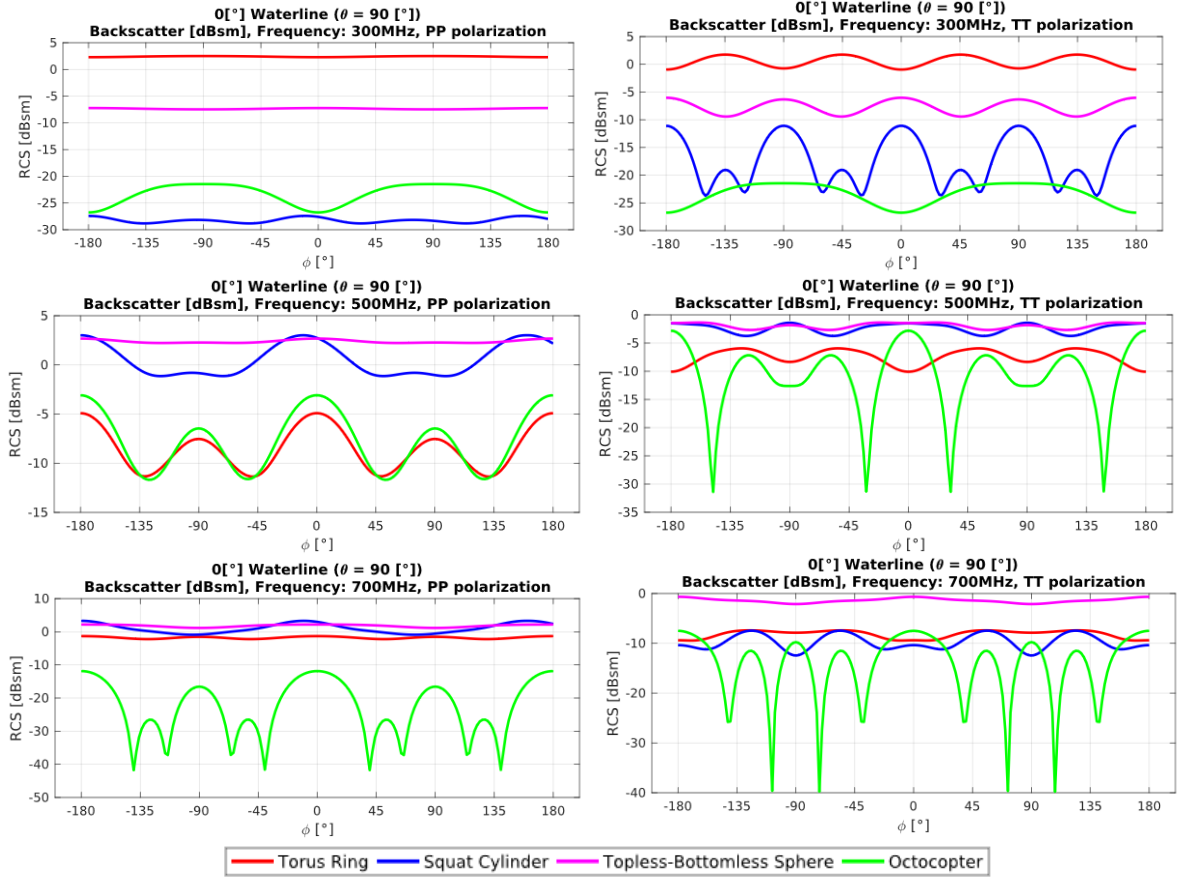


Figure 50. Waterline RCS Scans [300,500,700 MHz]

Figures 50 and 51 show a comparison of discrete frequencies (300, 500, and 700MHz). A torus ring geometry of similar dimension to the squat cylinder and T-B sphere is also presented for comparison. Its backscatter characteristics closely resemble the T-B sphere at lower frequencies. Comparing all the shield designs against the octocopter, it is apparent that each shield reduces the nulls seen in the octocopter-only measurement.

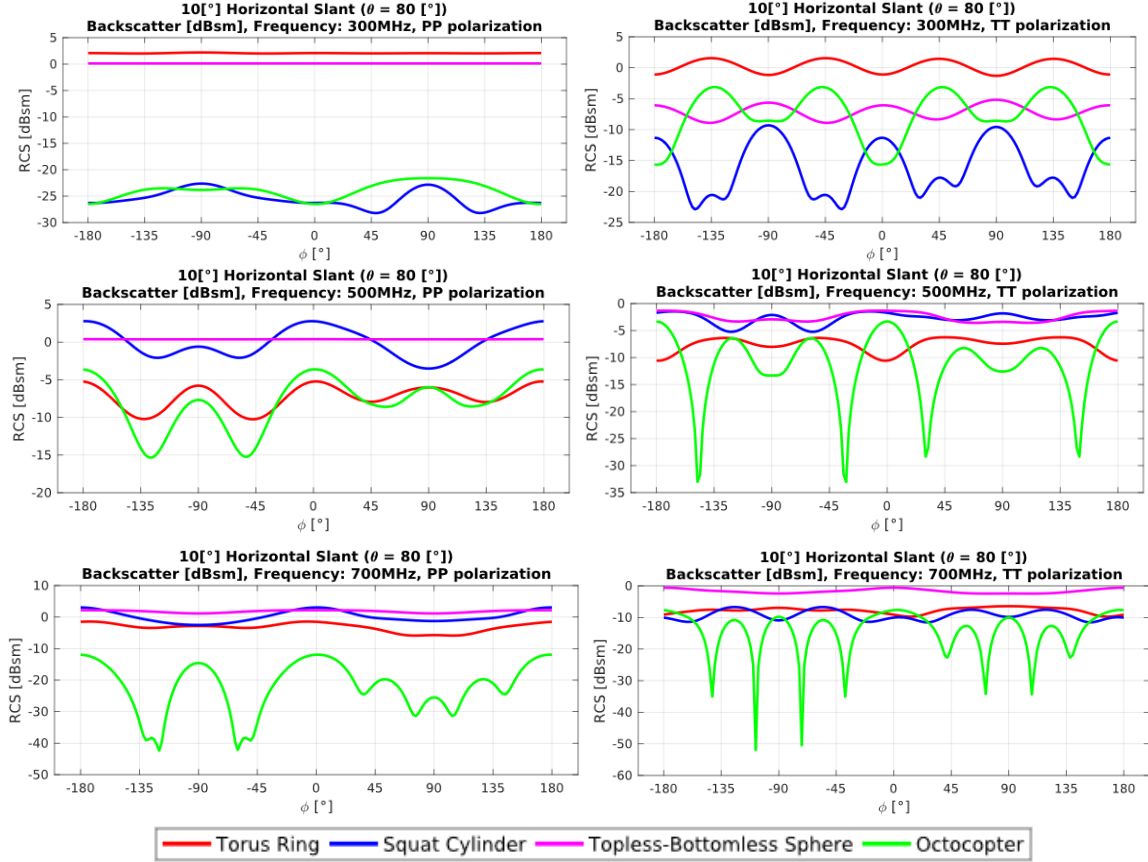


Figure 51. 10° Horizontal Slant Scan RCS Scans[300, 500, 700 MHz]

The creeping wave effect is apparent for the T-B sphere and torus ring for the TT polarization as the vertically polarized wave is incident upon the curved surface. As the frequency increases, the effect of the creeping wave is less apparent. The 10° horizontal slant further supports the idea that each shield is capable of satisfying the $\pm 10^0$ illumination threshold desired for RCS measurements conducted on the field probe, as the RCS remains consistent across each aspect angle for both TT and PP polarizations.

All designs are capable of providing the desired shield coverage for the octocopter. Ideally, the topless-bottomless sphere is the most effective shield design. The RCS properties are favorable considering its equal horizontal and vertical curvature. This provides the most consistent RCS measurement for the PP and TT polarized EM waves that are incident on the

shield's surface. The RCS response of the squat cylinder appears to be more sensitive to the polarization of the incoming EM wave as result of its curvature only occurring horizontally. However, from a construction standpoint, the squat cylinder is the most simple and practical design given the materials available for this research.

4.7 Field Probe Flight Testing and RCS Characterization

This section focuses on the results from testing the performance of the shielded octocopter and its characterization as a two-way field probe when operated at the outdoor radar cross section range. Testing includes determining whether or not the shield interferes with the communication link between the vehicle and the GCS, as well as the satellite reception of the GPS modules, u-blox and Piksi.

4.7.1 Squat Cylinder-Shielded Octocopter Flight Performance

Initial flight testing of the shield is critical to determine the vulnerabilities in the octocopter's positioning system and assess its ability to maintain a 3D fix. The communication link between the GCS and octocopter is monitored for signal strength. A simple test is performed by performing a takeoff and a minor pitch/roll/yaw maneuver to change position and orientation of the comm-link antenna relative to the GCS. It was clear from take-off that the weight of the shield has a negative impact on the lift capability of the octocopter, requiring 85% - 90% throttle to lift off the ground. This can cause a 75% reduction in the battery life, resulting in a 5 minute flight instead of a 20 minute flight. The solution is to implement a smaller battery, which uses 6000mA as opposed to the default 10000mA battery. The idea is to sacrifice a small

percentage of battery life to reduce the weight and therefore, reduce the throttle required to lift the shield off the ground.

The telemetry data acquired from the initial flight test of the shield is parsed into position, pose, and the number of satellites observed by the GPS, and signal strength. The ability to obtain position and pose data from the telemetry stream indicates that the communication link between the GCS and the octocopter is unperturbed by the shield. The satellite count observed by the u-blox LEA 6 GPS onboard the octocopter is shown in Figure 52.

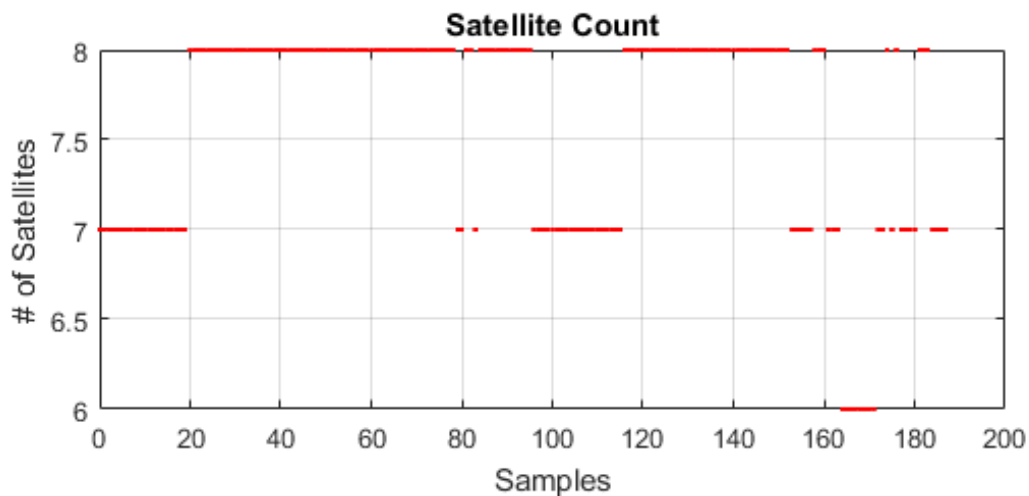


Figure 52. Initial Flight Test Satellite Count (u-blox LEA-6 GPS)

The satellite count indicates that the shield does not have any adverse effects on the number of satellites acquired by the u-blox LEA-6 GPS, as a minimum number of satellites (4) for the 3D fix to be achieved is exceeded throughout the duration of the flight. The unshielded octocopter typically yields 8 - 11 satellites for a given flight program. The Piksi rover module, however, was unable to acquire more than 4 satellites to achieve an RTK Fix. As a result, further testing is required to determine if this issue is related to the positioning of the Piksi patch antenna or the Piksi 3DR comm-link antenna inside the shield. Refer to Figure 24 for a visual on the u-blox and Piksi module placement.

The additional test for the Piksi rover involved placing the antenna outside of the shield in an open area where optimal satellite signal strength can be achieved. The purpose is to rule out the possibility that the comm-link between the base station and rover is dysfunctional as a result of attenuation caused by the shield. In this method, it was observed that the Piksi base station and rover communicated differential solutions to the GCS without issue. It should also be noted that the Piksi rover module placed outside the shield acquired up to 8 satellites. After this verification, the Piksi rover antenna was placed inside the shield. Immediately, it was observed on the Piksi Console software that the satellite count fluctuated between 4 and 5 satellites. Figure 53 shows the results from raising and lowering the Piksi rover antenna inside and outside the shield.

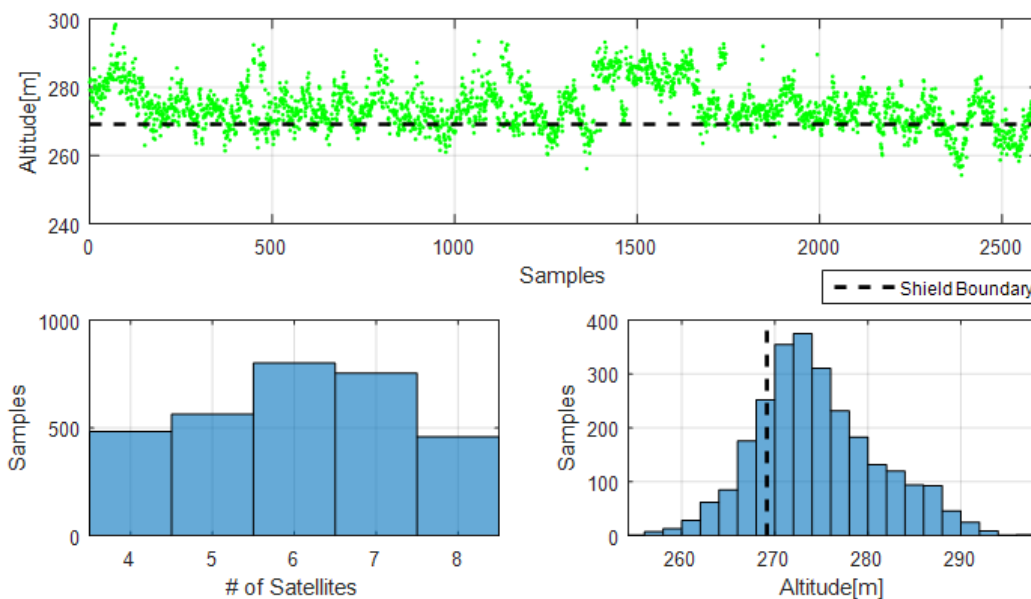


Figure 53. Piksi Altitude Samples vs. Acquired Satellite Samples

It can be seen that more samples were taken of the antenna at an altitude above the shield. This correlated to more satellite samples in which there are 6 or more satellites acquired by the Piksi rover. This was also observed on the Piksi console monitoring the satellite count. It was

determined that placing the Piksi rover antenna 3-5 inches above the shield is sufficient. The patch antennae used for the Piksi base station and rover are omni-directional. Clearance around the antenna is critical, as there is an angular dependence on acquiring the satellites while using this patch antenna configuration. It should be noted that these tests were performed when using the ground plane underneath the Piksi Rover. The ground plane was removed thereafter, as it is believed to adversely affect subsequent RCS measurements of the shielded octocopter.

The initial flight of the field probe with operation of the noise radar was conducted over two trials. Each trial revealed that the communication link between the octocopter and GCS is unaffected by both the shield and the noise radar. The flight duration lasted approximately 5 minutes due to the high percentage of throttle usage as seen in Figure 54. Landing the octocopter required 100% throttle towards the end of the flight.

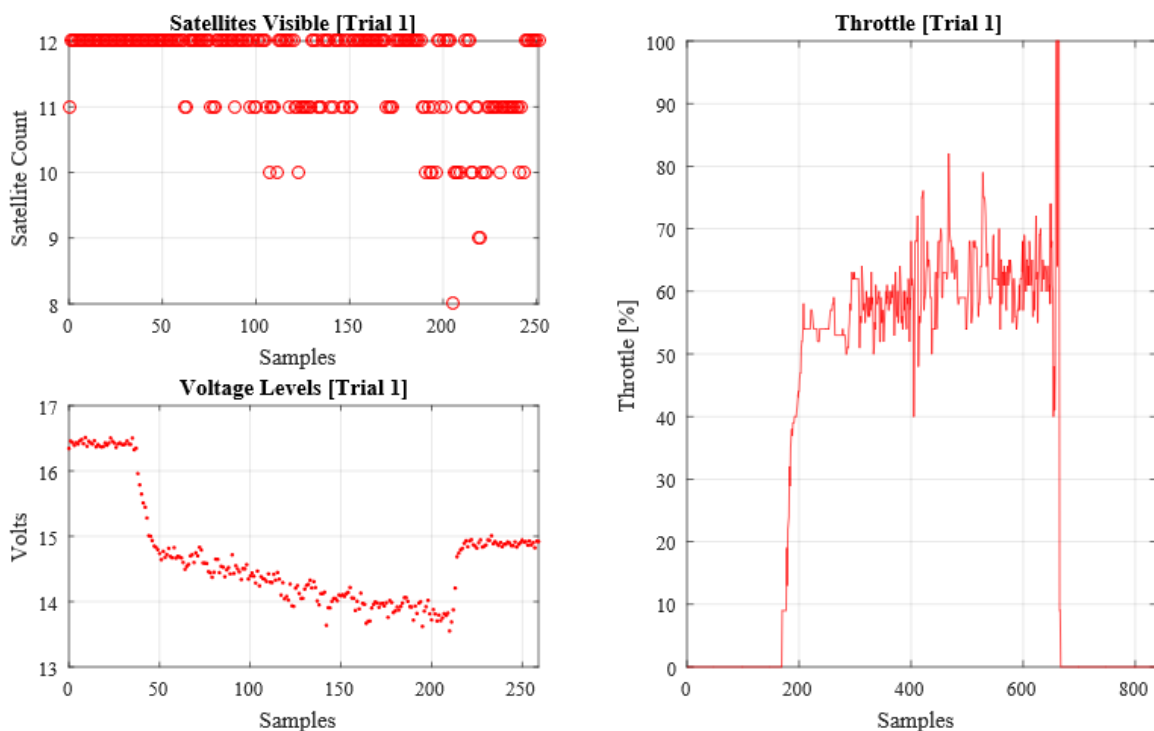


Figure 54. From top CCW, u-blox Satellite Count, Battery Voltage Level, and Throttle %

A separate flight test was conducted for the octocopter without the shield attached. The battery life lasted twice as long compared to the shielded flights. The throttle usage was approximately 14% less on average. Each of these flight tests did not result in conclusive RCS data from the noise radar. The noise radar did not have enough power to accommodate the down range distance of the field probe as it flew its mission plan. Further characterizations of the shield are needed to determine the RCS characteristics over a range of frequencies to assess the optimal operating conditions of the field probe.

4.7.2 High Frequency RCS Characterizations (Squat Cylinder)

The RCS measurements conducted at the ACER reveal the high frequency characteristics of the shielded octocopter, as well as the shield and octocopter as separate targets. Figure 55 shows the waterline Global RCS measurements of each target:

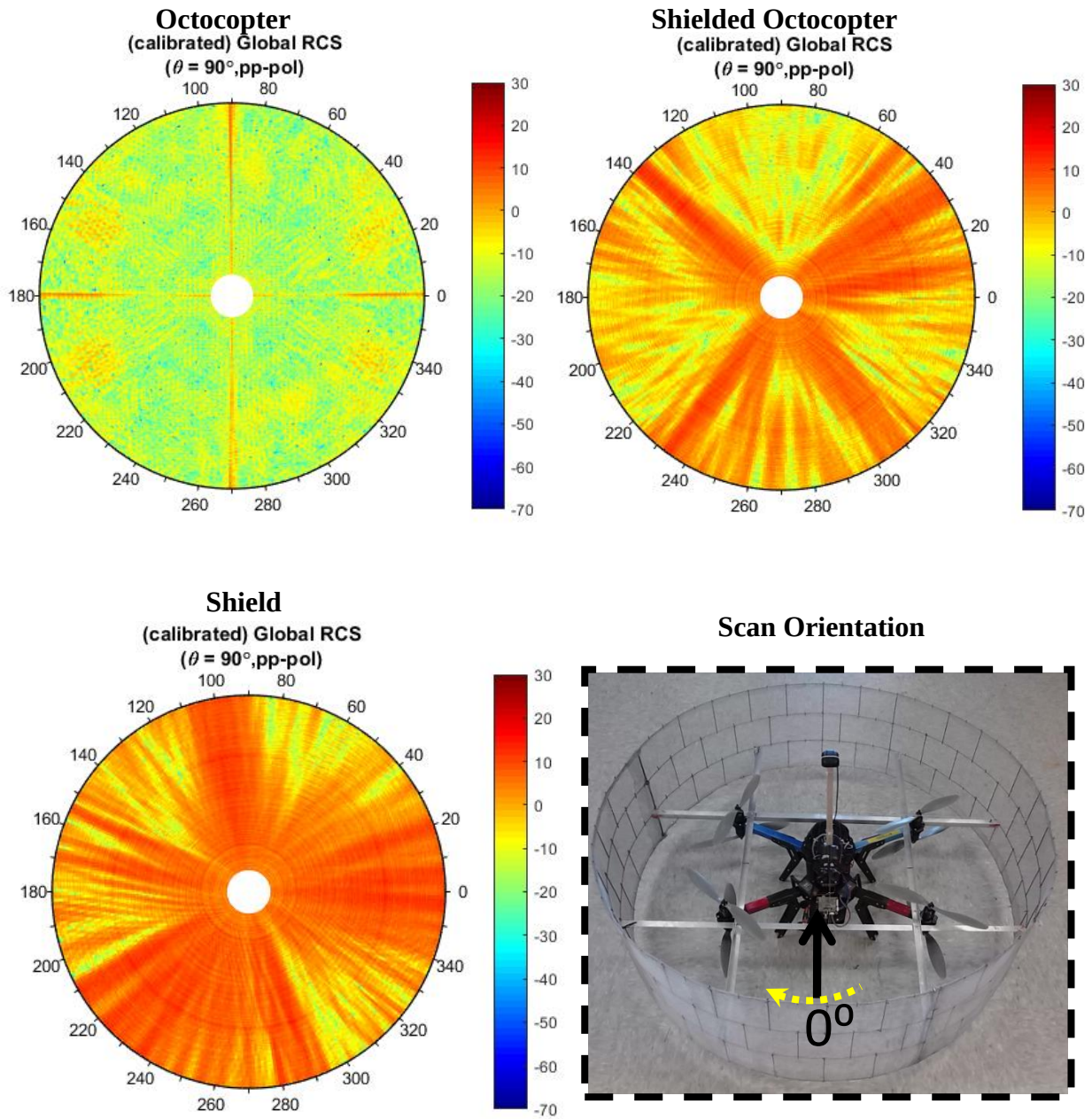


Figure 55. Global RCS Plots (0° Elevation "Waterline")

Examining the shield's response, it is evident that the RCS is most consistent across each aspect angle for the lower frequency band. As the frequency increases, the EM waves creep above and below the shield. The RCS of the octocopter reveals specular reflections occurring broadside to the aluminum L-channels at 0° , 90° , 180° , and 270° . Applying the shield to the octocopter, the RCS appears similar to the shield-only measurement. At higher frequencies, the response of the cylinder-shaped shield does not appear to be reminiscent of its true (cylinder) RCS profile.

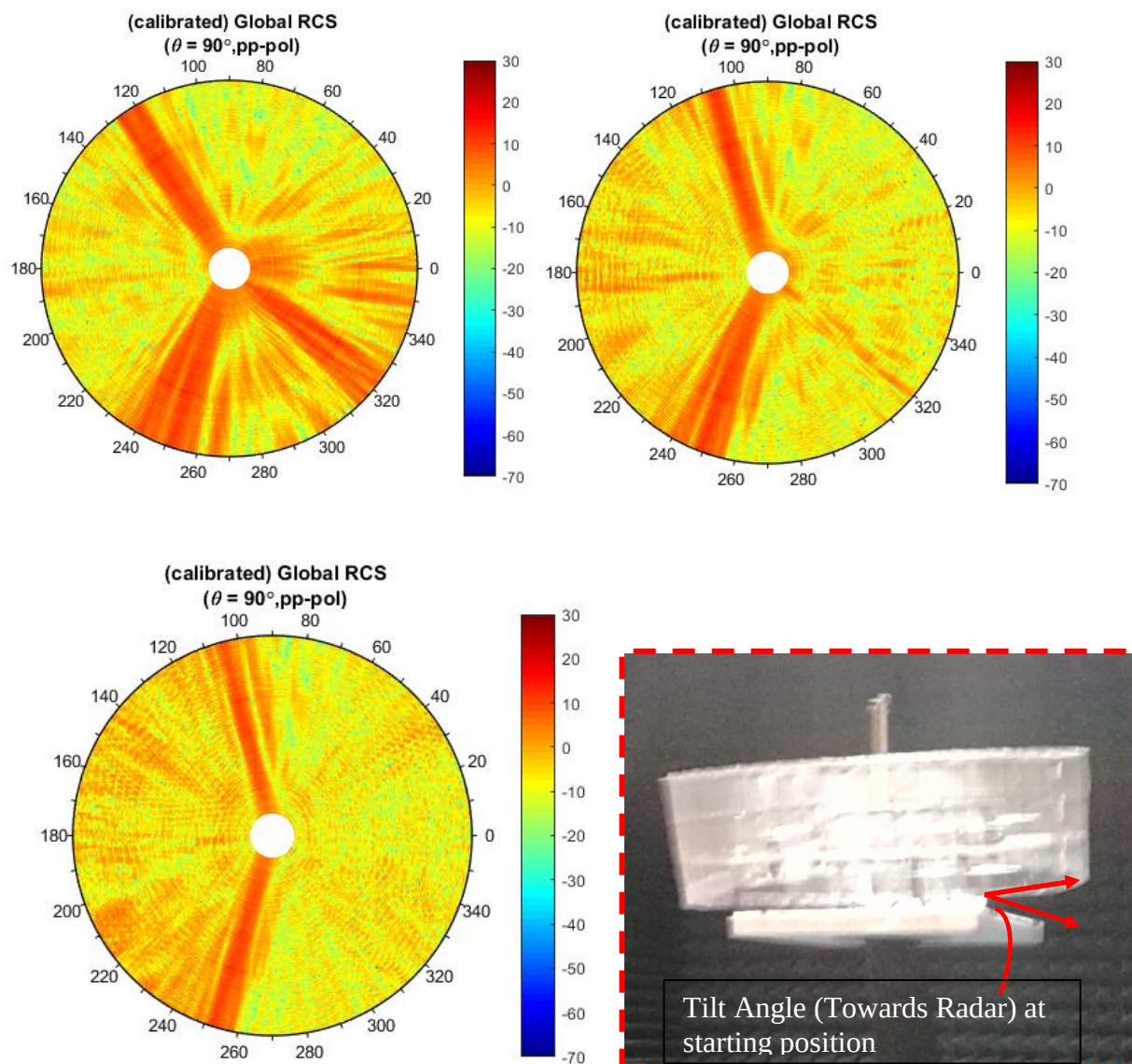


Figure 56. Global RCS Plots, Shielded Octocopter (Elevation Angle: 5° , 10° , and 15°)

The shielded octocopter is angled on the pylon at 5° , 10° , and 15° elevation angles as seen in Figure 56. Each successive angle reduces a specular response possibly caused by the legs of the octocopter. It is clear, however, that the body of the octocopter remains shielded, even at 15° . Figure 57 shows the composite ISAR for each target. The shield-only image reveals interference within the shield causing interference as the incident EM waves traverse above and below the shield. The octocopter-only ISAR clearly shows the illuminated L-channels and, legs, and motor casings.

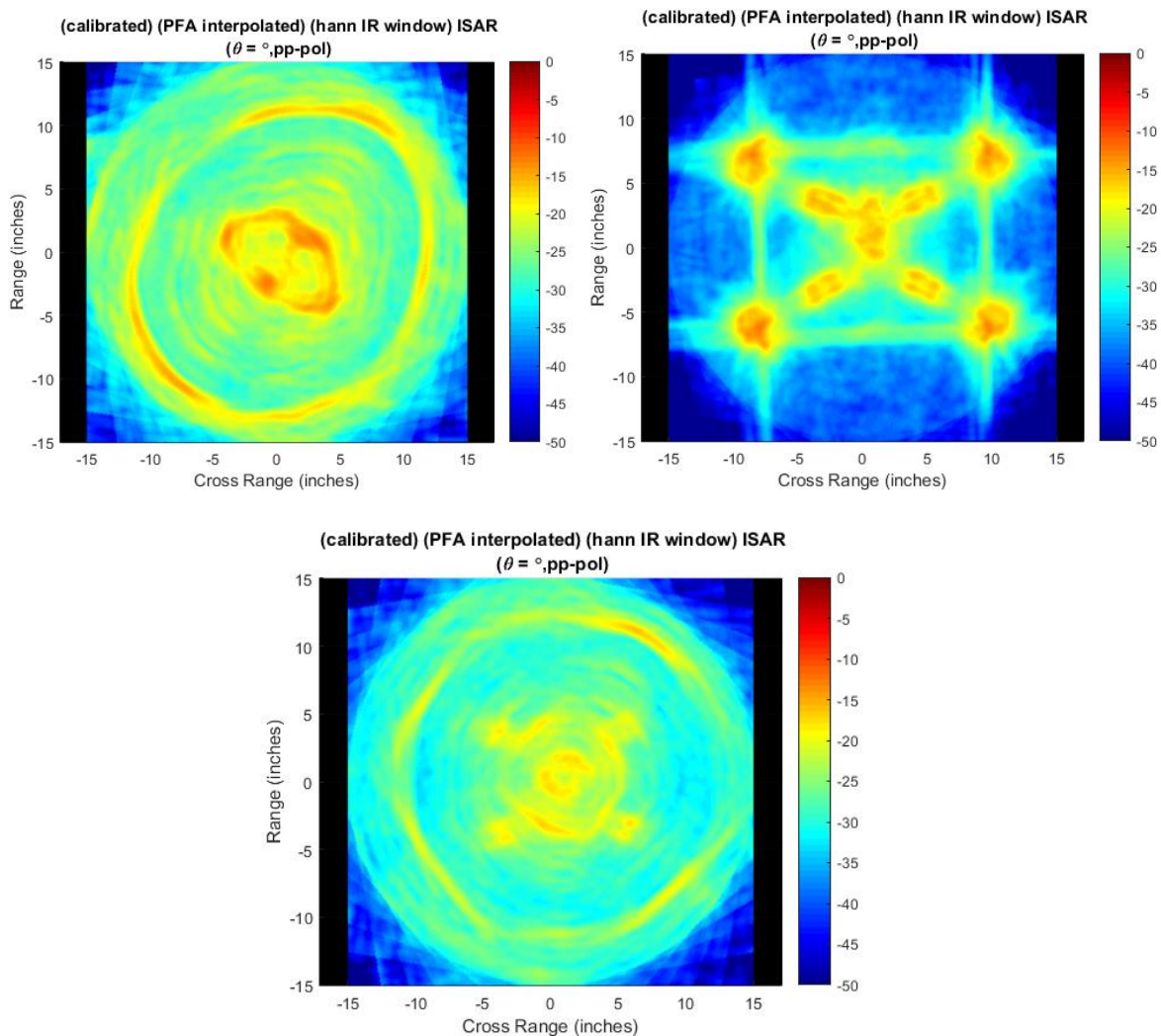


Figure 57. Composite ISAR (from top CCW), Shield Only, Octocopter Only, and Shielded Octocopter

Combining the shield and octocopter, the legs are still illuminated, protruding the bottom of the shield. However, the motor casings and L-channels are not illuminated, indicating the EM waves do not directly penetrate through the shield at high frequency.

Applying 4 sector cuts to the measured RCS of the shielded octocopter, each cut is averaged and compared for consistency as seen in Figure 58. This demonstrates the uniform nature of the shield's RCS response, an expected and required result.

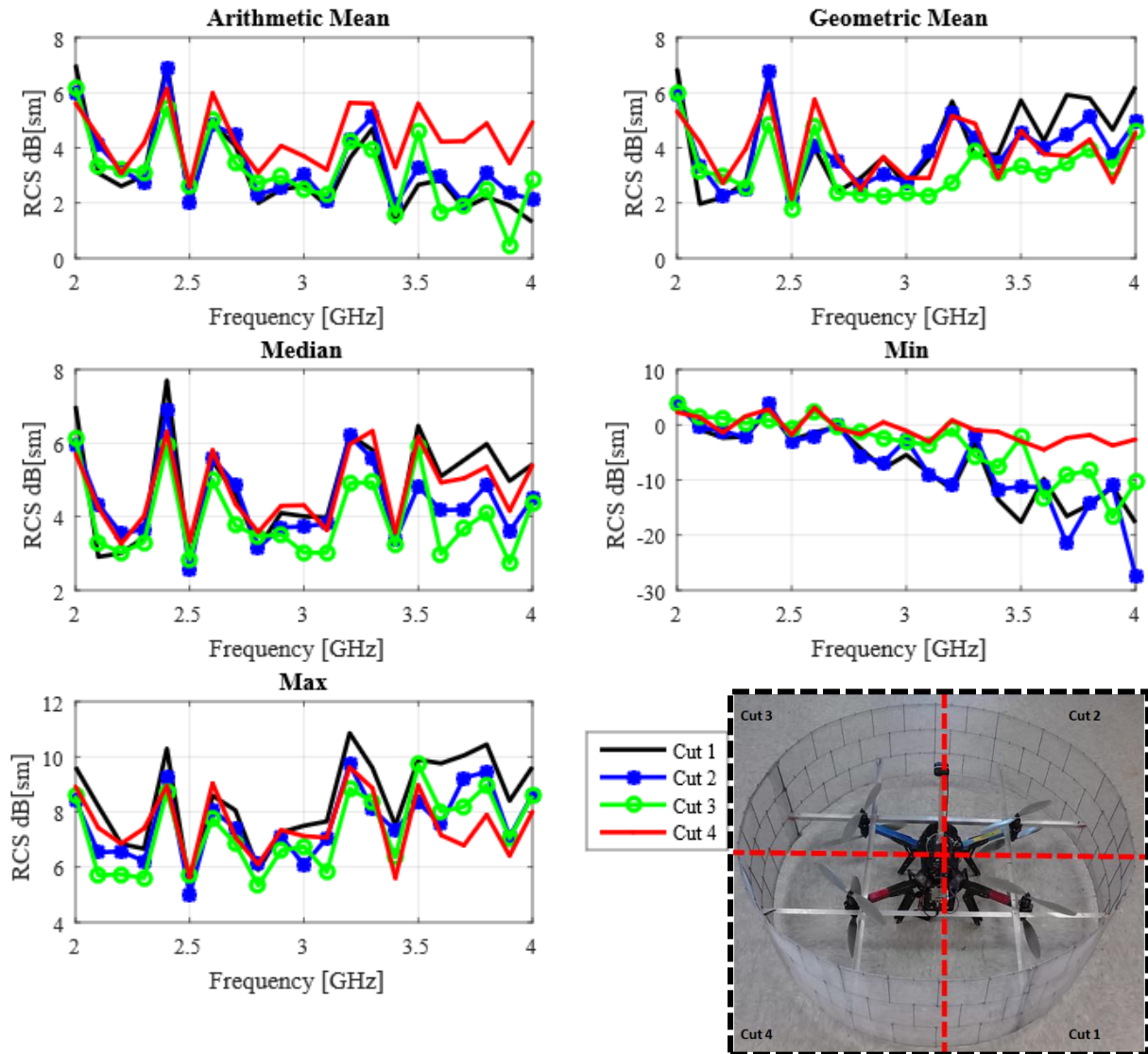


Figure 58. Shielded Octocopter Sector Averaging (Cuts 1-4, Elevation Angle 0°)

Figure 59 shows the sector averaging of one cut and comparing the response of each target. The results show that the shield and shielded octocopter had near identical RCS responses. This is a positive indication that the shield is the dominant structure in the overall RCS measurement.

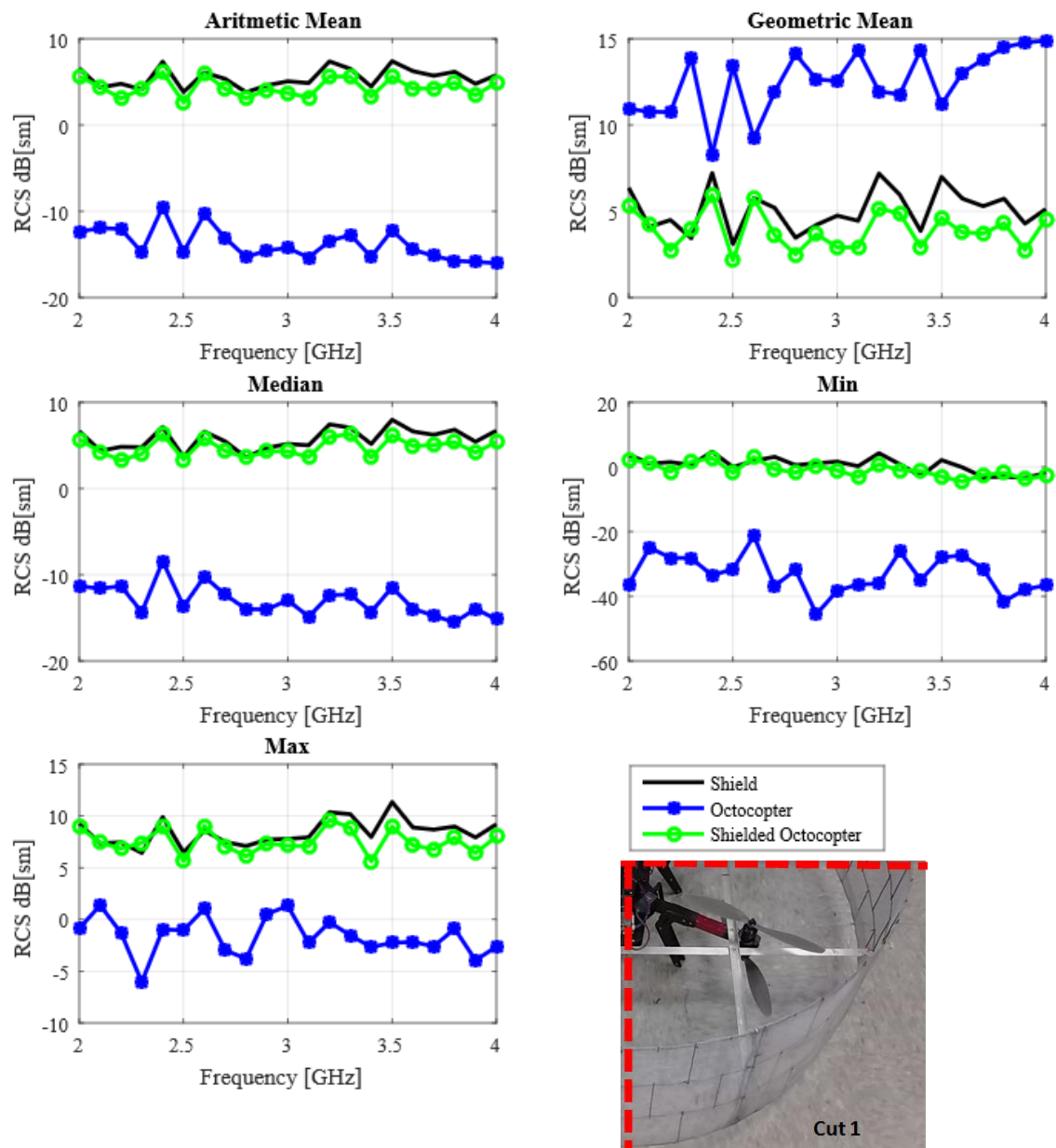


Figure 59. Sector Averaging (Cut 1, Elevation Angles 0°, All targets) 2-4GHz

Figures 60, 61, and 62 examine multiple sector averages for each target's minimum and maximum RCS measurements at 0° "waterline" elevation. Each sector contains 18 samples with a sliding average step size of 5.

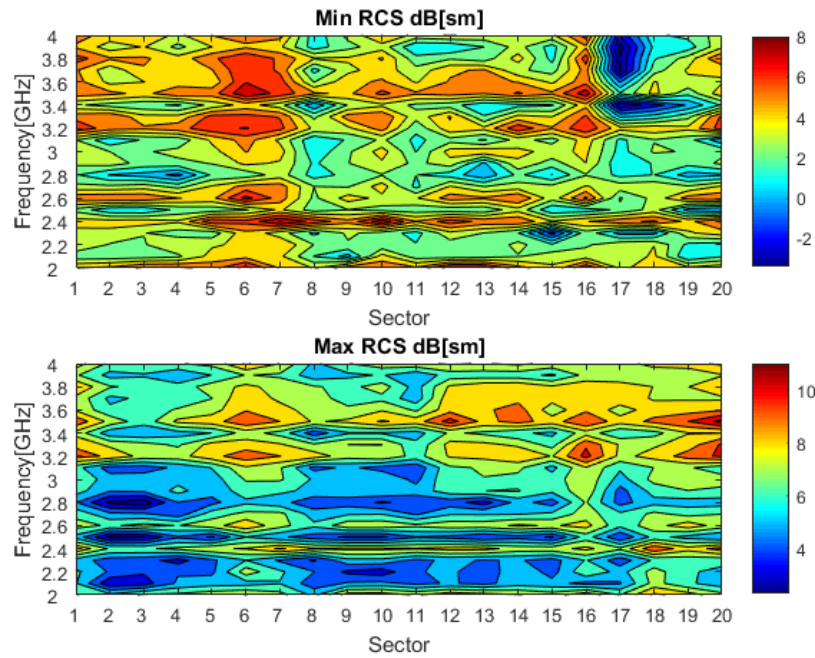


Figure 60. Shield Only RCS Sector Averages

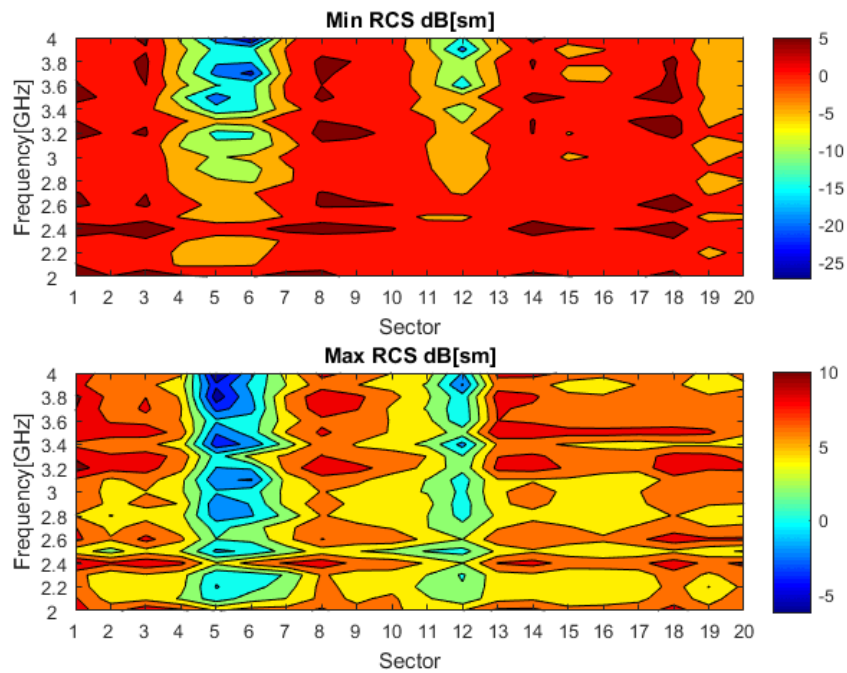


Figure 61. Shielded Octocopter RCS Sector Averages

Comparing the shield-only and shielded octocopter contour plots, it is evident that the RCS is relatively consistent at lower frequencies (2-2.8 GHz range). Beyond 2.8 GHz, increasing fluctuations in RCS across the sector averages are apparent. It should be noted that between sectors 4 and 7, the most prominent RCS response occurs with or without the octocopter placed within the shield. Irregularities in the shield such as a compressed surface may cause a flat aspect to the incoming EM waves. In Figure 62, the octocopter-only max RCS contour plot highlight the specular responses that occur at the broadsides of the aluminum L-channels.

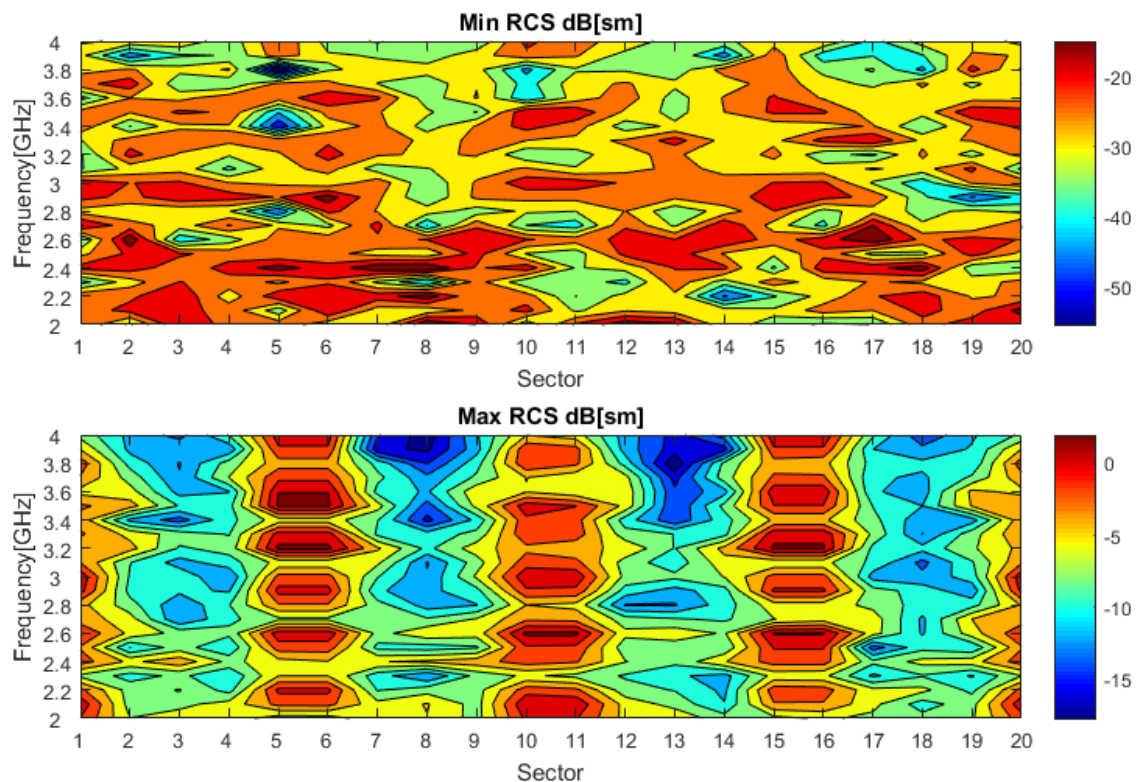


Figure 62. Octocopter Only RCS Sector Averages

The expected response at higher frequencies (above 4 GHz) is that the RCS response of the shielded octocopter will become less like the RCS of the shield-only measurement as a result of the EM waves interaction with the top and bottom edges of the shield, interfering with the octocopter inside as seen in Figure 63. It is seen that after 4 GHz, this response appears to occur.

The shield's RCS at 4 GHz and higher appears to no longer represent its true profile. Examining one sector cut at waterline scan, the RCS of the shielded octocopter diverges away from the shield-only response. The frequency in which the squat cylinder shield no longer shadows the octocopter when exceeded is determined to be approximately 2.8 GHz, where the first indication of this divergent response occurs.

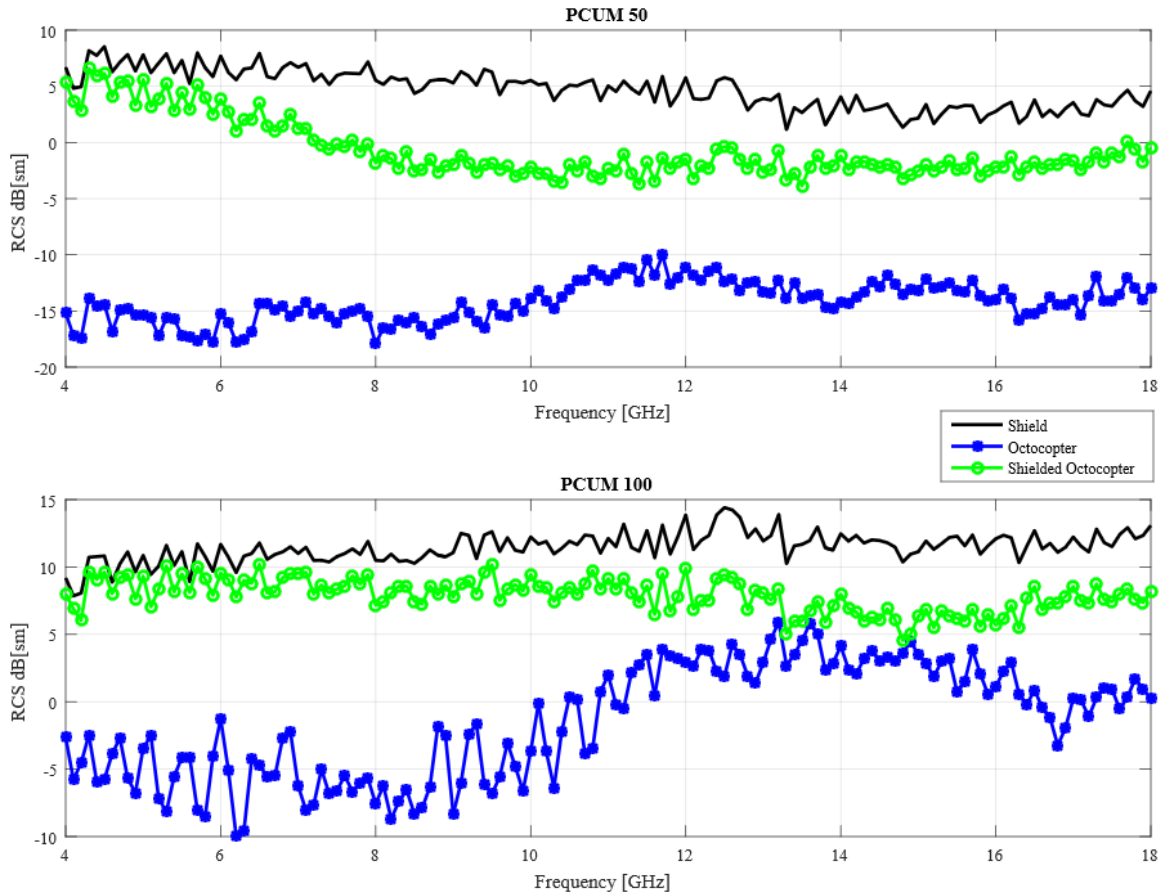


Figure 63. Sector RCS Averaging (Cut 1, Elevation Angle 0°, All targets), 4-18GHz

A comparison of select frequencies is examined between the ACER measurement and the SENTRi CEM measurements. The objective is to compare the ideal canonical shape's RCS response at high frequency to the actual canonical shield to determine if there is a resemblance. The ideal shape is based on a true solid cylinder as seen in Figure 64.

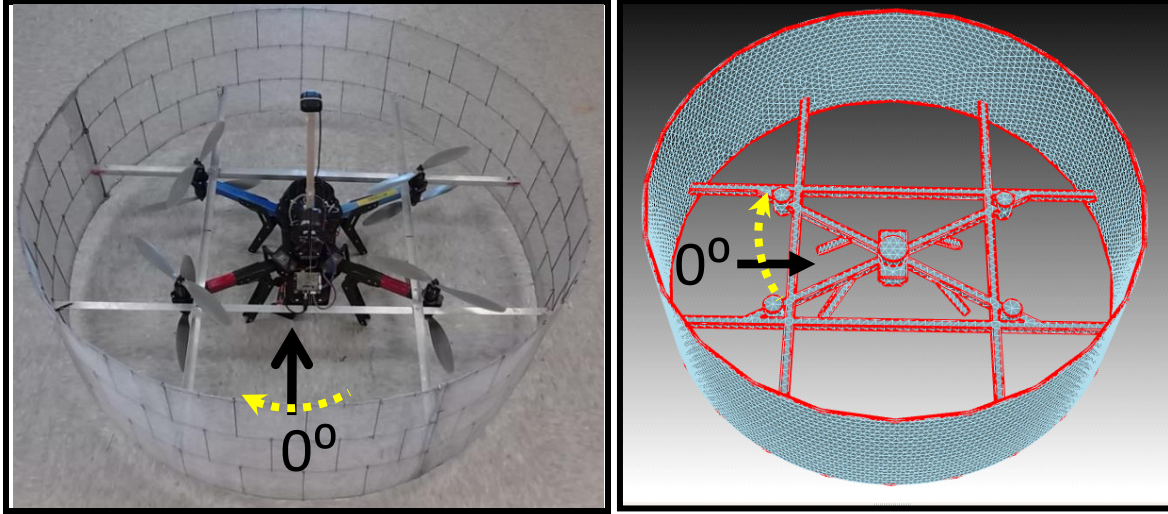


Figure 64. Actual and Theoretical Target Comparison

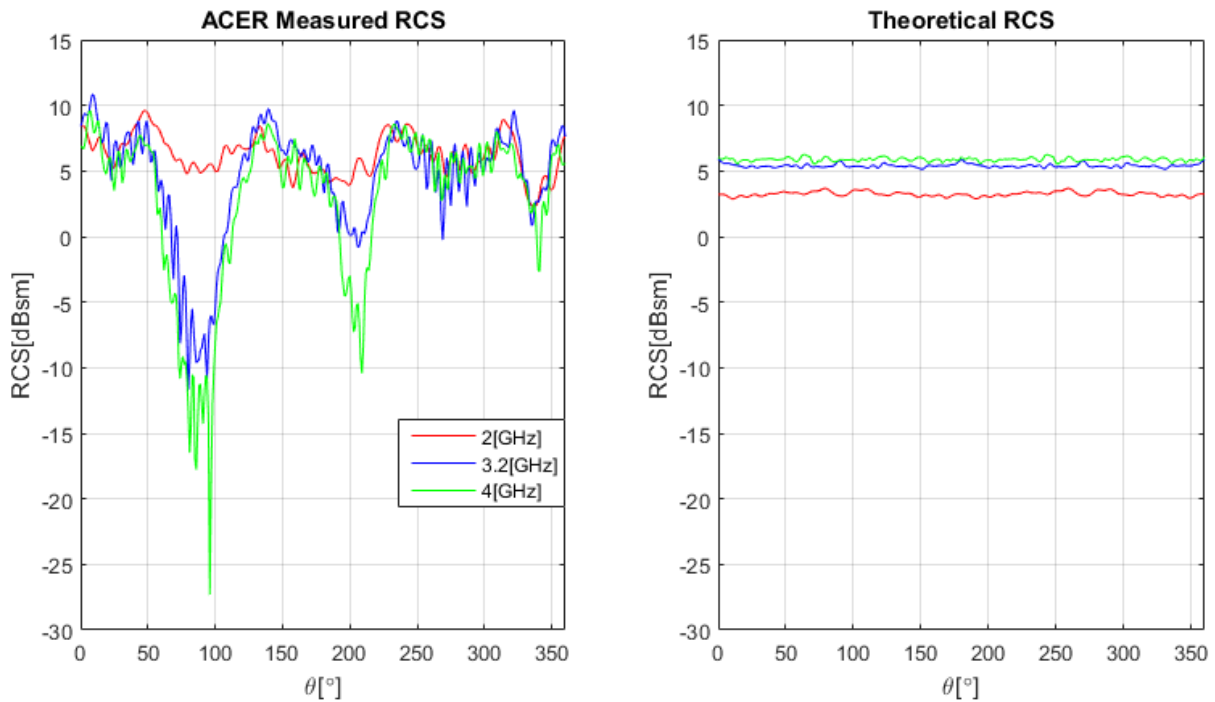


Figure 65. Shielded Octocopter ACER vs. Theoretical RCS, Waterline Scan

In Figure 65, the results of the waterline scan indicate that the actual shield's RCS has a similar pattern to the theoretical shield at lower frequencies. At higher frequencies, the RCS of the actual shield is inconsistent across its aspect angle range as interference caused from EM

waves scattering within the walls of the shield becomes more prominent in the measured response. Examining the immediate sequence of frequencies beyond 2.8 GHz, the initial indication of the non-uniform deconstructive interference is observed notably at around 100° and 200° seen in Figure 66. The result of the high frequency RCS measurements of the squat cylinder demonstrates that its ideal operational frequency range is within the ultra-high frequency (UHF) band, 300MHz to 3GHz.

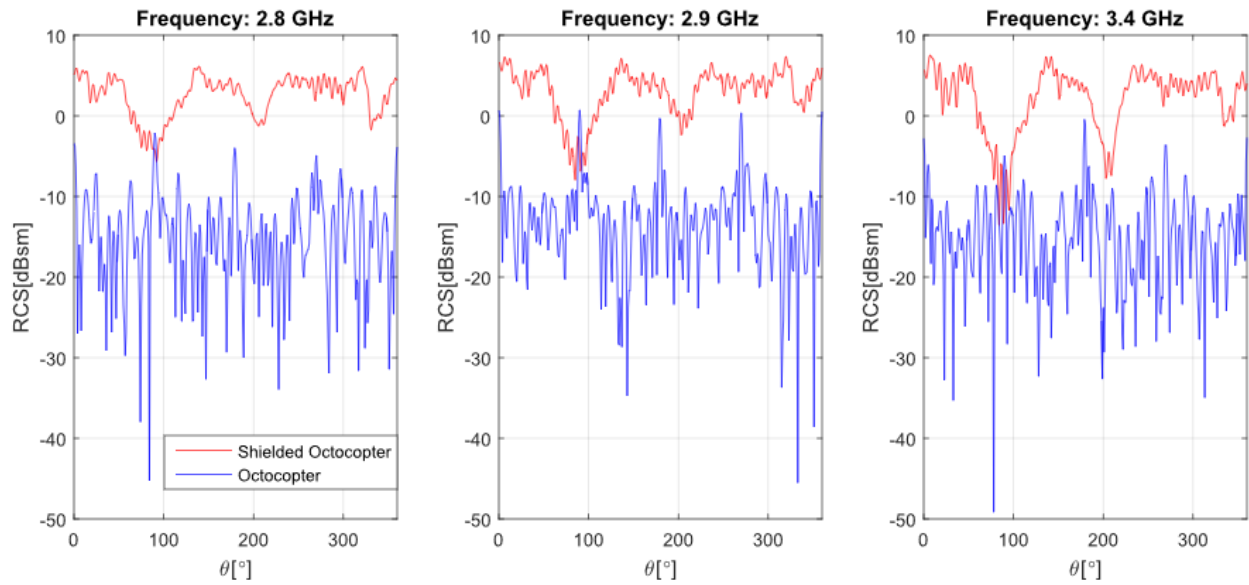


Figure 66. Shield Response Distortion Sequence

4.8 Summary

The characterization of the octocopter's position accuracy demonstrated that cm level precision may be achieved when supplementing the Pixhawk flight controller with the Piksi DGPS. Pose characterizations re-enforced the notion that the drone's accelerometers and gyroscopes are subject to angle drift, leading to errors greater than 1° , depending on the magnitude of an angle change for each orientation. The GPS and INS time differential characterization indicates that an offset occurs between position and pose as telemetry is

received by the GCS. CEM analysis of the various canonical designs revealed that the topless-bottomless sphere would be most ideal to encapsulate the octocopter. A squat cylinder was constructed and test flown, demonstrating that the octocopter's longevity (approximately 5 minutes) is limited due to the drone's thrust to weight threshold. However, the maneuverability of the drone was uncompromised, executing the desired waypoint patterns to be used in field probe application. The AFIT Random Noise Radar (RNR) was unable to transmit the thermal plane waves at high enough power to detect the shielded octocopter for a field probe measurement. High frequency RCS measurements conducted at AFIT's ACER facility reveal that the squat cylinder shield constructed for the octocopter has a 2.8 GHz cut-off frequency, suitable for the AFIT RNR range of 300MHz to 700MHz. It should be noted, however, that the flexing of the shield may result inconsistency between each successive RCS measurement. This flexing of the shield effected the shield-only RCS measurements the most, as, the inner walls were not supported by the octocopter's aluminum L-channels. This is consequently a hindrance to the repeatability of the ACER measurements presented in this chapter. The following chapter focuses on revisiting and answering the investigative questions proposed in this research regarding the design and development of the unique two-way field probe using a shielded octocopter.

V. Conclusion and Recommendations

This chapter provides the conclusion based on the analysis of the results from Chapter IV. The significance of these results are also discussed. Each investigative question posed in Chapter I is answered. Recommendations are provided to further develop and advance the design and methodology of this unique field probing technique.

5.1 Conclusions

This research effort involved a methodical approach to developing, designing, constructing, and testing the outdoor two-way field probe system. The first step is to establish the transitory vehicle required to navigate the field probe throughout the test volume. The X8 octocopter was selected to accomplish this task. The second step is to characterize the position accuracy, pose accuracy, and the time stamp differential acquired from the octocopter's telemetry. The third step is to develop a canonical shield to encapsulate the octocopter. Designing this shield involved using CUBIT and SENTRi software. This enables a CEM analysis to predict if the shield can provide a characterizable RCS profile within the constraints of the EM illumination field and operational frequency range of the AFIT RNR. The selected design is constructed and flight tested to determine the operational performance of the octocopter as it is fixed with the shield. The following investigative questions posed in chapter I are answered based on the outcomes of this research:

1.) How accurate is the octocopter's position and pose?

The GPS and DGPS accuracies were determined by using the ANT Center's NovAtel system as the truth source to determine the NED position errors relative to the known reference location reported by NovAtel's rover antenna. It was found that the u-blox LEA-6 and Piksi altitude accuracies greatly decrease the 3-dimensional accuracy of their positioning systems. The INS accuracies were determined by comparing the accelerometer, gyroscope, and compass measurements acquired from the octocopter's IMU to the iGaging angle cube truth source. The accuracy of the octocopter's position and pose was determined as seen from Table 14:

Table 14. (re-printed).Position and Pose Uncertainty Characterization

	X[m] North	Y[m] East	Z[m] Down
Piksi DGPS (RTK Fix)	0.024535 ±0.000315	0.009135 ±0.000745	0.26 ±0.0002
Piksi DGPS (RTK Float)	0.03617 ±0.002251	0.31950 ±0.0002348	-0.3386 ±0.002235
u-blox LEA 6 (Octocopter un-aided)	0.37615 ±0.02445	0.160902 ±0.0213	4.61911 ±0.04311
Inertial Navigation System	Pitch[°]	Roll[°]	Yaw[°]
	0.33927 ±0.00047	0.26172 ±0.00034	1.2312 ±0.0012

Future research will involve using these values in a Monte Carlo analysis to determine the uncertainty of incident EM wave deviations measured by the field probe. The position and pose accuracy directly contributes to the accuracy of the field probe measurement. The Monte Carlo approach will yield other possible RCS values observed in the test volume based on the position and pose uncertainty by integrating the probe's

position and pose with a truth data set of RCS values acquired at the phase center of the test volume.

2.) What is the time differential between the GPS and INS telemetry update rates?

In characterizing this time differential, it was noticed that each position/pose update was inconsistent with their respective telemetry rates. The GPS and INS exhibit different time stamp rates which can adversely affect the position and pose alignment with the RCS measurements of the field probe, especially if a GPS clock system is used to trigger radar pulses. A separate characterization was performed to determine the GPS and INS update frequencies, independently. The time difference between the position and pose updates and pulse update rate is shown below in Table 17.

Table 17. Position/Pose Telemetry Rate Characterizations

Characterization	μ [msec]
Position/Pose Time Differential	246.703798
Pulse Update Rate (GPS)	623.841
Pulse Update Rate (INS)	649.763

The cause for the time differential between the position and pose may be a direct result of range between the 3DR wireless communication link between the octocopter and GCS. This would explain the inconsistent time stamp differences observed among the various flight programs tested using the C++ time stamp/align program as each had varied ranges. When a serial link is used, greater consistency between the position and pose time stamp difference was observed between each trial as well as

reduced time stamp difference. The discrepancy between the position and pose time stamps may also reveal that the octocopter's navigation scheme is loosely integrated. The correction for this would involve using a clock system that is entirely independent of the Pixhawk flight controller onboard the octocopter. The external clock can time stamp the position and pose independently from the Pixhawk flight controller, providing consistent, time-aligned data.

3.) How does the selected shield design effect the octocopter's communication link and positioning system?

The communication-link between the GCS and octocopter appear to be unaffected by the shield design used in this research. The telemetry data acquired through Mavlink protocol was unperturbed as the octocopter flew its flight path at a varying distance from the GCS. The u-blox LEA-6 GPS onboard the octocopter was able to acquire more satellites (6-10) than required (minimum of 4) to obtain a 3-dimensional fix on the vehicle. The shield, however, had a profound effect on the Pixsi module's ability to acquire a fixed RTK solution. Consideration and planning must be taken to strategically place the Pixsi rover and 3DR telemetry communication link antennae onboard the shielded octocopter, allowing the transmit and receive signals to correlate a differential position solution. Further research should examine the 2v geodesic sphere's effect on the communication link and GPS satellite acquisition.

4.) What shield designs are ideal for this field probe technique?

Assuming a solid-based shield, the ideal shield design for this field probing technique is a spherical or torus shape in which the top and bottom are "open" to allow the octocopter to perform effectively from an aerodynamic standpoint and allow the communication-link and GPS satellite signals to remain un-attenuated. This design yields a consistent RCS measurement for horizontally and vertically polarized incident EM waves. However, the construction of a spherical shape involves a more sophisticated fabrication process to establish equal curvature at horizontal and vertical orientations. The squat cylinder geometry was simplest to construct using practical materials such as aluminum fencing and fine wire mesh that can simply be manipulated to form the cylindrical shape. The squat cylinder and topless-bottomless sphere designs proposed in this research satisfy the minimum requirements for use as a two-way probe. The most effective design in this research is the 2v geodesic sphere, as it provides more significant coverage around the octocopter when navigation requires more elaborate pose maneuvers. This is most desired from an RCS standpoint, because the shape of the geodesic sphere cage can provide a characterizable RCS when measured within low-band frequency.

5.) How is the octocopter's flight performance affected by the shield during an outdoor demonstration?

During the inaugural flight on the octocopter (with aluminum L-channels attached), it was noted that the flight time was approximately 10 minutes. The L-channels had little effect on the drone's stability while performing full yaw rotation or

pitch and roll maneuvers required to create a box pattern. Throttle usage was at approximately 40% - 50% for most of the flight. The addition of the shield created an added stress on the system. Approximately 60%-90% of throttle was used during the flight. This greatly reduced the battery life to about 5 minutes. When the battery voltage drops below the drone's "low battery warning", there was not enough thrust available to compensate for the weight of the shield. The result is an aggressive landing that causes minimal damage to the shield and frame. However, the octocopter was able to perform the same flight maneuvers as observed without the shield. The shielded octocopter can perform raster and box patterns, sufficient for probing a test volume at an RCS range. The GPS onboard the octocopter was able to maintain 4 or more satellites required for a 3-dimensional position fix. Telemetry was acquired from the shielded drone, proving that communication with the GCS is unperturbed. Further research is required to examine the octocopter's performance when encapsulated with the 2v geodesic sphere.

5.2 Significance

The significance of this research is that a prototype system utilizing a shielded octocopter as a two-way field probe to conduct outdoor RCS measurements has been developed. This proof of concept method of probing a test volume is efficient from a cost and time perspective. The particular use of the octocopter in this research is to navigate an outdoor RCS range. It was demonstrated that the octocopter achieved adequate aerodynamic flight performance while encapsulated in a shield. The following section provides recommendations for future research to improve the system.

5.3 Research Recommendations

Many alternative considerations should be made regarding the field probe's structural design. The foundation for implementing this field probe technique begins with the type of drone selected to accomplish the task. The lift capability of the drone is a limiting factor to the shield design integrated onto the system. The robustness of the shield is critical for structural integrity and endurance should in-flight mishaps occur with the drone. If a solid or finely meshed shield is the design of choice such as the shield used in this research, the top and bottom must be open for aerodynamic and signal communication purposes. If a cage design is considered, a 2v or 3v geodesic sphere would be ideal, as the top and bottom may be closed, allowing for a more definitive and consistent RCS characterization. However, the structural integrity of a cage design is more elaborate and complex. The actual design of the shield or cage may be determined by the operational features of the drone. For instance, if the drone utilizes an ultra-sonar sensor to detect altitude, the bottom side must be open. If the drone uses GPS to determine altitude, the bottom may be closed, assuming a cage design is used for the shield. These requirements also assume that a COTS drone is used for the field probe.

Ultimately, a custom drone should be constructed for the field probe. The design for the drone should be based around a pre-constructed shield that is proven to provide the desirable RCS characteristics for a notional frequency band and polarization while maintaining the aerodynamic features of the drone. The drones frame should consist of many attach points to the shield so that the frame does not flex when a pose maneuver is executed. The lift capability should permit the drone to take-off at a throttle level of 50% or less. This is critical for the duration of the RCS measurement, as the power utilized by the drone's motors is expended over time. Less throttle equates to lower battery consumption.

Another major consideration is the methodology of acquiring and aligning the position and pose data with the radar's RCS measurements. A software algorithm may be required to synchronize the frequency of the drone's telemetry with the radar's transmit pulse frequency. Generally, the frequency rate of the telemetry is dictated by the GPS update rate, (typically 10Hz). The benefit of controlling the radar pulse rate with the drone's telemetry rate is that the location and orientation of the drone can be accurately determined relative to the RCS measurement recorded at that time. The difficulty is determining if in fact that measurement occurred simultaneously with the reported telemetry.

The systems onboard the drone intended for guidance and navigation is another important consideration. The outdoor environment is complex. In this environment, the drone requires a wireless signal transmission and reception for communication and positioning. The antennae required to accomplish these tasks must be placed in an unobstructed manner on the drone frame or shield to allow for strong signal strength and reception. In addition to antenna placement, different antennae types such as patch, helical, loop, etc. should also be examined to determine their effect on range and signal reception. A greater range between the GCS and drone could provide ease and flexibility regarding the far-field requirements of the radar used to probe the shielded drone. The DGPS and GPS antennae must also be able to acquire as many satellites as possible to determine an accurate position. An issue faced in this research is the fact that it takes several minutes for the Piksi module to acquire an RTK fix. Satellite reception for the Piksi rover was also very sensitive. An alternative DGPS module that is a variant of the u-blox brand (known as u-blox C94-M8P) has been tested in Captain McCollum's research [2]. Implementing this system onto the Pixhawk flight controller may provide the most optimal position solution, as it is also able to acquire an RTK fix in less time compared to the Piksi. This system is also

capable of providing a 3D relative accuracy of 0.7 cm when in the RTK fix mode and 1.59cm in RTK float mode [2]. The altitude approximation is also far more accurate in comparison to the Pixsi module. However, research is still required to implement this system with the octocopter's Pixhawk flight controller. The limitations of DGPS may lead to a reassessment of the positioning methodology. Instead of GPS, an alternative navigation scheme such as vision-based infrared should be considered. Infrared technology such as optical sensors used to determine proximity may also be beneficial to the system design. Eliminating the need for more external signal communication systems would provide more options concerning the operable environment of the field probe, and the shield design. The navigation scheme implemented on the drone should also be tightly coupled to minimize the time stamp differential between the position and pose measurements observed. A tightly coupled scheme would incorporate the GPS and INS as a singular functioning unit as opposed to two independent modules external to the drone's flight controller.

5.4 Summary

The shielded octocopter developed in this research demonstrates that it is possible to use this unique configuration as a two-way field probe. Careful consideration in the design process must be taken to develop the octocopter's shield for both RCS purposes and flight performance, including the GCS communication link and GPS signal strength. The Pixsi DGPS module may provide the most accurate position solution to the user for a COTS product, however, alternative methods of navigation should be explored to suit multiple environments for field probe operation. As a result of this research, the unique two-way field probe concept will continue to evolve as a resourceful alternative that will supplement existing field probe techniques.

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14. ABSTRACT Accurate Radar Cross Section (RCS) measurements are most reliable if the uncertainty of these measurements can be quantified. The particular contributor to uncertainty examined in this research occurs when an electromagnetic (EM) wave transmitted from the radar deviates from its planar form as it traverses towards a target. The cause of this deviation results from interference within the test volume or medium between the radar and target. The method to quantify this uncertainty involves using a shielded octocopter as a unique two-way field probe. A canonical shield is required to encapsulate the octocopter, as it provides a predictable RCS profile used to quantify the test volume's effect on an EM wave. The shield designs to consider are canonical shapes drafted in CUBIT and measured in SENTRI software to simulate and assess backscatter RCS. A squat-cylinder shield is fabricated as a result of these simulations. High frequency RCS measurements (2 - 18GHz) of the shield reveal that a frequency less than 2.8 GHz effectively shields the octocopter from radar. Position and pose measurements acquired from the octocopter's u-blox GPS, Piksi DGPS, and INS modules are characterized to determine the uncertainty of the drone's navigation scheme as this can affect the accuracy of magnitude and phase measurements acquired when probing a test volume. The most effective position solution is acquired from the Piksi DGPS, accurate to 2.8 cm. The shielded octocopter developed in this research demonstrates that it is possible to use this system as a two-way field probe.					
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