



**CHARACTERIZATION OF QUAD-COPTER
POSITIONING SYSTEMS AND THE EFFECT
OF POSE UNCERTAINTIES ON FIELD
PROBE MEASUREMENTS**

THESIS

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AFIT-ENG-MS-16-M-014

**DEPARTMENT OF THE AIR FORCE
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Capt, USAF

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Abstract

When measuring the Radar Cross Section (RCS) of a test object, many uncertainties must be accounted for, such as the non-homogeneous nature of the medium between the radar test equipment and the platform under test. There are a variety of other error sources, including clutter and Radio Frequency Interference (RFI), motivating the development of techniques to measure and model the uncertainties in RCS measurements. The following research, in unison with prior and current efforts, intends to reduce the impact of these uncertainties by utilizing a unique two-way field probe in the form of a geodesic sphere encompassing a commercial quad-copter aircraft.

The probe is used to measure the incident fields in the target volume in an effort to quantify one of the key sources of uncertainty in an RCS measurement, distortions in the incident wave. In order to do this, the geodesic sphere must be fully understood. This research determined the uncertainty of the probe by creating a calibrated data set of the probe's RCS, extracting the calibrated RCS based on the measurement flight path, comparing the measured with the calibrated data, and determining the deviation in the difference.

The accuracy of the comparison, and therefore the measurement, depends on the accuracy of the flight path. An uncertainty in the probe's position and orientation during flight translates into a field measurement uncertainty. These uncertainties were determined for the Parrot Bebop quad-copter, a differential GPS, and a ViconTM system. Each uncertainty was fed into the measurement model and their measurement uncertainties were determined. Field measurement accuracies of $< 2^\circ$ in phase and $< 0.05V/m$ in magnitude were demonstrated.

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James C. Dossett

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CHARACTERIZATION OF QUAD-COPTER POSITIONING SYSTEMS AND THE EFFECT OF POSE UNCERTAINTIES ON FIELD PROBE MEASUREMENTS

I. Introduction

“I think we can say that the Battle of Britain might never have been won... if it were not for the radar chain.”
- Sir William Douglas, Royal Air Force [1]

1.1 Problem Background

Since the early days of radio detection and ranging (radar), the military force with better detection performance has had the strategic advantage. Shortly after the advent of radar, adversaries began to determine ways to defeat their foes' radar system. Countermeasures were developed followed by counter-countermeasures [2]. Soon, it was realized that an effective way to defeat a radar system was to make the aircraft's radar signature too small to be detected by the detection radar. This notion gave rise to the concept of RCS reduction.

Radar Cross Section is a representative area that relates the intensity of the incident electromagnetic (EM) wave to the intensity reflected back to the radar's location [3]. The size of the target RCS is the size of a perfectly conducting sphere that reflects the same amount of energy as the target in a particular direction [3]. This reflected energy is notoriously hard to accurately measure. RCS is traditionally measured by mounting the target on a pylon and radiating it with a known test radar signal. The reflected power is measured and compared to the transmitted

radar power. This ratio is defined as the RCS and is seen in Equation 1 where σ is the target RCS, R is the range from the radar to the target (approaching infinity to remove range dependency from the RCS), E_i is the EM field incident on the target, and E_s is the field scattered by the target [3].

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

Figure 1 is an example of an aircraft on a pylon undergoing RCS testing [4]. This particular image is from the National Radar Cross Section Test Facility (NRTF) at Holloman Air Force Base (AFB). NRTF is one of the major RCS testing facilities in the United States and is the sponsor for the research in this thesis.

1.2 Problem Statement

Accurately measuring a target's RCS requires accurately knowing the EM field, magnitude and phase, incident on the target. Many factors may distort the incident field from the time it is transmitted to the time it is reflected. These include, but are not limited to, atmospheric effects and ground bounce.

The most common way to determine how the propagated EM wave is affected by these distortions is to measure them with a probe [5].

In order to record relevant data, the probe must be located inside the area known as the test

volume. The test volume is comprised of the region surrounding the target that is



Figure 1. Low-Observable helicopter prototype model being measured at NRTF [4]

being measured by the radar's signal. The depth of the test volume is determined by the radar's coherent pulse interval and the height and width are functions of the incident EM wave's deviation from planarity in amplitude and phase in the cross-range dimensions. Planarity means the target is far enough away from the radar source that the spherical wave looks flat (just like the Earth looks flat while standing on it). The target needs to be positioned such that it is not ambiguous in range and close enough to the center of the wave as to take advantage of the wave's planarity.

While a probe is useful to record accurate data about the incident radar wave, a probe can introduce errors into the measurement. These errors are caused by interaction between the probe and the probe mount, probe sensor size, measurement distance, and cable connections [5]. Traditional probes are rigid structures capable of probing a small portion of the test volume at a time. In order to probe different portions of the volume, they must be taken down, moved, and set back up. These issues and limitations decrease the fidelity of probe measurements, add uncertainty to the data, and increase the timeline for a measurement.

This thesis continues research into a method of bypassing the limitations inherent in a traditional field probe. A two-way probe concept was previously proposed by the Air Force Institute of Technology (AFIT) in conjunction with NRTF. The work was introduced in a previous thesis [6]. The design called for placing a remote controlled (RC) quad-copter inside of a geodesic spherical cage. A quad-copter is a four rotor remote controlled aircraft that flies like a helicopter. A geodesic sphere is a sphere-like shape comprised of geometric triangular shapes. In this application, the geodesic sphere is placed around the quad-rotor and acts as an EM shielding cage. The geodesic sphere was designed to reflect the incident EM energy back to the radar in a statistically uniform pattern. The difference between

the expected and actual return signal gives insight into the perturbation of the illuminating field from the ideal plane wave.

This probe concept has two main advantages over the traditional field probe techniques. First, a quad-copter is agile and capable of traversing the entire target volume in contrast to a traditional linear probe which only scans in a line or on a plane. Second, the geodesic sphere provides a predictable reflection that can be scanned through any number of points anywhere inside the desired test volume. When the test radar's wavefront strikes the sphere, it reflects back to the test radar. These reflections are measured and compared to the known truth reflection profile of the sphere. A comparison between the truth data and the reflected test data allows the user in the field to determine how the original transmitted radar wave was perturbed from an ideal plane wave at that point.

A major challenge in the two-way probe concept is the need for accurate pose information. Pose information includes the position (x,y,z) and orientation (roll, pitch, yaw) data. The geodesic sphere surrounding the quad-copter is not a perfectly conducting sphere. Its orientation and position change the value of the perceived RCS. The pose accuracy of quad-copters is not well known. They are susceptible to inertial navigation system (INS) drift and often contain a low accuracy Global Positioning System (GPS). How these systems work and how they interact will be explored in Chapter II.

1.3 Research Focus

The overall objectives of this research are to determine the level of precision attainable for pose information, based on available navigation systems, and how positional uncertainties affect RCS measurements of the geodesic sphere. These objectives are achieved by accomplishing two secondary goals: determine the

accuracy and uncertainty in position and orientation of the chosen quad-rotor and determine and model how these pose uncertainties affect RCS measurements.

In order to accomplish the first goal, an accurate truth source for positional measurements will be developed and tested. This truth source consists of two separate systems. For GPS testing, a mobile differential global positioning system (DGPS) will be utilized. For INS testing, a digital angle meter will be used for roll and pitch and a digital turn table will be used for yaw testing. Next, the quad-copter positioning system will be tested and its uncertainties determined by comparing its data to the applicable truth source. The second half of the research will create an RCS model based on the position and orientation of the geodesic sphere. First, the RCS of the geodesic sphere will be measured and the uncertainties in the measurement determined. Next, the pose uncertainties will be considered. Using both of the types of uncertainty will result in a model output of a range of possible RCS values. These values will result in an uncertainty value for the overall measurement.

1.4 Investigative Questions

The research focus of this thesis strives to answer two investigative questions:

1. How accurate is the built-in quad-copter mounted positioning system?
2. What is the functional relationship between the pose errors of the quad-copter probe and the uncertainty in the probe measurement of the incident field in magnitude and phase?

1.5 Methodology Overview

The quad-copter chosen for this research is the Parrot Bebop drone, a commercial off the shelf (COTS) quad-copter. This quad-copter was chosen due to its small but capable size, low cost, availability, ease of use, and flight performance. The Bebop's navigation system uses a GPS and INS coupled system. A coupled GPS/INS system is a system which combines information from both the GPS and INS to correct issues such as drift and timing errors [7]. There are different methods and levels of combining the two systems. More information on coupled GPS/INS systems may be found in the Literature Review section of this thesis.

The two systems will be tested independently in order to determine their uncertainties. For the GPS test, the quad-copter will be mounted onto a golf cart, next to a DGPS. Both stationary and moving GPS data will be taken. The on-board drone GPS time stamped position will be compared to the time stamped truth data from the DGPS system and the GPS uncertainties will be determined. For the INS characterization, the drone's roll and pitch recordings will be compared with the values from the digital angle meter. The drone's yaw recordings will be compared with the yaw values of a digital turn table. The drone will be independently moved in each axis. Following data collection, the data will be analyzed and the position and orientation accuracy determined. These uncertainties will be fed into the developed model as uncertainty bounds.

The second aspect of this thesis is to characterize the geodesic sphere, with and without the quad-copter inside, by measuring it with a test radar in different positions and orientations. This characterization will be accomplished by placing the sphere on a foam mount in AFIT's Advanced Compact Electromagnetic Range (ACER) and systematically taking RCS measurements from different aspect angles (great circle cuts). The analysis will allow for the creation of a RCS model

based on pose of the geodesic sphere. This model is necessary to determine how position and orientation uncertainties affect the RCS of the sphere.

1.6 Assumptions

The following assumptions were made as part of the scoping of this thesis:

- The geodesic sphere will be optimized for AFIT's ACER operating frequency range
- In application, the flight plan will result in the geodesic sphere only being illuminated by the radar from $\pm 10^\circ$ in pitch
- Roll of the geodesic sphere will be ignored as it creates a polarization change in the reflected EM wave (this change is assumed to be negligible over $\pm 10^\circ$ in pitch)
- For all aspects of this research, the geodesic sphere will be illuminated by an ideal plane wave
- Positional truth data will be available by using a mobile DGPS
- Pose information does not need to be accurately known in real time because the data sets will be correlated by the appropriate time stamp
- Pose data will be recorded without the geodesic sphere installed on the quad-rotor during the GPS/INS navigation system characterization

1.7 Impact

Accurate RCS measurements are crucial to the development of modern aircraft programs. A problem in RCS measurements is determining the planarity of the

illuminating EM fields used to measure the target under test. There are many perturbations of the illuminating field between the radar transmitter and the target being measured. Current field probes are bulky, limited in their ability to efficiently scan the test volume, and can introduce additional scattering contamination into the measurement data. The two-way EM field probe discussed in this thesis will provide a radar engineer with more accurate information about the magnitude and phase of the incident radar wave.

This higher level of information will decrease RCS measurement uncertainty and increase measurement flexibility. Given the mobility of a quad-copter, the entire test volume will be able to be characterized between every test. Measurement projects will be shortened and money saved all while gaining a better understanding of the measurement and increasing the measurement accuracy of the target's RCS.

1.8 Thesis Overview

This thesis is comprised of five chapters. Chapter I is the introduction, which motivates and defines the research problem. Chapter II provides a summary of past and current research in this area of study and shows how that research applies to this thesis. Chapter III discusses the methodology and techniques for answering the thesis research questions. Chapter IV details the data collected, explains the analysis, and reviews the results. Finally, Chapter V reviews the research completed, summarizes the conclusions that were drawn, and discusses future research needed to expand and build upon this research.

II. Literature Review

“We may produce at will, from a sending station, an electrical effect in any particular region of the globe; we may determine the relative position or course of a moving object, such as a vessel at sea, the distance traversed by the same, or its speed.”

- Nikola Tesla [8]

2.1 Introduction

Radar Cross Section (RCS) measurements are complex and expensive. Current RCS requirements are increasing the need for accurate and timely RCS measurements. Since RCS measurements are conducted in an imperfect world, all measurements include differing causes and levels of uncertainty (Section 2.4 discusses these uncertainties). A common way to determine the uncertainties is to use a field probe. Traditional probe techniques, while effective, introduce their own, often unknown, errors into the measurement as discussed in Section 2.3.1 [5]. A two-way, self supported, probe is capable of bypassing a large portion of the errors present in traditional probe techniques.

The proposed two-way probe concept is a complicated, multi-disciplinary project. This thesis looks at determining the level of precision attainable for an on-board quad-rotor position and orientation system and how uncertainties in these parameters affect RCS measurements of the geodesic sphere, which in turn, affect the accuracy of the field probe measurement of the incident field. In order to characterize these issues, this research effort looks at how the following two ideas relate: accuracy of position and orientation information and uncertainties in RCS measurements. The interaction between pose accuracy and RCS measurement accuracy is fundamental to this research. As the error in the pose information

increases, the fidelity of the RCS measurement decreases. As the distance traveled by the wave to the probe and back is more accurately known, the incident phase will be better known, allowing for more precise phase deviation calculations.

The end goal of the two-way probe concept is to determine the variations in an incident radar wavefront across the desired test volume. This requires an accurate understanding of the pose uncertainties as well as the statistical nature of the probe's RCS. The exact value of the geodesic sphere's RCS at a particular orientation is not as important as understanding the relative changes in the RCS statistics as they vary with the position and orientation of the probe, hence the importance of accurate pose information.

Before beginning new research a fundamental knowledge base is required. This chapter provides the background information necessary to understand this research as well survey what has already been done in the area of electromagnetic field probes. In order to lay the foundation for the research presented, topics such as: radar fundamentals, RCS fundamentals, uncertainty in RCS measurements, RCS measurement techniques, and GPS/INS fundamentals are discussed.

2.2 Radar Fundamentals

In order to measure the RCS of an object, a radar system is needed. Radar is a system which emits radio frequency (RF) EM waves and determines the presence and location of objects in its field of view from the reflected EM waves. EM energy is radiated from the radar antenna, reflected off objects in space, and collected by the radar system. These reflections indicate the presence of a target as well as other target information such as electrical size, direction of movement, and speed. Radar is capable of performing in all weather conditions, day or night [9].

2.2.1 Radar System Components.

A basic radar system is depicted in Figure 2 [10]. The diagram includes the major elements involved in transmitting, propagating, and receiving a reflected radar signal. Every radar system is different, but all include a transmitter which creates the signal, an antenna which transmits the signal and receives the reflected signal, and detection equipment inside the receiver.

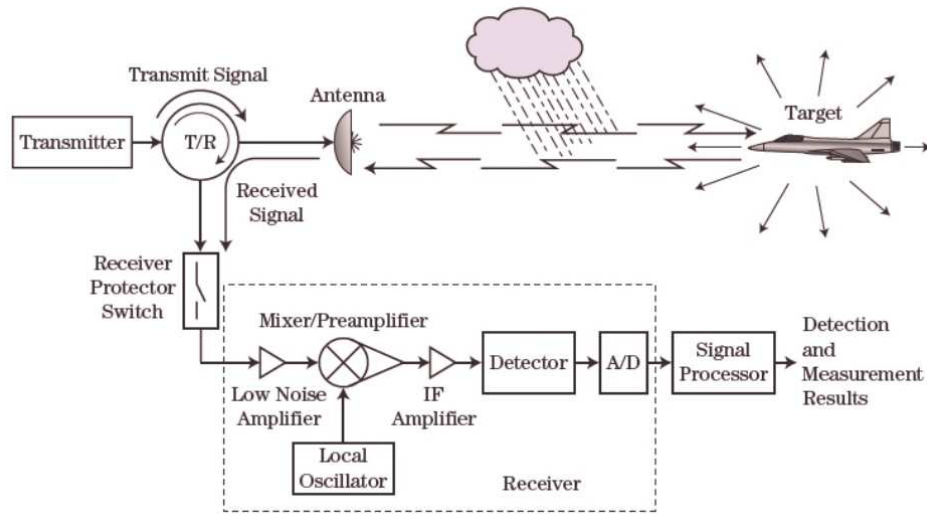


Figure 2. Basic Radar System Diagram [10]

Radar systems are either mono-static or bi-static. Mono-static systems have either a single antenna or two co-located antennas that functions as the transmitter and receiver. Bi-static systems have separate transmit and receive antennas with spacing sufficient to create two angles to the target [10]. The radar system used for this research is a mono-static radar.

2.2.2 Radar Range Equation.

The importance of RCS is easily seen by looking at the radar range equation (RRE). It is a mathematical formula for deriving any parameter of a radar

engagement depending on how the equation is manipulated. Equation 2 is manipulated to calculate the power received from a target [9]. An explanation of each of the terms is included below the equation. Radar Cross Section is mentioned here but will be discussed in the following section.

$$P_r = \frac{P_t G^2 \lambda \sigma}{(4\pi)^3 R^4} \quad (2)$$

Where:

P_r is the reflected power received by the antenna in Watts,

P_t is the power transmitted by the antenna in Watts,

G is the gain of the antenna,

λ is the wavelength of the radar wave in meters,

σ is the mean RCS of the target in square meters, and

R is the range from the antenna to the target in meters.

The higher the received power, the more reflected energy was received from the target. Power received can be increased by increasing the transmitted power, gain of the antenna, wavelength of the transmitted signal, RCS of the target, and by decreasing the range to the target. Transmitted power and antenna gain are limited to the hardware in the system and can be costly to increase. Wavelength is a function of frequency, which is a function of the radar hardware. When the frequency of an EM wave increases, the wavelength decreases. Longer wavelengths travel farther and as such, long range search radars use low frequency waves (which have less angular resolution). Shorter wavelengths cannot propagate as far, which is why short range targeting radars use high frequency waves (which have more angular resolution). Angular resolution refers to the ability of the radar to differentiate targets in azimuth and elevation [11]. Range to the target is determined

by mission constraints and is different for every engagement. The only remaining term in the RRE is σ , which is the RCS of the target and will be discussed below.

2.2.3 Radar Wavefront.

Conceptually, regardless of the pattern of the emitting antenna, a radar wave can be thought of as a spherical wave emanating from a point source with a constant phase front. A constant phase front means the phase of the wave at a given instant is the same at every point along the face of the wave. As this wave propagates out in space the front of the wave becomes more flat. When the target is approximately D^2/λ away (where D = the largest target dimension and λ = the wavelength of the EM wave), the entire target is illuminated by waves with approximately planar, constant phase surfaces. This means that the wave's phase is constant across cross-sectional cuts through the target area. The far field approximation states that an EM is considered planar if the phase front deviation across the largest target dimension is $\lambda/8$ [3]. In order to record accurate RCS measurements, a plane wave is required.

Depending on the size of the target, a large range is needed in order for the radar wave to become planar. This large area is not always possible. In order to reduce the required range enough to measure RCS indoors, a compact range is required. A compact range uses a calibrated radar reflector, or collimator, to align the phase front of the radar wave. One example of a collimator is a paraboloidal reflector. A paraboloidal reflector (Figure 3) creates a uniform plane wave by reflecting a wave from any direction in the same direction as all the other reflections. The phase and amplitude of the wave are independent of position along the direction of wave propagation. The amplitude of the wave away from the axis of propagation may change due to the distance traveled by each collimated ray. This amplitude profile is

also constant along the direction of propagation. Figure 3 diagrams the concept of a paraboloidal reflector. The constant phase front can be seen as well as the amplitude dependence on ray path distance. Amplitude dependence is driven by the distance each ray path has propagated. Since the wave transmitted by the feed structure is spherical, Ray #1 has traveled farther when it reaches P_1 than when Ray #2 reaches P_2 . This difference in ray distances causes an amplitude variation [3].

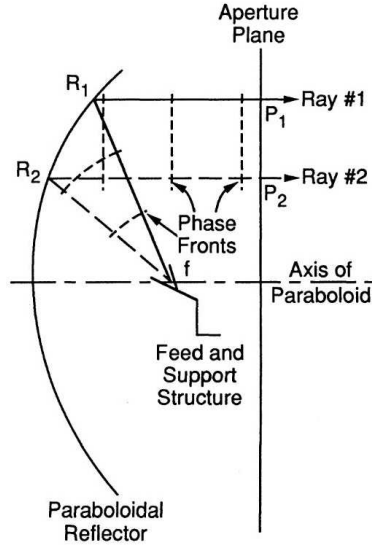


Figure 3. Diagram of the plane wave generation principle [3]

Whether RCS measurements are performed at a large outdoor range or in a compact range, it is highly likely that the wavefront illuminating the target is not actually uniform in amplitude and phase. Distortions in the field can be caused by imperfections on the collimator or perturbations in the atmosphere. One of the major applications of the two-way probe concept is to determine what the actual amplitude and phase front of the illuminating wave are at the target location.

2.3 Radar Cross Section Fundamentals

The RCS of the geodesic sphere is vitally important to this research. It is the statistical nature of the sphere's RCS that allows for the determination of the

non-uniformities in the transmitted radar wave. A target's RCS represents the magnitude of the reflected return signal from the target to the radar. According to Skolnik "the radar cross section of a target is the projected area of a metal sphere that would scatter the same power in the same direction that the target does" [9]. This cross section is found by using a ratio of the power reflected from the target back toward the source and the power incident on the target from the source. As previously shown, Equation 1 gives the mathematical definition of RCS [3]. This equation assumes the target is far enough away that the electric field looks planar to the target.

$$\sigma = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{|E_s|^2}{|E_i|^2} \quad (1 \text{ repeated})$$

The EM wave incident on a non-uniform target interacts with the different surfaces of the target through a variety of scattering mechanisms. These interactions result in reflections that vary in magnitude and phase which change as a function of the target's orientation. Therefore, RCS is a function of angle. As the incident angle changes, the reflected power changes, changing the RCS. Due to this angular dependence, the RCS of a target is not simply a number, but a three dimensional pattern. These patterns are usually displayed in polar plots which display only one elevation angle while rotating in azimuth. An example of such a plot is seen in Figure 4 [12]. It is clearly seen that RCS is anything but constant as the target rotates in the radar field.

A sphere was chosen as the reflector shape for the two-way probe concept for this thesis because of the azimuthal dependence of RCS. A sphere has a constant reflection regardless of orientation due to its symmetric curvature, the curvature is not a function of aspect angle and therefore the scattering from it is also independent of aspect angle. RCS is the coherent sum of all of the *scattering* mechanisms for a given wave and target. When EM energy hits a surface, the

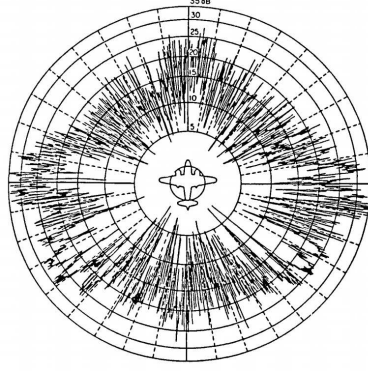


Figure 4. Measured Waterline RCS Plot for B-26 at 3GHz [12]

energy is dispersed in certain or all directions depending on the surface shape. These reflections are referred to as scattering. Scattering depends on the size of the object, L , relative to the radar wavelength (electrical size), polarization and the shape of the object.

There are three scattering regions, Rayleigh ($\lambda \gg L$), Resonant ($\lambda \approx L$), and High Frequency ($\lambda \ll L$) [9]. The scattering in every region is a function of target size and aspect angle. In the Rayleigh region, since the wavelength is much larger than the target size, the entire volume of the target sees an illuminating field at approximately the same phase. Therefore, the larger the target volume, the larger the scattering magnitude. In the Resonant region the RCS fluctuates with frequency. These fluctuations are caused by the phase of the surface currents over the entire object which vary as a function of frequency. These surface currents produce traveling waves along the individual wires of the geodesic sphere.

In the High Frequency, or optical region, scattering becomes localized. Local point scattering effects become more important than different scattering surfaces interactions. The non-specular scattering is closer in magnitude to the specular scattering in the resonant region which results in a larger scattering fluctuation as compared to the optical region. Each of the scattering centers is treated independently. Fluctuations occur in the optical region when creeping waves

constructively and destructively interfere with the direct reflection. A creeping wave is caused when energy travels along the surface of the target, around the back, and re-radiates back towards the radar. Figure 5 displays the different scattering regimes. RCS (σ) is normalized to the sphere's projected area and ka is the sphere's circumference normalized to wavelength [10].

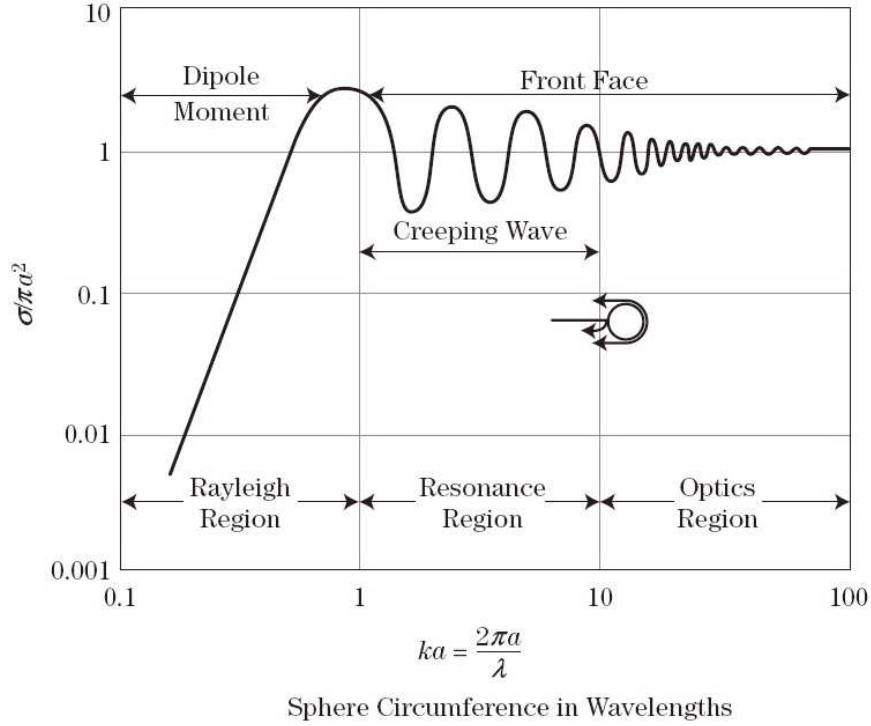


Figure 5. Normalized RCS of a Sphere [10]

The end application for the geodesic sphere will be to operate the radar in the Rayleigh region of the sphere. Rayleigh effects will cause the imperfect sphere shape to appear more sphere-like to the radar. Operating in the Rayleigh region will also reduce the traveling waves along the directly illuminated wires of the geodesic sphere. It will also allow the surrounding geodesic sphere to hide the quad-rotor from the radar as long as the incident wave's frequency is above the geodesic sphere's cutoff frequency. Cutoff frequency is the frequency at which the EM waves are not able to penetrate the sphere's surface because their wavelengths are longer than the opening is wide [13].

2.3.1 Traditional Radar Field Probe Techniques.

To achieve an accurate measurement, especially as targets' RCS continue to decrease, it is necessary to know exactly what field is illuminating the target. The assumption is that a perfect plane wave, with a constant phase front, is hitting the target. In reality, the wavefront is distorted. The most straightforward way to measure the actual field at the target (without the target present) is to use a "standard" probe. Three techniques are currently available for such a task. A one-way probe uses a receiving antenna such as an open-ended waveguide or small horn that is scanned through the test volume, or quiet zone. The field characteristics are recorded by the probe, albeit with the probes antenna pattern modifying the field.

Another method is to use a two-way probe. This involves moving a reflector with a known scattering behavior through the quiet zone. The reflector scatters the incident field back to the radar. The reflected signal is received with twice the phase deviation as the incident field. As with the one-way probe, the reflector's pattern is impressed on the waveform as well. The final common probe technique is to rotate a long thin rod in azimuth. Using Doppler processing, the returns can be separated from each position. This provides amplitude and phase reflections as a function of position [3].

A field probe is called *standard* when theoretical analysis can determine its receiving characteristics. When the probe is introduced into a field, a voltage is created on the probe. That voltage allows for the determination of the strength of the incident field. These voltage measurements are not trivial and improper measurements cause considerable errors in the final calculation. Different techniques are needed to measure the electric and magnetic fields. Electric field measurements are usually performed with an electrically short dipole; whereas magnetic field

measurements often use an electrically small, resistively-loaded loop. Single probes for simultaneous electric and magnetic field measurement do exist, but the theoretical analysis is much more difficult [5].

The intricacy of the measurement and extra analytical burden incumbent with producing a “standard” measurement probe demonstrate the desire for a simpler solution. Traditional two way probes utilize known scatterers such as spheres, flat plates, or corner reflectors [14]. Since the theoretical solution for simple shapes is relatively easy to calculate, by comparing the theoretical reflection to the measurement reflection, conclusions about the incident wave can be drawn. By using this method, it is possible to back out the differences between the desired and actual EM wave incident on the reflecting object. This measurement then needs to be repeated with the probe at a sufficient number of positions in the test volume.

The problem with any of the above methods is the unknown interactions between the incident wave, probe, and probe support structure. The probe support structure interactions are very hard to accurately determine and characterize and are often ignored, decreasing the fidelity of the probe measurement. By placing a quad-copter inside a geodesic sphere, the probe support structure is eliminated. This increases the mobility of the probe as well as decreases the measurement uncertainty due to the lack of other scattering objects in the test volume. As long as the RCS of the geodesic sphere is well characterized, the return signal the radar receives can be used to determine the wavefront incident on the geodesic sphere.

2.4 Uncertainty in Radar Cross Section Measurements

Even after the characteristics of the radar field are known through probing, there will still be uncertainty in any RCS measurement. All measurements, even the most meticulous, have some inherent uncertainties; no physical quantity can be perfectly

measured. Because of these errors, statistical quantities are used to put bounds on the data. The mean, or average, is a simple estimate of the true value from multiple measured values. The standard deviation gives insight into the average uncertainty over multiple measurements [15]. Characterizing the uncertainty in the RCS measurement of the geodesic sphere is one of the main thrusts of this research. The goal is to determine the actual RCS of the geodesic sphere. From this RCS, calibration values can be determined. These values will then be applied to any probe measurements taken of the geodesic sphere. By applying these calibration values to the measurements, the fluctuating nature of the geodesic sphere can be removed from the measurement, leaving only the two way wavefront data in the signal. By doing this at different positions in the test volume, a picture of the actual incident wave will be created.

In order to characterize the uncertainty, a measurement model has been developed. The standard measurement model for RCS measurements is seen in Equation 3 [16].

$$E_m = \frac{E_t - E_{bt}}{E_c - E_{bc}} E_p \quad (3)$$

Where:

E_m is the calculated calibrated EM field,

E_t is the measured target EM field with noise and clutter,

E_{bt} is the measured target background EM field with noise,

E_c is the measured calibration target EM field with noise and background,

E_{bc} is the measured calibration background EM field with noise, and

E_p is the mathematical EM field solution for the calibration target.

This equation subtracts the background from the target RCS measurement (the numerator of the equation) and applies a correction factor to calibrate the measurement. The lower the level of the calibration target background (E_{bc}), the

closer the correction factor gets to unity. The problem with the background subtractions (numerator and denominator) is that they are not all inclusive subtractions. The background subtraction is not perfect as it does not remove target-mount and target-chamber interactions, as well as system thermal noise and multiplicative errors. Multiplicative errors include system drift, frequency uncertainty, nonlinearity in the radar, and I-Q imbalance. A more sophisticated model that includes multiplicative errors does exist but the multiplicative errors are much less than the other system errors in the radar system used for this research [16]. The application of the background subtraction model (Equation 3) to characterize the uncertainty in a radar system is described in Section 2.5.1

Prior to applying the RCS uncertainty to the test data, the uncertainty needs to be decreased as much as possible. The most straightforward approach to decreasing measurement uncertainty is to record repeated measurements and use statistics (mean and standard deviation) to calculate a value for the uncertainty. Systematic errors will persist, however, because some errors in the measurement will repeat [15]. These errors will be accounted for through the radar calibration process, provided the interactions between the target and range are small.

Radar signals lend themselves well to the use of statistics since each measurement is recorded multiple times. These multiple measurements can be compared and an uncertainty determined. The uncertainty analysis performed during this research provides the model needed to correlate the uncertainties in the quad-rotor pose to the uncertainty in the measured RCS of the geodesic sphere. This connection is crucial to the viability of the quad-rotor driven geodesic sphere as two way field probe. Accurate knowledge of the pose information and the statistical variations in the geodesic sphere's RCS are required in order to determine any phase variations in the radar's wave front.

2.5 Radar Cross Section Measurement Techniques

One of the best ways to minimize RCS uncertainty is to use methodical and precise techniques for measurement. The most cost effective way to minimize RCS uncertainty is to begin with analytical prediction, move to computer simulation, and then end with either scale model or full-scale, far field, coherent measurements [17]. A coherent measurement is one in which the received signal is referenced to the transmitted signal frequency in order to determine phase shift in the received wave [9]. Coherent measurements are desired because they allow for the collection of phase information as well as amplitude which allows for Doppler measurements and radar imagery [3].

2.5.1 Measurement Setup and Process.

In order to accurately measure a target, it must be precisely held in position. The most common way to hold a target in position is a foam or metal column support. Interference from the column can be decreased by using a low RCS column, tilting the column away from the radar, or shaping the surface of the column. Another popular method is to suspend the target from low RCS cables [18]. After the support mechanism has been determined, the measurement effort can begin.

The beginning of every RCS measurement effort is a calibration measurement. A known standard target (sphere, cylinder, or flat plate) is put in position where the unknown target will be measured and a measurement sweep is completed [17]. This measurement is stored and later subtracted from the target data (Equation 3). This subtraction mostly eliminates the column and background reflections in the target measurement data [19]. This calibration method does not account for interactions between the target and the support. The target to column interface must be carefully designed in order to decrease the coupling between them [18]. An

assumption made in the calibration and measurement process is that the radar is operating in the linear region of the radar power gain. This allows for a direct reading of the RCS value based on the power out and power received to and from the radar system.

Following calibration measurements, the target is placed on the measurement column. Depending on the desired measurement, the target is either held stationary and a single measurement is recorded, or the target is rotated and multiple measurements are recorded. These measurements are often referred to as cuts. A cut is an RCS measurement that has been recorded over an entire azimuthal revolution of the target. These cuts can be either circular or conical. A circular cut means the target's plane of rotation is perpendicular to the radar. If the target's plane of rotation is tilted towards the radar, it sweeps a conical cut. Conical cuts provide greater coverage of the target per cut and are therefore more efficient [3]. The target orientation is changed between each cut until the entire target has been measured. The AFIT RCS range is setup for circle cuts and therefore is the type of cut used for this research.

2.6 GPS/INS Fundamentals

As previously discussed, one of the most important requirements for a successful RCS measurement is accurately knowing the pose of the target [18]. Without this information it is impossible to know how the orientation of the target influenced the reflection. For this two-way probe using a quad-rotor, the pose information will be provided by the quad-rotor's integrated GPS/INS system.

2.6.1 Global Positioning System Description.

The United States' GPS system is one of many Global Navigation Satellite System (GNSS)s around the world. The GPS is a 24 satellite system used for positioning, navigation, and timing. It was developed by the Department of Defense (DoD) in the 1960s and 1970s with the goal of aiding military navigation and timing [20]. The idea that a position can be obtained using distances to known objects is the basis for GPS. Position measurements are given by three coordinates (latitude, longitude, and altitude). In order to solve a problem with three unknowns, three equations with three known aspects are required [21].

The GPS data is transmitted at $1575.42MHz$, $1227.60MHz$, and $1176.0MHz$. These are called the L1, L2, and L5 bands respectively. L-band was chosen due to its effective transmission through the atmosphere. Three frequencies are used so the signals may be compared in order to determine and eliminate the ionospheric effects on the transmitted signal (only if the receiver is a dual-channel receiver). Every GPS satellite transmits on the same frequency so each satellite has a unique, non-interfering, code sequence. These code frequencies are read by the receiver, telling it which satellite the signal came from [20].

As depicted in Figure 6, at its most basic, GPS solves the above system of equations using the concept of time-difference-of-arrival [22]. Each GPS satellite knows its position and all of the satellites have the same time via atomic clocks. These positions and times are broadcast to Earth where a receiver anywhere in the world can receive them [20]. In order to calculate the distance from each satellite, the time delay of each signal must be calculated. This would be trivial if the receiver and satellite clocks were synchronized, which they are not. The receiver clock bias affects the recorded GPS signal transit time of all visible satellites equally. Since the bias is the same for all, but still unknown, the solution becomes a

system of four equations with four unknowns. This requires a fourth satellite to be visible to the receiver [21].

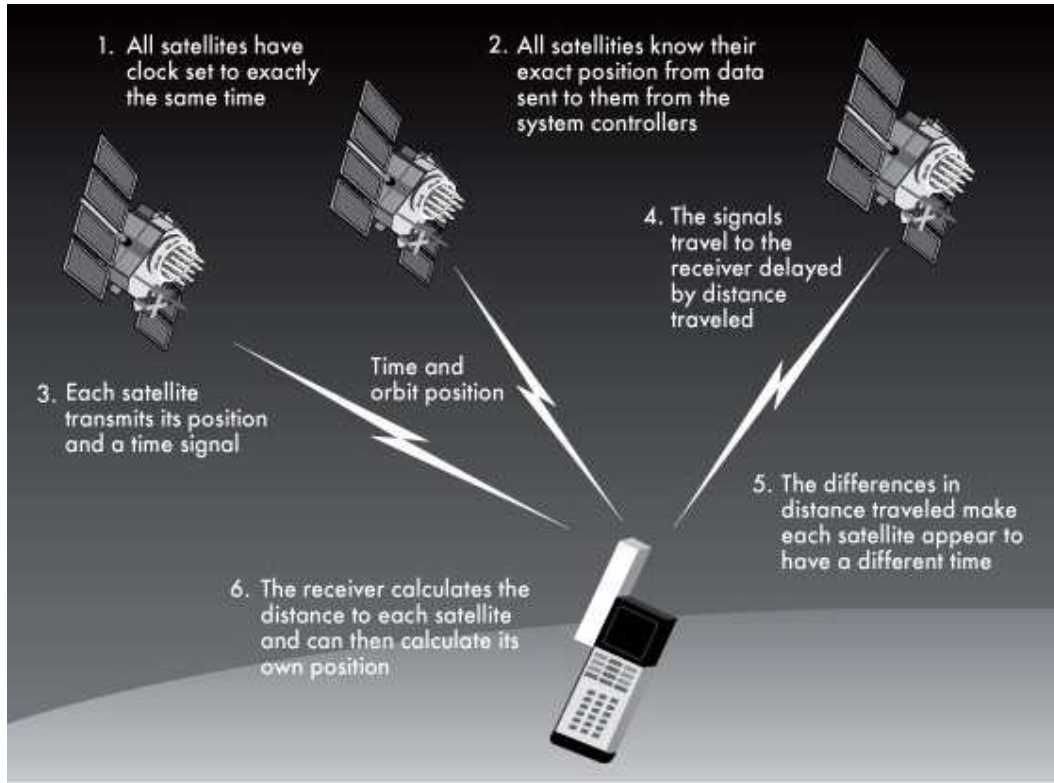


Figure 6. A pictorial description of the GPS system [22]

Once the receiver time bias is known, the time delay from each of the visible satellites and the distance from each of the satellites is calculated. These distances are approximate due to the errors in the accuracy of the satellites positions, effects of ionosphere and atmosphere on transit time (possibly different for each satellite), and internal receiver error sources. These unknowns increase the uncertainty of the calculated position (single channel: 5 – 20m, dual channel: 2 – 5m for civilian use) [20].

The Parrot Bebop's GPS system is a Furuno GN-87F Multi-GNSS Receiver Module. This module is capable of simultaneous reception of GPS, Global Navigation Satellite System (GLONASS) (Russia's version of GPS), and satellite-based augmentation systems. Utilizing multiple satellite systems provides

more satellites in view, faster position lock, and improved performance in traditionally degraded areas (city centers or canyons for example). The position data can be updated at a rate of $10Hz$ and the chip starts up in under 1 second. The stated positional accuracy of the GN-87F is $2.5m$ Circular Error Probability (CEP) [23]. This means that a circle with a radius of $2.5m$, centered on the truth value, contains 50% of the actual GPS measurements [20].

2.6.2 Differential GPS.

Some of the error sources inherent to GPS measurements can be easily mitigated. The errors for users near each other are nearly identical and change slowly over time. Error in the measurement can be estimated at a known receiver location. A DGPS system computes these error estimates and transmits them to other capable GPS receivers that are within $100km$ of the DGPS reference site. The closer the receiver is to the DGPS site the more accurate the receiver becomes. Accuracies down to $2cm$ are easily achievable near the reference site [21]. A DGPS system will be utilized as the truth source for the characterization of the Parrot Bebop's GPS system.

2.6.3 Inertial Navigation System Description.

Inertial navigation tracks the pose of an object relative to a known starting point using built in accelerometers and gyroscopes. An INS is made up of at least one inertial measurement unit (IMU). An IMU usually contains three orthogonal accelerometers and three orthogonal rate-gyroscopes with no external references. These components measure angular velocity and linear acceleration respectively. An INS takes the incremental angle and velocity output from an IMU and estimates the vehicles position, orientation, and velocity as a function of time. These estimates

are given in a vehicle specific navigation frame after combining the IMU data with reference time source and a gravitational field model [24]. Micro-machined electromechanical systems (MEMS) technology has greatly reduced the cost and weight of IMUs and has made them easier to integrate into a lightweight quad-rotor [25].

There are multiple types of navigation reference frames. The two types used in this research effort are global frame and body frame. A global reference frame is viewing the IMU's rotation from an external point of view. A body reference frame uses the navigation system as its point of view. Two styles of IMUs exist, and each uses a different frame of reference. These styles are a stable platform configuration and a strap-down system [25].

In a stable platform system, depicted in Figure 7, the IMU is isolated from the rotational motion of the body; it is held in alignment with the global frame of reference. The measurement platform containing the gyroscopes and accelerometers is held by two gimbals, allowing it to rotate in all three dimensions. Accelerometers and gyroscopes mounted on the platform detect any body motions. Torque motors are controlled by feedback from these detections in order to cancel out the body rotation and stay in line with the global frame. The orientation of the body is calculated from the angles between adjacent gimbals, using the angle pick-offs depicted in Figure 7. The accelerometer data is doubly integrated, after subtracting for gravity, to calculate the position of the body [25].

A strap-down system has the inertial sensors mounted directly to the body. This mounting method causes the sensors outputs to be measured in the body frame. The gyroscope signals are integrated and the accelerometer signals are converted to global coordinates using the orientation provided by the integrated gyroscope signals. This global acceleration data is then integrated in the same manner as the

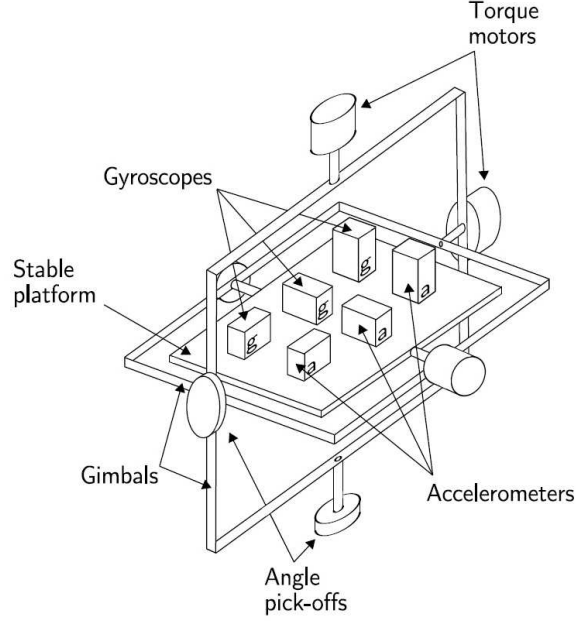


Figure 7. A stable platform IMU [25]

stable platform system. Due to this extra step of integration, strap-down systems require more computational ability in the IMU. Despite the extra computation, strap-down systems are much smaller than stable platforms due to their simplified mechanics [25]. For more information on GPS, INS, and their integration, see *Global Positioning Systems, Inertial Navigation, and Integration (Second Edition)* by Mohinder S. Grewal (ISBN: 978 – 0470041901).

The INS of the Parrot Bebop drone used for this research is comprised of two MEMS devices. The first device (Asahi Kasei AK8963) is a three axis magnetometer which acts as a compass. It is an integrated circuit, Hall-effect magnetic sensor [26]. The second device (InvenSense MPU-6050) is an integrated circuit, single chip, six axis device. It has a three axis gyroscope and a three axis accelerometer as well as a built in processor. It accepts the inputs from the three axis compass to provide a fused nine axis output. The gyroscope features an external sync signal, which can be provided by GPS. The MPU-6050's gyroscope is capable of measurement movements up to $2000^\circ/s$. Its accelerometer is capable of measuring and

withstanding up to 16 times the force of gravity [27]. These three chips, when integrated together, comprise the INS of the Bebop drone. They provide roll, pitch, and yaw angles as well as angular velocities to the drones navigation computer.

2.6.4 Integrated GPS/INS Systems.

Neither GPS or INS systems are flawless. GPS is not sensitive to small body changes in orientation. It is also susceptible to momentary signal dropout. INS is susceptible to drift and, without correction, will lead to large, unbounded errors in position and orientation. A small sensor bias at the beginning of a flight, left uncorrected, will become a large position error as the flight progresses. Inertial Navigation Systems are also susceptible to alignment errors. Starting position, orientation, and velocity inputs are needed for an IMU to perform accurately [24].

A technique for combating these issues is to blend GPS and INS into a combined system, utilizing the benefits of both systems while covering their flaws [28]. With the advancement of MEMS technology, low-cost, small sized, GPS integrated inertial sensors are decreasing in cost and increasing in availability [29]. While the cost and size of MEMS systems is lower than tactical grade systems, the intrinsic INS errors are greater and increase faster. A representative MEMS INS is only accurate enough for unassisted navigation for 10 – 20 seconds. Integrating GPS with the MEMS INS greatly increases the overall system capability and accuracy over either system alone [24].

There are three primary architectures for combining GPS with inertial systems: loose integration, tight integration, and ultra-tight integration. The level of integration depends on the desired accuracy and the level of computational power available to the navigation system. As the systems become more integrated, the accuracy and complexity both increase [30].

Loose integration is the most basic coupling scheme. It operates the GPS and IMU as independent subsystems, each estimating the position, orientation, and velocity of the system. An integration filter blends the independent outputs from each system to obtain a navigation solution. Figure 8 demonstrates loose integration. By blending the two solutions, the navigation solution has a higher bandwidth and lower noise than either system alone. The IMU biases are kept in check by a feedback loop from the navigation solution. A loose integration is sufficient if the GPS is stable and not susceptible to outages [7].

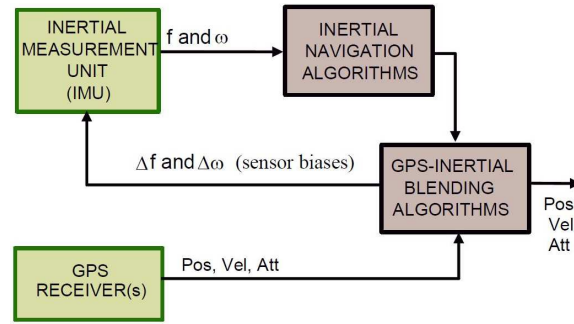


Figure 8. GPS/INS System with Loose Integration [7]

Tight integration has the same block diagram as the loose integration. Each system creates a separate navigation solution. In the tight integration scheme, the GPS calculates pseudo-ranges, Doppler, and carrier phase measurements. These are blended with the position, orientation, and velocity estimates of the IMU system. By blending dissimilar navigation solutions, a more accurate navigation solution may be found than with a loosely integrated system [7].

The most complex method of integrating GPS and INS solutions is the ultra tight scheme depicted in Figure 9 [7]. This scheme can improve GPS acquisition time, tracking performance, and Doppler and phase measurements. The motion dynamics, determined by the IMU, are injected into the GPS signal tracking loops, increasing the accuracy of the GPS system [7].

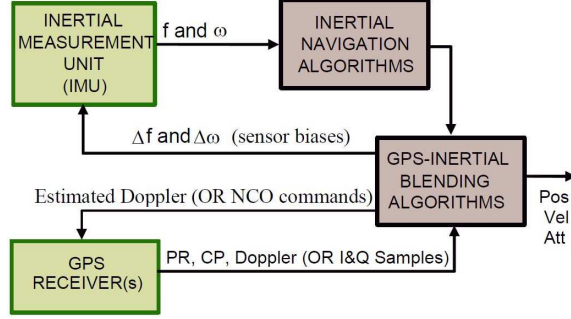


Figure 9. GPS/INS System with Ultra Tight Integration [7]

There is no literature on what coupling method the Parrot Bebop quad-rotor uses for its GPS/INS system. Given the design of the INS chip, it is more probable than not that a loose integration scheme is utilized. The actual scheme utilized is not as important to the research in this thesis as the resulting accuracy of the combined system.

2.7 Conclusion

Radar cross section measurements are increasingly important to modern aircraft designers. In order to achieve an accurate RCS measurement, it is necessary to know what EM field is incident on the measurement target. The radar wave that interacts with the target is not the same wave that was transmitted from the radar antenna. The wave is affected by imperfections in the radar equipment, atmospheric disturbances, and ground bounce among others sources.

A probe is used to determine what the incident field actually is. The current methods of probing introduce their own errors into the probe's measurement and are limited in their ability to scan the entire test volume. The proposed method of solving these issues is to encapsulate a quad-copter inside of a geodesic sphere. This geodesic sphere will act as a reverse Faraday cage, reflecting the incident radar signal back at the radar. Once the sphere's reflection phenomenon have been

characterized, it will be possible to determine the amplitude and phase of the incident wave based on the reflected wave received by the radar.

The expected reflections are highly dependent on the position in space and the orientation of the geodesic sphere. The uncertainty of the GPS and INS systems needs to be ascertained in order to determine the accuracy of the measured reflected wave. Due to the coupling of the navigation system (as described above), the GPS and INS system uncertainties will be isolated and then determined individually. The inner workings of each system are not as critical as their uncertainties.

This research touches a wide swath of technical disciplines. The basic concepts behind each discipline have been presented and the knowledge base developed. All of the subsequent research is not directly affected by the subtleties of each discipline but more by the resulting uncertainty of each discipline. For example, this research is not dependent on how GPS works, it is dependent on the accuracy of the reported GPS position. The following chapter develops the methodology that will determine the uncertainties of each of the systems involved in this research. Chapter IV will delve into the data analysis and create a model for relating all of the individual uncertainties into an overall probe measurement uncertainty.

III. Methodology

“Absolute certainty is a privilege of uneducated minds-and fanatics. It is, for scientific folk, an unattainable ideal.”
- Cassius Jackson Keyser [31]

3.1 Introduction

In order to accurately determine the amplitude and phase of the incident wave, an accurate understanding of the properties of the geodesic sphere is necessary. The effectiveness of the geodesic sphere relies on its ability to reflect the incident wave in a characterizable and repeatable manner and its ability to operate in a known and controlled position, at a designated orientation. The goal of this research was to determine the fidelity and repeatability of these characteristics.

RCS measurements as well as positional measurements are complicated and dynamic. As discussed in the previous chapter, many sources of uncertainty exist in both measurements. These uncertainties need to be characterized in order to understand their effect on the RCS of the geodesic sphere. This thesis is focused on understanding these issues. In order to characterize the necessary systems, data must be collected. These data must be applicable to the problem statement and must be capable of being analyzed.

Two separate types of data must be collected: the RCS of the geodesic sphere (amplitude and phase) and position and orientation (pose) accuracy data. The RCS measurements will provide the data needed to characterize the RCS of the sphere at various orientations. Once the RCS at different orientations is known and understood, the pose uncertainty must be determined.

Once the pose uncertainty has been determined, the data will be analyzed, resulting in a range of possible RCS values for the reported pose. This range will

form error bounds and will come from the deviations in the pose uncertainty. For example, if, during a flight test, the drone reports a pitch of 1° but the pitch uncertainty is 2° , the resulting RCS value will range based on the range of possible actual pitch angles. The resulting RCS range represents the accuracy of the measurement for that given pitch angle. This accuracy is the fidelity of the overall measurement. Similar measurements will be taken along the specified flight path and the resulting data will be smoothed together over various window sizes to decrease the standard deviation of the measurement. By smoothing the data, it reduces the effect of the scintillating nature of the geodesic sphere on the field measurement. Theoretically, the incident field is much smoother than the RCS of the geodesic sphere. Further information on the analysis, and the resulting data, are presented in Chapter IV.

In order to collect and analyze the necessary data, methodologies needed to be determined. The various methodologies for collecting the different data types will be discussed and the methods for analysis will be explained in the remainder of this chapter.

3.2 Geodesic Sphere Creation

The geodesic sphere utilized for this research was built by Dr. Peter Collins, AFIT Professor, specifically for this research effort. It was custom built to fit and attach to the Bebop quad-copter and act as a standard two frequency geodesic sphere. The sphere was comprised of lengths of aluminum tubing, both 100 and 112mm long (depending on which leg of the triangle), connected by 3D printed plastic hubs at 18° angles. The tubing was epoxied into each hub to create the structure. The sphere was comprised of two halves, top and bottom, with an equatorial line around the top half. The drone was connected to the top half of the

sphere via plastic arms stemming from the equator of the sphere. The two halves were joined together at each of the equatorial hubs by plastic clips.

One of the purposes of placing the quad-copter inside a geodesic sphere was to hide the quad-copter from the radar. Given the triangular design of the sphere's surface, no analytical solution exists for the cutoff frequency of the sphere. The cutoff frequency of a waveguide is the frequency at which the EM wave propagates through unattenuated [13]. After the first round of RCS measurements of the sphere (not specifically for this research effort), it was determined that the cutoff frequency of the sphere was around $3GHz$. In order to be able to take more data below the cutoff frequency (the radar used operates from $2 - 18GHz$), the triangle holes needed to be made smaller.

The first step to accomplish this was to purchase 24 gauge twisted aluminum wire and separate the individual smaller gauge wires. Next, the wires were twisted around and glued to the midpoint of one leg of each triangle and stretched to the midpoint of another leg. This was done to every triangle, effectively creating 4 triangles inside of each original aluminum tubing triangle. By closing off the large triangles, the theoretical cutoff frequency was increased to $\approx 4.5GHz$. This increase allowed for an increase in the measurement frequencies at which the geodesic sphere hid the quad-copter inside. All of the subsequent discussion concerns the wired geodesic sphere. Figure 10 is a picture of the top half of the geodesic sphere. The plastic hubs, aluminum tubing, and wrapped wires are clearly seen. This particular image was taken after the sphere had been significantly damaged during flight testing.

In order to achieve accurate measurements, it was necessary to know the orientation of the sphere during the RCS measurements. This was accomplished by placing 5 reflective ball markers at non symmetric points on the inside of the

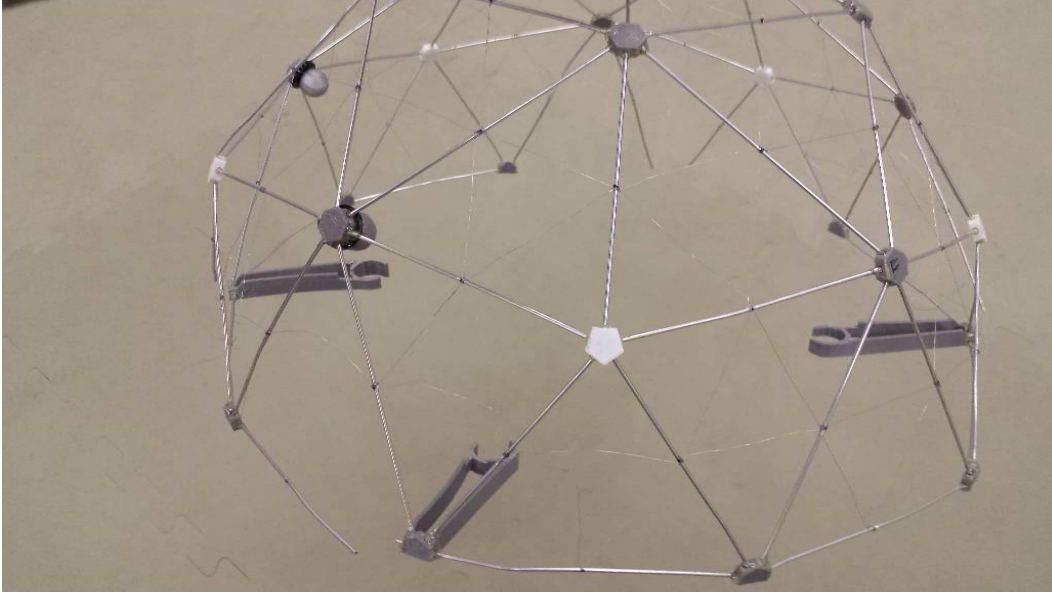


Figure 10. Close up view of the top half of the geodesic sphere

geodesic sphere. The markers were placed on the inside of the sphere in order to decrease their effect on the RCS of the sphere. These reflective balls were then selected in the ViconTM software and a model was created. The ViconTM motion tracking system is similar to what is used in movie motion capture systems. This system tracked reflective markers strategically placed on the sphere and reported the spheres current roll, pitch, and yaw. The markers are seen on the inside of the top half of the geodesic sphere in Figure 10.

3.3 Geodesic Sphere Characterization

The RCS of a geodesic sphere is highly dependent on the frequency and polarization of the radar wave and the orientation of the sphere. Frequency dependence is based on the size of the triangles, as discussed previously. Depending on the pose of the sphere, the radar will see reflecting surfaces at different angles. Because of these fluctuations, the sphere needed to be characterized so the radar reflections were known at each position and orientation.

The geodesic sphere was characterized through a series of RCS measurements. These measurements were performed at AFIT's indoor compact range. AFIT's RCS range is located inside an anechoic chamber with a low RCS pedestal, housing a rotation plate in the center of the room, to which objects under measurement are mounted. The radar system is a LINTEK 4000 radar implementing a square parabolic reflector feeding data to LabVIEW software. The system measured RCS data for $2 - 18\text{ GHz}$ in the vertical and horizontal polarizations.

The reflector columnizes the radar wave, effectively increased the distance between the radar antenna and target to allow for plane wave development, meeting the far field requirement [3]. It also provided a modest quiet zone of $3 \times 3\text{ ft}$ in which targets were placed. These targets could be measured at single angles or rotating angles (around the targets' waterline), and at one frequency or all available frequencies.

After the geodesic sphere was characterized, it was flown inside of the same indoor RCS chamber. Capt Lett [32] flew the probe back and forth across the expected quiet zone in a raster scan pattern while the radar was recording data. The purpose of this flight test was to record the reflected radar wave at different points in the quiet zone. These reflections will then be compared to the static measurement data and a picture of the actual incident radar wave will be created. The following sections detail the process by which data was collected in order to create the static measurement data, a calibrated look up table, for flight data comparison.

3.3.1 Radar Calibration.

The different methods for measuring RCS, were described in Chapter II. The method chosen for this thesis was the most straight forward, background subtraction. Prior to accomplishing any measurements, the radar must be setup

properly. The setup was accomplished in a LabVIEW interface on a desktop computer. The radar was setup for measurements from $2 - 18GHz$ in $0.05GHz$ increments. The necessary delay and gate timings were left as their default values.

The first step in any RCS data collection effort is to determine the background of the target area. Following the procedure discussed in Section 2.5.1, the foam calibration cylinder mount was set on the pedestal and a fixed angle frequency sweep measurement (all foam mounts and cylinders were assumed to be symmetric) was performed. Then the geodesic sphere foam mount was set on the pedestal and the measurement was recorded again.

Following both background collections, the 750 and 900 calibration cylinders were centered and leveled on the calibration mount, one at a time, and the same sweep was recorded. Centering was accomplished using a tape measure (all measurements $\pm \frac{1}{4}in$) and leveling was achieved using a Samsung Galaxy S5 with a level application (reported uncertainty of $\pm 1^\circ$). This technique represented the best available method and was applied to every cylinder. By measuring only the mount (background) and the cylinders (one at a time) on the mount, the background is able to be subtracted from the cylinder measurement leaving only the RCS of the cylinder in the measured data (see Equation 3).

After measuring the RCS of the background, the calibration background, and both calibration cylinders, the RCS of each cylinder was found using Equation 3. The resulting RCS of each cylinder was compared to its theoretical solution and the measurement uncertainty was determined. This uncertainty was also taken to be the uncertainty in the RCS measurements of the geodesic sphere.

3.4 Wired Geodesic Sphere RCS Measurements, Full Sphere

Following the calibration measurements, the geodesic sphere was measured. The sphere measurement process was very similar to the calibration process. By recording two separate measurements, it was possible to subtract the background from the sphere, providing a clean measurement of the sphere. All measurements consisted of a radar sweep from $2 : 18GHz$ in $0.05GHz$ increments. By sweeping the radar over a large range of frequencies, it was possible to determine the range of frequencies at which the geodesic sphere shielded the quad-copter from the radar's view.

The method used for measuring the geodesic sphere was mounting the sphere on top of a foam column mounted on top of the metal pylon. There were two different sphere foam mounts, a bar mount and a six point mount. These mounts were both measured and the appropriate mount was used depending on what geometry of the sphere needed to point toward the ground. The sphere was secured to the mounts with non conductive tape to ensure its stability during rotation. Figure 11 shows the geodesic sphere under test mounted on a foam column for RCS measurements. The sphere was rotated on the pylon until ViconTM reported a yaw of as close to 0° as possible. This yaw position was set as the zero rotation angle for the measurement. A rotation of the sphere was performed from $-10^\circ : 370^\circ$ in 1.0° increments creating a picture of the RCS for that orientation.

Next, the sphere was either pitched or rolled to change the slice of the sphere that was illuminated and the rotating measurement was repeated. Pitch and roll were determined via the ViconTM motion tracking system. The sphere was rotated to zero yaw and then pitched or rolled until ViconTM reported the desired angles for each measurement. The measurement process was repeated for all measurements listed in Table 1. These two dimensional measurement cuts, called great circle cuts,

were combined to create a three dimensional RCS data set over the measured region. These measurements provided the basis for the RCS model developed in Chapter IV. Figure 12 depicts notional great circle cuts of a spherical target. As the sphere's pitch is changed, the measurement plane changes accordingly. Each bisecting disk represents the measurement plane of the radar.

3.5 Wired Geodesic Sphere RCS Measurements, Bottomless Sphere

Capt Lett [32] determined a portion of the bottom of the sphere needed to be removed in order to improve the flight handling characteristics. Also, over his multiple flight tests, the sphere was badly damaged. Due to these changes to the sphere, it had to be remeasured prior to data collection during a measurement flight test.

Given the previously discovered frequency characteristics of the sphere and the nature of Capt Lett's flight plan for the probing measurements, it was determined that the new sphere measurements needed only to be from $2 : 6GHz$, from $-2^\circ : 20^\circ$ in azimuth, and $-5^\circ : 5^\circ$ in pitch. The measurements that were taken, and then treated as truth data for later analysis, are displayed in Table 2.

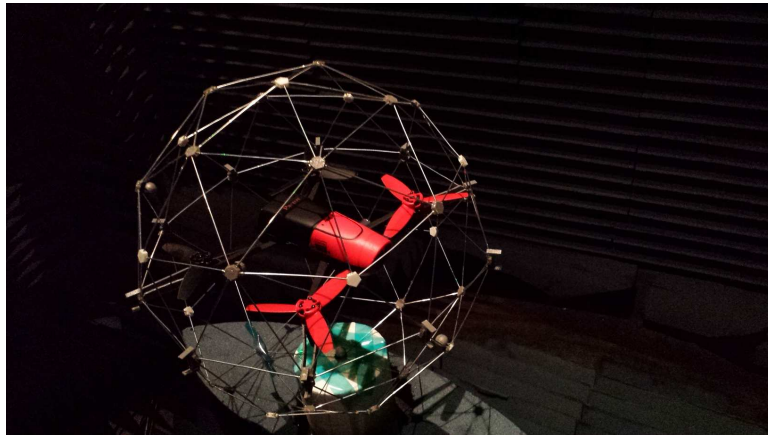


Figure 11. Geodesic sphere mounted on foam column for RCS measurements

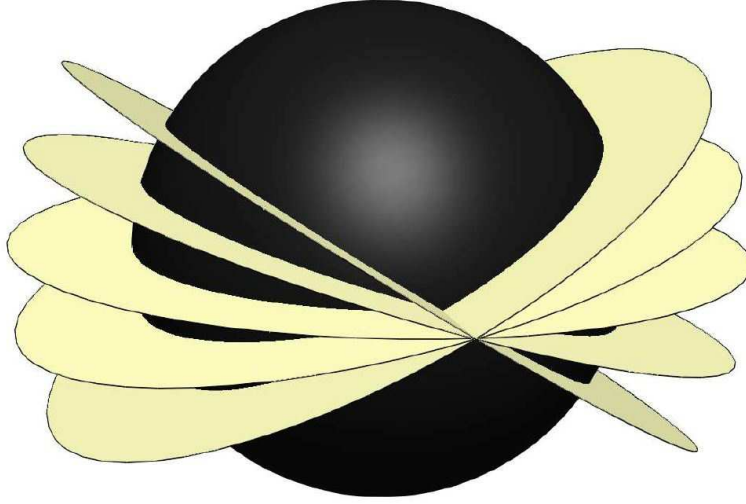


Figure 12. Notional great circle cuts, depicted as changes in pitch

The measurement process was nearly identical to the process found in Sections 3.3.1 and 3.4. The only differences were that, a large foam column was used instead of the metal pylon and since the geodesic sphere was flat on the bottom, a flat foam cylinder was used as the target mount for all geodesic sphere RCS measurements. The pitch was changed by placing a small foam wedge under either the front or rear of the sphere (positive or negative pitch respectively).

3.6 Bottomless Geodesic Sphere Flight Test

Following the calibration of the bottomless geodesic sphere, it was used for an actual radar field probe measurement. The indoor RCS chamber at AFIT was calibrated in the same manner as previously discussed. Using the installed ViconTM motion capture system as replacements for the Bebop's navigation system, the bottomless geodesic sphere was flown in a raster scan pattern through a slice of the purported quiet zone of the indoor chamber. Further details on the flight plan, its development, and implementation can be found in Capt Lett's thesis [32].

Table 1. RCS Measurements Collected

Measurement	Target	Pol	Freq(GHz)	Azimuth(deg)
–	750 Calibration Cylinder	HH/VV	2:0.05:18	0
–	900 Calibration Cylinder	HH/VV	2:0.05:18	0
–	Calibration mount	HH/VV	2:0.05:18	0
–	Bar Target mount	HH/VV	2:0.05:18	0
–	6pt Target mount	HH/VV	2:0.05:18	0
GeoSph1	Empty, 0°Roll, 0°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph2	Full, 0°Roll, 0°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph3	Full, -33°Roll, 0°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph4	Full, -18°Roll, 0°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph5	Full, -10°Roll, 0°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph6	Full, 9°Roll, 0°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph7	Full, 18°Roll, 0°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph8	Full, 30°Roll, 0°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph9	Full, 60°Roll, 0°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph10	Full, 86°Roll, 0°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph11	Full, 0°Roll, -31°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph12	Full, 0°Roll, -17°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph13	Full, 0°Roll, -7°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph14	Full, 0°Roll, 8°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph15	Full, 0°Roll, 16°Pitch	HH/VV	2:0.05:18	-10:1.0:370
GeoSph16	Full, 0°Roll, 27°Pitch	HH/VV	2:0.05:18	-10:1.0:370

The methods, flight path decisions, and requirements were not important for this research effort. What was important was the recorded pose of the sphere during the measurement and the associated radar data. Both data sets were time stamped to allow for merging during data processing. The time stamp was recorded at the beginning of every radar frequency sweep. This means that when the sphere moved between each radar pulse in a specific frequency sweep, the original position was still recorded. This resulted in a blurring of the recorded measurement. For this reason, the drone moved in a slow and smooth manner.

This research looks at two flight tests. The first flight was a raster scan in x and z only. The second flight was a similar raster scan that included movement in y as well. Both flights are described and analyzed later in the Data Analysis.

Table 2. RCS Measurements Collected, Bottomless Sphere

Measurement	Target	Pol	Freq(GHz)	Azimuth(deg)
–	750 Calibration Cylinder	HH/VV	2:0.05:18	0
–	900 Calibration Cylinder	HH/VV	2:0.05:18	0
–	Calibration mount	HH/VV	2:0.05:18	0
–	Target Mount	HH/VV	2:0.05:18	0
SphereRCS, P-5	Full, -5°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20
SphereRCS, P-4	Full, -4°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20
SphereRCS, P-3	Full, -3°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20
SphereRCS, P-2	Full, -2°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20
SphereRCS, P-1	Full, -1°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20
SphereRCS, P0	Full, 0°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20
SphereRCS, P1	Full, 1°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20
SphereRCS, P2	Full, 2°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20
SphereRCS, P3	Full, 3°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20
SphereRCS, P4	Full, 4°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20
SphereRCS, P5	Full, 5°Pitch	HH/VV	2:0.05:6.0	-20:0.5:20

3.7 Bebop Positioning System Characterization

Intrinsic to the accuracy of the two-way probe concept is the accuracy of the positioning system. If the geodesic sphere’s position is not precisely known, the reflected wave will not be representative of where the reflection is thought to have come from. If the sphere is closer to or farther from the radar, the reflected wave will have a lower or higher phase respectively than the actual phase at the perceived measurement position. If the sphere is displaced left, right, up, or down, the amplitude of the reflected wave will be displaced due to the inherent spherical nature of the wave (Section 2.2.3). These displacements create uncertainty in the resulting field probe measurement and add error bounds to it. If the incident wave was perfectly planar, as was assumed in the Data Analysis portion of this research, the wave would be uniform in phase and amplitude in the cross sectional planes.

In order to understand these uncertainties, the position and orientation systems of the Bebop quad-copter needed to be analyzed. The positioning system used for

this thesis was the built in GPS/INS of a Parrot Bebop quad-copter. A major effort of this work was to characterize the quad-copter’s positioning system and determine its uncertainties. These uncertainties may be caused by INS drift, lack of a precise GPS receiver, and imprecise MEMS accelerometers and gyroscopes. While each of these errors did not need to be individually quantified, the overall system accuracy needed to be determined. An accurate truth source was necessary in order to determine the errors of a dynamic, unknown positioning system.

The truth source for the INS portion of the characterization and for the indoor test flights was the ViconTM system installed in the AFIT RCS chamber. In order to treat the ViconTM system as a truth source, its applicable uncertainties need to be determined. The truth source for the GPS portion of the characterization was a surveyed DGPS system with a standard deviation of $0.02m$. The DGPS system was comprised of a large, surveyed, three frequency DGPS antenna mounted on the roof of the Autonomous Navigation Technology (ANT) center and a smaller GPS antenna and DGPS reference system in the back of the ANT center’s golf cart. The system in the back of the golf cart (Figure 13) consisted of a Novatel GPS-702L antenna, a Novatel DL-V3 Triple Frequency receiver, a DGPS reference antenna, and a Ethernet bridge that relays the DGPS reference signal to the DL-V3 receiver. The DL-V3 receiver records the GPS signal from the GPS-702L antenna and applies the corrections received from the DGPS reference antenna to improve the accuracy of the final solution. This solution was recorded on the Getac laptop connected to the DL-V3 receiver.

3.7.1 Bebop GPS Position Accuracy.

Testing of the Bebop’s GPS began with static measurements. Using a previously tested method [33], a second pole in the back of the golf cart allowed for mounting

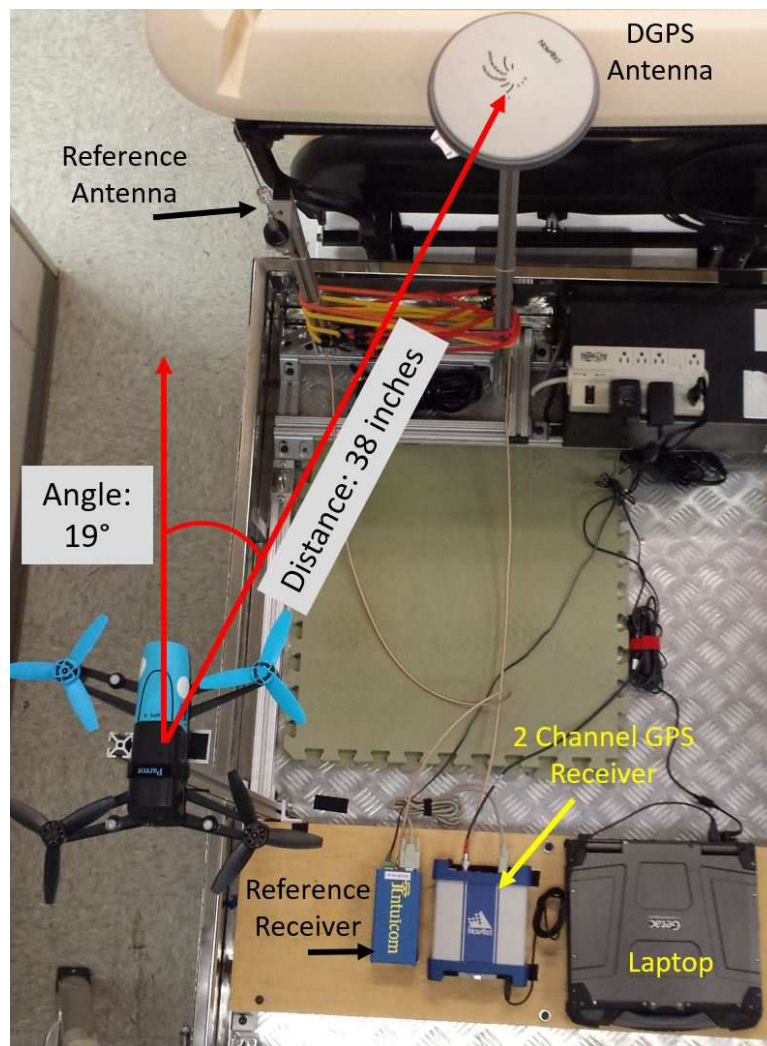


Figure 13. DGPS setup in the bed of the ANT center golf cart

of the Bebop at the same height, and a known distance away (38in) from the DGPS antenna. By recording the time stamped GPS data from each device it was possible to determine the accuracy of the secondary GPS device, in this case the Bebop's integrated GPS system. The two data sets will be time aligned during data analysis.

The Bebop quad-copter was mounted on the second pole. It was attached with blue painters tape and aligned by eyesight toward the front of the golf cart. Figure 14 depicts the mounting and orientation of the system (the image is looking toward the West). The orientation of the golf cart resulted in a heading of 93° from the Bebop to the golf cart DGPS. This heading was recorded using the compass on a Samsung Galaxy S5 cell phone.



Figure 14. Bebop Quad-rotor Mounted on Golf Cart for GPS Characterization

In order to characterize the Bebop GPS system, a method of recording both system's GPS data was needed. The DGPS system came with data recording capabilities but the Bebop did not. A third party software program, Paparazzi Control Software, was found as free-ware on-line (<https://gitter.im/orgs/paparazzi>). It allowed for the autonomous control of various unmanned ariel vehicle (UAV) systems, one of which was the Bebop. Every packet of data, including GPS and INS data, received from the drone by Paparazzi is recorded in a log. The main screen of Paparazzi is shown in Figure 15. It is a very simple interface. All that is required of

the user is to choose the correct aircraft, upload the settings to the drone, and execute the correct session. For the research in this thesis, all of the settings were left as their defaults.

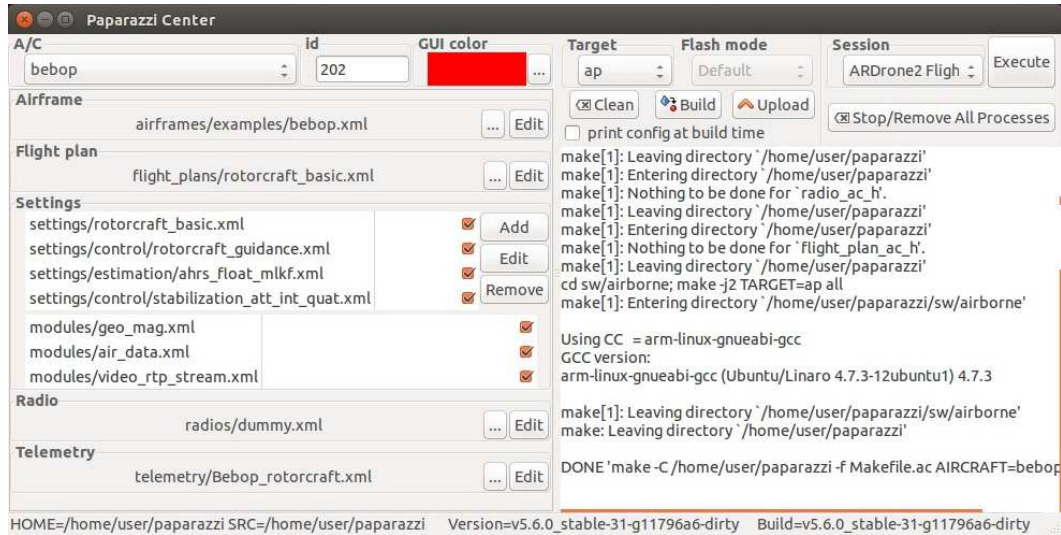


Figure 15. Paparazzi main build screen

Paparazzi was installed in Ubuntu on a Dell Latitude D630 laptop that had wireless Internet capabilities. The Paparazzi data recording process was the same for every navigation system effort (static GPS, dynamic GPS, and INS measurements). To begin, the Bebop was turned on, the laptop was connected to the drone's wireless Internet signal, and Paparazzi was launched. Next, the programs default quad-copter file was uploaded to Bebop and the Paparazzi Ground Control Software was opened. Figure 16 is a screen shot of the Ground Control Software after being connected to the drone. The upper portion of the display is a way-point and current position map of the drone (not used for this research effort). The lower portion of the display contained timing, link, position, altitude, battery, and primary flight display (roll, pitch, yaw) data. After the program was launched, it logged all of the desired data packets from the drone at the requested rate (up to the maximum data rate of each system).

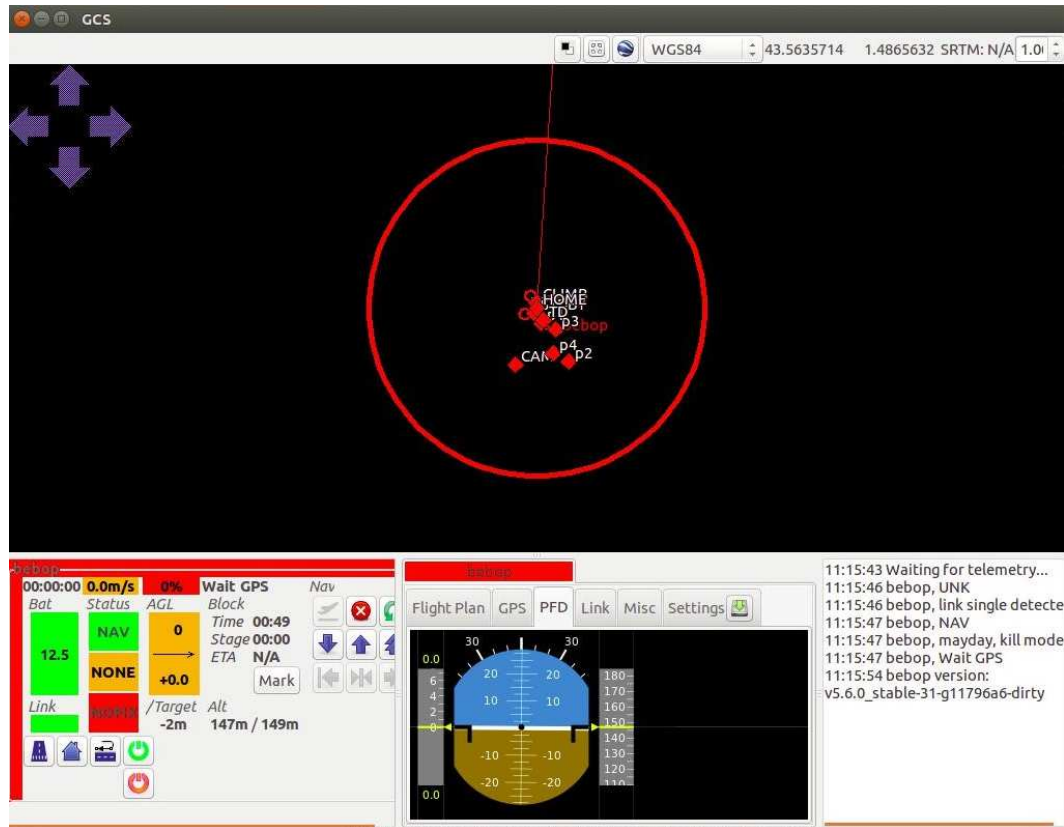


Figure 16. Paparazzi Ground Control Station display

For the static GPS measurements, the drone was setup on the stationary golf cart as previously discussed and left running for 30 minutes while the data was being recorded on both the laptop with Paparazzi and the laptop with the DGPS software. At the end of 30 minutes the drone was turned off and Paparazzi was closed. The result was a DGPS position data file to be used as a truth source and a Paparazzi log file that could be converted into usable data from the drone. The analysis of this data is presented in Chapter IV.

Dynamic measurements used the same methodology as the static measurements with the addition of golf cart motion. After mounting the drone on the golf cart and the data recording began, the golf cart was driven around the running track to the west of AFIT for 15 minutes. After an initial look at the data it was quickly determined that it was unusable. The cause for the invalid data was the unevenness

of the running track. Every pothole and speed bump along the way caused the pole mounted drone to sway back and forth, making it impossible to correct for the distance between the drone and the DGPS antenna in analysis.

A second attempt of the dynamic GPS test was accomplished in AFIT's western parking lot. This surface was smooth and free of large bumps. The golf cart, with the drone attached in the same way as before, was driven around the parking lot for 15 minutes, twice. Figure 17 shows the path driven for each of the runs (created at <http://www.gpsvisualizer.com>). Both paths were driven at approximately 5mph as displayed on the golf cart speedometer. Time stamped data along those paths was recorded at 10Hz for both GPS systems. The time stamp was critical for the upcoming data analysis as it allowed for the corresponding measurements to be aligned and compared.



Figure 17. Golf cart driving paths overlaid on AFIT's western parking lot

3.7.2 Bebop INS Pose Accuracy.

The RCS of the geodesic sphere varied with its roll, pitch, and yaw relative to the incident wave. In order to accurately determine the actual incident wave at the sphere's position, the sphere's orientation must be precisely known.

Characterization of the Bebop's INS system began with static measurements. By starting with static measurements, yaw was removed from the equation and only

roll and pitch were tested, each one independently. Three different methods were attempted, only one was successful.

For all three methods, the drone was connected to the laptop running Paparazzi as it was during the GPS tests. The drone always started at zero roll and pitch and then was tilted to a given angle. The drone was left at that angle for at least one minute. Then it was lowered back to zero roll and pitch for at least 30 seconds. It was once again raised to a different angle and the process was repeated. The first method created a hinged platform so the angle of the drone could be changed in a repeatable fashion. The ViconTM motion capture system in the ANT lab was utilized as the truth source for the drone's orientation. All of the positive pitch angles were recorded, the drone was spun 180° and the same angles (now negative pitch) were recorded. Next, the drone was rotated 90° clockwise and the same angles (now negative roll) were recorded. This was followed by another 180° spin to record the positive roll angles. Upon data analysis, this method was found to be flawed. It was determined that the roll, pitch, and yaw angles are coupled and by spinning the drone around, the data could not be separated into the desired measurements.

This issue was addressed and a new process developed. Instead of using the tilt table, leaving it in one orientation, and changing the drones orientation, the drone needed to be kept at zero yaw. The solution was to set the drone on the floor at zero yaw and place drink coasters under the necessary feet to get the desired angle for recording. For example, 10 coasters placed under both front feet of the drone resulted in a pitch of +6°. If the coasters were moved to the two feet on the left side of the drone, a roll of +6° was achieved. This process was repeated in 10 coaster increments up to 40 coasters (approximately a 22° angle). As with the first method, the ViconTM system recorded the truth angle data for comparison. Upon data

analysis it was determined that the Vicon™ angle data was extremely jumpy and resulted in an imprecise truth source.

The final process was the most basic: tape the drone to a piece of metal, remove the propellers for easier access, attach a digital level cube, and increase the pitch/roll angle by stacking Lego® Duplos® under the piece of metal. The setup is shown in Figure 18. An iGaging AngleCube (accuracy of $\pm 0.2^\circ$, resolution of 0.05°) was utilized as the truth source. The orientation indicated in Figure 18 is positive pitch. In order to test negative pitch, the Duplos® were placed under the front of the drone. To test positive roll the Duplos® were placed under the left side of the drone and they were placed under the right side for negative roll testing. This test followed the same procedure of one minute at angle and 30 seconds at zero angle between each angle test. The goal angles were $0^\circ - 25^\circ$ in 5° increments for positive pitch, negative pitch, positive roll, and negative roll. Actual and measured angles are listed in Table 1 in Chapter IV.

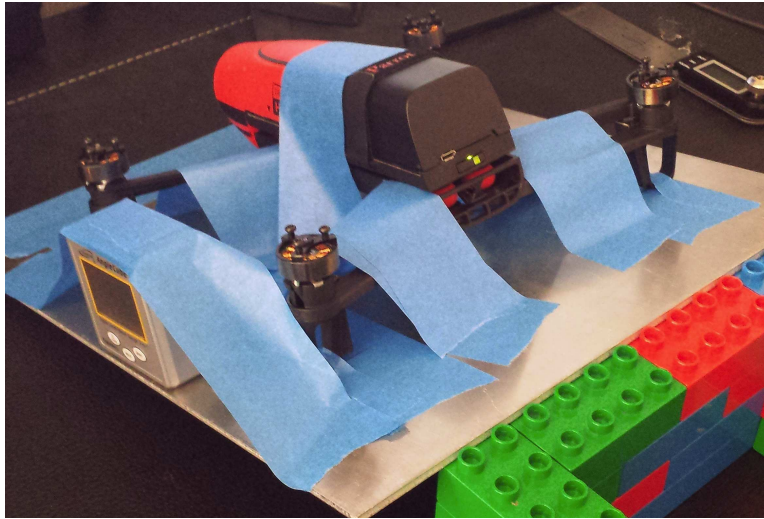


Figure 18. Bebop undergoing static INS testing

Determining the accuracy of the yaw portion of the INS proved to be much easier. The drone was attached to the metal plate and placed on top of a foam column on the target rotator in AFIT's RCS range. The rotator was controlled

through a LabView computer interface. The interface worked by entering a desired position and clicking move. The column would rotate the shortest direction to the desired position from the current position. The theory behind the test was that the accuracy of the INS lies in its ability to determine how far it rotated during each motion.

Therefore, the test consisted of rotating the turn table (with the drone on it) various angular distances and recording the INS data off of the drone, in the same manner as previously, in order to allow for a comparison of the two rotation values (rotator truth and INS reported rotations) during data analysis. Multiple rotations of 5° , 15° , 20° , 90° , 270° , and 360° were performed. The actual and measured rotation distances are recorded in Table 1 in Chapter IV.

3.8 Conclusion

The accuracy of the proposition put forth in this thesis of using a quad-copter inside of a geodesic sphere to act as a two-way probe for radar calibration is greatly dependent on the accuracy of the pose of the geodesic sphere, as well as the geodesic sphere's RCS. These dependencies drove the methodology for this research. The first objective was to determine the RCS of the geodesic sphere, with the quad-copter inside, from multiple elevation angles. Next, the accuracy of the pose systems needed to be determined. By testing the GPS and INS systems independently, it was possible to isolate their uncertainties in order to determine the ultimate uncertainty of the probe measurement. The analysis bridging from measurement to uncertainty is contained in the following chapter.

IV. Data Analysis

“If we have data, lets look at data.
If all we have are opinions, lets go with mine.”
- Jim Barksdale, CEO of Netscape Communications [34]

4.1 Introduction

This chapter is the culmination of the thesis effort. All of the research, methodology, planning, and data collection lead to the need for data analysis. In this chapter, the concepts, processes, and results of the analysis will be presented. This research effort encompassed multiple systems and components; each needing its own data analysis process. All of the data included herein was collected, processed, and analyzed by the writer of this thesis. The results of this research effort will form a baseline for the next researcher to develop the final quad-copter and geodesic sphere prototype. Due to the evolutionary nature of research, many tests (such as the geodesic sphere’s RCS) were performed multiple times. Each of these tests will be reported independently.

4.2 Main Tools Used

The main tool used for the data analysis portion of this research was MathWork’s® MATLAB® programming software. This software is ubiquitous in the engineering and academic circles and was provided for use by AFIT. Dr. Peter Collins created a RCS toolkit in MATLAB® called ALPINE®. The ALPINE® software provides a way to read the ACER’s radar data format, as well as calibrate, manipulate, process, and plot the data [35]. Various functionalities of both MATLAB® and ALPINE® were used and are discussed in the context of this

chapter. Specific details on the inner workings of the ALPINE[®] software are found in its help documentation as well as in [35]. The other major tool used was Microsoft's[®] Excel[®] software. This software is tailored to creating, editing, and digesting large amounts of row and column data. No special Excel[®] tools were used, only the basic common functionality.

4.3 Overall Radar Calibration

Given the scope of this thesis, the uncertainty of the RCS data taken in AFIT's indoor RCS chamber was not determined. The assumption was made that the standard deviation of the two cylinder calibration measurement would represent the uncertainty of the radar system. Since there were two aspects of the RCS measurement data being explored by this research, magnitude and phase, both types of uncertainty needed to be quantified. The quantification of the phase portion of the RCS was only accomplished for the Bottomless Geodesic Sphere as it was the only RCS measurement that was actually used for further data collection.

Following the methodology presented in Section 3.3.1, the radar was calibrated using the two calibration cylinders. A calibration script was written to read in the measured cylinder data using ALPINE[®]'s readLintek.m file and loaded the theoretical data for the two cylinders (provided by Dr. Collins). Then, ALPINE[®]'s calibrateRCS.m was used to perform the background subtraction calibration as described in Chapter II. The output of the calibrateRCS function was the calibration of the 900 cylinder. The standard deviation values provided by the calVerify.m ALPINE[®] module represent the error bounds in all subsequent RCS related analysis using this calibration measurement.

Next, the file converted the measured and theoretical data from normal RCS data to phase data by taking the angle of each measurement data point's I and Q

data and then converting to degrees. The converted I and Q data matrix was then passed into ALPINE[®]'s calibrateRCS.m as above. The standard deviation values represent the error bounds in all subsequent phase measurements or analysis using this calibration measurement. Every data collection effort, whether RCS characterization of the geodesic sphere or flight test data of the indoor RCS field, had its own radar calibration performed prior to the data collection event.

4.4 Original Geodesic Sphere Characterization

This characterization was of the original, non wire twisted, geodesic sphere. Due to the frequency and angle dependence of the sphere's RCS, it was necessary to characterize it's RCS as much as possible. The first step of any RCS measurement is radar calibration and the determination of the uncertainty in the RCS measurement.

4.4.1 Radar Calibration Verification.

Following the methodology presented in Section 3.3.1, the radar was once again calibrated using the two calibration cylinders. The calibration verification of the 900 cylinder, from $2 - 6GHz$, resulted in a $\mu = 0.02243dB$ and $\sigma = 0.3802dB$ for the tt polarization and $\mu = -0.4135dB$ and $\sigma = 0.4196dB$ for the pp polarization. These values were reported by the ALPINE[®] tool in the calibration verification plots. Figure 19 is an example of one of the calibration verification plots. Each stem bar represents the difference between the calibration measurement and the exact solution at that frequency. The standard deviation values represent the error bounds in all subsequent measurements using this calibration measurement. These error bounds were not shown in this research effort as these errors were not specific to the geodesic sphere and it's analysis.

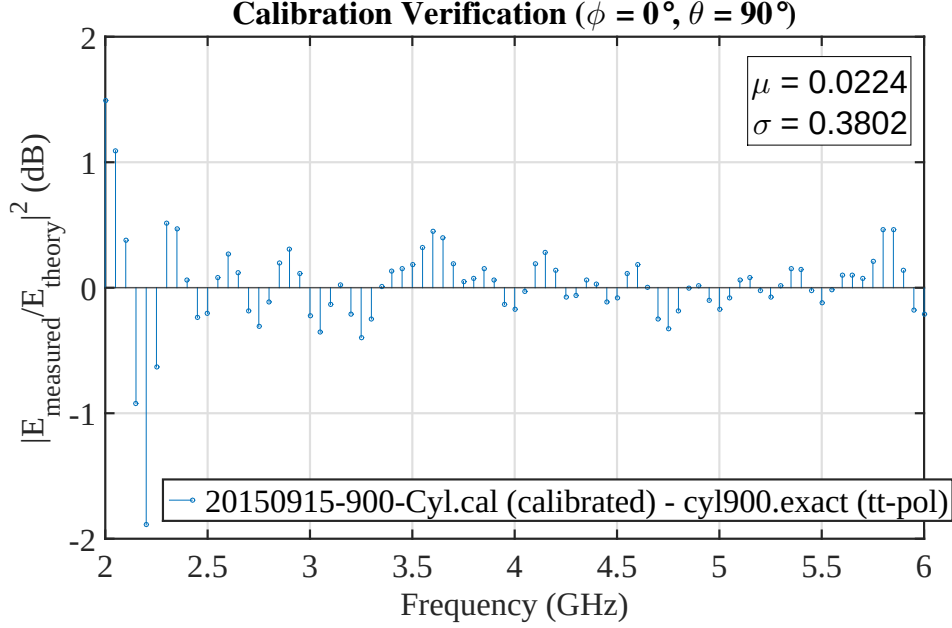


Figure 19. Calibration verification of Original Geodesic Sphere (tt)

4.4.2 Original Geodesic Sphere RCS.

After determining the calibration verification of the range, the original geodesic sphere was measured as previously discussed in Chapter III. Figure 11 depicted the geodesic sphere and quad-copter undergoing this RCS testing. Figures ?? and ?? are plots of the RCS of the original geodesic sphere as a function of frequency and yaw angle (ϕ). All global RCS plots are in dB . These figures are displayed in Section 4.5 to allow for a direct comparison that will be described in Section 4.5.

Some interesting phenomenon are clearly seen in both figures. The large red vertical lines near 90° and 270° from $14 - 18GHz$ look similar to the RCS pattern of a broadside flash of a flat plate or cylinder. Those angles correspond to when the quad-copter was broadside to the radar. The basis of the Bebop is a magnesium plate that runs lengthwise from front to back of the drone. The clear visibility of the broadside flash means the radar is not blocked at all by the geodesic sphere from $14 - 18GHz$.

As the frequency decreases, the RCS becomes more random. This seemingly random return is indicative of multi-path returns from inside the sphere. As the radar waves get longer, more and more of the wave is reflected, but some still gets through. These residual waves bounce around inside the geodesic sphere and finally bounce out and back at the radar. These random bounces are what produces the scintillating effect seen in the RCS from $8 - 14GHz$, evidence that the sphere is still not acting as a reflector.

From $4 - 8GHz$ the pattern changes again. Distinct lobes begin to appear and repeat as the geodesic sphere rotates in yaw. One clear example of this is seen at $4.75GHz$. Here, approximately every 30° , a bright spot is seen in the RCS. These 11 spots correspond to the 11 tubes that form the waterline of the original geodesic sphere. As these tubes present their broadside to the direction of the radar's propagation, their return became the strongest. These returns were direct evidence that the geodesic sphere is effecting the reflection of the radar waves in a definite way, it is no longer random.

Down in the $2 - 4GHz$ range, the RCS begins to blur, it becomes more constant. This is indicative of a perfect sphere. A perfect sphere has a RCS that is constant across all yaw angles. Using these patterns, it is estimated that the cutoff frequency for the original geodesic sphere is around $3GHz$ (where the smoothing of the RCS ends). As mentioned in the Methodology, a higher cutoff frequency was desired in order to increase the measurement range for the geodesic sphere.

4.5 Wired Geodesic Sphere Characterization, Full Sphere

After the wires had been applied to the geodesic sphere, creating more and smaller triangular faces, the measurements and analysis of the sphere's RCS was repeated.

4.5.1 Radar Calibration Verification.

Following the methodology presented in Section 3.3.1, the radar was once again calibrated using the two calibration cylinders. The calibration verification of the 900 cylinder, from $2 - 6GHz$, resulted in a $\mu = -0.022dB$ and $\sigma = 0.381dB$ for the tt polarization and $\mu = 0.413dB$ and $\sigma = 0.420dB$ for the pp polarization.

4.5.2 Wired Geodesic Sphere RCS, Full Sphere.

After determining the calibration verification of the range, the wired geodesic sphere was measured as previously discussed in Chapter III. The Bebop quad-copter was mounted inside the wired geodesic sphere, the sphere was positioned at waterline, with 0° corresponding to the drone facing the back wall of the chamber. Figures 20 and 21 are plots of the RCS of the original versus wired geodesic sphere as a function of frequency and yaw angle.

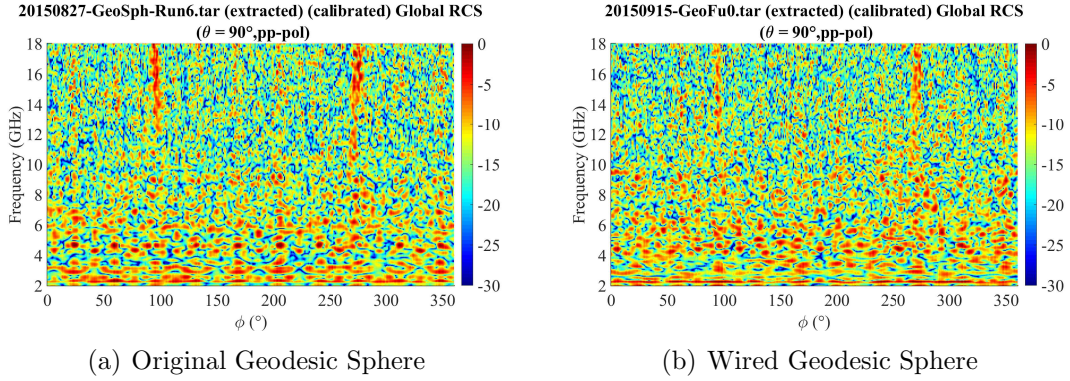


Figure 20. A comparison of the Original and Wired Geodesic Sphere's Global RCS at 0° of pitch (pp)

The RCS of the wired sphere looks very similar to the original sphere from $14 - 18GHz$. The broadside flashes are still clearly visible and the rest of the angles are random in nature. As the frequency decreases, the same phenomenon of lobing and then farther down of blurring once again occur.

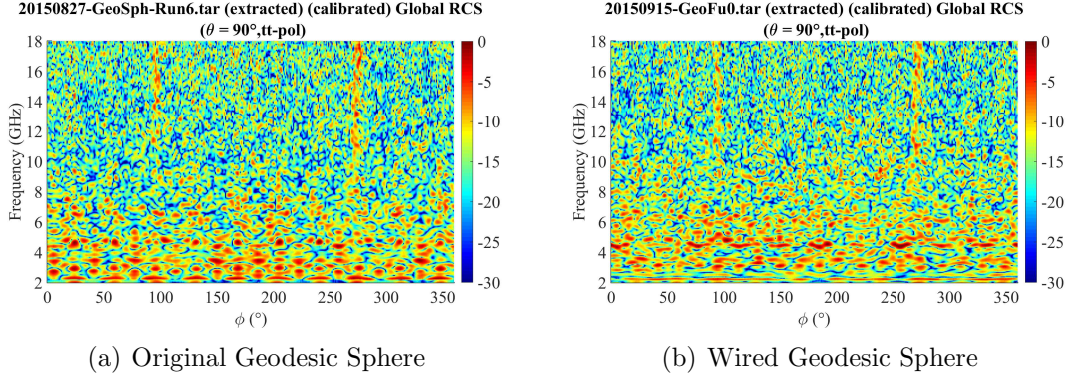


Figure 21. A comparison of the Original and Wired Geodesic Sphere's Global RCS at 0° of pitch (tt)

For the wired sphere, the distinct lobing pattern emerges around $10GHz$ instead of $8GHz$ for the original sphere. The smearing begins around $4.5GHz$, especially in the tt polarization. This increase in the smearing's upper limit, the cutoff frequency was estimated to be approximately $4.75GHz$ for the wired sphere. This increase goes along with theory, as the hole size decreases, the cutoff frequency increases.

4.6 Wired Geodesic Sphere Characterization, Bottomless Sphere

Through the research process, Lt Lett determined it was necessary to remove the bottom pentagon from the geodesic sphere [32]. This was required in order to improve the flight dynamics and overall stability of the Bebop inside the geodesic sphere. The sphere was also greatly damaged during his flight tests. For both of these reasons, the wired geodesic sphere needed to be remeasured.

4.6.1 Radar Calibration Verification.

Following the methodology presented in Section 3.3.1, the radar was once again calibrated using the two calibration cylinders. The calibration verifications of the 900 cylinder, from $2 - 6GHz$, for both polarizations, magnitude and phase, are seen in Table 3. The reason for the large increase in σ as compared to the previous

calibration verifications is unknown. The radar technician had implemented some changes in the timing and gating of the radar between the tests that may have had an effect on the performance in the $2 - 6\text{GHz}$ range.

Table 3. Two cylinder calibration verification results in phase and magnitude

Type	Pol	Mean (μ)	Std (σ)
Magnitude	pp	-0.10981 dB	1.3735 dB
	tt	-0.0062 dB	1.126 dB
Phase	pp	-0.8450°	9.911°
	tt	-0.01727°	7.413°

4.6.2 Wired Geodesic Sphere RCS, Bottomless Sphere.

After determining the calibration verification of the range, the wired, bottomless geodesic sphere was measured as previously discussed in Chapter III. Figures 22(a) and 22(b) are difference plots of the global RCS of the full wired and bottomless geodesic sphere as a function of frequency and yaw angle (ϕ°) for the pp and tt polarization respectively.

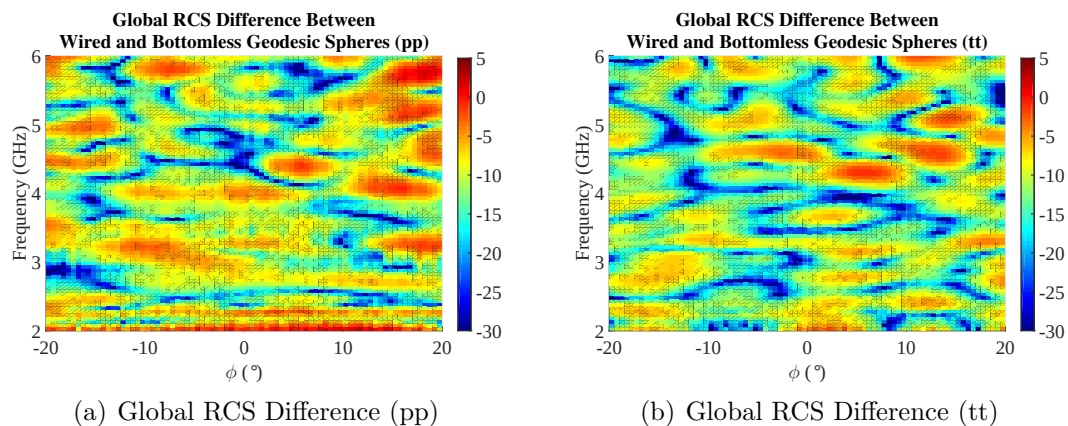


Figure 22. Difference between Wired and Bottomless Geodesic Spheres at 0° pitch: (a) pp polarization (b) tt polarization

The bottomless sphere was only measured from $-20^\circ : 1^\circ : 20^\circ$ in yaw and $-5^\circ : 1^\circ : 5^\circ$ in pitch so the full sphere data has been cut down to allow for a direct

comparison. The differences between the two spheres are clear and large. The positive values indicate where the RCS of the full sphere was greater and the negative values indicate where the bottomless sphere's RCS was greater.

This response was expected as many of the bottomless sphere's smaller wire triangles were broken or missing due to in flight mishaps. These differences are not important to the goal of this particular research effort. They are included in order to show the degradation of the performance of the geodesic sphere as a reflector when it is damaged. The bottomless RCS data were what was used later in the analysis for the flight test measurements, and therefore represent a "worst case" geodesic sphere.

4.7 Configuring Bebop for Data Collection

The Bebop quad-copter is a powerful system with many different positioning systems. The standard method of connecting to and flying the drone is through the use of an Android or iOS application called Parrot Free Flight 3. It is available for free download from the appropriate application store. Free Flight 3 allows the user to fly the drone and record video of the flight. It does not allow for recording of the drones position or pose. A reliable method of data collection was needed in order to be able to characterize the on board systems.

As discussed in the Methodology chapter, Paparazzi was the tool selected for this process. After some time of trial and error and reading the Paparazzi wiki page, it was discovered that the user is able to choose what data messages are sent over the data link and at what rate. All available messages are located here:

<https://github.com/paparazzi/paparazzi/blob/master/conf/messages.xml>. The Paparazzi wiki page (<https://wiki.paparazziuav.org/wiki/>) contains detailed

instructions on how to include the desired messages in the data stream between the drone and Paparazzi.

The messages necessary for this research were `GPS_INT` and `ROTORCRAFT_FP`. These messages included information on position and pose respectively. All of the subsequent Bebop data came from these two messages as recorded by Paparazzi. Both messages were set to record at a data rate of $20Hz$, which was faster than the systems update rate. This allowed for better time stamp matching as explained below.

4.8 Bebop GPS Characterization

The data products gathered during the Bebop GPS testing included DGPS data from the Novatel receiver in .txt format (truth data) and Bebop log data in Paparazzi. The log data was opened in Paparazzi and saved to a .csv file. The process for every GPS test, static and dynamic, was the same: record the data, import the data into Excel®, manually align the time stamped data, and import the data into MATLAB® for processing.

4.8.1 Time Stamp Alignment.

Every data set needed to be aligned in time in order to allow for a comparison between where the Bebop's GPS thought it was and where the DGPS said it was. This alignment was done by hand for every data file and the process was the same for all files. Figure 23 displays a sample of the GPS data as exported from Paparazzi.

The GPS data are in decimal format and are easy to deal with. The two time stamps are not in a standard form. The DGPS data, after being imported into Excel®, was time stamped in GPS week seconds with GPS data in decimal format.

	A	B	C	D	E
1	Time	UTC	GPS_lat(deg)	GPS_long(deg)	
2	7.715	01:59.7	39.78224909	-84.08197852	
3	7.765	01:59.8	39.78224909	-84.08197852	
4	7.815	01:59.8	39.78224909	-84.08197852	
5	7.865	01:59.9	39.78224909	-84.08197852	
6	7.915	01:59.9	39.78225053	-84.08197861	
7	7.965	02:00.0	39.78225053	-84.08197861	
8	8.015	02:00.0	39.78225053	-84.08197861	
9	8.065	02:00.1	39.78225053	-84.08197861	
10	8.115	02:00.1	39.78225053	-84.08197861	
11	8.165	02:00.2	39.78225053	-84.08197861	
12	8.215	02:00.2	39.78225053	-84.08197861	
13	8.265	02:00.2	39.78225053	-84.08197861	

Figure 23. Sample block of Bebop GPS data showing embedded time codes

This time stamp counts the number of seconds since the beginning of the week (0:00 Sunday) [36]. A conversion was necessary to be able to line up the two data sets in time in order to determine the accuracy of the Bebop GPS unit.

The first step was converting the Coordinated Universal Time (UTC) column from Excel®'s Time format to the Number or General format. This yielded a decimal number from 0 : 1 which represented the portion of the day that had elapsed. This decimal number was multiplied by $86400seconds/day$ which yielded the number of elapsed seconds in that day for each measurement. Next, the day of the week on which the measurement was taken (different for each measurement taken) was multiplied by $86400seconds/day$ and added to the Bebop time stamp. A final correction of $5hours * 3600seconds/hour$ was added to the Bebop time stamp (accounting for the time zone correction to UTC). The result was GPS week seconds which could be directly compared to the DGPS time stamps.

Before the time stamps were aligned, the Bebop GPS data needed to be parsed. The Bebop data was exported from Paparazzi at a rate of $20Hz$, even though the

Bebop's GPS unit was only capable of $10Hz$ updates. This allowed for choosing a time stamp closer to that of the DGPS (also at $10Hz$). Once the appropriate starting point was chosen in the Bebop data, every other line needed to be skipped in order to pull out the data at $10Hz$.

This was accomplished using the COUNT and MOD functions in Excel[®]. Each line was assigned a number from one to the end of the rows using the COUNT function. Next, the MOD function was used to either return a one or a zero depending on if the count value was even or odd (Excel[®] cell contained $= MOD(count, 2)$ for each row of data). MOD returns the remainder of a number (first function input) after being divided by the second input into the MOD formula (see Excel[®] for more information). Next, all of the rows containing either a zero or one (depending on which time stamp was farther from the DGPS data) was deleted, leaving the closest matching $10Hz$ Bebop GPS data.

Finally, the two data sets were merged by aligning the time stamps at the start of the measurement. This time stamp alignment process was repeated for every GPS accuracy test. The alignment was not perfect for each test, however, the offset between the Bebop and DGPS time stamps did remain constant throughout the duration of each test. The constant offsets for the Bebop were $+0.015seconds$ for the static GPS test, $+0.019seconds$ for the first dynamic test, and $-0.013seconds$ for the second dynamic test. These offsets were considered too small, given the slow speed of travel, to have any affect on the analysis as the golf cart only traveled $4cm$ in $+0.019seconds$.

4.8.2 Static GPS Accuracy Analysis.

The first test to analyze was the static GPS test. The analysis method was borrowed from Capt Kevin Hendricks. He provided two MATLAB[®] files from a

previous GPS class at AFIT. The first file, `decode_bestposa.m`, read the NovAtel DGPS file and converted it into a space-separated file. The output file format was readable by either Excel® or MATLAB® [33].

The second file, `Dossett_Static_GPS_Eval_8Oct.m`, read in the DGPS and Bebop GPS time aligned data and calculated the difference between where the DGPS said it was (truth data) and where the Bebop's GPS thought it was. This calculation was accomplished by shifting the drones data points to compensate for the constant offset between the DGPS antenna and the drones GPS antenna. The MATLAB® file Capt Hendrick's provided converted both data sets to Earth-Centered Earth-Fixed (ECEF) coordinates, set the reference point as the mean of the DGPS data, subtracted the two sets of points to determine the offset in ECEF, converted the difference to a local, east, north frame, corrected the constant offset between the two GPS antennas, and calculated the mean and standard deviation of the difference.

The ECEF coordinate frame's origin is at the Earth's core, and its axes are fixed with respect to the surface of the Earth. This means that the coordinates of a point on the surface of the Earth never change [37]. In order to make the error relevant in meters, the difference between the two sets of ECEF points need to be converted to a relative earth surface frame of reference. This was accomplished through multiplying by the matrix seen in Equation 4. After converting to local meters, the previously determined north and east corrections were applied to the data. This is the most straightforward way to analyze the static GPS data since the two antennas did not move.

$$CG = \begin{bmatrix} -\sin(lon) & \cos(lon) & 0 \\ -(\sin(lat) * \cos(lon)) & -(\sin(lat) * \sin(lon)) & \cos(lat) \\ \cos(lat) * \cos(lon) & \cos(lat) * \sin(lon) & \sin(lat) \end{bmatrix} \quad (4)$$

The only inputs to the second file were the two data sets (truth and measurement), the distance between the two antennas in inches, and the difference between north and the drone's heading. The distance between the two antennas was measured with a tape measure and found to be $38in$. The Bebop's heading was found via a compass to be 263° . The input heading then was $360^\circ - 263^\circ = 97^\circ$. The MATLAB[®] code then broke the heading into North and East correction distances using sines and cosines. Every Bebop GPS point was moved the resulting distance North and East to align the two antennas, allowing for the error calculations.

After running the evaluation MATLAB[®] file, the results were plotted as seen in Figure 24. The standard deviation (σ) is similar in the North and East directions as expected. The stated accuracy of the Bebop's GPS system is $\pm 2.5m$ if an external antenna is utilized. Given the lack of an external antenna, an accuracy of $3.7m$ is a reasonable number. What is seemingly unreasonable are the large mean values. The cause of the large difference in means (μ) is thought to be caused by multi-path effects from the building that was $40ft$ away. The sinusoidal nature evident in Figure 24 is characteristic of multi-path in a GPS measurement. This discovery was not made until it was too late to re-accomplish the static GPS test. The questionable nature of the static test results was not of major concern since the value needed for the Outdoor RCS measurement model developed later was the dynamic GPS accuracy.

4.8.3 Dynamic GPS Accuracy Analysis.

Static GPS measurements were helpful in determining a starting point for the Bebop's positional accuracy. However, a more applicable test was a dynamic test. In it's end application, the drone will be flying a designated profile through the

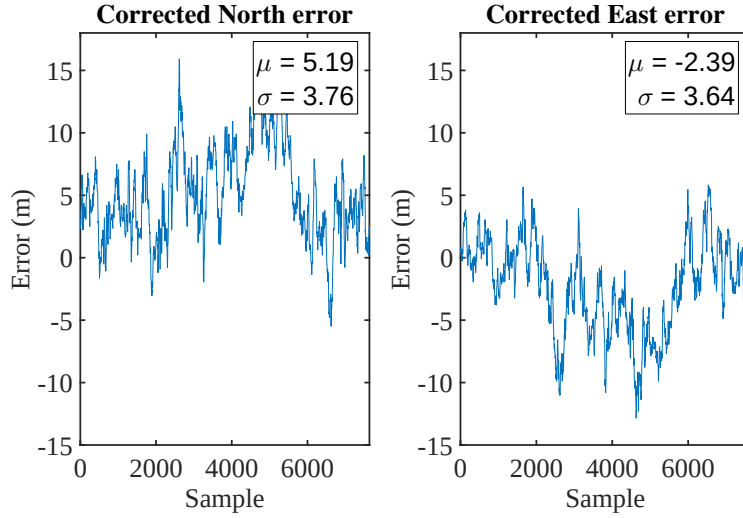


Figure 24. Static GPS error after correcting for antenna offset

desired test volume. It was necessary, therefore, to determine the GPS accuracy of the Bebop in motion.

Following the methodology presented previously, the dynamic data was recorded over two separate drives. Each drive was analyzed independently and using the identical process. The analytical process was similar to the static measurements in principle. The process was to determine the heading of the drone, calculate the appropriate North and East correction distances, move the drone data accordingly, and calculate the error between the two points. The major difference between the static and dynamic analysis was that the dynamic analysis required the reference point (the NovAtel antenna) to be changed for every data sample. It could no longer be the mean of the DGPS data.

The static GPS analysis code was changed to calculate the reference position of the DGPS antenna every sample, calculate the drone's heading for every sample, and then use those two changing values to perform the same analysis as was done for the static GPS test. The drone's heading was determined by calculating the heading

between the current data point and the subsequent data point using Equation 5 [38]. This heading was found prior to converting the data points to ECEF.

$$Dh = rad2deg(mod(atan2(sin(lon2 - lon1) * cos(lat2), cos(lat1) * sin(lat2) - sin(lat1) * cos(lat2) * cos(lon2 - lon1)), 2 * pi)); \quad (5)$$

After the point by point headings and reference points were calculated, the correction angle needed to be determined. In the static test, the correction angle was simply a single $\sin()$ or $\cos()$ relation based on the static coordinate quadrant. In the dynamic test, the quadrant the heading was in depended on the current heading. This analysis resulted in the code seen in Listing IV.1. The heading_true(ii) variable was the previously found DGPS heading (Dh) with -6° added to it to compensate for magnetic declination. The dist variable was the distance from the Bebop GPS antenna to the DGPS antenna (*38inches*).

The remainder of the dynamic GPS analysis was the same as the static analysis with the caveat that the reference point and North and East correction distances were different for every data point. The results for each run are seen in Figure 25. The average of the four error values (a north and east error for each run) was $0.987m$. This was the value that was loaded into the Outdoor Flight Test model, discussed later in this chapter, as the uncertainty in position (x,y) of the Bebop quad-copter. The dynamic GPS accuracy was much greater than the static accuracy (24) due to the lack of multi-path effects on the data. Since the dynamic tests were performed in an empty parking lot, there were no sources of multi-path which led to a more accurate measurement.

The Bebop's GPS not only provided position information in x and y but in z (height) as well. The analysis of the altitude portion of the dynamic GPS analysis

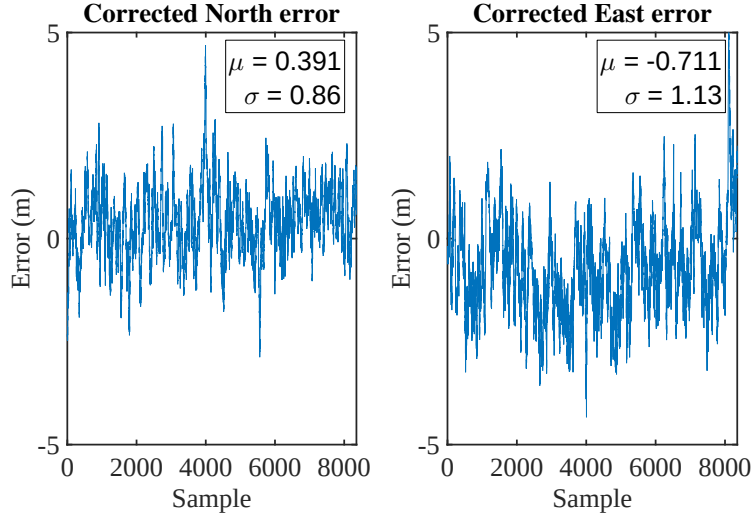
Listing IV.1. Correction Angle Calculation

```
1  if 0 < Dh(ii) && Dh(ii) ≤ 90
2      theta(ii) = pi()/2 - heading_true(ii);
3  elseif 90 < Dh(ii) && Dh(ii) ≤ 180
4      theta(ii) = heading_true(ii) - pi()/2;
5  elseif 180 < Dh(ii) && Dh(ii) ≤ 270
6      theta(ii) = 3*pi()/2 - heading_true(ii);
7  elseif 270 < Dh(ii) && Dh(ii) ≤ 360
8      theta(ii) = heading_true(ii) - 3*pi()/2;
9  end
10
11  corr_north = dist*sin(theta); % lat
12  corr_east = dist*cos(theta); % long
```

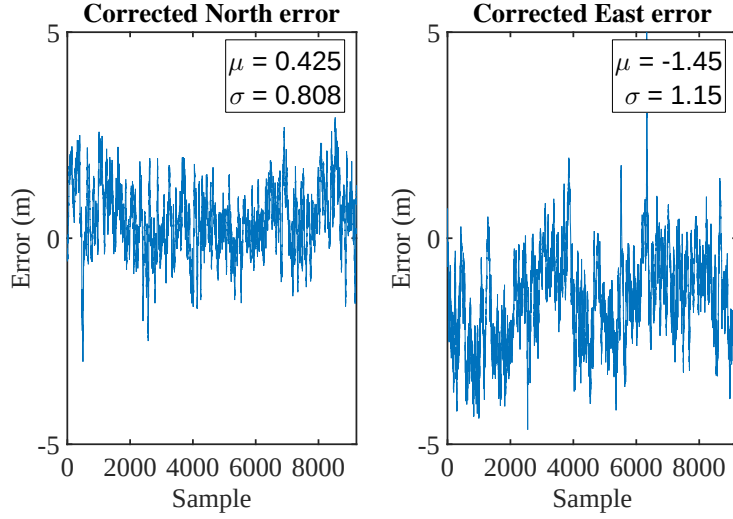
was straightforward. The time stamped GPS altitude values from the Bebop and the DGPS were aligned, subtracted, and the standard deviation and 95% confidence interval were found using Excel®'s Descriptive Statistics module. The error of the Bebop GPS in altitude was found to be $1.975m \pm 0.0277m$. This altitude uncertainty was used in the Outdoor Flight Test model. The Bebop did have an internal barometer that was fed into the overall positioning solution, but this was ignored for the purposes of the dynamic GPS characterization and its accuracy was not determined.

4.9 Bebop INS Characterization

The Bebop's positioning system also includes an internal INS system. It measures the roll, pitch, and yaw of the quad-copter. Just as the data were collected via two different tests (one for roll and pitch and one for yaw), two different analyses were employed.



(a) Run 1



(b) Run 2

Figure 25. (a) Dynamic GPS error after correcting for antenna offset (Run 1). (b) Dynamic GPS error after correcting for antenna offset (Run 2).

4.9.1 Bebop Roll and Pitch Characterization.

Two data collection systems were used for this test as explained in the Methodology chapter. The Angle Cube readings were recorded by hand in a notebook for each of the test points (it reports all angles as positive). The Bebop INS data stream was recorded separately for roll and pitch. After it was saved to a

.csv in Paparazzi the theta and phi columns were multiplied by 0.0139882 to convert them to degrees. The conversion factor was provided by Paparazzi.

Next, the data were pulled into Excel®, plotted, and then manually parsed. The process for parsing was to look at the data plot and determine where the drone stopped and started moving. The stationary values in between the movements corresponded to the stationary test point. These stationary values were averaged together, resulting in a reported roll or pitch value for that test point. The standard deviation of each block of stationary test points was also calculated. It represented the error bounds on the mean value. As will be seen in Tables 4 and 5, the standard deviation values were far below the error values for each measurement. The mean was calculated by using the AVERAGE function in Excel®. The standard deviation was calculated by using the STDEV.P function in Excel®.

This analysis process was repeated for all stationary test points. Figure 26 shows the reported pitch values from the Bebop's INS that were manually parsed. The level data between the movements is what were taken as the actual Bebop INS data for that test point. An example of the manual data picking process is illustrated by the pink line.

Roll test point data were in the Bebop ROTORCRAFT_FP:phi message and the pitch test point data were in the ROTORCRAFT_FP:theta message. Each test was considered independent of all the others and only the applicable rotation angle data were analyzed. The tests included placing the drone flat on the testing surface between each roll or pitch test point. This allowed the internal INS to remove any bias due to the prolonged angle exposure. The Angle Cube was also zeroed, flat on the same testing surface, between each test. This test was not to compare how close the drone roll or pitch angle was to the Angle Cube's reading, it was to determine if when the Angle Cube said the drone was tipped at an angle from the testing

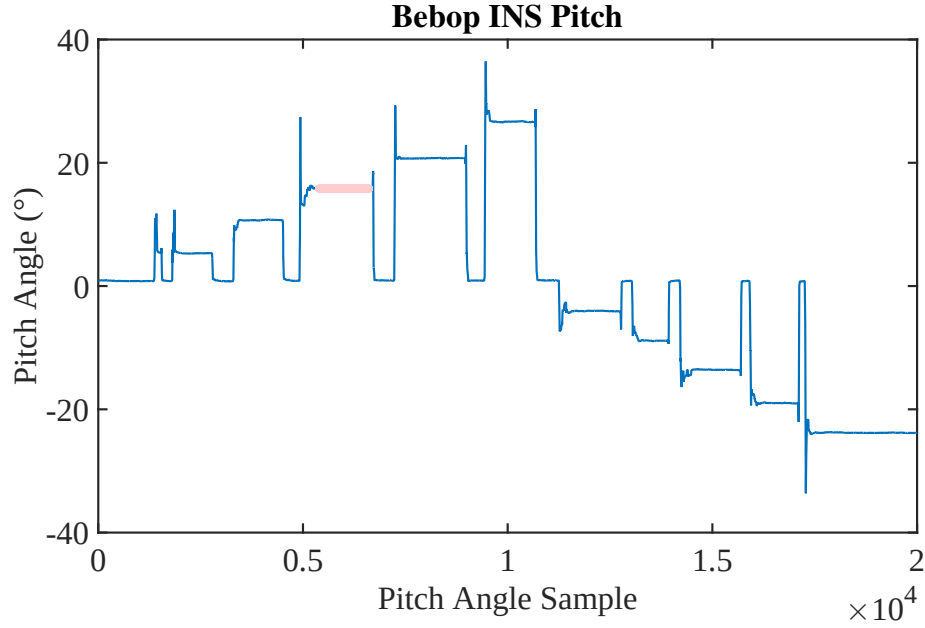


Figure 26. Bebop INS Pitch Angles from Static INS Test

surface, did the drone report the same angle. By looking at the data this way, any bias in the testing surface would be eliminated.

In order to calculate the measurement error, the bias needed to be removed. The error for each test was calculated using Equation 6 where Z is the Zeroed Angle Cube angle, $Mean$ is the respective angle mean from the Bebop, and $bias$ is the mean zero value. Z is negative if the roll/pitch was negative and positive otherwise. The mean zero value was determined by taking the mean of all of the zero points in the data stream for both ϕ and θ independently.

$$Error = |\pm Z - Mean| - bias \quad (6)$$

The same analysis was performed for all test points seen in Tables 4 and 5. These two tables display the standard deviation of each test in the analysis. In order to determine the 95% confidence interval for these calculations, the Descriptive Statistics module in Excel® was utilized. It was set to report the

summary statistics with a 95% confidence level for the mean. The resulting error bounds were applied to the data in the tables.

When the accuracy of the INS is used in future analysis, the mean roll and pitch errors will be used. Since the truth source used for this test, the iGaging® Angle Cube, was only accurate to within $\pm 0.2^\circ$, the Bebop roll and pitch errors could range from 0.2° above or below the listed average error.

Table 4. Bebop INS Roll Measurements and Results

Movement	Zeroed Angle Cube ($^\circ$)	Phi Mean ($^\circ$)	Phi Std ($^\circ$)	Error ($^\circ$)
Roll	24.90	-24.649	0.0512	0.2511
Roll	20.15	-20.003	0.0459	0.1478
Roll	15.80	-15.723	0.0455	0.0778
Roll	9.70	-9.495	0.0431	0.2052
Roll	5.00	-4.975	0.0395	0.0256
Roll	0.00	0.000	0.0525	0.0000
Roll	5.05	5.099	0.0525	0.0487
Roll	10.00	10.267	0.0392	0.2673
Roll	15.85	16.393	0.0299	0.5433
Roll	19.90	20.347	0.0412	0.4479
Roll	24.55	25.220	0.0805	0.6706
		Totals	0.1027	0.2437

4.9.2 Bebop Yaw Characterization.

The Bebop INS yaw data was recorded using a very different method from the roll and pitch data and yet a similar analysis method was employed. To collect the data, the drone was slewed in a circle on a rotating table. It rotated a set number of degrees, stopped, and rotated again. The stop in rotations allowed for the breaking up of the rotation data into individual tests. Each test began with a stationary period, included a rotation period, and then ended with another stationary period that acted as the beginning stationary period of the next test. The accuracy of the rotation table was unknown so it's error was assumed to be negligible.

Table 5. Bebop INS Pitch Measurements and Results

Movement	Zeroed Angle Cube (°)	Theta Mean (°)	Theta Std (°)	Error (°)
Pitch	25.00	-24.685	0.0259	0.3152
Pitch	20.00	-19.822	0.0374	0.1788
Pitch	14.50	-14.411	0.0324	0.0893
Pitch	9.80	-9.701	0.0400	0.0997
Pitch	5.00	-4.881	0.0348	0.1198
Pitch	0.00	0.000	0.0426	0.0000
Pitch	4.50	4.495	0.0650	0.0048
Pitch	10.00	9.850	0.0957	0.1500
Pitch	15.00	14.980	0.0921	0.0204
Pitch	20.05	19.898	0.0337	0.1520
Pitch	26.00	25.819	0.0443	0.1814
		Totals	0.1144	0.1189

The truth data for this test came from hand written angles for each of the test rotations. These angles were read from computer software that controlled the rotation platform. The test data once again came from the Bebop through Paparazzi. The message containing the yaw data was the ROTORCRAFT_FP:psi message. The test data was broken up into three individual tests, large ($90^\circ : 360^\circ$), medium ($5^\circ : 20^\circ$), and small movements (5°). Each test was analyzed independently but identically.

The recorded Bebop yaw data was multiplied by 0.0139882 (from Paparazzi) to convert the values to degrees. Next, the data was read into MATLAB[®] to begin analysis. Bebop's INS records yaw values from $-180^\circ : 180^\circ$. In order to remove the jumps in data at each $\pm 180^\circ$ crossing, the unwrap function was applied to the data. Unwrap is a default function in MATLAB[®] which operates by adding 360° to any $\pm 180^\circ$ crossing to smooth the data. The result was a continuous plot of the yaw movements. Unwrapping the yaw angles did change the individual angle values, but all that was needed for the analysis was the difference between each set of stationary periods. This unwrapped yaw data was plotted with respect to data samples to

allow for manual analysis. Figure 27 shows the unwrapped yaw rotation profile. The small, medium, and large rotations can be seen mixed throughout the test profile.

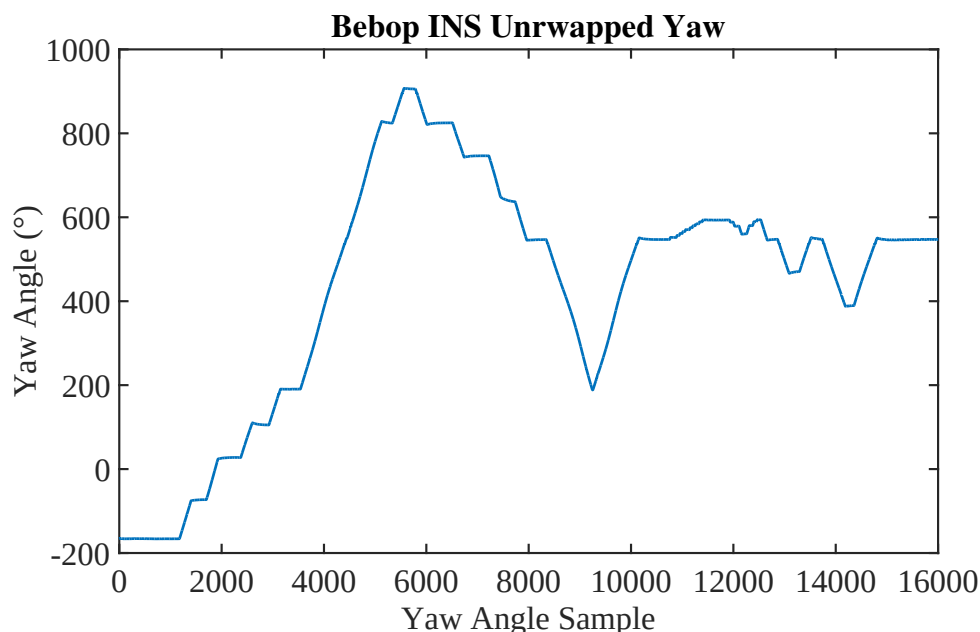


Figure 27. Bebop INS Yaw Angles from Static INS Test

The start and stop samples for each rotation were manually picked from the plot based on when the slope of the rotation leveled out. These points were recorded as the appropriate rotations start and stop points. Figure 28 illustrates the points chosen as the start and stop points (pink dots on the yaw profile). A stationary period was designated by a rotation stop and the subsequent rotation start point. the mean of the stationary period was calculated and used as the reported Bebop current yaw value. A pair of stationary periods bracketed every yaw movement. The value of the difference between the mean of the pair of stationary periods was taken as the reported Bebop yaw value for that rotation. This analysis resulted in a list of yaw movements as recorded by the Bebop INS.

These recorded Bebop yaw movements (recordings were degrees of rotation for each rotation) were compared to the truth rotation angle as recorded from the

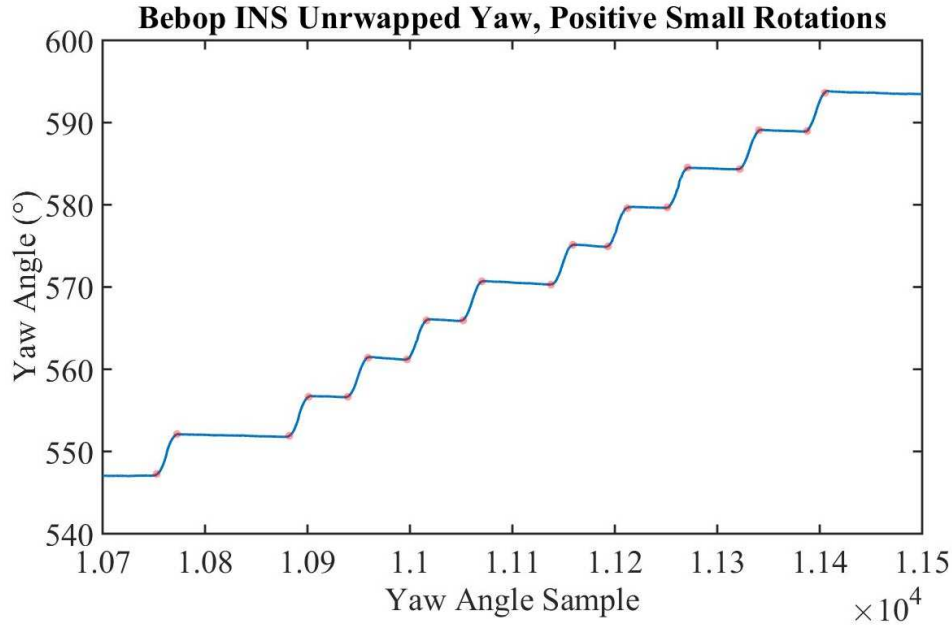


Figure 28. Bebop INS Yaw Angles from the Positive Small Rotations of the Static INS Test

rotation table. Each small, medium, or large measurement was compared to its truth rotation. The difference in the values was the error for that rotation. All of the errors for the small, medium, and large rotations were averaged, with respect to the rotation size, and the standard deviation was taken. The resulting errors are seen in Table 6. The mean was calculated by using the mean function in MATLAB®. The error bounds were calculated using the Descriptive Statistics in Excel®.

Table 6. Bebop INS Yaw Accuracy (95% confidence intervals)

Rotation	Mean ($^\circ$)
Small	0.3803±0.1781
Medium	0.5202±0.4902
Large	7.4059±4.1544

The accuracies for yaw are much less than those of roll and pitch. Since roll, pitch, and yaw each have their own, identical accelerometer in the INS, the expectation was that the accuracies would be much closer. The two methods of testing were very different. The expected cause of the decrease in accuracy for the

yaw test is that the yaw test was a dynamic test whereas the roll and pitch tests were static. The constant movement during the test could lead to larger errors in the accelerometers. What this really points to is that the roll and pitch accuracies are most likely better than would be seen during flight.

Since the end use of the drone and geodesic sphere will be in flight, and the radar will be illuminating the geodesic sphere much faster than the Bebop's INS can record, the rotations between data points will be small. For this reason, the small rotation mean and standard deviations were used in the overall system uncertainty analysis. The overall analysis combines the GPS and INS uncertainties to create a total uncertainty in the RCS measurement of the geodesic sphere in flight.

4.10 Bebop GPS and INS Characterization Conclusion

The Bebop's positioning system was characterized through the previous analysis. The accuracies of each component in the GPS and INS were determined and are listed in Table 7. These values are what will be used in the Outdoor Flight Test model in order to determine how accurate of a probe the Bebop quad-copter can be. The Roll, Pitch, and Yaw accuracies include the 95% confidence intervals. The GPS and Altitude values do not since the method used to calculate them did not lend itself to a confidence interval calculation at this time.

Table 7. Overall Bebop 95% confidence accuracies

Attribute	Accuracy
GPS	0.9870m
Altitude	$1.975m \pm 0.0277m$
Roll	$0.2440^\circ \pm 0.1037^\circ$
Pitch	$0.1190^\circ \pm 0.1144^\circ$
Yaw	$0.3803^\circ \pm 0.1781^\circ$

4.11 ViconTM Characterization

While the Bebop's GPS and INS were eventually utilized for outdoor probe measurements, they are not available used in indoor measurements. The position and pose of the geodesic sphere must still be known in an indoor environment. The solution utilized for this research was a ViconTM motion capture system installed inside the indoor RCS chamber. Each ViconTM system is unique and their unique uncertainties would have to be determined prior to using the geodesic sphere as a two-way probe in that range.

The characterization of the system in AFIT's RCS chamber was only a basic characterization and was performed by Lt Nathan Lett. First, the ViconTM system was calibrated according to the manufacturers instructions. This involved waving a factory calibrated wand around the chamber until the ViconTM computer program said to stop. Next, the geodesic sphere (marked with reflective dots) was placed on the floor of the RCS chamber. The computer was set to record the position (x, y, z) and pose (roll, pitch, yaw) over night. The result was a text file containing the specified information recorded at an interval of $25ms$ over the 6 hour 24 minute test (terminated when the computer ran out of memory).

This data was loaded into Excel[®]. The standard deviation of a 95% confidence interval of the x, y, z, roll, pitch, and yaw was calculated using the Descriptive Statistics module in Excel[®]. The standard deviation of each attribute represented the jitter in the measurement. This jitter represents the uncertainty in the ViconTM reported position and pose. ViconTM records in *mm* so all of the resulting values were divided by 1000 to convert them into *meters*. These accuracies are seen in Table 8. The micrometer column is included to give a sense of scale of the uncertainty in the ViconTM system. Due to the minuscule standard deviation values, the assumption that the ViconTM system acts as a truth source is validated.

Table 8. AFIT’s RCS Chamber Vicon™ Accuracy

Total Statistics			
	Std		Std
X	$5.489m \times 10^{-05}$	$\pm 8.677m \times 10^{-7}$	$54.89\mu m$
Y	$3.920m \times 10^{-05}$	$\pm 6.197m \times 10^{-7}$	$39.20\mu m$
Z	$1.681m \times 10^{-04}$	$\pm 2.657m \times 10^{-6}$	$168.1\mu m$
Roll	$6.637^\circ \times 10^{-07}$	$\pm 1.007^\circ \times 10^{-8}$	
Pitch	$6.368^\circ \times 10^{-07}$	$\pm 1.049^\circ \times 10^{-8}$	
Yaw	$7.009^\circ \times 10^{-08}$	$\pm 1.108^\circ \times 10^{-9}$	

4.12 Probe Model Development

The effectiveness of the geodesic sphere as a probe relies on its ability to reflect the incident wave in a characterizable and repeatable manner and its ability to operate in a known and controlled position, at a designated pose. The original plan was to spin the geodesic sphere through enough yaw angles at each x, y, and z position in the flight path that after smoothing the return RCS, the geodesic sphere scattering would be statistically similar to a real sphere. The goal was to find a statistically aspect independent quantity in order to be able to determine the incident wave after accounting for the smoothed pattern of the spinning geodesic sphere.

A statistically aspect independent quantity was never found. Figure 29 is a plot of the RCS of the wired geodesic sphere at $2.1GHz$ around the waterline of the sphere. The pattern is clearly not aspect independent. The geodesic sphere’s pattern had too many lobes and nulls for smoothing to be able to overcome. This resulted in a framework change for the probe model. Instead of spinning the drone and using a smoothed, statistical quantity, a look up table of calibrated RCS measurements would be created. This would allow any measured return from the geodesic sphere to be compared to the known return from the calibrated data. After this comparison, the difference would be the variation in the incident wave.

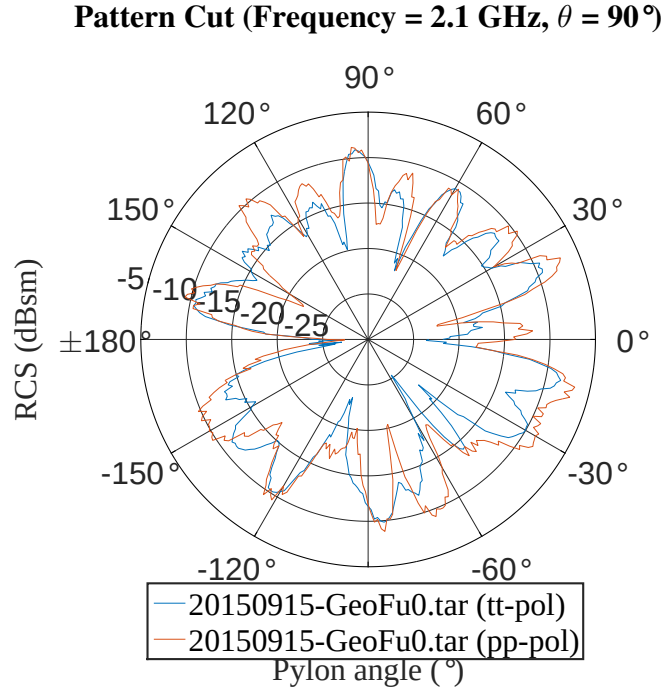


Figure 29. Polar RCS of Wired Geodesic Sphere at 2.1GHz

In order to compare the measured test data with the calibrated measurement data, the position and pose of the geodesic sphere needed to be known, and the uncertainties determined. These characteristics were all quantified in the previous uncertainty analysis. The outdoor model utilizes the Bebop's GPS and INS uncertainty. The only uncertainty applicable to the indoor model is the ViconTM uncertainty. Using the appropriate uncertainty, the goal of this research (to determine the fidelity and repeatability of these characteristics) could be accomplished through the use of the models developed in the subsequent sections.

4.13 Calibration Data Creation

The Indoor flight test model was a complicated analysis that looked at the multiple disciplines inherent in the probe measurement concept. Figure 32 is the visual representation of the Indoor model development flow. Each of the images are

discussed below. The Indoor model creation began with capturing the calibrated RCS of the geodesic sphere at multiple pitch and yaw angles. The calibrated measurement data was integral to the development of both models. It was also the same for each model. Following the stated methodology, the geodesic sphere, with the Bebop inside, was systematically measured. The ViconTM position of the sphere was recorded at each measurement position. Lt Lett and a laboratory technician setup the radar data collection software to pull in the current ViconTM position of the sphere at the beginning of each measurement frequency sweep and for each polarization.

The radar was setup to measure the geodesic sphere every 0.5° of yaw. The geodesic sphere was rotated 0.5° , stopped, the radar performed the frequency sweep measurement, and then the sphere was rotated another 0.5° . The fact that the geodesic sphere was stationary for each measurement ensured that it was in the same position for every frequency in the frequency sweep. An example snapshot of this RCS collection is seen in Figure 32. It shows the waterline cut of the bottomless, wired geodesic sphere.

After collecting the RCS and coordinated position and pose information, the calibration data set could be created. Since the RCS measurements were only taken every 0.5° in yaw and 1.0° in pitch, the data needed to be interpolated in order to allow for the RCS at any yaw or pitch to be determined. This was crucial to the application of this calibration data. The model would be used on RCS recordings of the geodesic sphere as it flew in the radar field during which the pitch and yaw, as seen by the radar, would not be in 0.5° increments.

The type of calibration data needed for the model depended on what aspect of the RCS was being looked at. The model allows for looking at normal RCS, the magnitude of the RCS, or the phase of the RCS. The first step of creating the

calibration data was extracting the desired data from the RCS measurement of the geodesic sphere. If normal RCS was desired, nothing was done to the data. If the magnitude was desired, the absolute value of the I and Q channels was taken. If the phase was desired, the angle of the data was taken (using `angle` in MATLAB®), then it was divided by two (to account for the two way distance traveled by the reflected wave), and the resulting phase was converted to degrees (using `rad2deg` in MATLAB®).

The I and Q channels refer to the *In-phase* (I) and *Quadrature-phase* (Q) signals. The I signals are a mix of the received signal and the local oscillator signal that is in phase with the transmitted radar wave. The Q signals are created by shifting the received signal by 90° and mixing it with the same local oscillator signal. The creation of these two channels from the received signal creates data with phase and amplitude information from the received radar waveform [3].

Following the parsing of the data, the position and pose of the geodesic sphere for each measurement were extracted from the recorded data. The x, y, and z data were divided by 1000 to convert the data into meters. The roll and pitch data were switched since they were recorded backwards during the pedestal measurement of the geodesic sphere. Both the radar and position/pose data manipulations were performed for each calibration data file (11 measurement files corresponding to the 11 pitch angles). Each data matrix (one for radar data, one for position/pose data) was concatenated into vector format with each subsequent measurement data following the previous.

The data was not taken on regular grid spacing since the pitch of the sphere changed as it rotated in yaw. In order to interpolate between non gridded points, the MATLAB® function `scatteredInterpolant` must be used. According to the MATLAB® help files, `scatteredInterpolant` performs an interpolation on a 2-D or 3-D scattered

data set. When a set of (x,y) points and their corresponding values (v) are passed to `scatteredInterpolant`, it returns a surface that relates x , y , and v by $v = F(x, y)$. The function ensures that the surface always passes through the v values at each (x,y) location. This surface can then be queried at any point and a value is produced. The default interpolation method is linear and was used for this analysis.

Yaw (x) and pitch (y) vectors were passed into the `scatteredInterpolant` for both polarizations. This resulted in two functions, `F_pp` and `F_tt`, which could be evaluated at any yaw and pitch inside of the bounds of the measured data set and return the calibration RCS. These two functions made up the calibration data set that was used as the truth source for future flight test measurements. Figures 30 and 31 were created by passing a meshed grid from $-20 : 1.0 : 20$ in yaw and $-5 : 1.0 : 5$ in pitch into the `pp` and `tt` calibration functions respectively. Each resulting surface was plotted in MATLAB® using the `surf` command. These surfaces represent the phase response of the geodesic sphere over the indicated yaw and pitch angles. The large variations in the phase of the RCS of the geodesic sphere demonstrate why a point to point comparison was necessary instead of an orientation invariant statistical quantity. The differences between the two polarizations are also seen and were expected given the physics of the two waveforms.

4.14 Indoor Model Development

The basis of the probe model was the position and pose of the probe and the measurement data taken at each position during the measurement flight. Position, pose, and RCS data were all recorded into one ALPINE® data file for each flight. The desired position at each measurement point was also recorded in a separate text file. After developing the calibration data function, the flight path data was extracted from the ALPINE® data. One such flight path is seen in Figure 32c (not

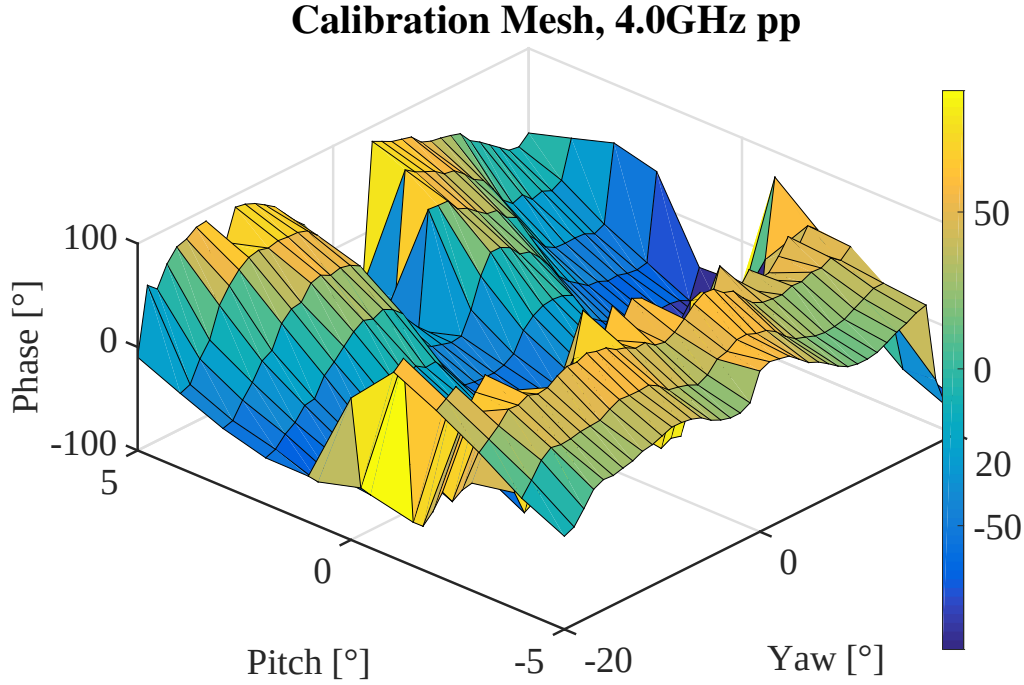


Figure 30. Mesh grid representation of the interpolated phase calibration data at $4.0GHz$ (pp)

including the pitch and yaw). This flight path was passed into F_{pp} and F_{tt} , resulting in calibrated results for each position and pose along the flight path which are seen in Figure 32d.

The flight test measurement data was then parsed in the same manner as the calibration data was previously; the normal RCS, the magnitude of the RCS or the phase of the RCS was taken from the flight test data. Phase results for one measurement flight are seen in Figure 32e. The recorded flight path was not exactly the desired flight path due to the capability of the drone inside the cage. These errors needed to be compensated for.

The flight test data and the calibrated results were then motion compensated in the y direction (Figure 32f). This was accomplished by comparing the ViconTM reported position and the desired position for that measurement. The difference between the two in y was the offset distance. This offset distance was multiplied by

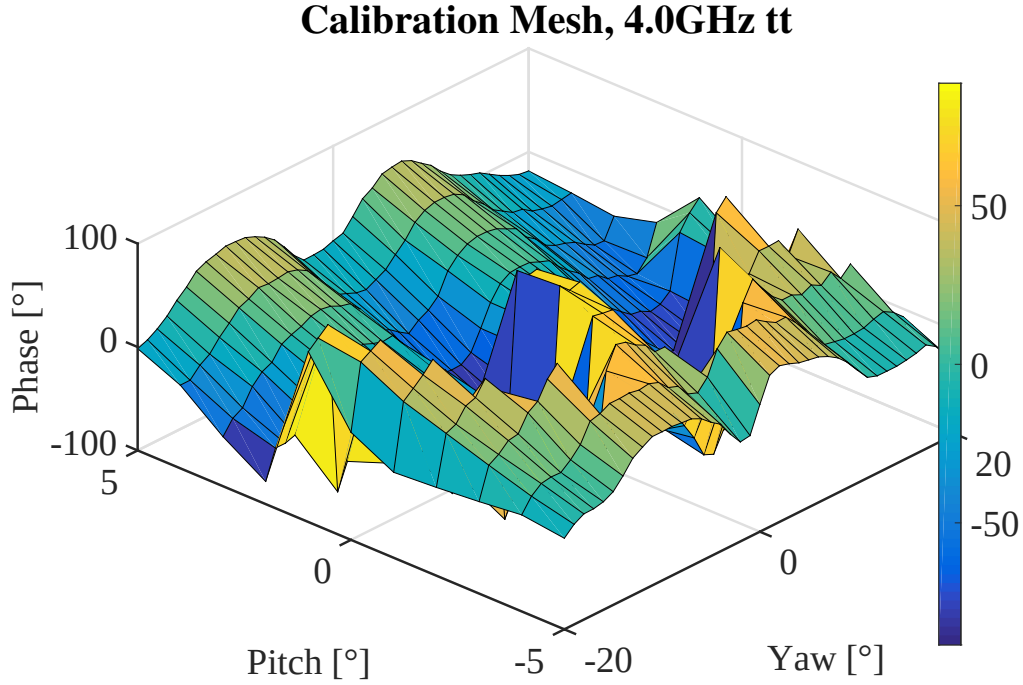


Figure 31. Mesh grid representation of the interpolated phase calibration data at 4.0GHz (tt)

the phase coefficient, $\beta = 360/\lambda$ where λ was the wavelength of the frequency under analysis. The result was the degree offset from the desired position in y. The motion compensation was only performed in y since phase is only affected by movement to and from the radar.

Following motion compensation of the data, it was smoothed by the desired window sizes which were specified in number of samples (Figure 32g). Smoothing the data allowed for imperfections in the geodesic sphere or flight path to be leveled off. It was accomplished using the smooth function in MATLAB®. Smooth.m uses a moving average window to smooth the data. The size of the averaging window can be input by the user. Part of the model was to specify what smoothing window sizes were desired. The output of the smoothing function was a smaller subset of samples. The smoothed data was not kept until the entire smoothing window was

over the data in order to avoid windowing edge effects. This threw away half of the window size at the beginning and end of the data under test.

The smoothed flight test data was then subtracted from the smoothed calibration results point by point (Figure 32h). The resulting difference represented the error in the incident radar field, assuming the geodesic sphere was actually where ViconTM said it was. As was shown earlier, the errors in ViconTM's reported position are very small. However, these errors needed to be considered. The difference is the error in the measurement, not a deviation in the measured field because this analysis effort assumes a perfectly planar illuminating wave.

4.14.1 Monte Carlo Uncertainty Analysis.

These errors were considered through a Monte Carlo analysis. Each Monte Carlo run consisted of determining a perturbed flight path, calculating the pitch and yaw as seen by the radar, interpolating the calibration data mesh along the perturbed flight path, and motion compensating the resulting data. Each run of the Monte Carlo analysis could be thought of as a radar pulse. Each successive pulse on the geodesic sphere in a given position in space could be integrated. These integrated pulses decrease the uncertainty in the measurement. By including the errors in the positioning system in the Monte Carlo analysis and by increasing the number of runs, it was possible to determine how pulse integration would benefit the probe measurement.

A subsidiary benefit to multiple pulses at each position on the flight path would be statistical in nature. The mean and standard deviation of the return for each pulse could be analyzed. The mean could be treated as the actual reflection value and the standard deviation would characterize the uncertainty of the measurement in that flight path location.

To start the Monte Carlo loop, the ViconTM accuracies were loaded into the Monte Carlo simulator. Random values between plus or minus the uncertainty value were found for each measurement point and for each location attribute (x, y, z, roll, pitch, yaw) based on the ViconTM accuracy. In order to create a worst case scenario, the random values were created using the rand function in MATLAB[®]. This function returns the desired number of values from a uniformly distributed set of random numbers within the specified bounds. Position and pose errors are better represented by the normal distribution, but the resulting errors were less due to the clustering of the random values near the mean. These random values were added to their respective location attribute to create fuzzy flight paths.

Next, the fuzzy flight path was passed into F_pp and F_tt, resulting in a fuzzy flight test measurement result for each position and pose along the fuzzy flight path. These values were passed into the calibration data functions F_pp and F_tt that were previously created. The result was the calibration data for the calculated fuzzy flight path. The errors caused by the ViconTM system would be determined by comparing the error data to this calibration data.

The fuzzy flight test data were then motion compensated in the y direction as previously described by adding the phase offset to both the pp and tt simulated fuzzy flight test data. This was the end of the Monte Carlo loop. The loop was repeated n times for each flight.

The result of the Monte Carlo loop was a matrix that was m flight path positions (in time) by n loops in size. The mean and standard deviation of each flight test point were taken across all n loops. This created a single data vector for each flight that incorporated the error caused by the drone's GPS and INS (Figure 32i).

Next, the truth and fuzzy data were smoothed by the desired window sizes as previously described. The smoothed fuzzy flight test data was then subtracted from

the previously calculated smoothed calibration results point by point. The resulting difference represented the error in the probe measurement due to the uncertainty in the position and pose of the geodesic sphere.

The error from the positioning system uncertainty was not the only error in the measurement. The standard deviation from the original two cylinder calibration verification represented another source of error, the uncertainty in the radar itself. Due to the accuracy of the ViconTM system, the uncertainty in the radar was orders of magnitude greater than that caused by the uncertainty in the ViconTM position measurements. As a result, the uncertainty caused by the ViconTM system became lost in the graphs. An example of the previously found errors in the incident radar field and the ViconTM uncertainty error bars are seen in (Figure 32j). Actual data and numbers will be presented later.

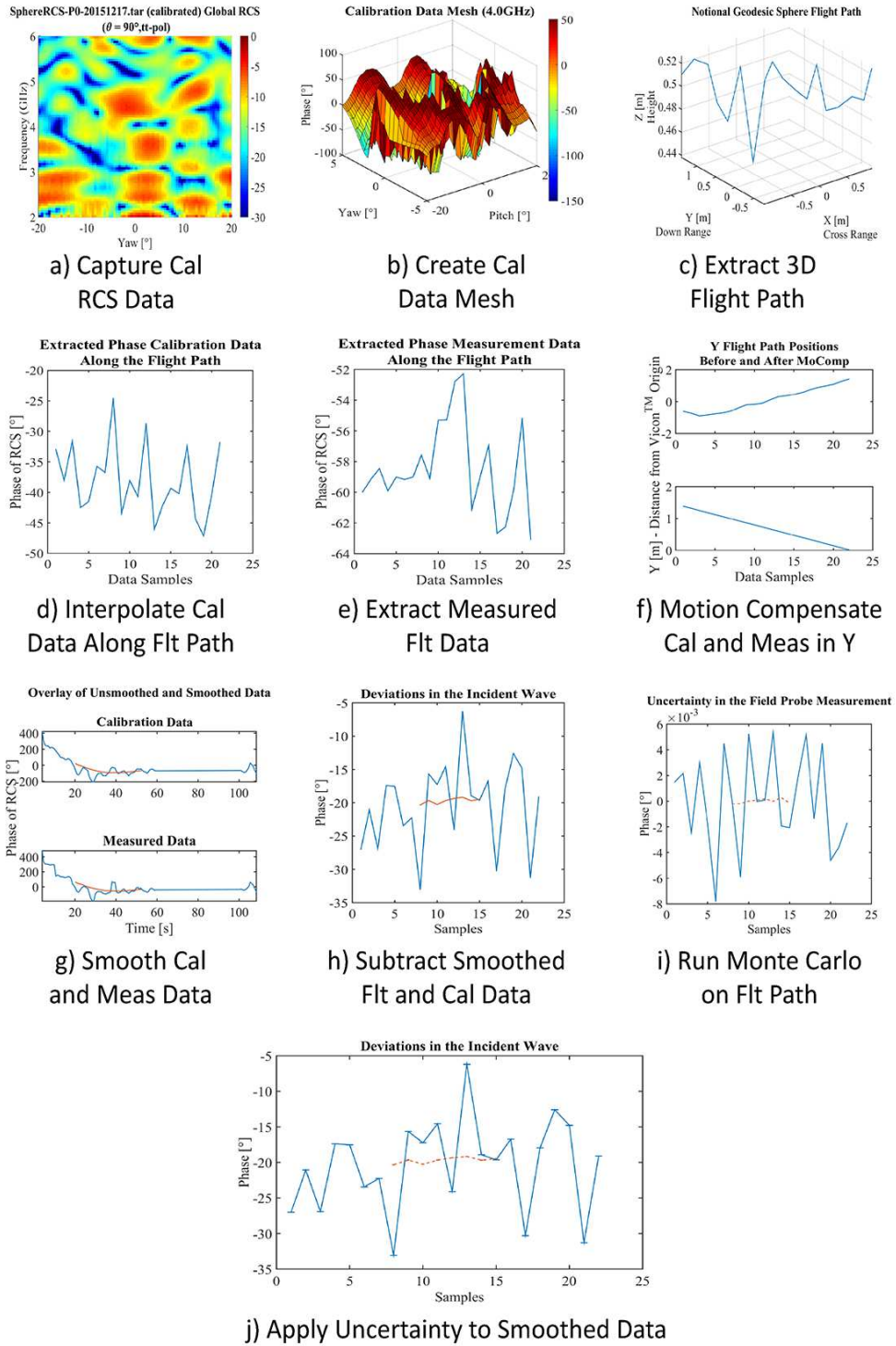


Figure 32. Flow diagram for the Indoor Model

4.15 Outdoor Model Development

The basis of the outdoor probe model was also the position and pose of the geodesic sphere. The major difference between the previously discussed Indoor model and the outdoor model was that there was no flight test measurement data. While the Indoor model was developed to analyze actual probe data and determine its uncertainty, the Outdoor model was designed solely to determine the uncertainties in a probe measurement based on the accuracy of its positioning system. This model assumed the geodesic sphere was being illuminated with a true plane wave. It also normalizes the cumulative phase by setting the phase at the flight path origin to be zero. The resulting errors are due to the uncertainties in the geodesic spheres position and pose. This model utilizes the same calibration functions (F_pp and F_tt) as the Indoor model.

Since this was a simulated model, a flight path was created for analysis. This flight path represented the truth positioning source for the Bebop to be compared to. In order to account for the errors in the Bebop's GPS and INS, a very similar Monte Carlo method that was described in the Indoor model was utilized. Each Monte Carlo run consisted of determining a perturbed flight path, calculating the pitch and yaw as seen by the radar, interpolating the calibration data mesh along the perturbed flight path, and motion compensating the resulting data. Again, each Monte Carlo run represented a radar pulse on the geodesic sphere.

To start the Monte Carlo loop, the Bebop's GPS and INS accuracies were loaded into the Monte Carlo simulator (any GPS or INS accuracies could be used). The fuzzy flight paths were created as in the Indoor model. Prior to passing the fuzzy flight path into the calibration data functions, a step unique to the Outdoor model needed to be taken. Given the nature of an outdoor range setup and the necessary flight path, the look angle from the radar to the target was important. This look

angle determined what surface of the geodesic sphere was seen by the radar. The roll, pitch, and yaw angles recorded by the drone needed to be converted into roll, pitch, and yaw seen by the radar for each flight path position.

This was accomplished by calculating the boresight distance from the radar to the geodesic sphere. The boresight distance was simply the hypotenuse of the triangle created by the ground distance to the arbitrarily assigned flight path origin plus or minus the distance the geodesic sphere was away from that point in y and the height in z. The origin was defined at a set distance away from the radar with positive x defined as the radar's right, positive y defined as away from and in line with the radar along the ground, and z pointed away from the ground. Next, given the height (z) of the geodesic sphere, the elevation angle from the radar to the geodesic sphere could be determined. Subsequently, the azimuth angle was determined based on the lateral (x) distance from the bore-sight of the radar.

Next, the azimuth and elevation angles from the radar to the geodesic sphere for each point in fuzzy flight path were determined, the azimuthal angle was added to the fuzzy yaw angle and the elevation angle was added to the fuzzy pitch angle. Next, the fuzzy flight path (its yaw and pitch as seen by the radar) was passed into F_pp and F_tt, resulting in a fuzzy flight test measurement for each position and pose along the as seen fuzzy flight path.

The simulated flight test data were then motion compensated in the y direction. This was accomplished by comparing the vector distance along the bore-sight of the radar from the radar to the fuzzy position for each measurement point. This distance, r , was calculated using the standard three dimensional right triangle method. The difference between the truth and fuzzy positions in r was the offset distance. This offset distance was multiplied by the phase coefficient, β . The result was the degree offset from the desired position in y. The motion compensation was

only performed in y since phase is only affected by movement to and from the radar (plane wave was assumed for this analysis). This offset was added to both the pp and tt simulated fuzzy flight test data. This was the end of the Monte Carlo loop. The loop was repeated n times for each flight.

The Outdoor model's output is the same as the Indoor model, a single data vector for each flight that incorporated the error caused by the positioning system (the drone's GPS and INS). This vector was then smoothed by the desired window sizes and subtracted from the smoothed calibration results point by point. As with the Indoor model, this difference represented the error in the probe measurement due to the uncertainty in the position and pose of the geodesic sphere.

4.16 Indoor Flight Tests Introduction

The purpose of the indoor flight test was not only to determine the effects of the ViconTM uncertainty on the measurement, but more importantly to determine the ability of the geodesic sphere to measure the incident probe in a predictable fashion. By determining the error between the flight test measurement data and the predicted calibration data, it was possible to predict the accuracy of future measurements. All of the flights analyzed below were performed inside AFIT's compact range. Figure 33 is a still frame from a video from a raster scan flight flown on 6 January 2016.

Indoor flights have the potential to be much more accurate than their outdoor counterparts. This is due to the accuracy of the off-board positioning system. The system utilized in AFIT's compact range is a ViconTM system as previously described and characterized. The accuracies of such systems are much greater than that of even DGPS. As such, the resulting measurement uncertainty will be decreased. Two flight tests were looked at in this analysis, an x and z raster scan and an x , y ,

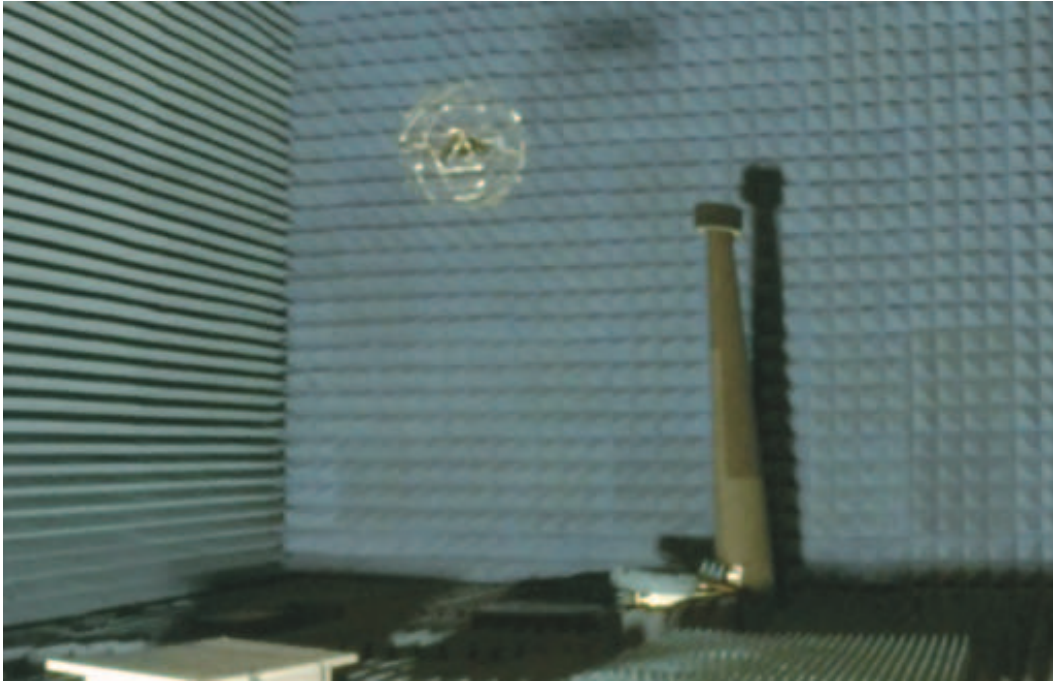


Figure 33. Video screen grab of the geodesic sphere flying inside AFIT's indoor compact range during a field measurement flight test

and z slant angle scan. These tests were designed and largely executed by Lt Lett as part of his thesis research. The following analysis utilized the previously developed Indoor Model and the ViconTM uncertainties. For each flight, the ViconTM position data was treated as truth for the analysis with its associated error bars applied on top of the results. This process was be validated during the forthcoming analysis.

One aspect of the indoor measurement uncertainty that cannot be fully quantified was the relationship between the radar pulses and the position of the geodesic sphere. The radar recorded positional information of the geodesic sphere at the beginning of each polarization's frequency sweep. Each sweep took $\approx 0.3seconds$. The drone was set to traverse the raster scan at a speed of $0.1m/s$. This meant that the geodesic sphere moved $0.3m$ during each frequency sweep. This could potentially lead to the assumed position of the geodesic sphere being incorrect for certain frequencies during analysis. For the forthcoming analysis, this source of

uncertainty was determined to be in the noise given the benign nature of the flight path of the geodesic sphere.

Bebop was controlled through a LabVIEWTM interface that utilized the current position as reported from ViconTM during all flights. For information on how the data were recorded or how the Bebop was controlled, see Lt Lett’s thesis documentation [32]. The following analysis looked only at the resulting data, not the method’s by which they were recorded.

4.17 X and Z Raster Scan Flight

Lt Lett designed this flight with a three level raster scan pattern. The movement was restricted to x and z only with all points at $y = 0.360m$ from the ViconTM origin. The desired flight paths for each of the legs is seen in Table 9. The pitch and yaw of the Bebop were left under control of the LabVIEWTM interface. Their values remained close to zero due to the slow and even movement called for in the flight plan. This flight was the second flight flown and recorded on 17 December 2015 at AFIT’s compact indoor range. Only three frequencies (3.5, 4.0, 4.5GHz) and the tt (vertical) polarization recorded in an attempt to speed up the radar and minimize the position error discussed above.

Table 9. Inputs to the 17 December X Z Raster Scan

Attribute	Leg 1	Leg 2	Leg 3
X [m]	-1.0 : 1.0	1.0 : -1.0	-1.0 : 1.0
Y [m]	0.360	0.360	0.360
Z [m]	0.757	0.300	-0.157
Yaw [°]	0.00	0.00	0.00
Velocity [m/s]	0.10	0.10	0.10

The as flown flight path was recorded and is displayed in Figure 34. The motion of the geodesic sphere was fairly steady, but did drift around in y. These drifts

would be addressed via motion compensation in the Indoor model. For this raster scan, every point was motion compensated to $0.36m$ in y as that was the desired plane of flight.

As can be seen from Figure 34, only three legs of the desired raster scan were completed before the drone needed to be landed due to growing instability. Each of the three legs of the raster scan were analyzed independently in order to get an idea of the error in the measurement for each leg.

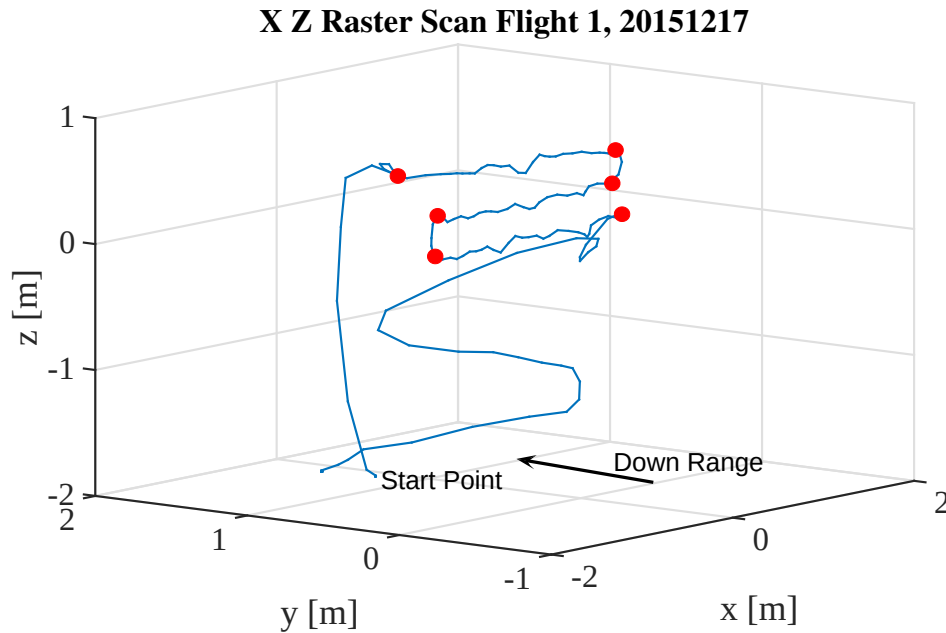


Figure 34. The recorded flight path of the geodesic sphere during the raster scan pattern flight test measurement

The start of this, and any indoor flight analysis, was to determine the start and stop indices for each of the raster portions. To do this, the flight path was plotted with respect to time, x , and z . Next, each of the start and stop points were selected using MATLAB®'s brushing tool. The selected data was copied to the clipboard and pasted into an Excel® spreadsheet. The resulting data was arranged into a matrix of start and stop points for each leg of the scan. This data was read back into MATLAB® and the index corresponding to each start and stop time was determined

using the find function in MATLAB®. These indices then became the start and stop points for all aspects of the recorded data, both radar and position data. The start and stop points for this scan are represented by the red circles in Figure 34.

These chunks of data were then individually run through the Indoor model as previously described in the Indoor model development. Given the small number of points in each chunk of data, the smoothing window sizes were set to 1 and 15. The end result of each run was a plot of the measurement error from the calibration data with uncertainty bars that corresponded to the uncertainty caused by the imperfect motion capture of the Vicon™ system for that chunk of flight test data. All of the chunks of data are reported below. Each plot is with respect to radar samples in order to remove any position backtracking during the flight.

4.17.1 X and Z Raster Scan Flight - Radar Calibration.

Prior to flying the geodesic sphere as a probe, the radar needed to be calibrated in magnitude and phase. This calibration verification was performed in accordance with the methodology stated in Section 3.3.1. This specific calibration verification was analyzed at $3.5 : 0.5 : 4.5GHz$, and only for the tt polarization, since those were the frequencies and polarization at which the flight measurement was taken.

Both the magnitude and phase uncertainties needed to be determined. The magnitude uncertainty was accomplished through the standard ALPINE® calibrateRCS.m. The phase uncertainty was accomplished by modifying the ALPINE® calibrate.RCS.m to operate on the $\text{rad2deg}(\text{angle}(\text{I and Q data}))$ as was previously accomplished in the model development. Each function was passed a frequency band of $\pm 0.1GHz$ around the desired calibration verification frequency. The results are seen in Table 10. Given these results, $4.0GHz$ was chosen as the analysis frequency for the X and Z Raster Scan Flight below. $4.0GHz$ was the best

blend of a low magnitude and a fairly low phase calibration verification. The calibration verification values were an additional source of error in the probe measurement. However, these are systematic errors, they are present and assumed to be consistent in every measurement. They also differ from range to range and day to day. As such, they are not included in this analysis effort other than to give insight to the actual accuracy of the data presented below.

Table 10. Radar calibration results for 17 December, prior to the X Z Raster Scan

Cal Type	Freq [GHz]	Std (σ)
Mag []	3.5	0.414
	4.0	0.274
	4.5	0.237
Phase [°]	3.5	12.9
	4.0	9.76
	4.5	16.1

4.17.2 X and Z Raster Scan Flight, Phase.

The x and z raster scan was broken up into three legs (the three horizontal lines in Figure 34). Each leg was an x pass at a particular altitude in z. The first chunk of data was from index 31 to 57 which corresponded to the upper leg of the raster scan. The direction of motion was from negative x to positive x. The second chunk of data was from index 55 to 81 which corresponds to the middle leg of the raster scan. The direction of motion was from positive to negative in x. The third chunk of data was from index 85 to 100 which corresponds to the bottom leg of the raster scan. The direction of motion was from negative to positive in x. Each of these segments were run through the Indoor model individually. The different legs are all slightly different in their size in samples. This is due to the flight characteristics of the probe. The data was not counted for a leg until consistent movement in the desired direction was achieved.

The first results from the model were the uncertainty in the measurement caused by the ViconTM accuracies seen in Table 8. As described in the Indoor model development, a Monte Carlo simulation was run to determine the effect of the positioning system inaccuracies on the overall measurement. This Monte Carlo simulation was run 1000 times for all chunks and flights. This number was chosen due to the results from the upcoming Outdoor model analysis. Increasing the number of trials above 1000 had very little effect on the accuracy of the results. The resultant phase uncertainties for each leg and for the tt polarization (the only polarization for this flight test) are seen in Figure 35. The uncertainty values are different for every x position of the flight. All of the errors are extremely small given the precision of the ViconTM system. The uncertainty portion of the model only looked at the yaw and pitch errors.

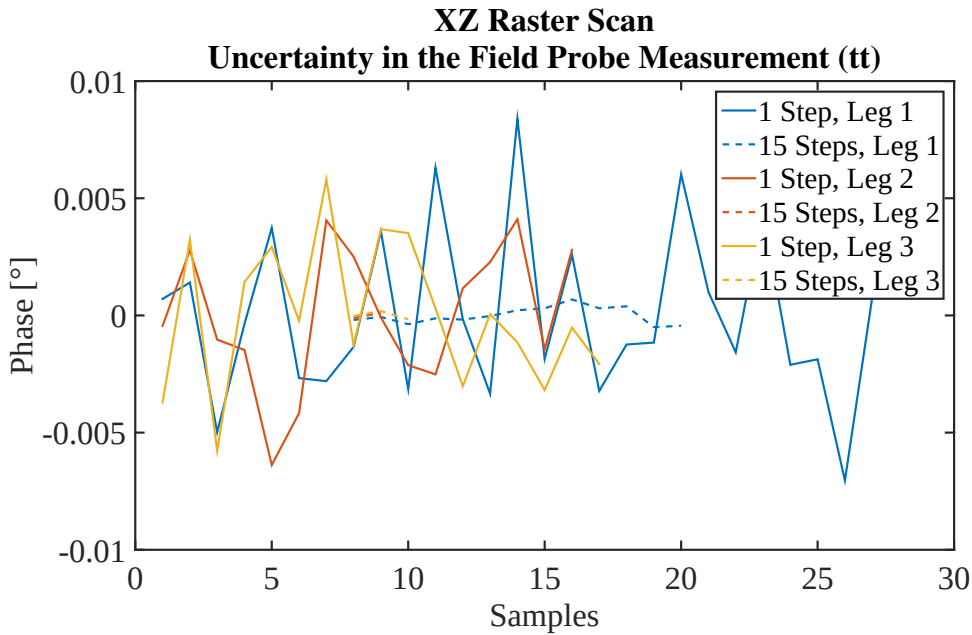


Figure 35. Phase uncertainty (tt) of all legs of the x and z raster scan measurement caused by the inaccuracies of the ViconTM measurement system

After determining the uncertainty of the measurement, the Indoor model subtracted the calibration measurement from the flight test measurement and the

uncertainty error bars were applied (for each flight leg). The resulting differences are seen in Figure 36. These differences represent the measurement error. Since the assumption for this research was perfect plane wave illumination and perfect knowledge of the sphere's position and pose, the resulting measurement errors were interpreted as a function of the geodesic sphere itself.



Figure 36. Phase errors (tt) in the incident field measurement of all legs of the x and z raster scan measurement with the ViconTM uncertain error bars applied

In order to better understand the error and to quantify the measurement, the Indoor model took the mean and standard deviation of each measurement error. The mean represents the average difference between the calibration draw and the flight test measurement caused by an error in the geodesic sphere, most likely due to damage. The standard deviation numbers represent the accuracy of the probe measurement along each flight path. Results for all of the flight legs are seen in Table 11 in the conclusion of this flight's analysis.

4.17.3 X and Z Raster Scan Flight, Magnitude.

The exact same analysis process was completed for the magnitude analysis as was done for the phase analysis. The only difference was the type of data being analyzed. The magnitude data was the absolute value of the I and Q channels (unit-less). After the Indoor model was run in magnitude mode, the uncertainty for the tt polarization was created for each leg and are seen in Figure 37. The magnitude uncertainty values are different for every x position of the flight. All of the errors are extremely small given the precision of the Vicon™ system.

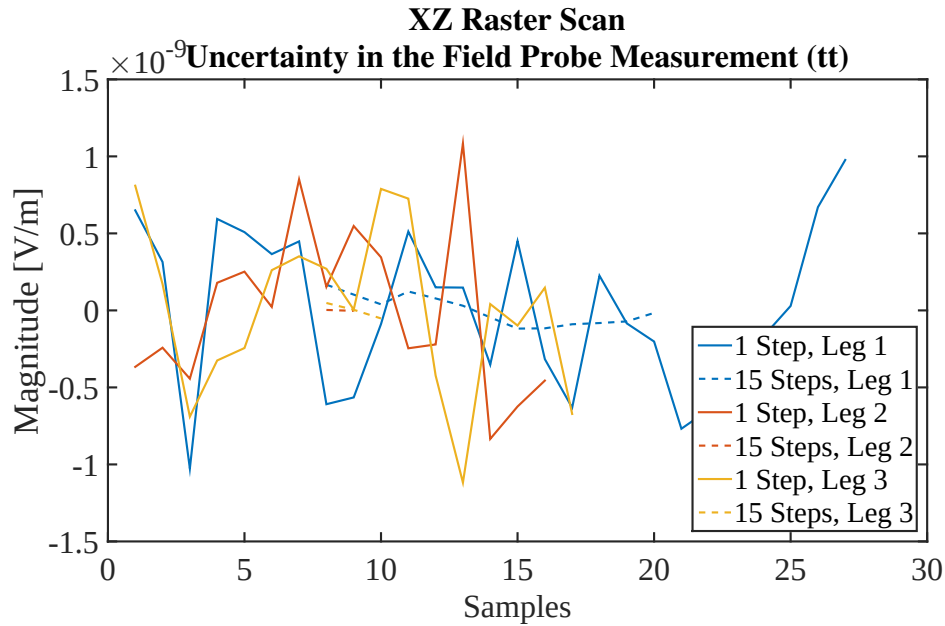


Figure 37. Magnitude uncertainty (tt) of all legs of the x and z raster scan measurement caused by the inaccuracies of the Vicon™ measurement system

After determining the uncertainty of the measurement, the Indoor model subtracted the calibration magnitude measurement from the flight test magnitude measurement and the uncertainty error bars were applied. The resulting differences are seen in Figure 38.

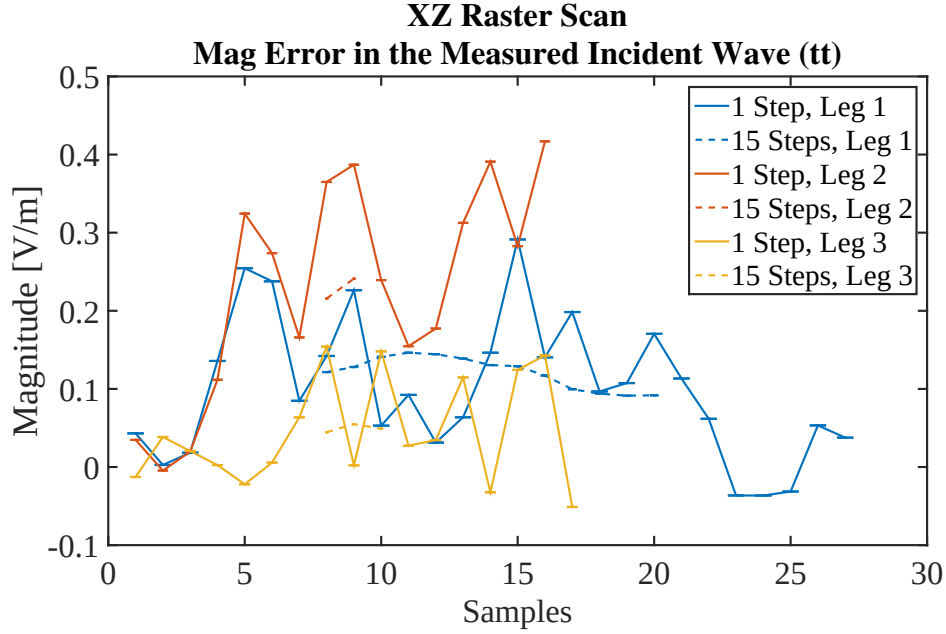


Figure 38. Magnitude errors (tt) in the incident field measurement of all legs of the x and z raster scan measurement with the ViconTM uncertain error bars applied

Once again, the mean and standard deviation of the measurement error were calculated for each leg of the flight. The results are listed in Table 11 in the conclusion of this flight.

4.17.4 X and Z Raster Scan Flight Conclusion.

The purpose of this flight profile was to probe a single plane of the indoor range at three different heights. The nature of this research effort and its subsequent analysis was not to determine what the incident wave actually looked like but to determine the accuracy of and the uncertainty in an indoor measurement. The phase and magnitude results for all three legs of the x and z raster scan are seen in Table 11.

While the one step phase error standard deviations are higher than desired, the error is quickly decreased through smoothing of the data. The uncertainties of all of the measurements, due to the ViconTM accuracy, were very small and do not cause a

Table 11. Overall error means and standard deviations in phase and magnitude for the x and z raster scan flight test measurement (tt)

	Phase				Magnitude			
	μ Error [°]		σ Error [°]		μ Error [V/m]		σ Error [V/m]	
	1 Step	15 Steps	1 Step	15 Steps	1 Step	15 Steps	1 Step	15 Steps
Leg 1	41.93	44.85	63.83	5.754	0.0100	0.1210	0.0893	0.0205
Leg 2	42.49	45.84	57.37	0.1327	0.2282	0.2284	0.1386	0.0180
Leg 3	-0.9541	1.656	49.45	2.182	0.0447	0.0495	0.0675	0.0052

decrease in the measurement capabilities of the geodesic sphere. The largest error source may be the geodesic sphere itself. The difference in means between legs 2 and 3 may support that belief. This will be looked at in the following sections.

4.18 Slanted Raster Scan Flight

Lt Lett designed this flight with a three level slanted raster scan pattern. The pitch and yaw of the Bebop were left under control of the LabVIEW™ interface. Their values remained close to zero due to the slow and even movement called for in the flight path. This flight was recorded on 7 January 2016 at AFIT's compact indoor range. After Lt Lett made some tweaks to speed up the system, the test was run from 2.0 : 0.1 : 5.0GHz for both the pp and tt polarizations without slowing down the measurement time period. The desired and actual flown flight paths for each of the legs is seen in Figure 39. It is clearly seen that the motion of the geodesic sphere was fairly steady, but did drift around in y. These drifts would be addressed via motion compensation in the Indoor model. For this raster scan, every point was motion compensated to its desired point (blue line) in y. Each of the three legs of the raster scan were analyzed independently in order to get an idea of the error in the measurement for each leg.

The start of this, and any indoor flight analysis, was to determine the start and stop indices for each of the raster portions. To do this, each of the start and stop

Desired and Actual Flight Paths, Slanted Raster Scan, 20160107

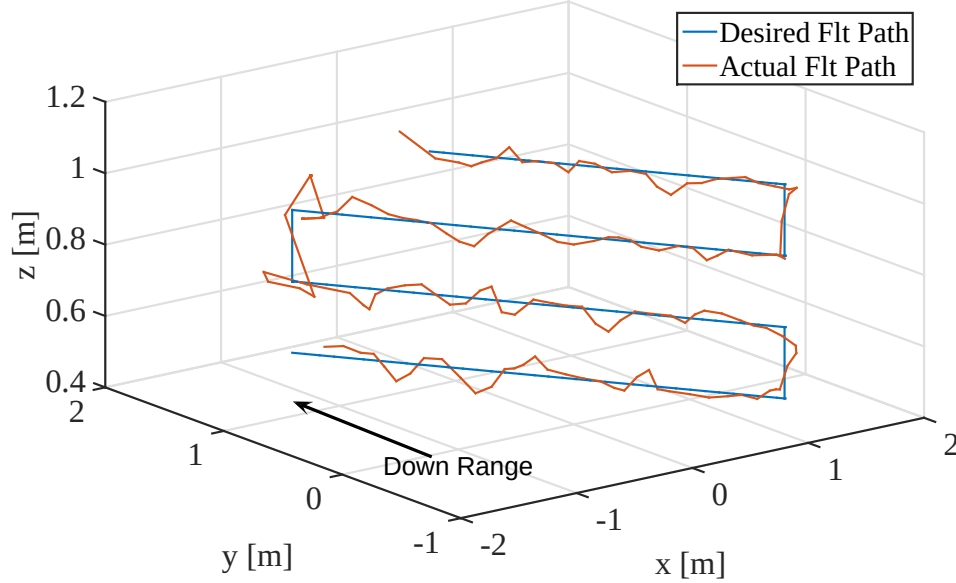


Figure 39. The desired and actual flight paths of the geodesic sphere during the slanted raster scan pattern flight test measurement

points were selected from Figure 39 using MATLAB®'s brushing tool. The indices were found in the same manner as the x and z raster scan and they became the start and stop points for all aspects of the recorded data, both radar and position data. These chunks of data were then individually run through the Indoor model as previously described in the Indoor model development. Given the small number of points in each chunk of data, the smoothing window sizes were set to 1 and 15. The end result of each run was a plot of the measurement error from the calibration data with uncertainty bars that corresponded to the uncertainty caused by the imperfect motion capture of the Vicon™ system for that chunk of flight test data. All of the chunks of data are reported below.

4.18.1 Slanted Raster Scan Flight - Radar Calibration.

As with the x and z raster scan flight, the radar needed to be calibrated in magnitude and phase. This calibration verification was performed in accordance

with the methodology stated in Section 3.3.1. This specific calibration verification was analyzed at $3.5 : 0.5 : 4.5 \text{GHz}$, for both polarizations, in order to give a direct comparison to the x and z raster scan calibration verification (tt polarization).

Both the magnitude and phase uncertainties were determined using the same method as the x and z raster flight. This was accomplished for the pp and tt polarizations. The results are seen in Table 10. Given these results, and the previous analysis of the x and z raster scan at 4.0GHz , 4.0GHz was chosen as the analysis frequency for the Slant Raster Scan Flight below. This allowed for a direct comparison of the results from each test.

Table 12. Radar calibration results for 7 January, prior to the Slanted Raster Scan

Cal Type	Freq [GHz]	pp Std (σ)	tt Std (σ)
Mag []	3.5	1.19	0.645
	4.0	0.810	0.595
	4.5	0.254	0.334
Phase [°]	3.5	11.9	10.7
	4.0	12.1	18.3
	4.5	12.5	18.4

4.18.2 Slanted Raster Scan Flight, Phase.

The slanted raster scan was flown in three legs, as such the data was broken into three legs. The first chunk of data was from index 49 to 74 which corresponded to the upper leg of the slanted raster scan in Figure 39. The direction of motion was from negative to positive in x and positive to negative in y. The second chunk of data was from index 81 to 109 which corresponded to the middle leg of the slanted raster scan. The direction of motion was from positive to negative in x and negative to positive in y. The third chunk of data was from index 131 to 153 which corresponded to the bottom leg of the slanted raster scan. The direction of motion was from positive to negative in x and negative to positive in y.

Following the same analysis pattern that was previously utilized for the x and z raster scan, the resultant phase uncertainties for the pp and tt polarization are seen in Figures 40 and 41 respectively. All the plots for this scan pattern are plotted with respect to samples since the various position entities are conjoined for this flight path. The uncertainty values were different for every sample of the flight. All of the errors are extremely small given the precision of the ViconTM system.

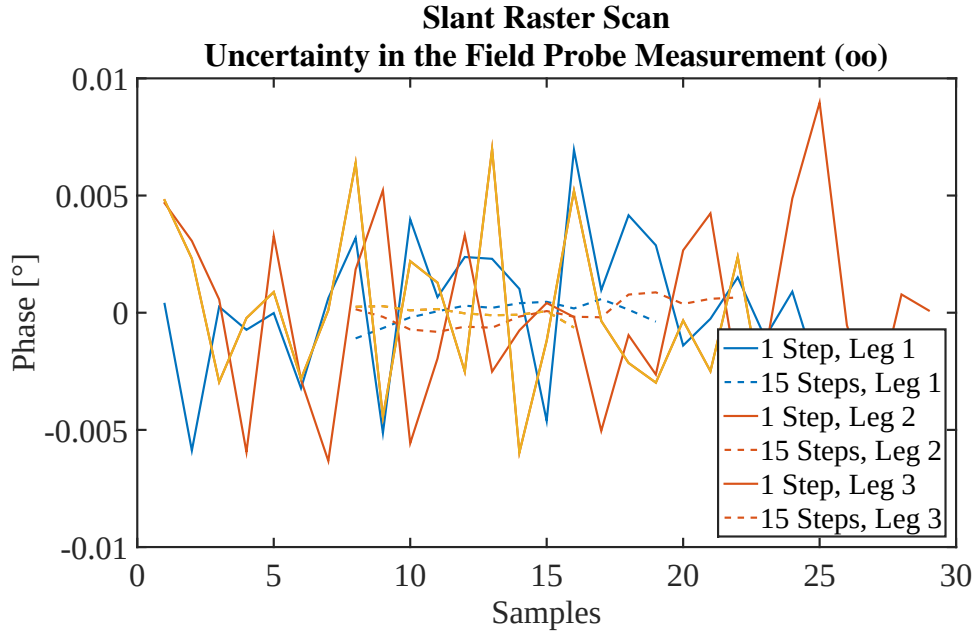


Figure 40. Phase uncertainty (pp) of all legs of the slanted raster scan measurement caused by the inaccuracies of the ViconTM measurement system

After determining the uncertainty of the measurement, the Indoor model subtracted the calibration measurement from the flight test measurement and the uncertainty error bars were applied. The resulting difference for the pp and tt polarization respectively is seen in Figures 42 and 43.

The Indoor model then took the mean and standard deviation of the measurement error. These values are reported with all the other measurements in Tables 13 and 14 in the conclusion of this section.

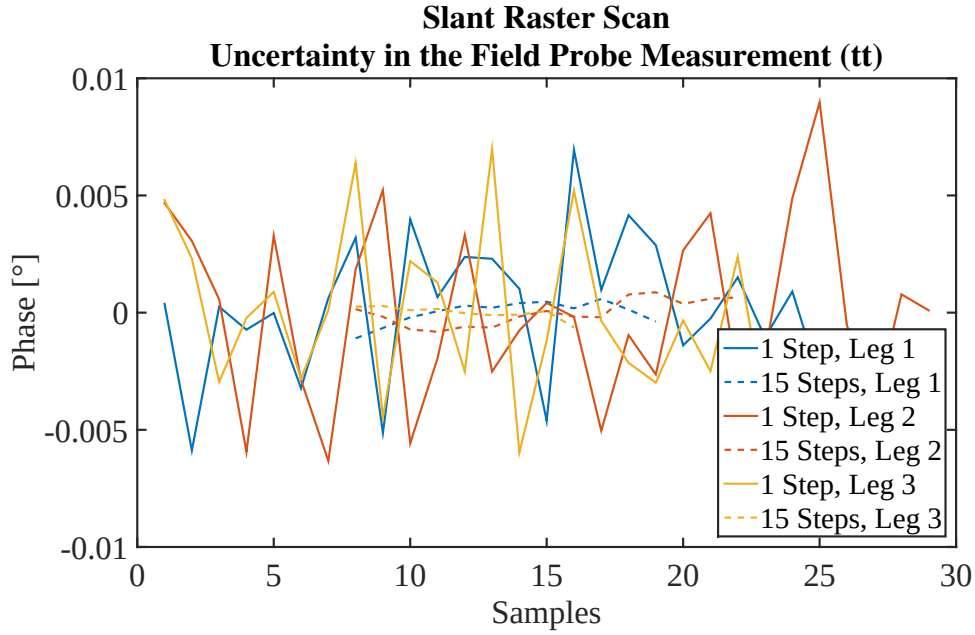


Figure 41. Phase uncertainty (tt) of all legs of the slanted raster scan measurement caused by the inaccuracies of the ViconTM measurement system

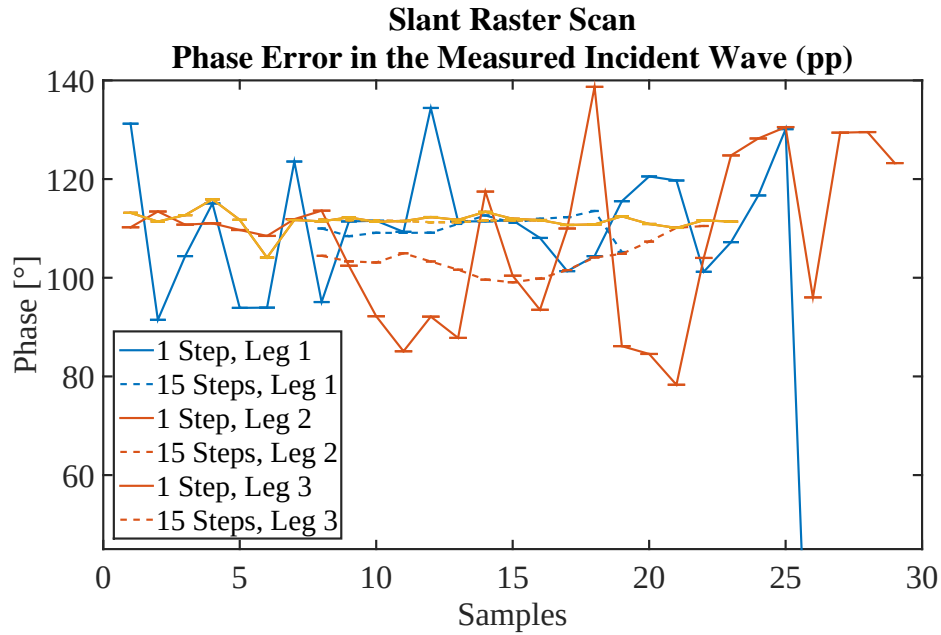


Figure 42. Phase errors (pp) in the incident field measurement of all legs of the slanted raster scan measurement with the ViconTM uncertain error bars applied

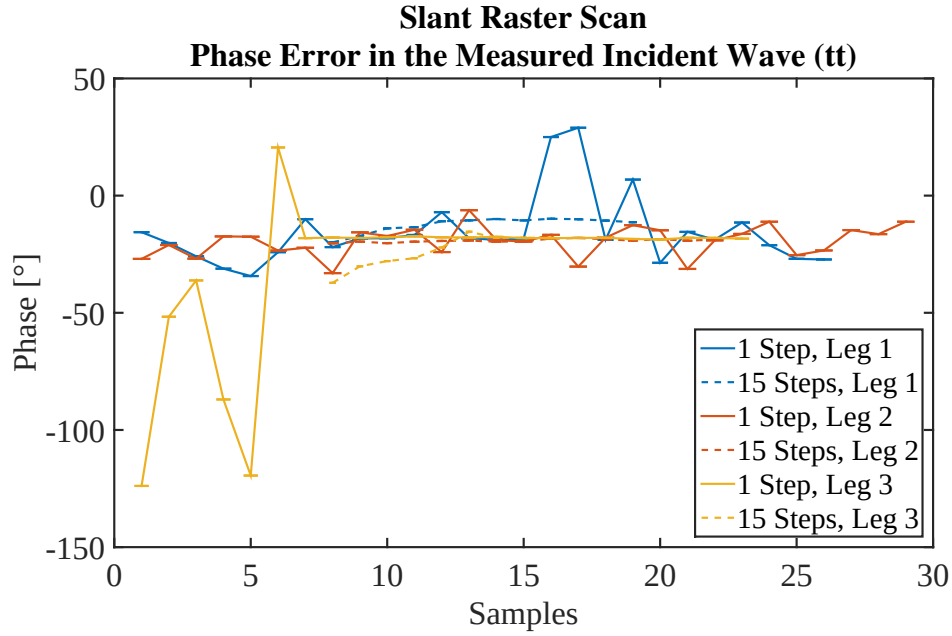


Figure 43. Phase errors (tt) in the incident field measurement of all legs of the slanted raster scan measurement with the ViconTM uncertain error bars applied

4.18.3 Slanted Raster Scan Flight, Magnitude.

The Indoor model was once again run in magnitude mode, the uncertainty for the pp and tt polarizations were created for each leg and are seen in Figures 44 and 45.

After determining the uncertainty of the measurement, the Indoor model subtracted the calibration magnitude measurement from the flight test magnitude measurement and the uncertainty error bars were applied. The resulting differences are seen in Figures 46 and 47.

Once again, the mean and standard deviation of the measurement error were calculated for each leg of the flight. The results are listed in Table 11 in the conclusion of this flight.

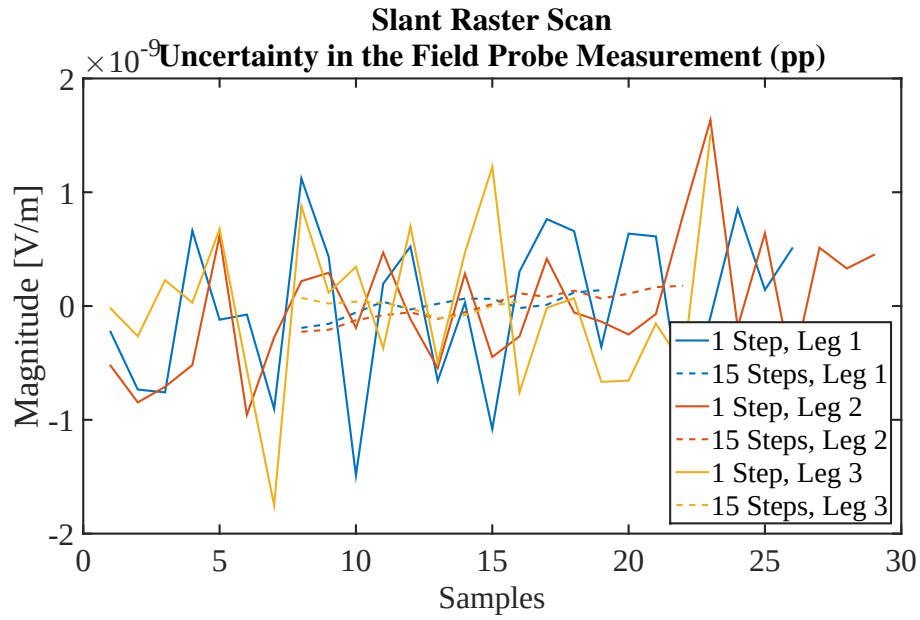


Figure 44. Magnitude uncertainty (pp) of all legs of the slanted raster scan measurement caused by the inaccuracies of the ViconTM measurement system

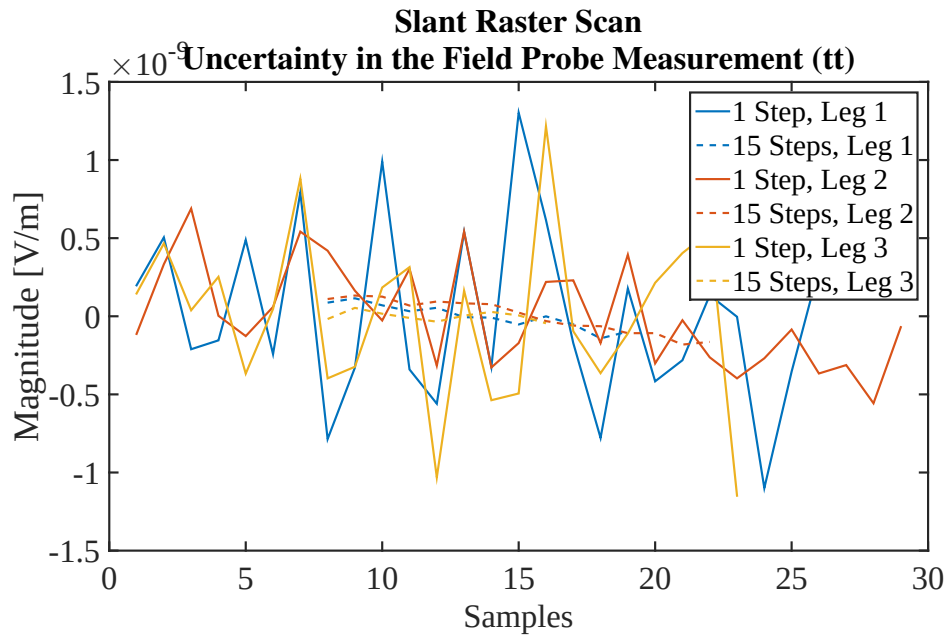


Figure 45. Magnitude uncertainty (tt) of all legs of the slanted raster scan measurement caused by the inaccuracies of the ViconTM measurement system

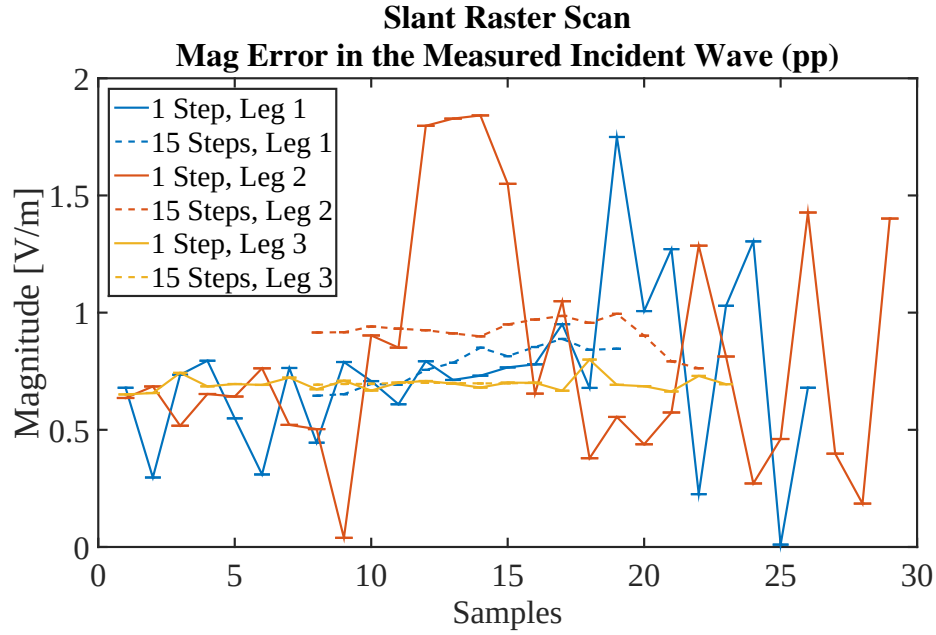


Figure 46. Magnitude errors (pp) in the incident field measurement of all legs of the slanted raster scan measurement with the ViconTM uncertain error bars applied

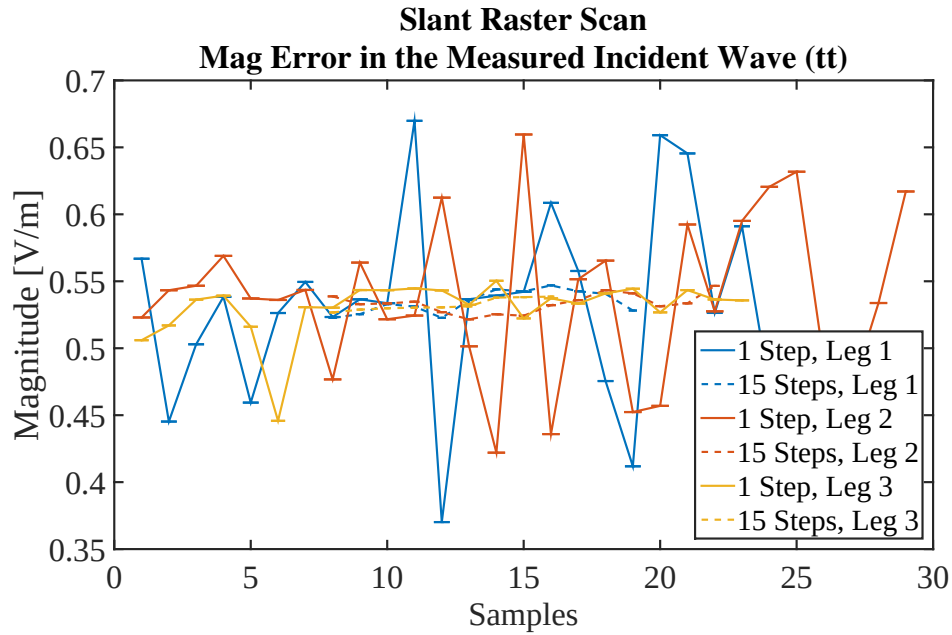


Figure 47. Magnitude errors (tt) in the incident field measurement of all legs of the slanted raster scan measurement with the ViconTM uncertain error bars applied

4.18.4 Slanted Raster Scan Flight Conclusion.

The purpose of this flight test was to probe the radar field in an efficient fashion. By moving in x and y, the cross range and down range accuracy of the geodesic sphere can be determined simultaneously. Tables 13 and 14 contain the results for all of the phase and magnitude runs discussed above for the slanted raster scan.

Table 13. Overall error means and standard deviations in phase and magnitude for the slanted raster scan flight test measurement (pp)

	Phase				Magnitude			
	μ Error [°]		σ Error [°]		μ Error [V/m]		σ Error [V/m]	
	1 Step	15 Steps	1 Step	15 Steps	1 Step	15 Steps	1 Step	15 Steps
Leg 1	106.1	110.3	27.28	2.281	0.7448	0.7766	0.3556	0.08578
Leg 2	107.7	103.8	16.13	3.444	0.8144	0.9168	0.5016	0.06388
Leg 3	111.6	111.5	1.996	0.1843	0.6964	0.6978	0.0320	0.002704

Table 14. Overall error means and standard deviations in phase and magnitude for the slanted raster scan flight test measurement (tt)

	Phase				Magnitude			
	μ Error [°]		σ Error [°]		μ Error [V/m]		σ Error [V/m]	
	1 Step	15 Steps	1 Step	15 Steps	1 Step	15 Steps	1 Step	15 Steps
Leg 1	-15.65	-12.38	14.99	3.221	0.5298	0.5346	0.07047	0.008661
Leg 2	-19.53	-19.23	6.375	0.6625	0.5386	0.5335	0.06034	0.007068
Leg 3	-30.61	-23.74	34.08	7.240	0.5304	0.5324	0.02136	0.004478

Similar patterns to those in the x and z raster flight are evident. As the smoothing window size increases, the standard deviation of the errors goes down. Both tables also add to the notion that the geodesic sphere is excellent at magnitude measurements, with and without windowing.

The phase of an EM wave changes with propagation. The consistent nature (both in mean and small standard deviation) of the phase error data for all three legs indicates that the flight test measurement technique was consistent. The large mean indicates that the geodesic sphere had a large and uncharacterized effect on

the incident field it was attempting to probe. As long as this effect was constant with respect to position in the field, its effects can be mitigated. This effect was largely polarization dependent in mean, but had very little effect on the standard deviation once windowing had been applied.

A false trend is seen in Table 13. As shown, it seems that as the leg number increases the standard deviation of the error decreases, while it happened in this case, it was not an observed trend across multiple flights. As can be seen in Table 14, the legs do not have any bearing on the size of the error. Each leg was treated independently and was flown in a different level of the incident radar wave. Each level can have its own errors and perturbations.

Just as in the x and z raster scan, the uncertainty in each measurement was negligible, both for phase and magnitude. This is due to the accuracy of the ViconTM system. These error bars would change based on the accuracies of the ViconTM system utilized in the range being probed.

4.19 Post Flights Geodesic Sphere Characterization

The geodesic sphere was crashed many times throughout the flight test process. Each crash resulted in a deformed and further broken geodesic sphere. By the last flight test, most of the wires that created the smaller triangles were broken, as were a few of the aluminum tubes; all of the aluminum tubes were bent in some way. This obvious damage and the drastic difference in the phase means of the two test flights were cause for concern as to the validity and accuracy of the original geodesic sphere calibration mesh model.

In order to quantify the effect of the physical damage on the phase characteristics of the geodesic sphere (the magnitude results were very consistent across the flights), a second geodesic sphere characterization effort was undertaken.

This characterization followed the same process and techniques as the first. The only difference was that the calibration RCS data of the geodesic sphere on the foam column was only taken from $-10^\circ : 1^\circ : 10^\circ$ in yaw and $-2^\circ : 1^\circ : 2^\circ$ in pitch. The measurement range was decreased due to the small range of yaw and pitch seen during flight. A new calibration mesh for each polarization was created for the post flight measurements.

A grid of data points was created in MATLAB[®] from $-1^\circ : 0.1^\circ : 1^\circ$ in yaw and $-1^\circ : 0.1^\circ : 1^\circ$ in pitch using the meshgrid command. This grid was passed into both the preflight and post flight calibration data meshes. The resulting calibration values were subtracted from each other grid point by grid point. The resulting surfaces are seen in Figures 48 and 49.

The differences between the two calibration meshes are drastic, $\pm 100^\circ$ in some places. To get a better idea of how the model's results could have been affected by the damage to the geodesic sphere, the first leg of the x and z raster scan yaw and pitch values were passed into both of the calibration functions. The results are seen in Figure 50. The standard deviations of the effect are small, $\sigma_{pp} = 0.1161^\circ$ and $\sigma_{tt} = 2.846^\circ$. These values provide error bounds of sorts for the standard deviations presented previously for the indoor test flights. This signifies that the damage to the sphere was consistent across the yaw and pitch values seen during the flight tests (these values were small for all flights).

However, the obvious issue is the large mean of the differences ($\mu_{pp} = -91.19^\circ$ and $\mu_{tt} = -69.90^\circ$). A phase difference of 91 corresponds to a shift in y of $1cm$. This provides no explanation since, a shift in y was not possible as only yaw and pitch values are inputted into the calibration meshes. This large change in the phase response of the geodesic sphere can only be attributed to the damage done to the geodesic sphere. An accurate correction for this damage could not be made since

Difference Between Before and After Spheres (4.0GHz, pp)

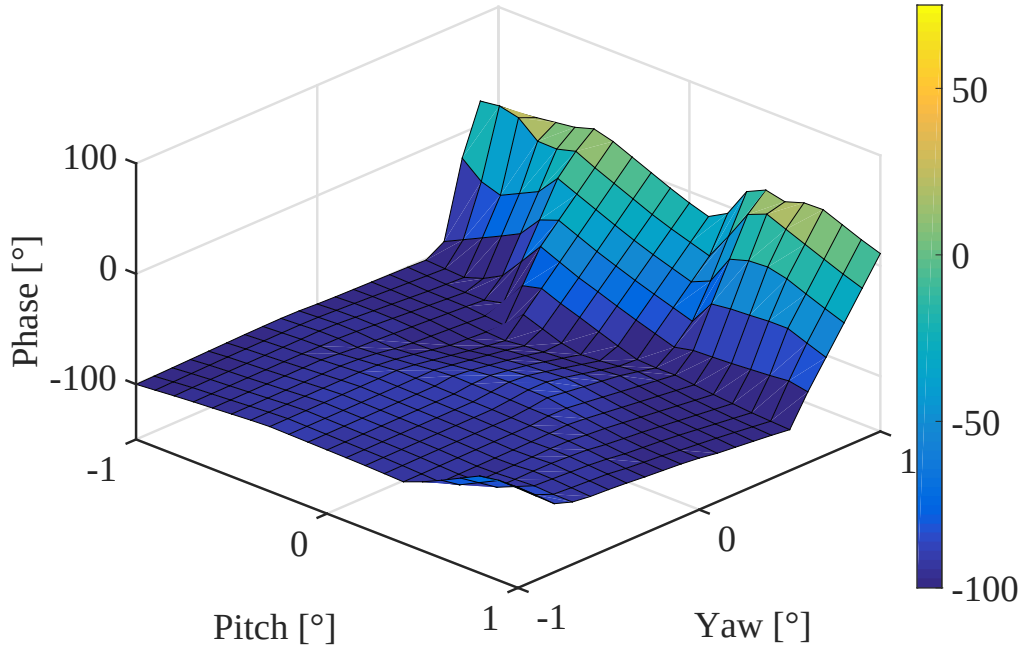


Figure 48. Mesh grid representation of the difference between the pre and post flight calibration data (pp)

Difference Between Before and After Spheres (4.0GHz, tt)

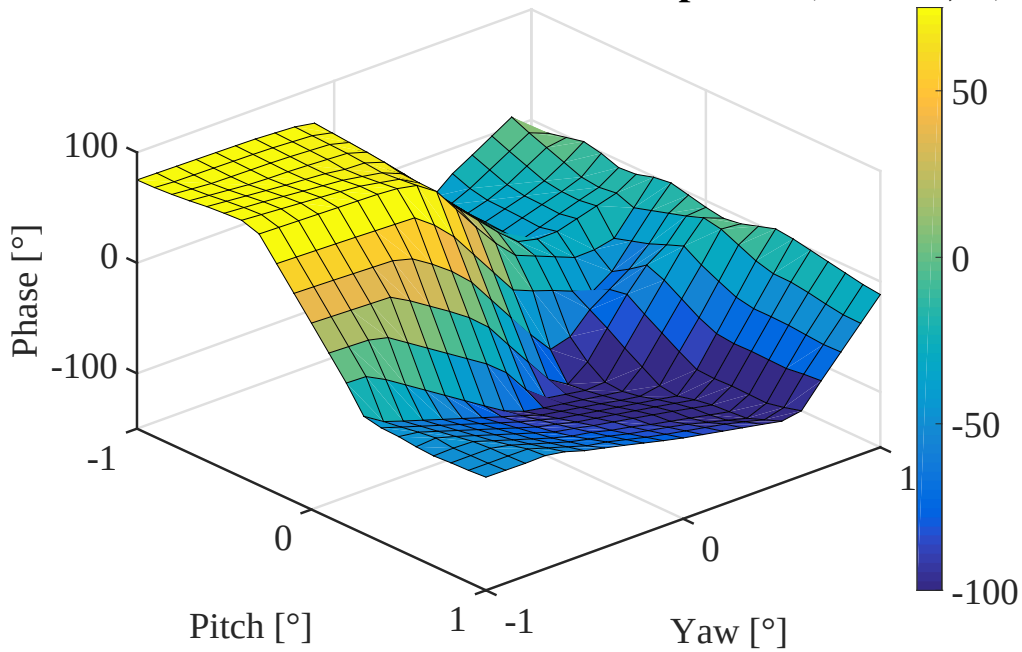


Figure 49. Mesh grid representation of the difference between the pre and post flight calibration data (tt)

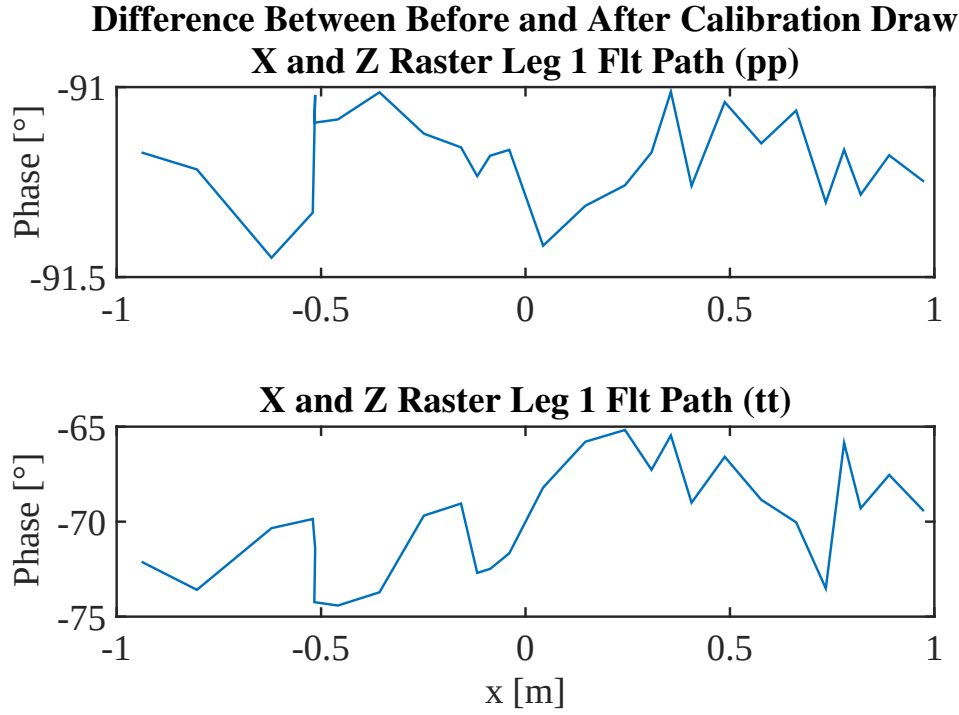


Figure 50. Difference between the pre and post flight calibration data along the first leg of the x and z raster scan

the geodesic sphere was damaged and repaired between every flight. The only way to characterize this issue would be to create the calibration data mesh before and after every flight. This would require taking the foam column measurements before and after each flight, something that was not done for this research effort.

4.20 Indoor Flight Test Conclusions

Given the variations in the before and after calibration data meshes, the means of the Indoor model results presented above for both the x and z raster and the slanted raster scans are questionable at best. The standard deviations remain unchanged, with their respective error bounds around them. The overall standard deviation of the geodesic sphere was calculated by taking the tt results for all legs and both flights and averaging them for each step size, magnitude and phase. These

results are seen in Table 15. The results for the pp polarization are simply the average of the three legs of the slanted raster results as that was the only pp flight.

Table 15. Average standard deviation values for the geodesic sphere over both flights

	Phase σ_{tt} [°]	Mag σ_{tt} [V/m]	Phase σ_{pp} [°]	Mag σ_{pp} [V/m]
1 Step	18.483	0.05492	15.14	0.2964
15 Steps	3.708	0.006352	1.970	0.05079

Traditionally, a radar wave is assumed planar if the phase front incident on the target has a taper of less than ≈ 22 . Using the above numbers, the geodesic sphere, even damaged, is capable of measuring that difference. It cannot however, determine with any accuracy what the phase actually is at each position, just the deviation from a perfect plane wave. For a detailed analysis on what the field was actually doing for each of the measurements, see the parallel research by Lt Lett [32].

4.21 Outdoor Simulations Introduction

The concept of a flying two-way probe is also applicable for use at an outdoor RCS range. The unknowns about the incident field are often greater at outdoor ranges. Therefore, the purpose of the outdoor model and the subsequent simulations was to determine the uncertainty of any probe measurement caused by the uncertainties in the GPS and INS of the geodesic sphere. In application, this model allowed for the comparison of different GPS and INS in terms of their effect on the accuracy of the quad-copter, geodesic sphere probe measurement system. The following sections explore different flight paths and GPS and INS accuracies in order to determine what is necessary to achieve a desired level of accuracy in an actual outdoor flight test.

Inputs to the Outdoor Model include a flight path, desired GPS and INS uncertainties, frequency, distance from the radar to the geodesic sphere, the desired

averaging item, interpolation method, window sizes (steps), number of Monte Carlo trials (n , integrated radar pulses), and calibrated RCS data of the geodesic sphere. The range is only used to determine the look angle at the geodesic sphere and the phase offset for motion compensation. Each flight path presented below was analyzed at multiple frequencies and Monte Carlo trial numbers.

4.22 X Only Flight Path

The flight path utilized for this data analysis effort was a simple straight line across the radar bore-sight along the x axis (negative (left) to positive (right)). Motion compensation was applied to the fuzzy measurements in order to align them with the desired x only flight path. The geodesic sphere was fixed at zero yaw (pointing away from the radar), zero pitch, and zero roll. This was the most basic flight path.

The 1000 point x axis flight path was created from $-1m : 1m$ in x . It was used as an input to the Outdoor model previously developed. The settings for this simulation are seen in Table 16. The number of Monte Carlo runs was determined by increasing the number of trials until diminished gains were achieved. The range was chosen to approximate the length of the RCS range at NRTF. The frequencies were chosen to be below the observed cutoff frequency of the sphere and inside of the frequencies at which the geodesic sphere was characterized (pp and tt polarizations were run). The step sizes were chosen based on the average length of the data files recorded during flight test measurements with the geodesic sphere. These flights averaged 200 measurement positions, necessitating a window size of less than 100 samples.

This model was designed to allow a flight path of any length. A similar flight path to that flown in the Indoor flight tests was chosen in order to determine the

Table 16. Inputs to the Outdoor Model for the X only flight path

Input	Value
n	10, 100, 500, 1000, 2500
freq	2.1, 3.1 GHz
R	2500m
Average Item	Phase, Mag
Steps	15, 45, 91
Uncertainties	Bebop, DGPS

accuracy of a similar measurement with an actual perfect plane wave. The Indoor measurement had unknown errors caused by the imperfections in the incident field. The Outdoor model simulates the measurement, so the assumption of a perfect plane wave is valid. Hence, but choosing a similar flight path to the Indoor flights, it is possible to directly apply the Outdoor model probe based uncertainties to future Indoor measurements, allowing for the determination of the Indoor illuminating fields.

4.22.1 X Only Flight Path - Phase.

Using the previous values and the basic X only flight path, the Outdoor Model was run for each number of trials, for each frequency, looking at the phase error of the probe. The model provides results in the form of error in the phase of the return (one way) at every point on the flight path as well as the standard deviation of the error across the flight path.

For this first measurement, a few plots are displayed to help explain the model's process. Following the Outdoor Model development, after the calibration mesh were created (Figures 30 and 31), the perfect flight path was passed into each calibration mesh resulting in calibration values for this specific flight path, frequency, and polarization. These values are displayed as the nearly straight line in Figure 51.

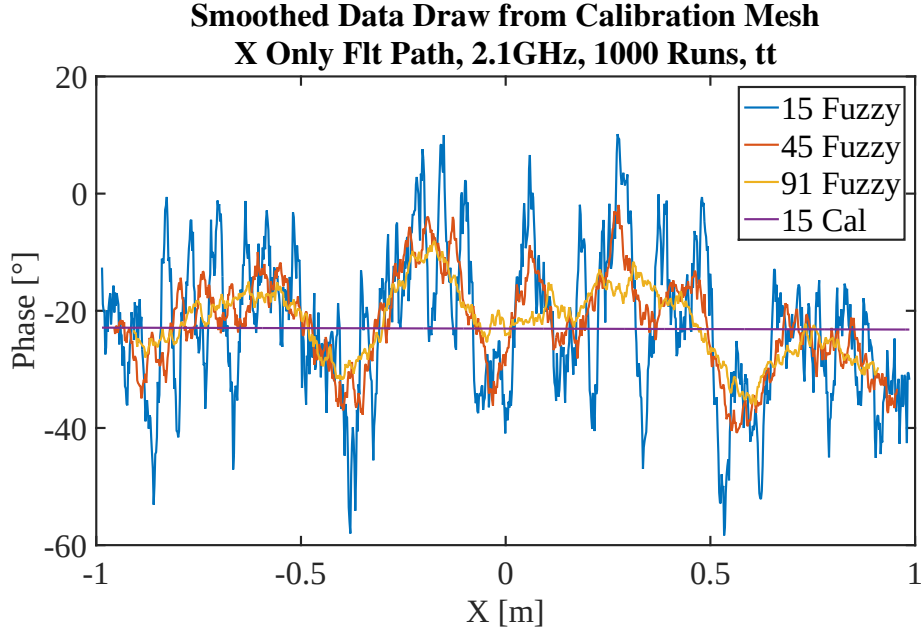


Figure 51. Data draws from calibration mesh for both the fuzzy and perfect flight paths using Bebop's accuracies at 2.1GHz along the X only flight path

Assuming perfect plane wave illumination, the expectation was that the calibration phase measurement would be a flat line at zero since the motion was along the x axis (y remained zero the entire flight). The bias in the phase away from zero is believed to have been caused by the interaction of the geodesic sphere with the radar wave. Given the spherical and permeable nature of the geodesic sphere, the incident wave does not get directly reflected. Due to this interaction, the phase is less than zero even though the flight path was along the normalized phase origin.

The pitch seen by the radar for the x only flight path was zero for the entire flight. The yaw seen by the radar was $\pm 0.023^\circ$. Figure 52 is a detail view of the bottomless geodesic sphere calibration mesh. The linear nature of the phase in this region is clearly seen, as is the phase value of $\approx 23^\circ$. This explains the bias seen in Figure 51. This bias is normalized out when the fuzzy data (developed next) and the calibration data are subtracted from one another.

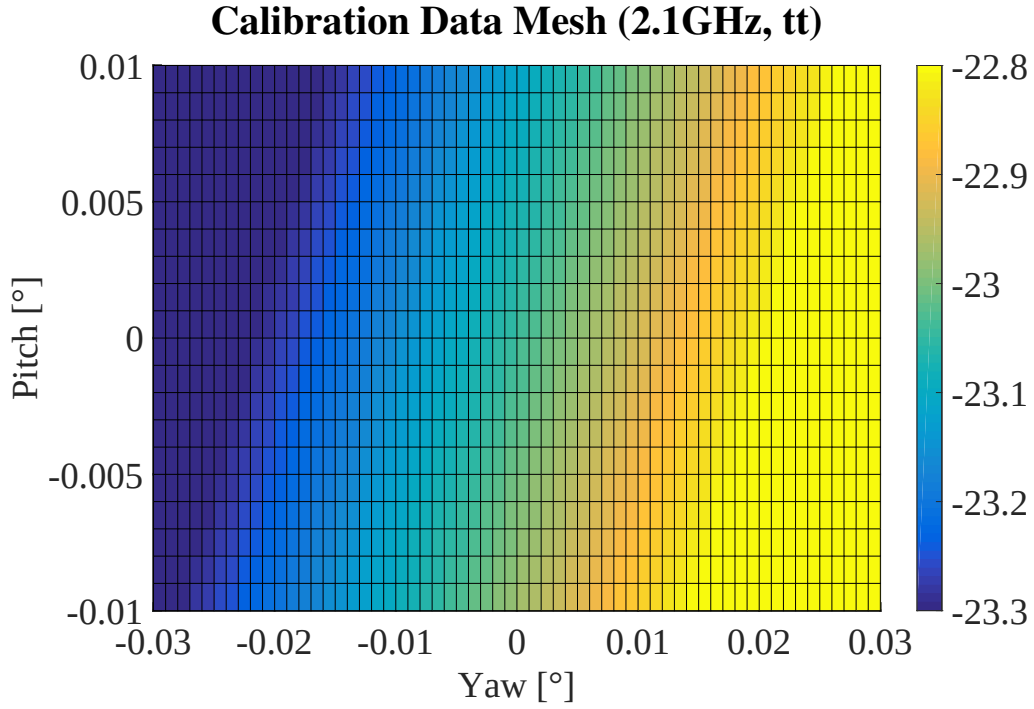


Figure 52. Calibration mesh around the as seen pitch and yaw at 2.1GHz along the x only flight path

Next, the Monte Carlo analysis was performed on the perfect flight path. Each version of the fuzzy flight path (one for each run of the Monte Carlo) was passed into the calibration mesh and motion compensated to the true flight path position. After completing the runs, the resulting phase measurements were averaged down the n runs dimension. This produced a single, fuzzy, data draw from the calibration mesh. This single draw, smoothed with different window sizes, was plotted against the calibration data draw. The results are seen in Figure 51. Only the tt polarization is shown as the pp polarization was nearly identical due to the benign nature of the flight path.

These two data sets were subtracted from one another to produce the error in the measurement caused by the uncertainty in the Bebop's positioning system. Figure 53 is a plot of the phase error for each smoothing window as a function of X. Given

the constant nature of the calibration values, the shape of the fuzzy paths remains the same in Figures 51 and 53. The only change is the mean of the waveform.

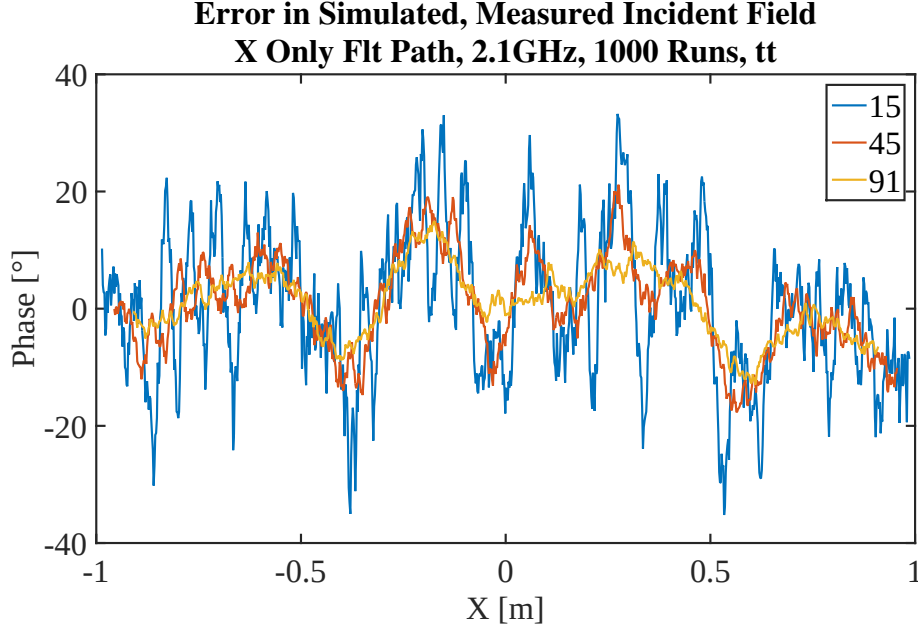


Figure 53. Error in geodesic sphere phase measurement using Bebop's accuracies at $2.1GHz$ along the x only flight path

The identical analysis at $3.1GHz$ reveals almost identical results. These results are seen in Figures 54 and 55. The changes are on the order of single degrees which are not evident in these plots due to the scale. These changes will be investigated next.

One of the features of the geodesic sphere utilized for this research is it's frequency dependence. There are three ways to mitigate the error in the positioning system of the drone. The first way is to choose a frequency at which the reflected phase is less angle dependent. The second method is to increase the radar pulses on the geodesic sphere at each position of its flight path. Third is smoothing the resulting data. The larger the window size, the more smooth the data, but, the more data that needs to be taken. The following analysis looks at all three methods simultaneously.

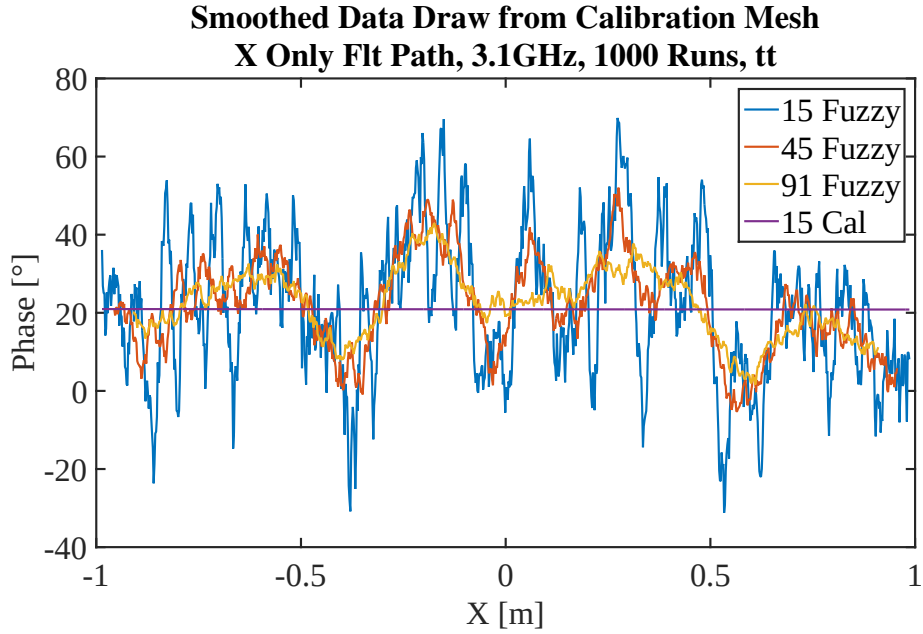


Figure 54. Data draws from calibration mesh for both the fuzzy and perfect flight paths using Bebop's accuracies at 3.1GHz along the x only flight path

The last step of the Outdoor model was to calculate the standard deviation of error over the entire flight path. This value was recorded for both of the frequencies and all of the Monte Carlo iteration values. All of the data points were tabulated and plotted in Figure 56. This figure clearly demonstrates that as the window size increases, the standard deviation of the error decreases. The same relationship is true for the number of Monte Carlo runs; as the number of runs increases the standard deviation decreases. A drastic increase is seen in the first 500 pulse integrations, the effect of more pulses quickly diminishes thereafter.

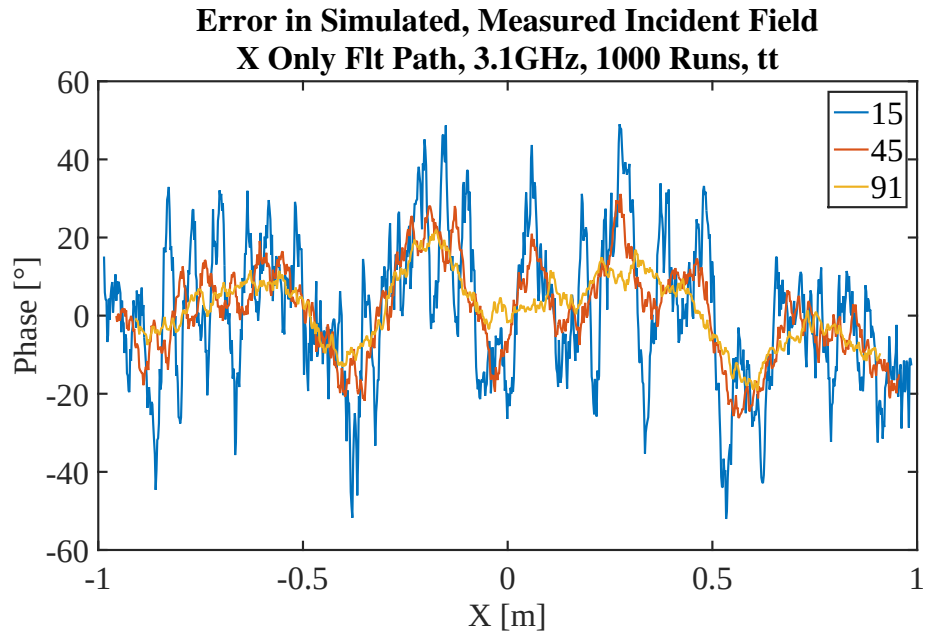


Figure 55. Error in geodesic phase measurement using Bebop's accuracies at $3.1GHz$ along the x only flight path

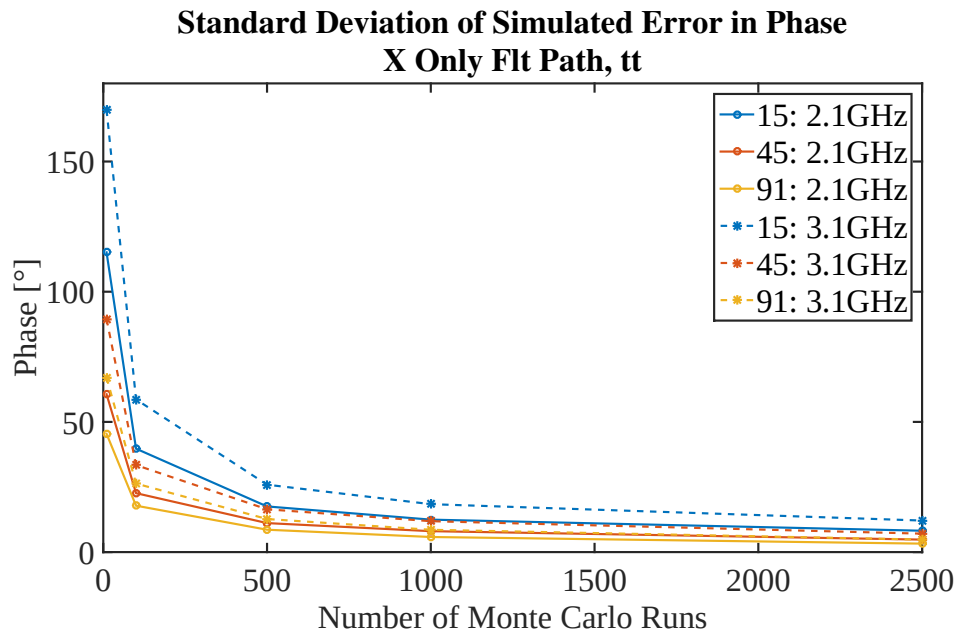


Figure 56. Comparison of the standard deviation of the error in phase over the entire x only flight path using Bebop's accuracies over multiple frequencies and Monte Carlo iterations

4.22.2 X Only Flight Path - Magnitude.

The same flight path and model inputs were utilized for this magnitude data analysis effort. The Outdoor Model was run for each number of trials, for each frequency, looking at the probes error in magnitude. The model provides results in the form of error in the magnitude of the return at every point on the flight path as well as the standard deviation of the error across the flight path. Motion compensation was not performed for any magnitude run as it would have no effect on the end result.

The Outdoor Model was run in order to determine the accuracy of the geodesic sphere with the Bebop's accuracies for magnitude measurements. The results are seen in Figures 57 and 58. The errors are almost zero for every frequency, window size, and pulse integration number. A similar shape to what was seen in Figure 56 is seen in Figure 58. This is expected given the iterative nature of the Monte Carlo process. The more pulses that hit the target at a given position, the more accurate the measurement. Once again, only the tt results are shown since the pp results act the same way and have similar values.

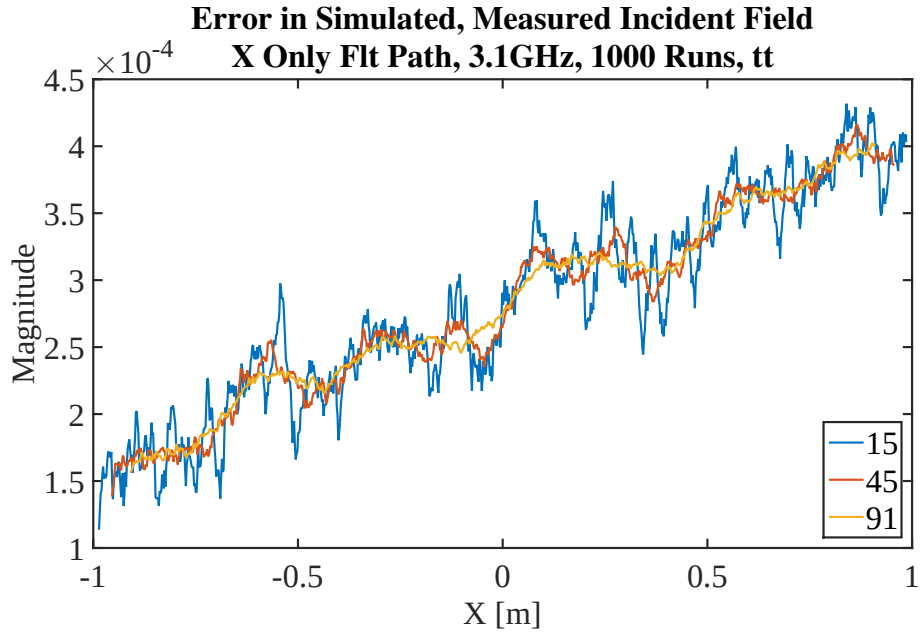


Figure 57. Error in geodesic magnitude measurement using Bebop's accuracies at 3.1GHz along the x only flight path

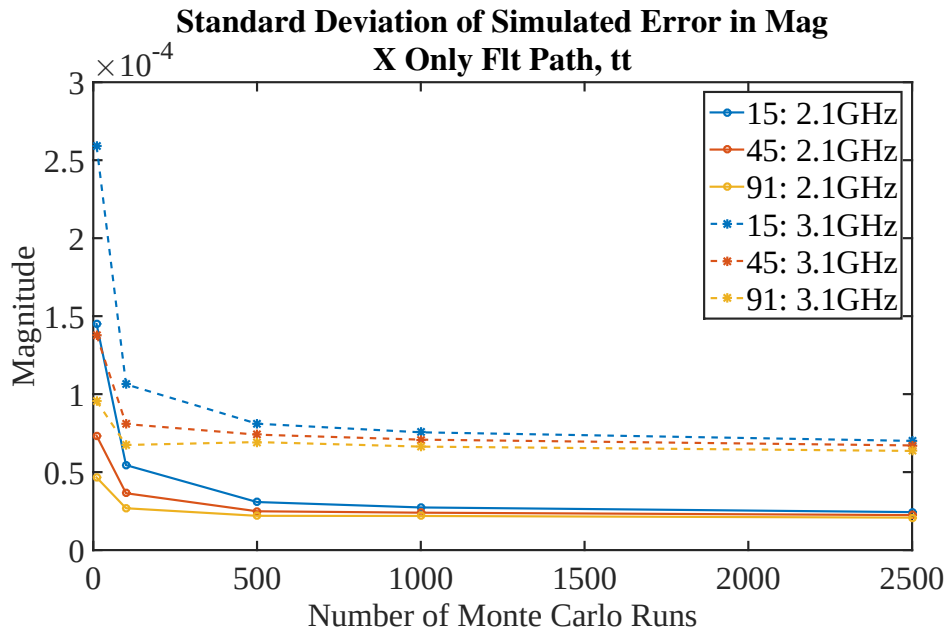


Figure 58. Comparison of the standard deviation of the error in magnitude over the entire x only flight path using Bebop's accuracies over multiple frequencies and Monte Carlo iterations

4.22.3 X Only Flight Path - DGPS Accuracies.

An easy improvement to the Bebop's positing system would be to add a DGPS unit to the quad-copter (inside of the geodesic sphere). No modifications to the Bebop would need to be made. The Bebop's internal positioning system would still be used for flying the drone, but the external DGPS would provide more accurate x, y, and z positions. The Bebop's internal INS would still be utilized. It is possible to use a more accurate INS as well, but the uncertainty due to the positioning system is much greater than those of the pose system.

A comparison of the two GPS's accuracies is seen in Table 17. The DGPS accuracy values came from the reported standard deviations of the Novatel DGPS system utilized in the Bebop's GPS characterization. The uncertainty of $\pm 0.02m$ was reported for latitude, longitude, and height.

Table 17. Overall Bebop and DGPS accuracies

Attribute	Bebop Accuracy	DGPS Accuracy
GPS	$0.987m$	$0.02m$
Altitude	$1.975m \pm 0.0277m$	$0.02m$
Roll	$0.2440^\circ \pm 0.1037^\circ$	
Pitch	$0.1190^\circ \pm 0.1144^\circ$	
Yaw	$0.3803^\circ \pm 0.1781^\circ$	

The same Outdoor Model was run for 1000 iterations, at both $2.1GHz$ and $3.1GHz$, in order to determine the phase error in the measurement. The magnitude error was also determined but not reported on since the difference in error in magnitude between the Bebop GPS and the DGPS was less than 0.0005%. Table 18 displays the results for the x only flight path after a 1000 iteration Monte Carlo for both frequencies. The improvement in the error by increasing the accuracy of the GPS is drastic. This result was expected given the dependency of phase measurements on y. The less error in y, the less error in phase.

Table 18. X Only Flt Path Phase Error (1000 iterations)

Freq (GHz)	GPS	Steps	Error Std (pp°)	Error Std (tt°)
2.1	Bebop	15	12.47	12.47
		45	8.042	8.041
		91	5.803	5.801
2.1	DGPS	15	0.5053	0.5049
		45	0.3260	0.3252
		91	0.2350	0.2336
3.1	Bebop	15	18.41	18.41
		45	11.87	11.87
		91	8.565	8.570
3.1	DGPS	15	0.7451	0.7483
		45	0.4799	0.4844
		91	0.3452	0.3509

Given the obvious benefit of using a DGPS, especially for phase measurements, it was desirous to look at the effect of pulse integration on the DGPS results. The same inputs seen in Table 16 were input into the Outdoor Model, this time with the DGPS accuracies. Figure 59 shows the decrease in phase error as a result of increased pulses on the target. The $3.1GHz$ lines are not visible because they exactly overlay the $2.1GHz$ lines. The pp polarization graph is exactly the same. Even with only 10 integrated pulses, the phase error for the x only flight path was 4.669° for both frequencies and both polarizations.

4.23 X Y Slant Flight Path

The flight path utilized for this data analysis effort was a simple straight slant in x and y across the radar bore-sight (negative to positive). The 1000 point flight path was created from $-1m : 1m$ in x and $-0.2m : 0.2m$ in y. It was used as an input to the Outdoor model previously developed. Motion compensation was applied to the fuzzy measurements in order to align them with the desired x y slant. The geodesic sphere was fixed at zero yaw (pointing away from the radar), zero pitch, and zero

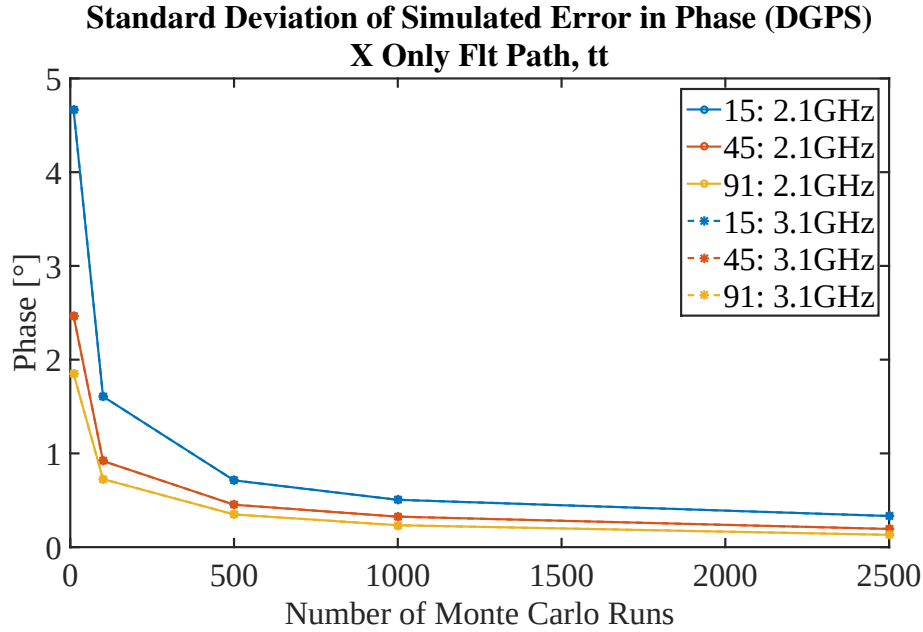


Figure 59. Comparison of the standard deviation of the error in phase over the entire x only flight path using DGPS accuracies over multiple frequencies and Monte Carlo iterations

roll. The settings for this simulation were the same as the x only flight path and are seen in Table 16 with an additional run of 5000 iterations. The only input that changed from the x only run to this x y slant run was the flight path.

The expected results are what theory dictates. As the probe moves away from the radar in y, the phase should increase. Since plane wave illumination is assumed, the movement in x should not have any effect on the phase measurement.

4.23.1 X Y Slant Flight Path - Phase.

The analysis that was performed on the x only flight path was also performed on this x y slant path. Figure 60 shows the expected slanted phase line for the calibration data. The fuzzy data oscillates around the calibration line as expected.

After both sets of data were created, the two were subtracted. The resulting error in the probe measurement is seen in Figure 61. This error is a result of the

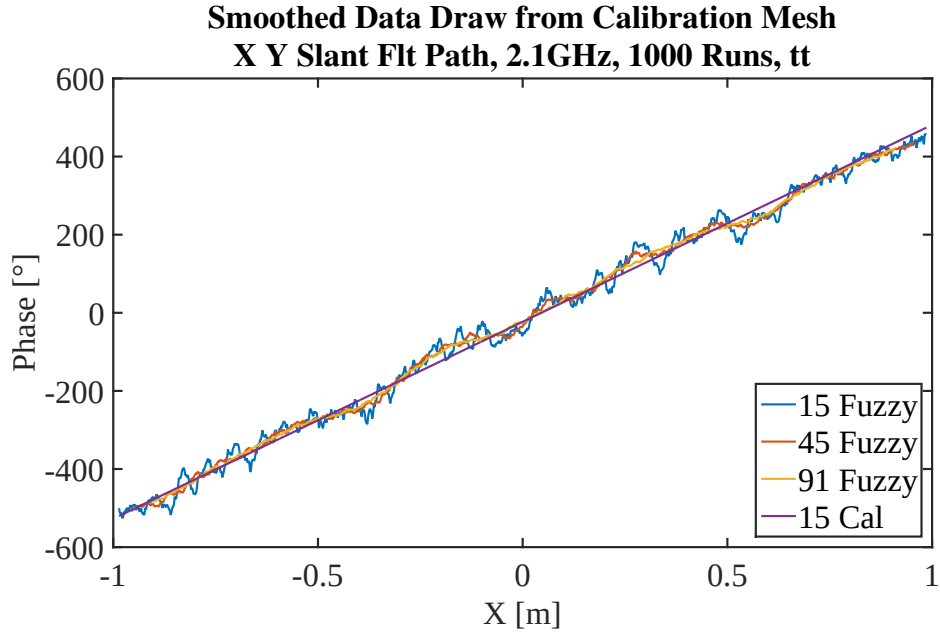


Figure 60. Data draws from calibration mesh for both the fuzzy and perfect flight paths using Bebop's accuracies at 2.1GHz along the x and y slant flight path

uncertainty in the Bebop's positioning system. The performance of the probe at 3.1GHz is virtually identical. The graphs are omitted but the standard deviations will be reported in tabular form.

Just as with the x only flight path, all of the data points were tabulated and plotted in Figure 62. This figure clearly demonstrates that as the window size increases, the standard deviation of the error decreases. The same relationship is true for the number of Monte Carlo runs; as the number of runs increases the standard deviation decreases. A drastic increase was seen in the first 500 pulse integrations, the effect of more pulses quickly diminishes thereafter.

These results are consistent with the x only flight path as they should be. In both flight paths, the pitch and yaw seen by the radar were very similar and very close to zero. This causes the probe to act the same way over both flight paths.

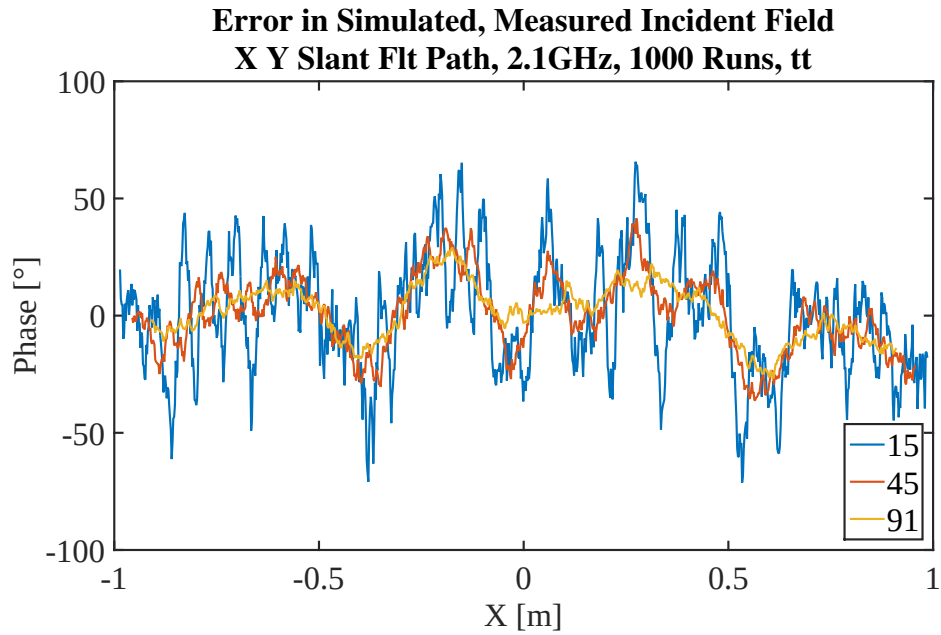


Figure 61. Error in geodesic phase measurement using Bebop's accuracies at $2.1GHz$ along the x and y slant flight path

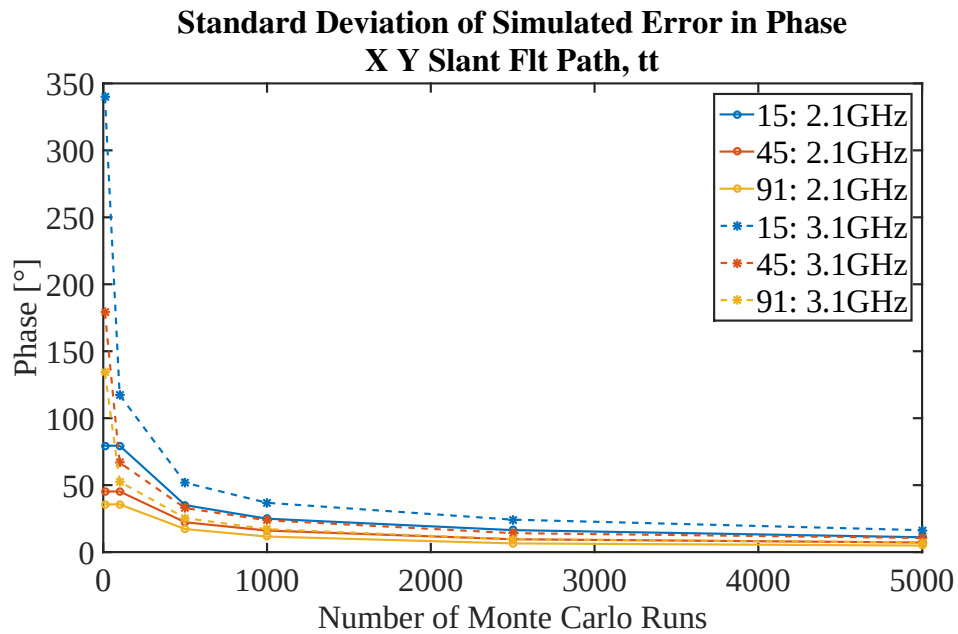


Figure 62. Comparison of the standard deviation of the error in phase over the entire x y slant flight path using Bebop's accuracies over multiple frequencies and Monte Carlo iterations

4.23.2 X Y Slant Flight Path - Magnitude.

The same flight path and model inputs were utilized for this magnitude data analysis effort. The Outdoor Model was run in order to determine the accuracy of the geodesic sphere with the Bebop's accuracies for magnitude measurements. The results are seen in Figures 63 and 64. The errors are almost zero for every frequency, window size, and pulse integration number. A similar shape to what was seen in Figure 56 is seen in Figure 64. This was expected given the iterative nature of the Monte Carlo process. The more pulses that hit the target at a given position, the more accurate the measurement. For comparison, the pp polarization is shown here. It is nearly on the same scale and has the same shape as the results from the x only flight.

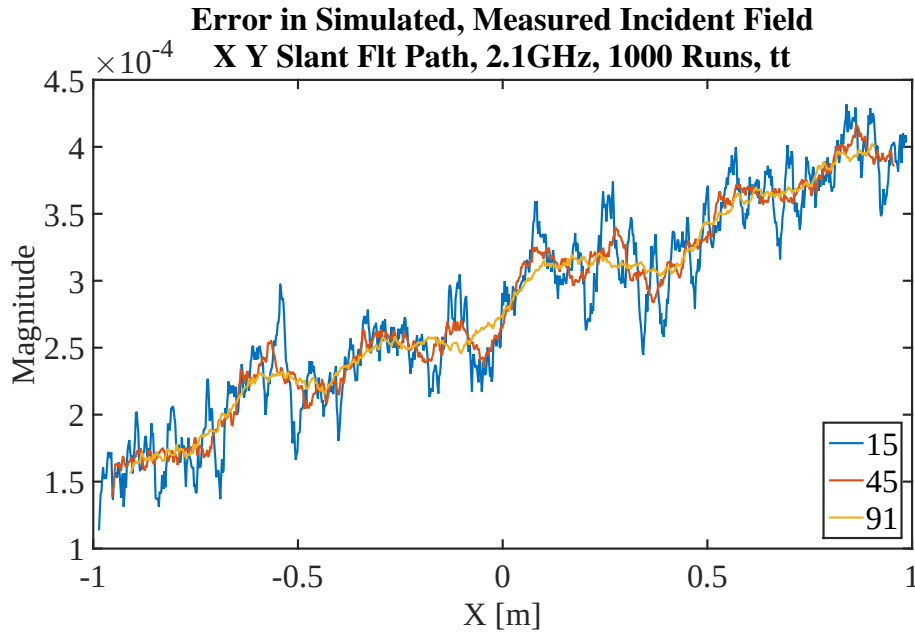


Figure 63. Error in geodesic magnitude measurement using Bebop's accuracies at 3.1GHz along the x and y slant flight path

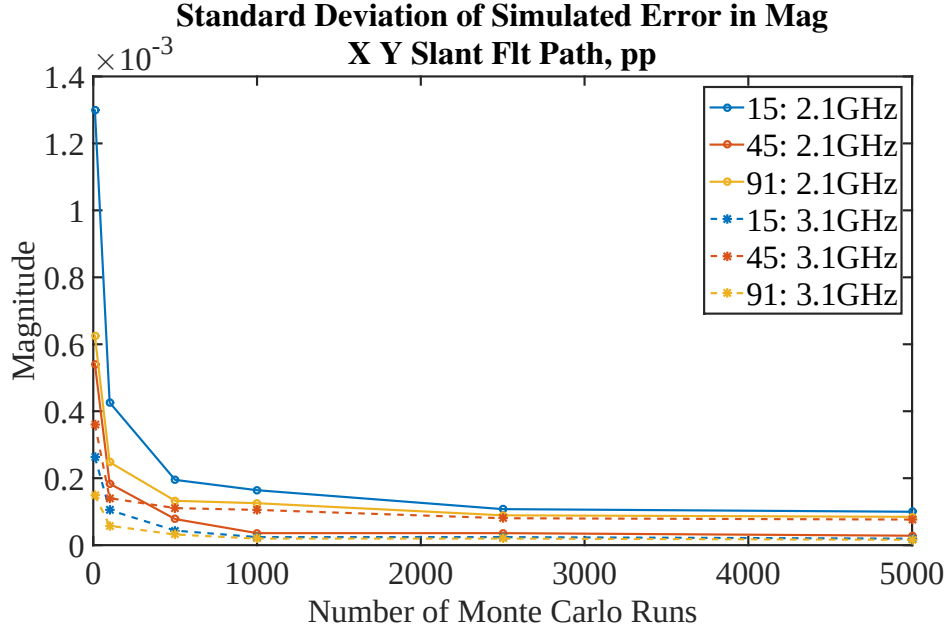


Figure 64. Comparison of the standard deviation of the error in magnitude over the entire x y slant flight path using Bebop's accuracies over multiple frequencies and Monte Carlo iterations

4.23.3 X Y Slant Flight Path - DGPS Accuracies.

The same Outdoor Model was run for 1000 iterations, at both $2.1GHz$ and $3.1GHz$, in order to determine the phase error in the measurement. The magnitude error was also determined but not reported on since the difference in error in magnitude between the Bebop GPS and the DGPS was less than 0.0005%. Table 19 displays the results for the x y slant flight path after a 1000 iteration Monte Carlo for both frequencies. The improvement in the error by increasing the accuracy of the GPS is drastic. This result is expected given the dependency of phase measurements on y. The less error in y, the less error in phase.

The DGPS results are the exact same as for the x only flight path. This is good news for the concept of a two way probe. The goal is to be able to fly the probe throughout the test volume and determine the incident waveform at various

Table 19. X Y Slant Flt Path Phase Error (1000 iterations)

Freq (GHz)	GPS	Steps	Error Std (pp°)	Error Std (tt°)
2.1	Bebop	15	24.94	24.94
		45	16.08	16.08
		91	11.61	11.61
2.1	DGPS	15	0.5053	0.5049
		45	0.3260	0.3252
		91	0.2350	0.2336
3.1	Bebop	15	36.81	36.82
		45	23.74	23.75
		91	17.13	17.14
3.1	DGPS	15	0.7451	0.7483
		45	0.4799	0.4844
		91	0.3452	0.3509

locations. In order for this to be possible, the accuracy of the probe needs to be the same regardless of the position or orientation.

4.24 Outdoor Simulations Conclusion

The purpose of the outdoor model and the subsequent simulations was to determine the uncertainty of any probe measurement caused by the uncertainties in the GPS and INS of the geodesic sphere. The goal was to use the model to determine what accuracy and pulse integration was necessary for making accurate and repeatable phase and magnitude measurements of the incident EM field. The error in magnitude measurements were nearly zero for all flight paths, smoothing, window sizes, frequencies, number of pulses, and GPS accuracies.

The error in the phase measurements had a strong connection to the number of pulses; as the number of pulses went up, the error in the phase measurement went down. It did not, however, have a large dependency on flight path, frequency, or polarization. This was due to the benign nature of the flight paths and the small range of pitch and yaw seen by the radar.

The largest affect on the accuracy of the phase measurement was the accuracy of the GPS used. This dependency was caused by the uncertainty in y, which lead to an uncertainty in phase. The smaller the y errors in the flight path, the smaller the phase errors in the measurement. This is why the DGPS system had the same error for both flight paths.

Table 20 illustrates the conclusions above. The data chosen is for the best case for the radar, a low number of pulse integrations (10) and a small smoothing window size (15 steps). These choices would allow for a fast and nimble scan of the test volume.

Table 20. Comparison of X Only and X Y Slant Flight Paths (10 iterations, 15 steps)

X Only Flight Path			
Freq (GHz)	GPS	Error Std (pp°)	Error Std (tt°)
2.1	Bebop	115.1	115.1
	DGPS	4.669	4.669
3.1	Bebop	169.9	169.9
	DGPS	6.890	6.898

X Y Slant Flight Path			
Freq (GHz)	GPS	Error Std (pp°)	Error Std (tt°)
2.1	Bebop	79.46	79.45
	DGPS	4.669	4.669
3.1	Bebop	339.9	339.9
	DGPS	6.890	6.898

4.25 Conclusion

This research effort was designed to determine the uncertainties in a EM field measurement using the geodesic sphere. The uncertainties due to the sphere itself as well as the positioning system were analyzed and determined. Two specific indoor flight test measurements were utilized to determine the uncertainty of the geodesic sphere itself while simulated data were used to determine the effect of position and

pose uncertainty a probe measurement. It was determined that the geodesic sphere as a two way probe can be effective and accurate if an adequate positioning system is used and the geodesic sphere is characterized before and after each measurement flight.

An aspect independent statistical quantity was not found, but the calibration data draw method proved effective and straightforward. The interpolation between full degree increments in the calibration measurement data is most likely a large driver of the uncertainty of the geodesic sphere given the sharp changes in the calibration data mesh (Figures 30 and 31). Ways of fixing the issues found during this analysis will be discussed in the following chapter.

V. Conclusions and Recommendations

“If we knew what it was we were doing, it would not be called research,
would it?”

- Albert Einstein [39]

5.1 Introduction

This final chapter summarizes the findings previously presented. It discusses the overall conclusions drawn from the previous analysis, both in terms of the uncertainty and the applicability of the geodesic sphere as a two way probe. It also presents follow-on research related to this effort.

5.2 Analysis Conclusions

The specific conclusions of each analysis effort were presented in their respective analysis sections. This section serves to bring all of the final conclusions together in order to gain a complete understanding of the research and analysis that was completed. There were many aspects of this research effort, all with the common goal of determining the uncertainty in a geodesic sphere probe measurement.

The first research topic that was analyzed was the RCS response of the original, wired, and bottomless geodesic spheres, both in phase and magnitude. No aspect independent statistical attribute was found upon analysis. Since the measurement of the geodesic sphere could not be used by itself for probing the field, a truth source needed to be developed. This truth source was created (referred to as the calibration data mesh) and utilized in both the Indoor and Outdoor models.

Prior to developing any model, the quad-copter being used (Parrot Bebop) needed to be characterized. This involved both static and dynamic testing of its

internal GPS and INS. Each quantity was treated independently, creating a worst case analysis. The DGPS uncertainties were read from the computer controlling the Novatel DGPS system in the golf cart. The results of that analysis were shown in Table 17 reprinted here.

Overall Bebop and DGPS accuracies for each subsystem

Attribute	Bebop Accuracy	DGPS Accuracy
GPS	0.987m	0.02m
Altitude	$1.975m \pm 0.0277m$	0.02m
Roll	$0.2440^\circ \pm 0.1037^\circ$	
Pitch	$0.1190^\circ \pm 0.1144^\circ$	
Yaw	$0.3803^\circ \pm 0.1781^\circ$	

The indoor positioning system used in this research was the ViconTM system in AFIT’s radar range. This system was utilized as the truth source for the indoor flight test measurements. The results were tabulated in Table 8. The largest standard deviation was in the z direction and was $186.93\mu m$. All the levels of uncertainty were determined to be negligible, validating the treatment of the ViconTM system as a truth source.

The assumptions for this research are listed in Section 1.6. The biggest assumption in the list was that the geodesic sphere would only be illuminated by an ideal plane wave during this research effort. This allowed for a “perfect” calibration data mesh to be created. This mesh was the basis for both the Indoor and Outdoor models. It was created from the foam column RCS measurements of the geodesic sphere. The mesh served as the truth source for both models as well as the data from which the Outdoor model simulated flights were drawn.

Once the Indoor model was developed, and the flight test measurements accomplished, the uncertainty of the geodesic sphere could be determined. This was possible due to the fact that the ViconTM position and pose uncertainty was so low

it acted as an error free source. This uncertainty was determined to be a different value for each leg of each flight. This is understandable due to the unsymmetrical damage to the geodesic sphere. Each facet, angle, and rotation would have a different effect on the uncertainty of the probe. Once a more pristine geodesic sphere is created and flown, the expectation is that the variations in the standard deviation for each run should decrease.

The average of the results from both flights and all legs was seen in Table 15. These numbers provide a performance benchmark of what the geodesic sphere two-way probe is capable of assuming a perfect illumination field. This assumption did decrease the possible level of understanding in the Indoor model. Errors in the incident field were treated as errors in the two-way probe. In hindsight, a more complete analysis would have involved repeating the measurement of each leg multiple times. This would allow for a determination of the uncertainty in the measurement due to the geodesic sphere and possibly remove some of the incident field errors.

The Outdoor model took a different route for its development and analysis. Since no outdoor flight test data was taken, the measurement data needed to be simulated. The same calibration mesh that was used for the Indoor model was utilized for both the truth source and the measurement in the Outdoor model. The relationship between the standard deviation of the error, frequency, window size, and pulses on the target was explored. It was determined that theory held true; as the window size and number of pulses increased, the standard deviation decreased.

The most promising results were when only 15 samples were averaged together and each sample consisted of only 10 pulses, with a DGPS system, the standard deviation of the error was $\approx 6.9^\circ$. This is well within the typical 22° requirement for the plane wave assumption. Meaning, the geodesic sphere two way probe concept

may be a viable option for outdoor field probing. These results would need to be confirmed with actual outdoor RCS measurements as opposed to testing the system with the truth source plus random error.

After all of the testing and analysis, the geodesic sphere probe concept appears to be viable and extremely customizable. The frequency dependent performance can be modified to fit the users needs based on the size of the triangles, and the repeatability of the measurements bodes well for multiple tests. The accuracy of the Bebop's internal position and pose system was determined and the resulting uncertainty in a probe measurement was characterized.

5.3 Research Significance

The concept of using a quad-copter inside a geodesic sphere to provide a flexible and maneuverable measurement probe is a revolutionary concept. This probe will provide measurement capability with little to no extra infrastructure at a range, is wireless, and very inexpensive. The ability to measure the incident field, magnitude or phase, at any RCS range, anywhere in the radar field, and at any frequency will provide cost and time savings to every range that utilizes this two-way probe. The time required to setup, perform, and take down the probe will be decreased from an entire shift to less than one hour. This will allow for probing between target measurements, before and after scene changes, and as a part of each range calibration. All of these benefits increase the fidelity of RCS measurements while decreasing the time and cost.

5.4 Recommendations for Future Research

The largest hindrance to this research effort was the malleability of the geodesic sphere. Every bump, mishandle, or crash resulted in a deformation of the sphere.

Each deformation caused a change in the RCS of the geodesic sphere. These changes eliminated the ability of the two-way probe to make accurate measurements of the incident field. These changes are also believed to be the cause of the variable and large means in the indoor measurement flight tests. As such, the first priority for future research would be to design and construct a more resilient system.

One possible solution to this problem would be to create the geodesic sphere out of Nitinol. Nitinol is a metal alloy consisting of nickel and titanium. It is capable of shape memory and is super elastic. Once trained into the desired shape (or laser machined), if it gets bent, simply apply heat and it reforms back to its trained shape [40]. The outside of the geodesic sphere could be made entirely of Nitinol. This would allow the sphere to be reset to its original, measured, position prior to every flight, removing any ambiguity in the integrity of its shape.

As far as conductivity of the material, it is comprised of 55% nickel and a mix of titanium and other trace elements [40]. Nickel's conductivity is 40% of that of aluminum. As such, prior to utilizing this material, its ability to act as a strong enough radar reflector would need to be examined.

The second priority for future research would be to procure and characterize a small, lightweight DGPS system. One such system is the Piksi GPS receiver. It is fairly low cost (\$1000) and, at 32g, lightweight. With some software processing, the manufacturer specifies centimeter level accuracy. If two systems are utilized in tandem, it is possible to use them as a differential INS of sorts. Another benefit to this application is its 50Hz position solution [41]. This would allow for increased sampling by the radar along with time stamped GPS information.

Once the new geodesic sphere is made (out of any material), it would be necessary to create a new calibration mesh with the new geodesic sphere and GPS combination. A better solution for the calibration mesh would be to measure the

geodesic sphere in a more capable and accurate RCS range. This would allow for a larger frequency measurement as well as allow for a more fine sampling of the sphere in both yaw and pitch. By increasing the frequency range and the yaw and pitch sampling, a finer calibration mesh could be created. This would decrease the amount of interpolation necessary over a given flight path. The less interpolation needed, the more accurate the measurement. Finally, actual outdoor measurements would need to be taken to test the concept and prove its utility.

5.5 Summary

A geodesic sphere is very capable of shielding an object inside of it from incident radar waves. It is also able to reflect the incident wave in a characterizable and repeatable fashion. When utilized in the indoor RCS range, average standard deviations of $< 4^\circ$ were seen across the various flight tests and down to $< 2^\circ$. In an outdoor setting, with a less accurate positioning system, average standard deviations of $< 7^\circ$ were seen across the various simulated flight paths and down to $< 5^\circ$. The standard deviation of the error of the measurement of the incident wave decreased with an increased smoothing window size and an increased number of pulses on the geodesic sphere. After a few modifications to the geodesic sphere and the encompassed quad-copter, the two way probe will be off and flying.

The models developed in this research are capable of being utilized at any range, indoor or outdoor, with any type of RCS measurement. All that is needed is an accurate calibration measurement of the probe and the pose uncertainties of the quad-copter being used at that range. They provide the baseline capability for this project and serve as a launching point for any future research.

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14. ABSTRACT This research intends to reduce the impact of uncertainties caused by errors in the incident field by utilizing a unique two-way field probe in the form of a geodesic sphere encompassing a commercial quad-copter aircraft. The probe is used to measure the distortions in the incident fields in the target volume to quantify one of the key sources of RCS measurement uncertainty. This research determined the uncertainty of the probe by creating a calibrated data set of the probe's RCS, extracting the calibrated RCS based on the measurement flight path, comparing the measured with the calibrated data, and determining the deviation in the difference. The accuracy of the comparison, and therefore the measurement, depends on the accuracy of the flight path. An uncertainty in the probe's pose during flight translates into a field measurement uncertainty. These uncertainties were determined for multiple positioning systems. Each uncertainty was fed into the measurement model and their uncertainties were determined. Field measurement accuracies of $< 2^\circ$ in phase and $< 0.05V/m$ in magnitude were demonstrated.						
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