Space Debris Tracking CubeSat

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Background and Contextual Significance of Space Debris

Throughout the past 60 years, the realm of satellite and space technology has experienced a momentous growth technologically. As of 2024, more than 10,000 active satellites orbit Earth, all belonging to various nations that have access to such capabilities (Mack, 2024). Many of those satellites have top of the line technology, such as outstanding automation and orbit survivability abilities. Prior to these technological breakthroughs, however, the risks of component and system failures were much higher, leading to an increased risk in satellite collisions. Prior to 2009, all collisions and failures occurred strictly from satellites colliding with either broken-off components or left-behind rocket stages. In 2009, though, the first ever satellite to satellite collision occurred between a United States based Iridium 33 and a retired Russian Cosmos 2251, resulting in an exponential increase in debris concentrations (Capel, 2024). Roughly two-thousand pieces of debris, all varying in size, dispersed into Earth's orbit as missile-like projectiles traveling with random trajectories and extremely high speeds.

The large accumulation of orbital debris has presented a dire threat to the current satellite infrastructure that the world utilizes as there are now roughly 170 million pieces of debris in Earth's orbit (Iyer, 2023). Moreover, the immediate threat resides in the fact that only about 30% of these objects are currently tracked by the Department of Defense's global Space Surveillance Network (SSN), which has the capacity to detect objects usually above ten centimeters in diameter. The remaining 70% of objects, currently unidentified and untracked, pose the same danger to satellite networks existing today, and it is an imperative to discover a method of detecting those objects.

A Potential Solution to Untracked Space Debris

In order to assess the pressing matter of growing debris concentrations in low Earth orbit (LEO), our team has made it the objective to conceptually design and prototype a method of detecting space debris smaller than ten centimeters in diameter. We hope to develop a technological breakthrough that would not only detect debris through the utilization of radio frequency transmission, but also extract useful information from the particles such as relative velocity, size, and distance from the radar. With said information, the intention would be to register it to a database that tracks the currently unidentified objects in orbit so that existing satellites can plan their orbital maneuvers accordingly, as well as prevent the accumulation of debris through further collisions.

In the early stages of the project, the emphasis was placed on designing a 3U CubeSat that would hoist the technology capable of detecting this small, untracked debris. Following the Preliminary Design Review, however, the attention was directed away from designing the CubeSat and shifted towards conceptualizing and prototyping the sensor that would perform our mission goals. This shift reshaped many of the initial objectives, constraints, and design requirements, yet it has honed the focus of the project on a singular satellite subsystem that would serve as its payload. The mission statement as a result of this transition has been to design and test a sensor capable of detecting orbital debris smaller than 10 cm, taking the technology from a Technology Readiness Level (TRL) of 1 to 3. The implementation of the TRL levels have highlighted a milestone for our team to achieve, improving the design from a TRL of 1, entailing that the basic principles have been observed and reported, to a 3, where an analytical or critical function has been developed as a proof of concept (Manning, 2023).

Key Mission Parameters

The main objectives of this restructured project trajectory have been centered around developing a proof of concept for this sensor, as well as creating simulation and environmental modeling that is able to verify results gained from the sensor. Primarily, we want to ensure that the developed sensor is capable of detecting debris under that ten centimeter threshold, then we intend to build and test a lab-scale prototype to demonstrate the sensor's core detection capabilities under controlled conditions. More secondary objectives include creating those simulation models to verify certain sensor results and the creation of code-based algorithms that are capable of extracting meaningful data from the debris detected, such as orbital position, velocity, and size. The concept of doing this would match the ideal payload design, which was formulated in the PDR. When selecting the ideal sensor type for achieving mission goals, we prioritized size, output, complexity, and compatibility with a CubeSat. This ultimately led to the decision to pursue a continuous-wave radar detection method. The concept of detecting debris via this method is as follows: send out a high-frequency signal from a transmission horn antenna, achieve detection if the signal reflects off of a metallic object that is likely debris if untracked, then receive the signal through a receiving horn antenna if the reflection was successful. While this concept has guided our entire prototyping process, it has also given way to new constraints.

The constraints of this design mainly entail finances and test setting considerations. Firstly, the group is operating at a budget of $1800, which has been fairly achievable due to many components being readily available at the University of Virginia. Furthermore, some test setting constraints that have inhibited the ability to perform successful radio frequency (RF) analysis include excessive noise in the test environment needing to be filtered and the inability to utilize actual rooms designed for RF work. In regards to the actual mission, some of the simulation models are restricted to frequency and locational constraints due to Charlottesville needing to be the ground station for communications. Despite these constraints, however, the system-level requirements are directed towards developing a proof of concept that will help achieve the mission objectives.

The system-level functional requirements, which are necessary functions that a system must perform to achieve given objectives, are mirrored by the primary mission goals. In terms of debris detectability, the sensor must be able to detect debris smaller than ten centimeters, and any sensitivity from prototyped detection should be documented for future experimentation. As for the acquisition of data through the current experimentation process, the system will be required to decipher raw data and perform basic processing that will delineate true detection events from false positives. Furthermore, the system shall be able to acquire certain debris attributes such as position and velocity. In addition to functional requirements, the design will also have system-level operational requirements that will ensure that constraints are considered and assessed in the design process. Firstly, the test environment will need to be manipulated so that it can observe varying independent variables such as frequency, and the environment should be optimized to reduce any noise interference from metal or other objects emitting frequencies. Next, in terms of spacecraft integration, a computer-aided design model will be developed to ensure that integration of the sensor will be possible. Moreover, simulation models will be built and utilized to observe how the sensor will truly operate while in orbit. To address mission objectives, constraints, conceptual operations, and system-level requirements simultaneously, it was imperative that the team follow a structured problem assessment strategy while maintaining ethical engineering practices.

Ethical and Professional Considerations

Problem Assessment Strategies

The Space Debris Tracking CubeSat project employs a rigorous problem assessment strategy, beginning with clearly defined mission objectives, requirements, and constraints. These were established based on extensive literature reviews, consultations with technical advisors, and iterative feedback processes. A structured risk management approach was adopted, utilizing a NASA-inspired risk matrix to systematically identify, assess, and prioritize potential risks, including technical, safety, cost, and scheduling factors. Specific strategies, such as sensitivity studies and optimal test environment assessments, were developed to mitigate identified risks. Additionally, simulation and modeling methods have been employed to anticipate system performance and validate debris tracking capabilities in realistic orbital scenarios, thereby reducing uncertainty in performance predictions and ensuring alignment with the project's operational and technical objectives.

Ethical Considerations

The ethical considerations inherent in this project center around the responsible use of space, addressing the critical issue of space debris. By developing technology capable of detecting debris smaller than 10 centimeters, this project aims to mitigate risks posed to current and future orbital operations, adhering to the principles of sustainability and responsibility in aerospace endeavors. Ethical responsibilities also extend to ensuring the CubeSat itself does not contribute to debris; thus, plans include careful end-of-life management, ensuring the satellite safely de-orbits and burns up in Earth's atmosphere. Furthermore, transparency in data collection, processing, and dissemination is maintained, along with adherence to regulatory standards and frequency licensing requirements. Professional integrity and transparency have been prioritized through diligent documentation, consistent engagement with technical advisors, and structured peer reviews to ensure technical rigor and ethical compliance throughout the project lifecycle.

Project Management

The managerial aspects of this capstone design project have secured a consistent and stable flow of operations throughout the entire project life cycle. From the project manager to each individual subteam member, every actor in the project has fulfilled distinct roles to deliver mission goals through the execution of specific tasks that have been allocated to them. Since the team is burdened by the small number of active members, it has been challenging to restrict certain members into one specific field of study. Furthermore, many aspects of the project have been altered during the Spring semester to shift focus away from the CubeSat and prioritize the debris-tracking sensor's design.

A general work week entails three meetings involving all team members, where work specific to upcoming deliverables are discussed and completed. At the beginning of each meeting, all teammates are briefed on current project timelines and certain goals needing to be met, which is also displayed via a work breakdown structure (WBS) excel spreadsheet. The WBS provides specific task categories, start and due dates, progress percentages, and the member that the task is assigned to. This spreadsheet is updated weekly to keep track of where specific tasks are in terms of progress as well as notify other members if they are on schedule for completion. There have been numerous benefits to utilizing this, as it has provided a strong organizational structure for work monitorization. The work being completed has been very specific for each team member as well due to the shift in design focus.

Since the team is fairly small in terms of member count, each person has fulfilled specific roles in the critical design and prototyping phase of the debris-tracking sensor. In the Fall semester, the team was split into two independent subteams. One subteam focused on the electronics and communications side of the design, where the other focused on the structures and integration side. As a result of the design focus shift, however, new teams arose to focus more on the prototyping and simulation verification aspects of the project. Three team members were allocated to working on the software defined radio (Ryan, Frances, Kenji), which involved designing a digital radio frequency flowchart that would demonstrate the sensor's concept of operations. For the physical representation of the debris, three members of the team were to focus on 3D printing and building a setup that could be used in a test setting (Owen, Alex, Swar). The remaining three members (Drew, Will, and Justin) were directed towards creating the simulation models that will be used to verify detection results from the software defined radio prototype. This organization of work has been very effective in making sure that the team is not stretched too thin in terms of workload and skill sets.

Design Development

Ideal Debris-Tracking Sensor Design

Radars operate by emitting radio waves and analyzing reflections bounced off objects, making them especially effective in space environments. Unlike optical systems, radar does not rely on sunlight and can detect objects regardless of lighting or orientation. This makes radar particularly useful for identifying non-cooperative targets like debris, which do not emit signals of their own. For our project, this means radar is a natural fit for detecting untracked particles that pose danger to satellites or spacecraft.

Our sensor will use continuous wave (CW) radar, a system that continuously transmits a steady radio frequency signal. This differs from pulsed radar, which emits short bursts and then waits for returning echoes to measure distance. Although CW radar does not naturally provide range, it can be enhanced with a frequency-modulated chirp, where the signal sweeps through a range of frequencies over time to calculate distance to an object. This capability allows us to infer not only whether debris is nearby, but how far away it is, which is a critical component of our CubeSat's detection model. Another advantage of CW radar is its ability to measure Doppler shift which is a change in the frequency of the received signal caused by the relative motion between the radar and the debris. This shift reveals the object's velocity. This a consideration in the ideal sensor design but is important to acknowledge.

The accuracy of a radar system is influenced by the size, shape, and material of the object being detected, as well as the wavelength of the radar signal. Smaller debris generally requires shorter wavelengths, or higher frequencies, to reflect a detectable signal. That's why our system will operate in the Ka-band, specifically at 30 GHz, which enables detection of debris as small as one centimeter. This frequency choice helps increase the radar cross-section, which is just a measure of how detectible an object is by a sensor.

Even at high frequencies, certain small or misshaped debris can produce weak received signals. To combat this, our sensor will need to include a signal amplification to ensure that small echos can still be post processed to gather information. Finally, the simplicity of continuous wave radar makes it well-suited for a CubeSat system. In relation to pulsed, optical, or passive bistatic radar systems, CW radar is a great balance of power usage, design simplicity and processing abilities.

Design Requirements

There are four main design requirements for the development of the ideal debris-tracking sensor. The first requirement is that the sensor continuously transmits 30 GHz radio waves. It is critical to use this high of a frequency so debris smaller than 10 centimeters can be detected. The second requirement is to amplify the received debris echo by 60 dB. This is a necessary function because the return signals from the small debris will be too weak to detect, so they need to be strengthened in order to analyze the data. The third requirement is that the design must sample intermediate frequency signals at a rate of 6.24 MHz. This sampling rate corresponds to the Nyquist frequency for the expected Doppler shift, which is necessary to process the signal data effectively. These three design requirements will be verified through analysis, which includes making sure the calculated numbers follow the used theoretical concepts, can be validated through simulations, and can meet the specifications of selected components for the sensor.The last design requirement is ensuring the system can extract the amplitude, frequency, and phase shift of the detected signals. Accomplishing this will allow for the detected debris to provide meaningful data to determine its speed, size, and trajectory. Knowing these characteristics are important so infrastructure and launches to LEO can avoid collisions with these debris particles. This fourth design requirement will be verified through experimental testing, by running actual signal processing tests to extract these signal characteristics.

Design Layout

The ideal debris-tracking sensor design is made up of two main sections, one for transmitting signals and the other for receiving signals. The transmitting section contains the oscillator, amplifier, and TX antenna. The oscillator will first generate the 30 GHz signal, the amplifier boosts this signal so it can be transmitted effectively, and then the TX antenna radiates the signal into space to detect debris. After radiating off of any space debris particles, the signal will then contact the receiving section of the sensor. This section includes the RX antenna, low noise amplifier (LNA), bandpass filter, mixer, IF amplifier, low pass filter, and analog-to-digital converter (ADC). The RX antenna receives a weak signal in which the LNA strengthens so it can actually be useful. The bandpass filter removes unneeded frequencies that are outside the signal range, and the mixer converts these to IF signals which are amplified by the IF amplifier. Lastly, the low pass filter will remove high-frequency noise from the signal, and the ADC will digitize this final signal so it can be used for data processing and analysis. Figure 1 shows a top-down view of these individual components to depict the flow of the signal through the sensor system. After the needed components and layout of the sensor was identified, it was necessary to ensure that it could fit into a CubeSat's size constraints. This was verified by taking the 3D layout model and consolidating it so it could be housed in 1U of a 3U CubeSat model, as shown in Figure 2.

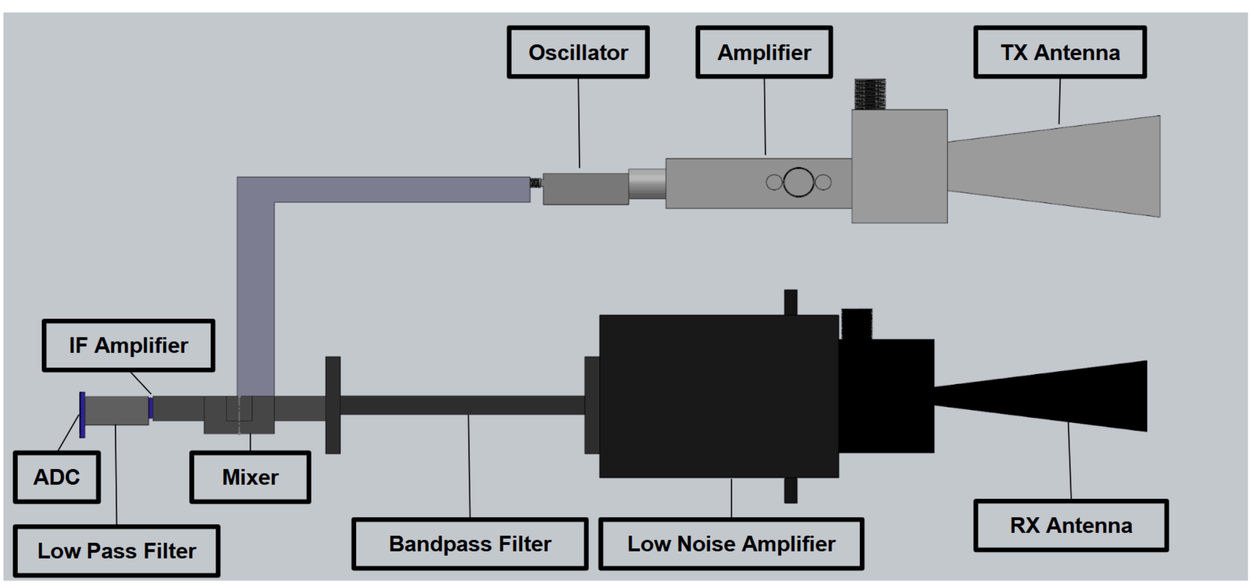

Figure 1: Top-Down View of Ideal Debris-Tracking Sensor via SolidWorks.

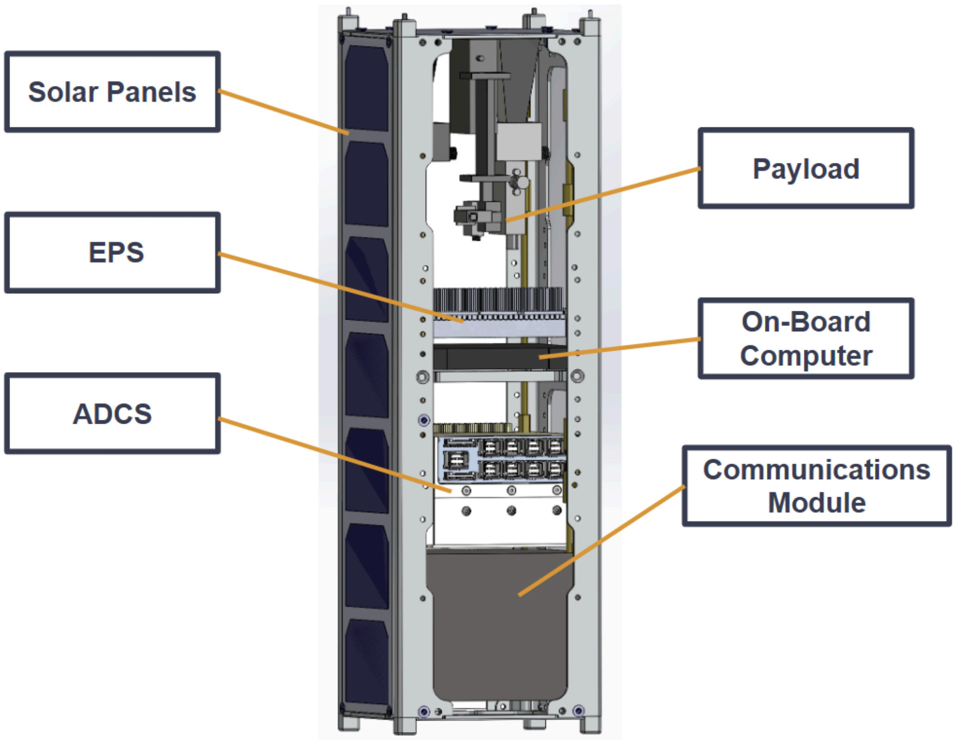

Figure 2: Ideal Debris-Tracking Sensor Integrated into 3U CubeSat Chassis (Static View).

Connection to Prototype Development and Design

In making sure that design could be experimentally tested, the team decided to create a setup that could simulate space debris for our software defined radio to detect. This setup involves having a tripod onto which a mount for a DC motor is attached, as well as a housing for the necessary electronics. On the DC motor mount, it is designed in order to allow the motor to spin simulated space debris about a vertical axis (level elevation) or a horizontal axis (changes elevation in orbit). This will allow us to simulate varying motions of space debris, as not all of the debris spins about the same axis when it orbits Earth. To the motor, we have 3D printed adapters onto which fishing lines can be woven through. This fishing line ties onto spheres of various sizes, ranging from one centimeter in diameter to ten centimeters. These are all smaller than the current debris tracked by space debris, and is the aim for our project. On top of varying the sizes of the space debris, we are also varying the length of the fishing line connecting the debris to the motor. The reason for doing such is to vary translational speeds of the debris, which is proportional to the orbital radius and angular velocity. From this, we have a range of translational speeds from fifteen to thirty miles per hour, for which our radar system aims to not only detect the debris but also acquire the speed of the moving debris. From the electrical connections, we have an arduino board that connects to the motor, and this controls the RPM of the motor, which we can change based on how well the radio system is detecting the debris. Altering the RPM here is analogous to changing the orbital speed of the debris, and from this, we look to measure the doppler shift in the received signal, which can inform the speed at which the debris is moving. All of these spheres will be covered in reflective radar paint, to ease in detection. Additionally, prior to all of the spheres being attached to the motor and spun around, we have a large metal plate. This plate is also covered in the reflective paint, and will be utilized prior to any of the small spheres to be used as a calibration for the radio system. With this prototype design, we aim to test the feasibility of our radar system see the limitations of our detection methods, and extrapolate velocity of sample debris on top of just detecting particles.

Prototype Layout and Configuration

The budget for this project fell far under the total cost necessary to build. The objective of the project was transitioned to testing a radar system effective at detecting space debris, which was feasible within the project budget. To accomplish this, a Universal Software Radio Peripheral (USRP) was utilized to consolidate most of the necessary signal processing hardware into an experimental environment. The software interface compatible with the USRP, GNU Radio, is a block-style program, where pre-programmed tools like a low-pass filter, or analog-to-digital converter can be implemented within the software, rather than purchasing a hard-coded tool. Signal processing can be accomplished via this software interface, such as a fast-Fourier transform (FFT), in between blocks as well.

However, limitations of the USRP led to a change in prototype objectives being necessary. The USRP allows for transmission of up to 6 GHz and power output of 15 dBm, both of which were not ideal for detecting debris within the initial desired range of around 1-3mm in diameter. Maximum detectable range is adversely affected by this reduction in frequency, or increase of transmitted wavelength, due to the reduction of normalized circumference, shown in Figure 3.

In turn, this reduction in normalized circumference with a frequency reduction results in a more fluctuated and generally lower receivable radar cross section (RCS), which is directly proportional to the effective detection range. Alongside this reduction in frequency, the reduction in power transmitted from the ideal also negatively affected the maximum detection range. Conversely, if the desired maximum detection range were to be a fixed value, the smallest detectable debris size would need to increase because of the reduction in transmission frequency and power.

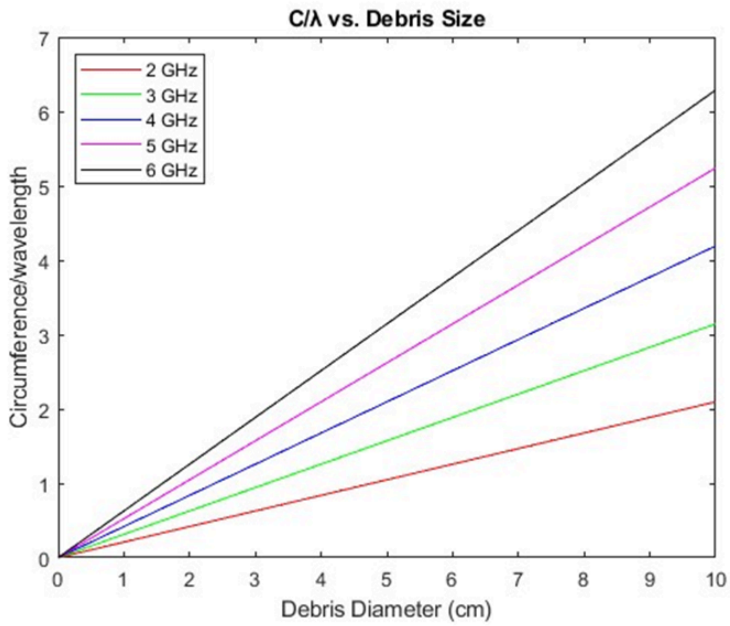

Figure 3: Normalized Circumference vs. Debris Diameter & TX Frequency

As a result, the decided course of action was to treat detection range, and debris size (and with that, RCS) as the free variables that data can be gathered on. Detection range is a simple variable to control, where the distance from the transmitting antenna can simply be increased by moving our detected object further. In altering the debris size, as mentioned before, four spheres of 1 cm, 3 cm, 5 cm, and 10 cm were 3D-printed and coated with metallic paint to maximize their surface conductivity and thus reflectivity. The variability in debris shape and material content proved difficult to simulate, and decidedly outside of the scope of the project. However, this did not go without consideration, and for the purpose of determining the effective range of detection for each debris size, the decision to simply use various sized spheres proved the most feasible.

For the USRP setup, the antenna baseline transmission antenna was a log-periodic antenna of 6 dBi gain, and an operation frequency of 0.8-6 GHz. An isotropic receiving antenna was used in conjunction with the log-periodic; it is useful in applications where the relative position of the received signal is uncertain. The first step of the testing process was to transmit signals at a large, conductive plate, as mentioned earlier, to assure the USRP was transmitting and receiving properly. Secondly, the next step was to spin the conductive spheres and ensure that the system could detect a small, moving object. Third, the next goal was to learn how to detect the Doppler Shift in the received versus transmitted signal, to then accurately calculate the object's speed. These tests were created with the goal of successfully building a radar system that could detect a moving object, and to be able to gather data from the received signal, i.e. the velocity from the Doppler shift.

Simulations Overview

In order to validate the effectiveness of the CubeSat, three simulations were constructed to model different aspects of both the CubeSat's mission and surrounding environment. Each simulation model is constructed using C++ code and has been run locally using 18 cores.

To further understand the conditions of LEO, a Debris Distribution Model (DDM) was constructed to simulate a realistic population of orbital debris, accounting for variations in altitude, inclination, and other classical orbital elements in order to assess potential collision risks and sensor coverage performance. To accurately describe the realistic debris distribution in LEO, data was extracted from a Low Earth Orbit Visualization software entitled *LeoLabs*. This dataset is not nearly as vast as the true number of debris in orbit, so the DDM propagates the 10 thousand data points provided into 120 million pieces of debris with the same mathematical distribution. The desired output of the simulation is a comma-separated values (CSV) file that contains 120 million values for each of semi-major axis (a), eccentricity (e), inclination (i), right-ascension of the ascending node (*RAAN*), argument of perigee (ω), and mean anomaly (*M*). The following figure compares the distribution of semi-major axes depending on debris altitude modeled by the LeoLabs software in comparison to the propagated data simulated by the DDM.

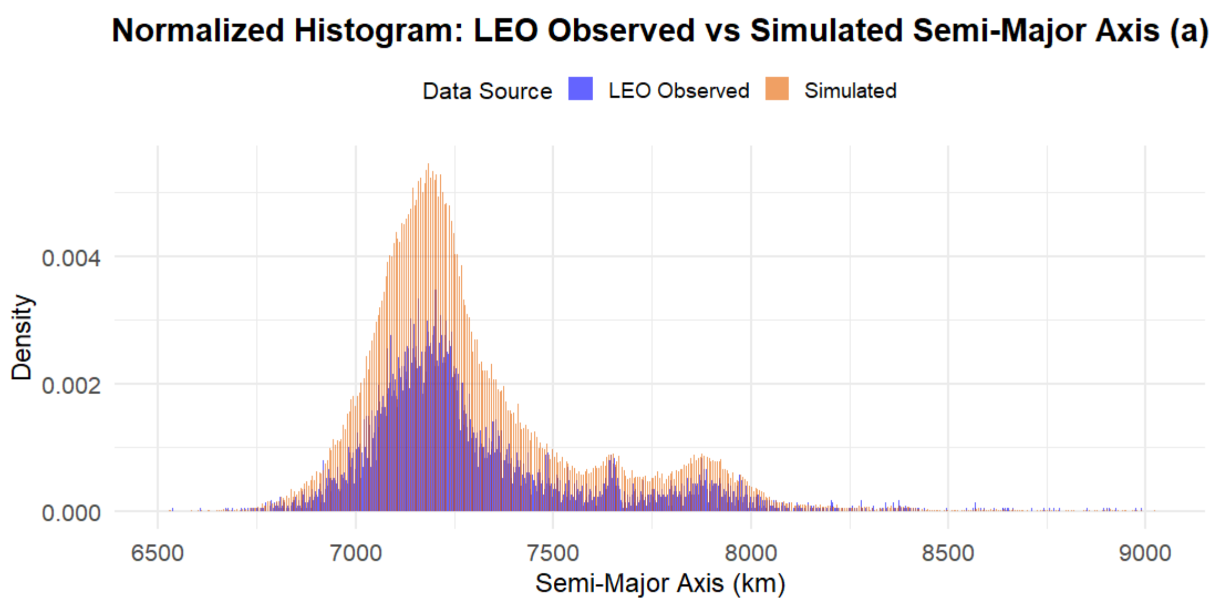

Figure 4: Histogram of Semi-Major Axis Distribution Comparing Data from *LeoLabs* and Propagated Data (LeoLabs, n.d.)

The models show a consistent distribution of debris based on the disparate altitudes with a notably higher concentration of debris at around 850 kilometers above Earth's surface.

The next simulation created was the Orbit Determination Model (ODM) designed to predict the most optimal orbit for the CubeSat. The desired orbit is one in which the CubeSat maximizes its time over the Charlottesville ground station. In order to do this, the simulation is provided with a range of orbital parameters that may be desired, and iteratively determines which of the orbits has the greatest time over Charlottesville given a single sidereal day. The output of the simulation is similar to the DDM output in that it is a CSV file containing classical orbital elements, but also provides a total amount of time the CubeSat communicates with the Charlottesville ground station. The following table demonstrates the optimal orbit for the CubeSat along with a visualization of the orbit.

Table I: Optimized Orbit Derived from Orbit Determination Model

a (km)	*e*	*i* (°)	*RAAN* (°)	ω (°)	*Overpass Time* (min)	*Daily Time* (min)	*Orbital Period* (min)
6,928	0.000	37.56	200.0	0.000	8.608	129.6	95.65

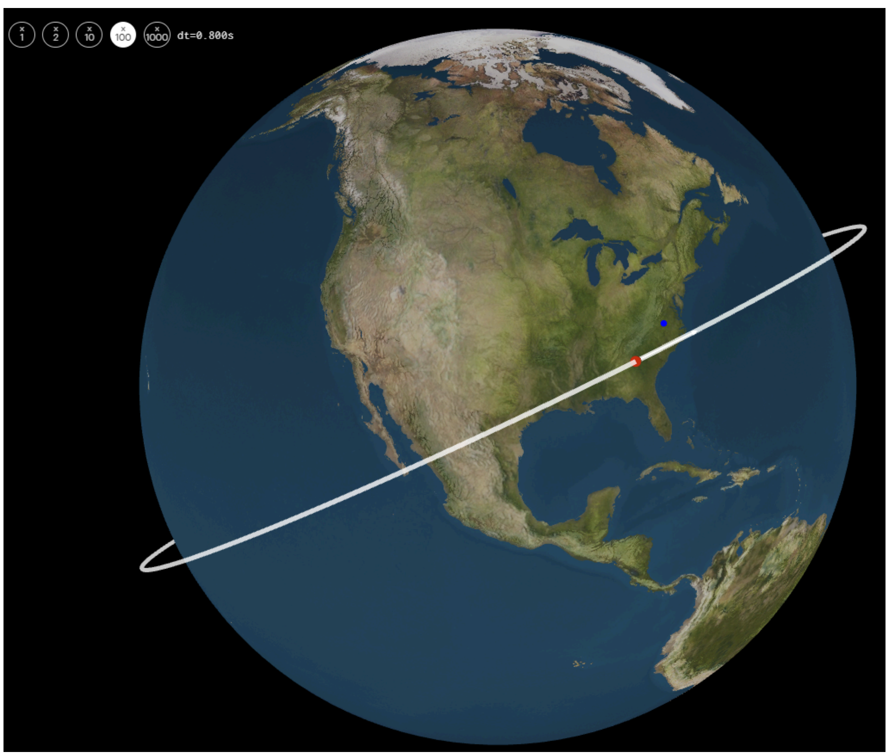

Figure 5: Orbit Visualization of Optimized Orbit (Wertz, n.d.)

The final and most comprehensive simulation, the Orbital Debris Detection Model (ODDM), integrates the outputs of the previous models to evaluate the CubeSat's in-orbit performance. Its primary goal is to assess the CubeSat's effectiveness in detecting orbital debris. To do this, the ODDM reconstructs the debris environment generated by the DDM, places a model CubeSat into the orbit defined by the ODM, and tracks the number of debris objects successfully detected by the CubeSat over time. This model implements information acquired from the prototype setup including the Radar Cross Section (RCS) of the CubeSat. This value helps accurately describe the range and angles of detection the CubeSat can see debris from. The simulation outputs a text file containing a log of detection events and a total count of debris observed during one complete orbital pass. After a full scale simulation containing physics modeling of radar detection, the CubeSat was able to detect five pieces of debris within one orbit around Earth. These results help quantify the CubeSat's detection capabilities and inform design trade-offs, such as optimal orbit selection, sensor placement, or improvements to detection algorithms. Future iterations of the ODDM could incorporate multiple orbits, varying sensor configurations, or probabilistic models to further refine detection predictions and mission planning. The end goal of the project is to have multiple CubeSat modules in addition to multiple orbits per day, so this result will be propagated to a much greater number of debris detected.

These simulations are essential for the design of the CubeSat because they allow for a detailed evaluation of its performance in a realistic orbital environment before any physical deployment. By modeling the distribution of debris, the CubeSat's orbital path, and its detection capabilities, the simulations help identify potential limitations, optimize sensor placement and orbital parameters, and reduce mission risk. They also provide insight into how effectively the

CubeSat can fulfill its objective of tracking space debris, guiding design decisions and ensuring the mission is both technically feasible.

Results and Discussion

Prototype Testing Results

In analyzing results from the testing setup with the USRP N210 Board and GNU Radio, it was determined that the test environment and limited equipment served as an obstacle for obtaining meaningful data.The first difficulty with testing came from interference within the USRP board. The received signal was not changing based on distance between the sensor and transmitter leading to the conclusion that the radio frequency was bleeding into the receiving frequency within the board itself. A HackRF One was connected to a separate computer and acted as the receiver. With isolated receiver and transmitter setups, the incoming signals were able to accurately detect a sawtooth chirp signal that was programmed into GNU. Unfortunately, even with isolated subsystems, there was a significant amount of interference and noise in our testing environment and there were no conclusive results for bouncing our signal off the copper coated plate. As a result, we decided to shift our focus towards the use of an off-the-shelf radar to hopefully suffice our testing objectives.

Pulse Radar sensor Results

To evaluate the viability of a pulse radar system for detecting sub-10 cm orbital debris, we conducted controlled laboratory experiments using the SparkFun A111 radar sensor. The test involved 3D-printed debris analogues of varying diameters—1 cm, 3 cm, 5 cm, and 10 cm—each coated with RF-reflective paint to simulate metallic space debris. For each trial, the sample debris was initially suspended 240 mm directly above the radar sensor. Using a custom pulley mechanism, the sample was then gradually raised at a constant rate of 10 mm per second until the radar could no longer detect its signal return. This dynamic approach allowed for the precise measurement of the maximum effective detection range for each object size. The corresponding radar "score" was recorded throughout, and the resulting signal-versus-distance data was fitted to a fourth-order polynomial with an R^2 value of 0.976, providing a reliable model of signal attenuation.

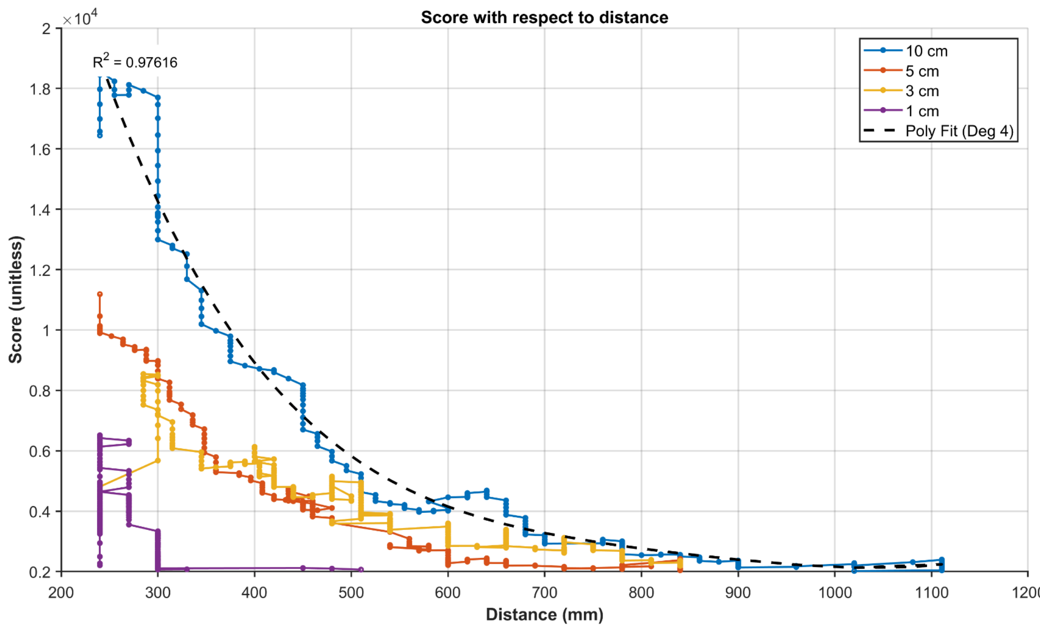

Figure 6: Chart Displaying Presence Score Versus Distance Away from Sensor

To determine the system's sensitivity, we used a 10 cm square aluminum plate with a known theoretical radar cross section (RCS) of 0.064516 m² to calculate the minimum power receivable by the sensor. By rearranging the radar range equation to solve for received power (P_r) and inputting known values, such as transmit power (10 dBm = 0.01 W), antenna gain (6 dBi = 3.981 linear), wavelength (~0.005 m), and a max range of 2.1 m, we found the minimum detectable power to be approximately $6.614 \cdot 10^{-12}$W. This calibrated value enabled us to compute the experimental RCS of the smaller debris samples by solving the radar equation in reverse, using their respective maximum detection distances. These values were tabulated alongside theoretical RCS estimates for idealized shapes (see Table II).

Table II: Radar Cross Section Calculations for Each Debris Sphere

Debris Sphere Radius (cm)	10	5	3	1
Max Distance (m)	1.14	0.84	0.72	0.36
Theoretical RCS (πr^2 m²)	0.0314	0.00785	0.00283	0.000314
Experimental RCS (m²)	0.00560	0.00165	0.00089	0.000056
Percentage	17.8	21.0	31.5	17.7
Effective Radius (cm)	4.22	2.29	1.68	0.421

Across all tests, experimental RCS values were substantially lower than their theoretical counterparts, ranging from 17.7% to 31.5% efficiency. These discrepancies were attributed to non-idealities in target shape, surface finish, and reflective coating application, as well as environmental noise in the lab. Crucially, these findings informed our orbital debris detection simulation. By anchoring the simulation's RCS range to experimentally observed values—from 0.000056 m² to 0.0056 m²—we ensured that the modeled detection rates accurately reflected the practical performance of the radar system, enhancing the realism and applicability of the mission design.

Simulations Results

The simulations created to model the effectiveness of the debris-tracking CubeSat in the LEO environment proved that the use of this module would perform the necessary operation. The DDM simulation helped to create an accurate prediction of the debris. The resultant model utilized a Kernel Density Estimation (KDE) of the distributions of each classical orbital element derived from a *LeoLabs* dataset. This formulaic estimator is used to create a functional prediction of a histogram model. The KDE function is as follows:

$$\widehat{f}_h(x) = \frac{1}{n}\sum_{i=1}^{n} K_h\left(x - x_i\right) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right)$$

K represents the kernel, a non-negative function with subscript h, denoting the scaled kernel. The independent and identically distributed samples, x and x_i, are the samples drawn from the different bins derived from the histograms of the *LeoLabs* classical orbital elements. Since each of the bins of the histograms are projected to have the same distributions with $i = 1000$ bins, the KDE is a good approximation of a piecewise model for the DDM.

Utilizing the information derived from the KDE, the known data was then propagated to accommodate debris on the order of approximately 120 million pieces. The accuracy of the data was verified by plotting comparative plots of each classical orbital element similar to the one shown in Figure 4 for semi-major axis distribution.

The results associated with the Orbit Determination Model are demonstrated in Table 1. Generally, the values make physical sense in terms of the classical orbital elements determined from the simulation. With a semi-major axis of 6,928 km and an eccentricity of 0, the CubeSat has an ideal orbit that is circular approximately 550 km above the Earth's surface. This altitude matches the reasonable range for LEO. The values determined for the argument of perigee and the right ascension of the ascending node are simply meant to maximize the amount of time the

CubeSat remains over the Charlottesville ground station for data relaying. By using this iterative solver to identify key, ideal orbits, there is a better understanding of the most probable orbit for the CubeSat in order to achieve the ultimate goal of detecting debris and transmitting data.

The final results of the Orbital Debris Detection Model (ODDM) reflect the information provided by the two other simulations created. Through the parsing of the 120 million pieces of debris pulled from the DDM and the idealized CubeSat orbit derived from the ODM, there were 30 successful detections of debris. This case utilized an idealized form of detection with negligible radar cross sections. Instead, this case simulates a static radar detection range that does not rely on the sizes of objects. Overall, this method worked properly, but is not in compliance with the final goals of the project.

To enhance fidelity, the simulation was updated to account for the potential detection ranges of the CubeSat given reasonable physical parameters associated with continuous wave (CW) detection. The new simulation parameters include a radar transmit power of 5 watts, antenna gain of 10 dBi, operating frequency of 30 GHz, and a bandwidth of 1 MHz. The radar system operates at a high temporal resolution, with a timestep of 0.0001 seconds to account for fast-moving targets in low Earth orbit. Additionally, debris objects were assigned randomized radar cross sections (RCS) ranging between 0.00001 m^2 and 0.0001 m^2, representing small-scale debris.

Using these parameters, the model calculates detection probability by applying a radar equation suited for CW systems, accounting for signal-to-noise ratio (SNR) and range-dependent loss. A conservative false detection probability of 0.01% was also introduced to simulate realistic system imperfections and noise. This revised model significantly improves the accuracy of the debris detection framework, providing a more physically grounded estimate of the CubeSat's detection capabilities and informing the sensor design trade space for future iterations. As a result, the full-scale simulation output led to 13 debris detections for one orbit of the CubeSat.

Due to the intense computation necessary to complete a full run of the ODDM, several efficiency tactics were taken into consideration to improve the model's run time. Given the amount of debris simulated in the DDM, it would take several days worth of run time to calculate trajectories of all 120 million debris. To limit this level of computation, the ODDM performs a proximity filtering around the CubeSat's orbit. By culling the debris, there is a significant reduction in the shear number of debris trajectories calculated. For the finalized run of the model, the total number of debris culled was approximately 1.7 million pieces, which is a significant drop off from the original 120 million. In turn, the simulation run time was 19.5 hours to complete the full culling process and run the detection model.

Conclusion

In completion of testing, the TRL level increase to a *Level Three* is unwarranted based on the inconclusive results from the radar prototype. The team experienced many obstacles in the attempt to create a proof of concept for a continuous wave radar, provoked by issues surrounding exterior radar frequency interference and improper test environment circumstances. While we were unable to obtain a conclusive result regarding the possibility of this technology, we firmly believe that it is possible to develop a functional prototype given a proper testing environment. If this project is to be pursued following this year, then future teams should aim to tackle the propagation methods of making the test environment mock orbital conditions as accurately as possible. This method will likely guarantee success in creating a proof of concept, and it is where we fell short during our time working on this project. By creating a functional proof of concept, the TRL level increase to a *Level Three* and beyond will be warranted. With respect to the success we did have, we can at least increase our TRL to a *Level Two* on the basis that we did formulate a technological concept that was capable of fulfilling our mission objectives. While it was not proven experimentally, we are confident that the concept can be proven successful on an application basis given the correct circumstances. Nonetheless, we absorbed tremendously valuable experience developing this debris-tracking sensor, and it will serve as beneficial assets to our success in future endeavors.

References:

Capel, M. (2024, May 29). *Satellite collision, space debris and pets - how privacy-preserving technologies can advance space situational awareness*. Inpher. https://inpher.io/blog/satellite-collision-space-debris-and-pets-how-privacy-preserving-technologies-can-advance-space-situational-awareness/

LeoLabs. (n.d.). *LeoLabs space safety platform*. https://leolabs.space/

Mack, E. (2024, August 1). *There are 10,000 active satellites in orbit. most belong to elon musk*. Forbes. https://www.forbes.com/sites/ericmack/2024/07/19/theres-now-10000-active-satellites-in-orbit-most-belong-to-elon-musk/

Manning, C. (2023, September 27). *Technology readiness levels*. NASA. https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

Wertz, J. R. (n.d.). *Orbital Mechanics*. https://orbitalmechanics.info/