# Tracking Cislunar Orbits

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## A Brief Summary

Space is becoming more and more accessible and with that, more and more satellites and resulting debris are put into orbit. Debris can be catastrophic to equipment in space and not only to the equipment, but also the companies making the equipment as it can cost upwards of $600 million dollars. Our goal is to create a “cheap” and effective system of satellites to track space debris (also known as space junk) in order to help bring awareness and allow critical equipment to avoid devastating collisions.

First, the cost program takes inputs including satellite weight, run time, quantum efficiency of the camera, camera lens radius, fov (field of view), shutter speed, and finally the number of satellites. The program can then calculate the cost by taking the total estimated cost of the satellite parts and adding it to the cost of the run time and cost to orbit. A total cost is outputted and the camera specs of the satellite are sent to the luminosity program.

The luminosity program checks if there is any debris in the field of view of the satellites. If there is, the program uses the known distances from celestial bodies to calculate the angle of the debris to the satellite which is then used to find the phase of the debris according to the perspective of the satellite. Then, the program calculates the amount of light going from the sun to the debris by using the inverse square law. That number is then multiplied by the surface area of the debris, which is assumed to be a perfect sphere of a diameter equal to 1 kilometer, and multiplied again by the debris’ material reflectivity, which we have assumed to be approximately 0.14 percent. The outcome of that problem is then multiplied by the phase of the debris calculated earlier. The inverse square law is brought to light once again when it is used to find the amount of light from the debris that enters the lens of the satellite. Here, factors including quantum efficiency, lens surface area, and shutter speed are taken into account, turning the luminosity that reaches the satellite into joules.

The information from the program is then sent to the simulation software which is used to simulate the debris path saving its position and an appropriate time stamp to a file. Based on the orbit and position we can find the debris’ velocity making it possible to predict its future path. This data can then be used to alert satellites and other equipment in the predicted path of the debris so that measures can be used to avoid the debris, therefore avoiding catastrophic collisions.

With all three sections of the code working in unison, we are able to track the path of the debris’ orbit allowing for the avoidance of $600 million dollar collisions. By stopping these collisions we can also keep more debris from being created by resulting collisions therefore making space safer than ever.

## Terminology

The following are important terms that will be used throughout the report:

- **Cislunar space -** the space within the Earth's and the Moon's gravitational field, excluding Earth itself.
- **Satellite vs debris -** the satellite in this case is referring to the man-made cube satellite. Debris is the potentially hazardous object that the satellite is observing.
- **Cube Satellite -** a cheap, small satellite shaped like a cube. For our purposes, this is the satellite we would most likely be working with in real life.
- **Law of Cosines -** a mathematical concept which states that, given all three side lengths of a triangle, we can find all unknown angles of any triangle.
- **Inverse Square Law -** a law of physics which states that the amount of light decreases exponentially the further you get from the source of the light (see this article for more information).
- **Luminosity -** a measure of radiated light from a light source, written in joules per meter squared per second (see this article for more information).
- **Quantum Efficiency -** the percentage of photons that are actually registered by a camera (see this article for more information).
- **Uniform circular motion -** celestial body programmed to uniform orbit in space without the interference of non-central celestial bodies.
- **Elliptical motion -** celestial body programmed to move with its orbit dictated by 2 or more celestial bodies.
- **Geosynchronous orbit -** an orbit path at an altitude of 37,000km and stays above the same spot on Earth.

## The Problem

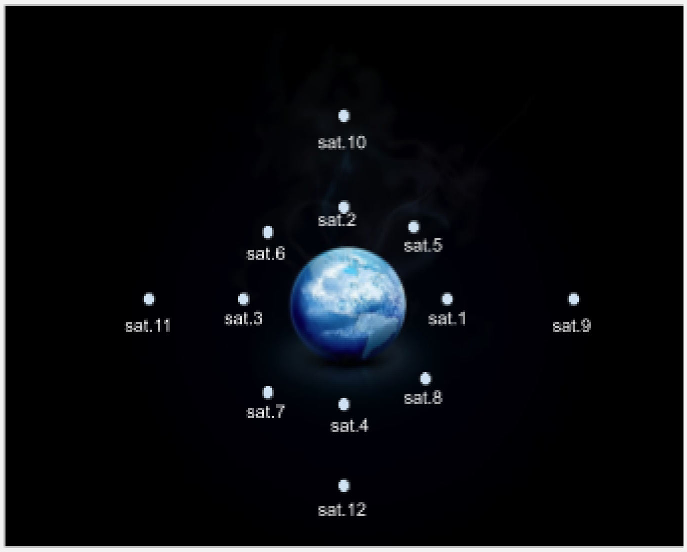
As space becomes more accessible and more satellites are put into orbit, the odds of a collision between a satellite and a piece of debris increase significantly. A collision may cause a significant amount of damage - a 'cheap' satellite costs several hundred thousand dollars to get into orbit, and the cost increases exponentially from there. According to the GAO(Government Accountability Office), there are almost 5,500 satellites in orbit as of spring 2022, and many more will be launched over time: it is estimated that an additional 58,000 satellites will be launched by 2030. Immediate development of a tracking system is necessary to avoid the severe property damage and destruction of satellites that may be crucial to things such as national security or scientific research.

## The Solution

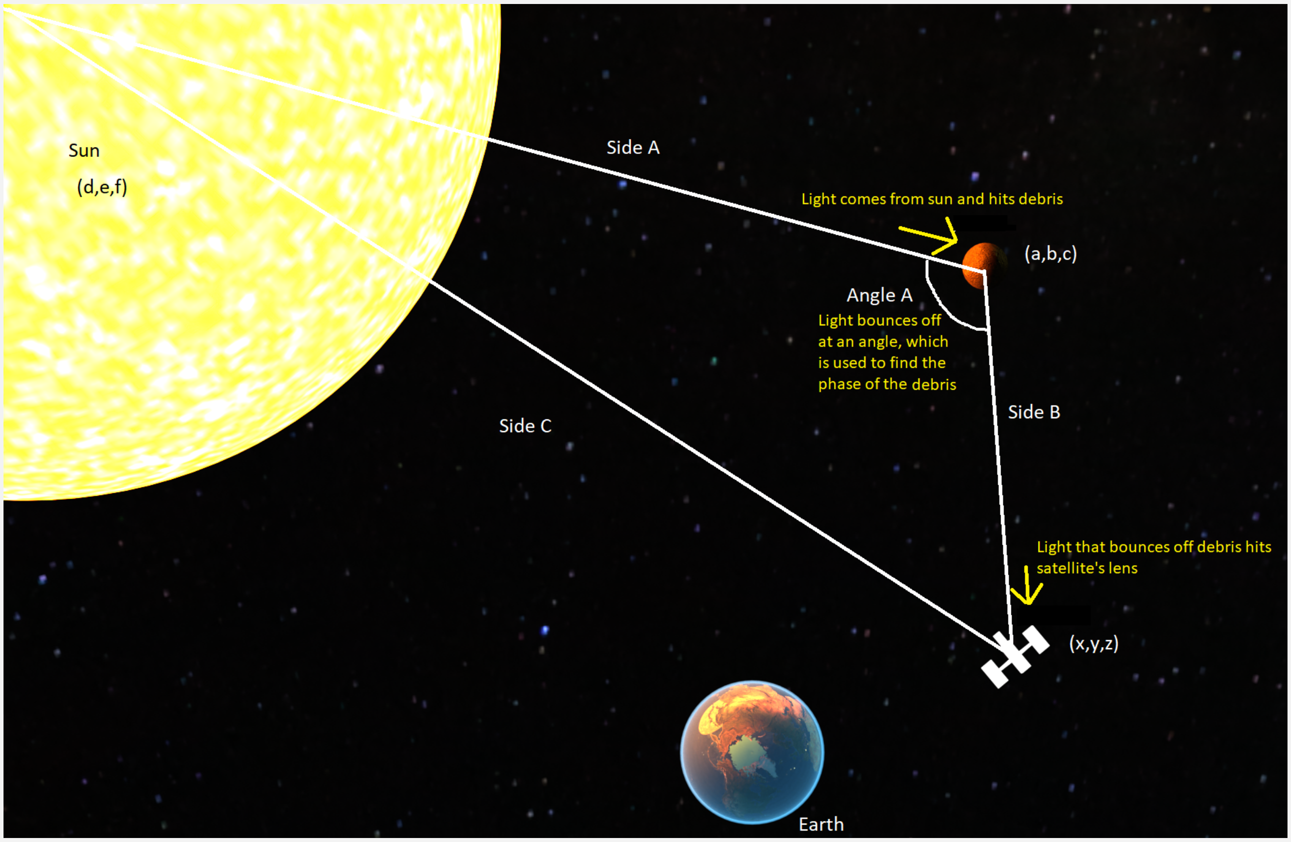
Our goal is to find the optimal satellite configuration to track objects in cislunar orbit taking into account cost production, maintenance, and view of debris. Finding a cost-effective tracking system for objects in geosynchronous orbit to cislunar orbit can help prevent collisions between debris and satellites. With that in mind, here are the steps that our program goes through to achieve this:

- **The simulation:**

The simulation is composed of two programs that produce the positions for all the satellites and the debris used within our cislunar space. The first program produces the chaotic orbits for the debris one at a time and saves the positions for each time step to a file. The debris orbits generated vary in both position and velocity. The position ranges from 50,000 km to 384,000 km away from the earth. The velocity runs through an assortment of different magnitudes and directions. The second simulation runs through the satellite positions and changes the velocity to stay in circular orbit accordingly. The location for the satellites runs through eight positions at an altitude of 2,000km (low earth orbit) above earth, and four orbiting at 5,000km. The velocity changes accordingly so the satellite orbits in near circular motion. The accuracy of these programs depends heavily on the dt, or ‘time step’ being used. The greater the time step, the less accurate the data will be.



https://www.youtube.com/watch?v=2h8doa_Indg*(video of the physics simulation running for 6 months, at a timestep of 10 seconds)* *[https://www.youtube.com/watch?v=e2lvFIXgcWE](https://www.youtube.com/watch?v=e2lvFIXgcWE)(video of the physics simulation running for 6 months, at a timestep of 100 seconds)*



- **The Luminosity:**

The luminosity section of the code runs after the simulation data has been compiled. Given the positions of the satellite and debris at various points in time, as well as the specifications that are generated for the satellite's camera, the code iterates through each satellite orbit and each debris orbit and works through over 1,000 different combinations of debris and satellite to find the total light gathered by each satellite in each situation.

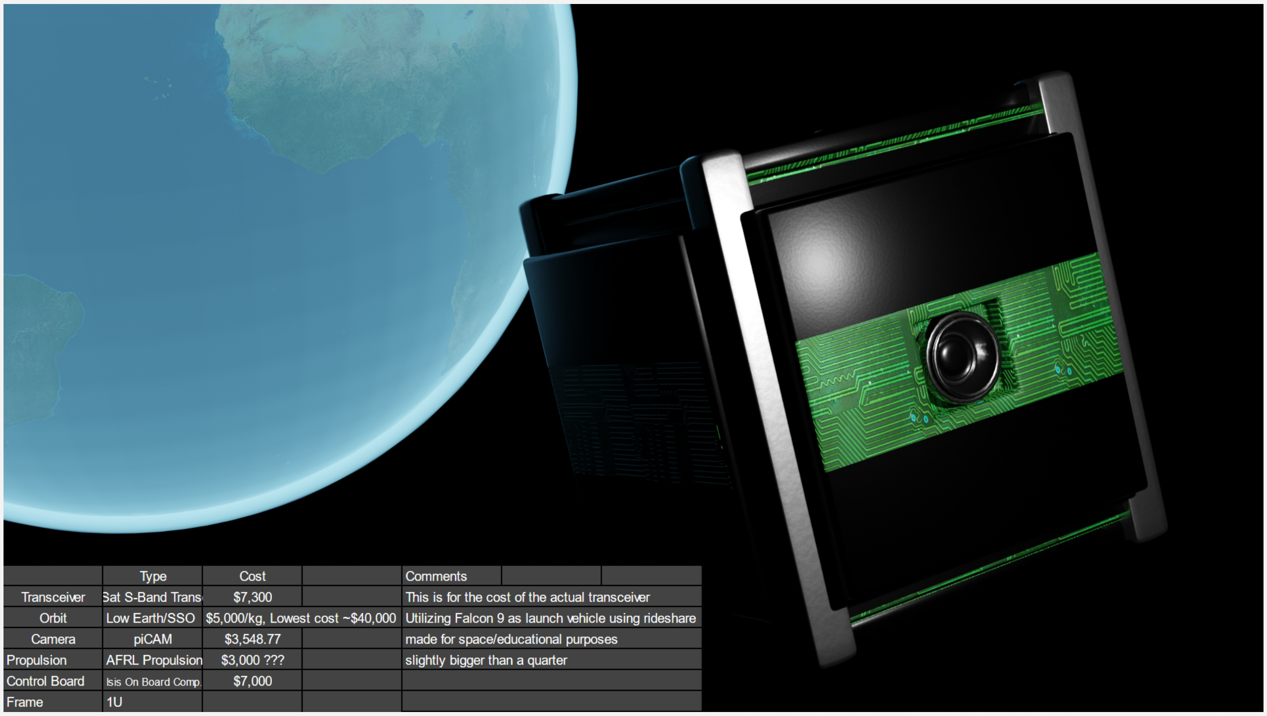
The program starts by using the coordinates of each celestial body(shown as [x,y,z], [a,b,c], and [d,e,f] in the diagram) and finds the side lengths of the triangle between the sun, the satellite, and the debris(shown as side A, B, and C in the diagram). Given the side lengths, the Law of Cosines is used to find the angle from the debris to the satellite(shown as angle A in the diagram) which is used to find the phase of the debris from the perspective of the satellite.

Before calculating how much light from the debris the satellite sees, we need to find whether or not the satellite can see the debris in the first place. To do this, the satellite's field of view is taken into account, assuming it is facing directly away from the Earth. If the angle of the debris falls within the angle range between the two edges of the satellite's view, it can be seen. If not, the rest of the loop is skipped. If the debris can be seen, however, the bulk of the calculations begin.

First, the amount of light from the sun to reach the debris is calculated with the Inverse Square Law. This number is multiplied by the debris surface area(assumed to be a perfect sphere 1 kilometer across for ease of calculation), multiplied by the reflectivity of the debris' material(around 14%) and the phase of the debris that was calculated in the early stages of the loop. The inverse square law is once again used to find the amount of light from the debris that reflects into the lens of the satellite, where the quantum efficiency, lens surface area, and shutter speed are taken into account, turning the luminosity that reaches the satellite into joules. After this is done, the program writes the results to a file with its timestamp and moves on to the next loop.

- **<u>The Cost</u>**

Our goal is to have a cheap way to track debris in a cislunar orbit. In order to track debris in space, putting satellites into orbit, and close to the same vicinity as the debris, is the best way of accurately tracking it without the interference that a tracking system on the ground would have to deal with. While satellites are becoming more common as accessibility to space increases, they remain incredibly expensive to build and maintain.



| | Type | Cost | | Comments | | |
|---|---|---|---|---|---|---|
| Transceiver | Sat S-Band Trans | $7,300 | | This is for the cost of the actual transceiver | | |
| Orbit | Low Earth/SSO | $5,000/kg, Lowest cost ~$40,000 | | Utilizing Falcon 9 as launch vehicle using rideshare | | |
| Camera | piCAM | $3,548.77 | | made for space/educational purposes | | |
| Propulsion | AFRL Propulsion | $3,000 ??? | | slightly bigger than a quarter | | |
| Control Board | Isis On Board Comp. | $7,000 | | | | |
| Frame | 1U | | | | | |

For example, the James Webb Telescope, although serving a different purpose than our satellites would, cost around $10 billion dollars. This is an excessively large number considering our budget and purpose, so with that in mind we turned to the cubesat.

The cubesat is an innovative way to fit the necessary components of a satellite into a small frame, about 10cm^3, while still being able to effectively accomplish our goals. According to our cost calculations it would only cost about $700,000 per satellite. This cost evaluation takes into consideration things like cost to launch (using a rocket like the Falcon 9), cost to run (mostly sending and receiving data from the satellite(s)), and the actual parts being used in the cubesat. With an average lifespan of around one year and a low cost per satellite, compared to the larger current satellites the cubesat is the perfect fit for our needs.

## Verification of our data

To verify that our data from the 3-body simulation was accurate, we designed a visualizer in the Unity game engine that would read from the various data sets we generated and show the positions of the satellite and debris in motion, giving us an idea of whether or not our calculations were accurate.

To verify the luminosity calculations, we used the visualizer to see whether or not it was feasible for the satellite to see the debris given its field of view, as well as references from previous physicists who attempted similar things, examples being finding the lux, which can be translated into luminosity, of the moon (see this article for more information) and then plugging in variables that matched the situation they worked with to see if we could replicate their results.

The costs for the satellite were taken from various vendors of satellite parts, as well as NASA's own projection of the average costs for a satellite to be built and launched. Since a great deal of the work for this part of the code was in researching typical costs per part,

## Conclusions

link to the generated data

While comparing the results of the luminosity data, some interesting patterns emerged. For instance, the first 3 satellite orbits were able to cover each other's blind spots relatively well. They also occasionally overlapped viewing times, which allows for better tracking of the debris. However, with such a small setup, there were still large blind spots spanning hours or sometimes days. A fourth and fifth satellite at complementary orbits would help keep more than one satellite tracking the debris at a time, and also reduce the time where the debris was continuously out of sight. 8 satellites spaced evenly around the globe would have been optimal, and rotated at slightly different axes to catch debris coming from any unexpected angles. In terms of the amount of light received, it ended up being rather small due to the large distance between the two objects. More expensive cameras with higher quantum efficiency, longer shutter speed, and other types of satellite cameras that don't rely on visible light to locate things would all be helpful in better locating the debris.

## Reflection

Our most significant achievement was undoubtedly the 3-body simulation of cislunar space. The amount of fine-tuning and error fixing that it had to go through made its verification a team effort, and also the most intricate part of our project.

We could also have done quite a few things better during the process. Overall, we lacked organization and throughout the project had trouble communicating what needed to be done by whom. These flaws in our strategy left us constantly scrambling to meet deadlines, which resulted in last-minute crunch time on more than one occasion. The fact that everything in our project relied on the progress of a central, sometimes finicky piece of code only one person could work on at a time further hindered our efforts since often two people would need to wait in order for one person to fix the issues before anyone could progress. During the start of the project we were also unable to come to a solid decision of what to do, effectively wasting two months of the time we had. In our future attempts at the challenge, it would be advantageous to have a formal repository for code so we can better share in the creation of code, rather than having most of the programming be offline. The final mistake we made was our last minute realization that an increase in delta time(dt) caused the satellite positions that we had generated ended up building so much percent error that for the past 3 months, none of the data was valid. We were able to generate a couple more accurate simulations near the end with a lower dt, but by that point we didn't have the weeks it would take to compute the billions of lines of data we needed.

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