Final Paper:
Asteroid Classification-Capable Monostatic Radar

ELEG 492: Introduction to RADAR Systems

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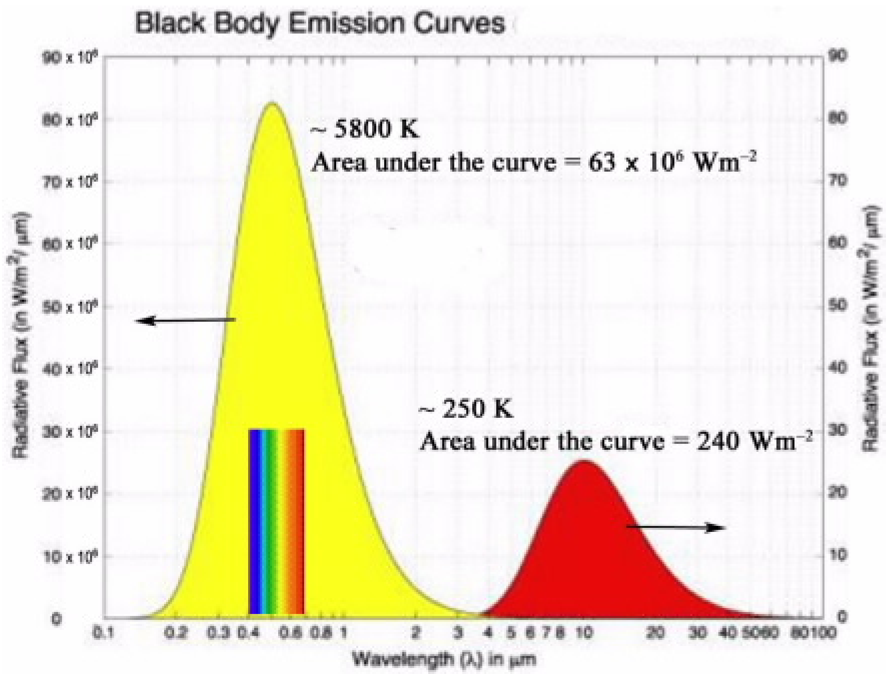
Section 1: Introduction

Section 1a: Abstract

This paper specifies a monostatic radar designed to classify NHATS-Compliant NEAs (more info on NHATS-Compliant NEAs in Section 2). Using NHATS public information, the radar would be powered on whenever the main controller detects that a desired asteroid should be in its frame of view. Using complicated tracking algorithms which use parameters from the NHATS public information, the radar can hone in on the asteroid without having to track the asteroid itself. The radar must operate in the radio window of RF waves in order to escape Earth's Atmosphere into free space (roughly 30 MHz to 3 GHz, VHF and UHF). It's angular resolution is critical in this case in order to block out as much noise from the background as possible. The radar will need to transmit at many different frequencies (broadband) and accurately predict doppler effects on the frequency response in order to correctly classify the asteroid. This will add a lot of noise to the system (i.e. thermal noise), in order to counteract this there will need to be

many repeated readings in rapid succession to filter out the signal from the noise (Coherent Integration). All data collected by the radar will be released to NHATS and, most importantly, the public.

Section 1b: Earth and Sun's Black Body Plots



Credit: United States Geological Survey

The Sun and the Earth's atmosphere's allow different wavelengths to escape into free space. Therefore, the radar system must be designed to transmit and receive at the Earth's atmosphere's emission spectrum (broadband) and the signal processor must take the Sun's atmosphere emission spectrum into account. It is important to note that these plots are not continuous, "Fraunhofer lines", the name of these discontinuities, are what allows us to classify asteroids.

Section 1c: Atmospheric Refraction

If a radar tries to transmit energy at a wavelength that is not permissible through the Earth's atmosphere, the effective index of refraction is increased and the signal is reflected back to the Earth's surface. Transmitting at correct wavelengths, the effective index of refraction is decreased to a value that allows the signal to travel through the atmosphere with some refraction.

Section 1d: Asteroid Classification

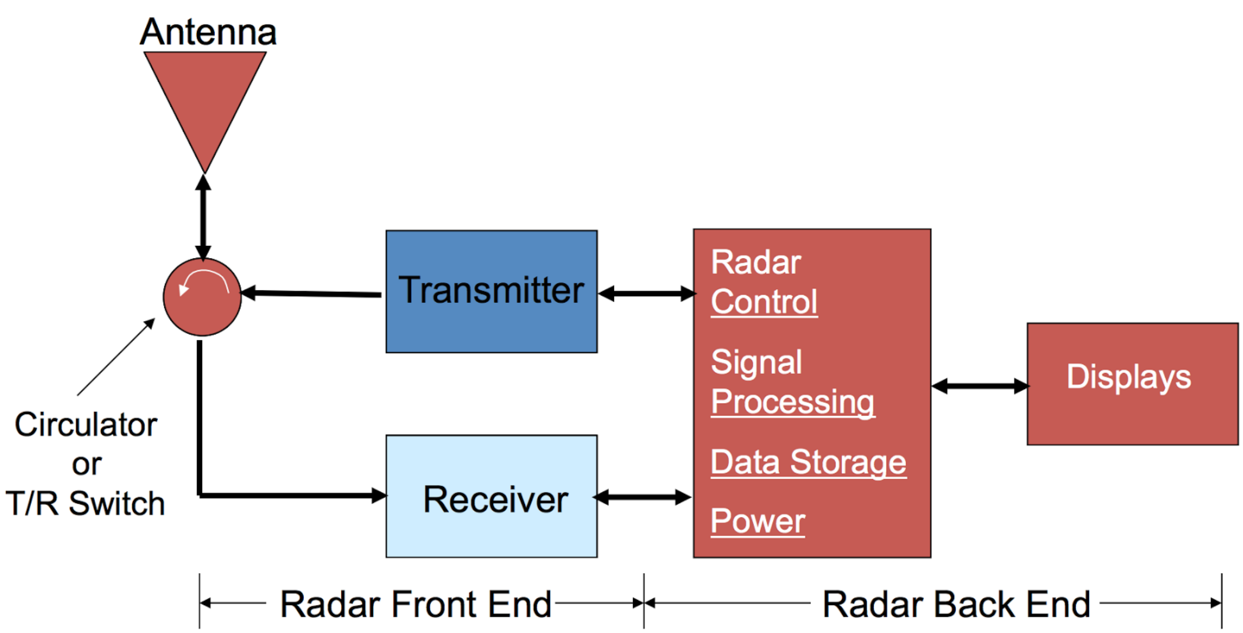
Unfortunately, currently standing classification schemes only take wavelengths around visible light into account. Classifying asteroids based on radar returns is a relatively new technique, due to the difficulty of getting the desired angular resolution in order to minimize the signal-to-noise ratio.

Section 1e: NHATS and NEAs

I reference NHATS and NEAs in this document. NHATS stands for Near-Earth-Object Human-Space-Flight Accessible Targets Study and NEAs stands for Near-Earth Asteroids, which is a type of Near-Earth Object (NEO). NHATS supplies public information on all of the NEOs which it calculates to be accessible by human space flight. I can further sort the information from the database to my needing. This will come in handy with the radar control, power consumption, and antenna positioning.

Section 1f: Antenna System Block Diagram

Here is a general antenna system block diagram for your reference.



This is the basis for all of the radar front end and back end section headings, each heading corresponds to a part of this diagram.

Section 2: Planning

Section 2a: Size of Asteroids

Table 1: Brief Summary Data for the Current Top 25 NHATS-Compliant NEAs

Designation	*n*	Estimated Diameter (m)
2000 SG_{344}	3302638	27 - 85
1991 VG	2737751	5 - 16
2006 BZ_{147}	1674416	20 - 63
2001 FR_{85}	1618888	30 - 96
2008 EA_{9}	1597844	7 - 22
2010 VQ_{98}	1580174	6 - 18
2007 UN_{12}	1443703	4 - 14
2006 RH_{120}	1283817	3 - 10
2010 UE_{51}	1242487	5 - 17
2008 HU_{4}	1227757	6 - 17
2007 VU_{6}	1186902	12 - 38
2008 UA_{202}	1114827	3 - 10
2010 UJ	1082350	14 - 45
2011 BQ_{50}	1010896	5 - 16
2004 QA_{22}	1008597	6 - 20
2001 GP_{2}	980724	10 - 32
2009 HE_{60}	970582	18 - 56
2010 JR_{34}	960736	7 - 22
2009 BD	936904	5 - 16
2011 MD	936324	6 - 18
2010 TE_{55}	920319	6 - 20
2008 JL_{24}	904774	3 - 9
2011 BL_{45}	865199	9 - 28
2007 YF	791134	27 - 85
2010 JK_{1}	773964	32 - 100

Credit: NASA

The current top 25 NHATS-Compliant NEAs, based on the number of viable trajectory solutions offered denoted as *n*, fall in the range from three to a hundred meters in estimated diameter. This isn't what their RCS will be, but it will a good estimate. Taking into account the range of each of these asteroids, I can calculate a rough angular resolution range that I need to achieve.

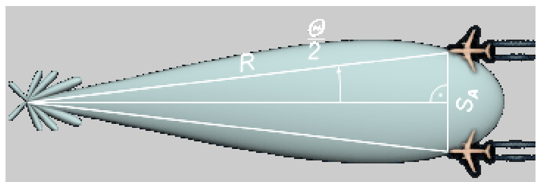
Section 2b: Tracking an Asteroid

In the same way that NHATS had combined databases from various different observatories around the world, I'd need to collect all tracking information on a desired asteroid in real time. A comprehensive algorithm would be required for precisely angling the antenna towards the target asteroid given this database to work with. This would be one of the harder obstacles to overcome in the design of this radar system.

Section 3: Front End

Section 3a: Antenna

The radar system will be designed to target asteroids which are within an astronomical unit ($\sim 1.5 * 10^{11}$ meters) away. The angular resolution at this range can be calculated.



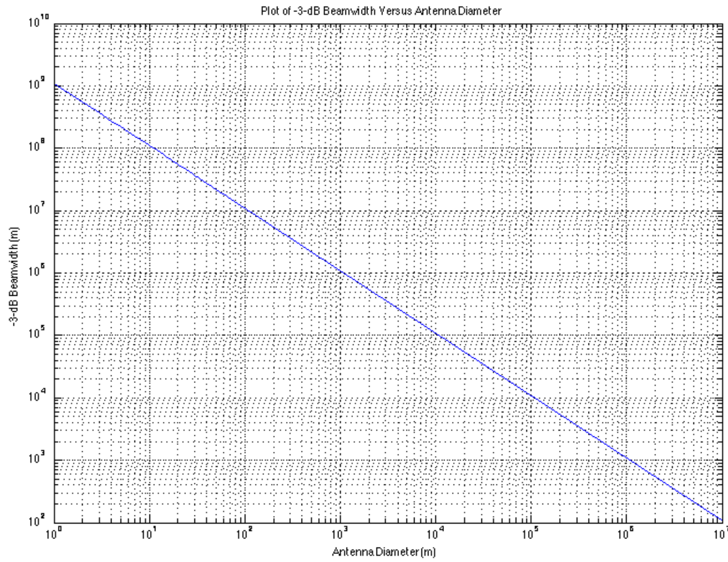
Credit: radartutorial.eu

The important thing to take away from the image above is S_A, the -3-db beamwidth:

$$S_A = 2 * R * sin(\frac{\Theta}{2})$$
$$\Theta = sin^{-1}(\frac{\lambda}{D})$$
$$S_A = 2 * R * sin[\frac{1}{2} sin^{-1}(\frac{\lambda}{D})]$$

I plotted the above function in MatLab with $R = 10^{11}$ meters, $\lambda = 0.11$ meters against D, the antenna's effective diameter.

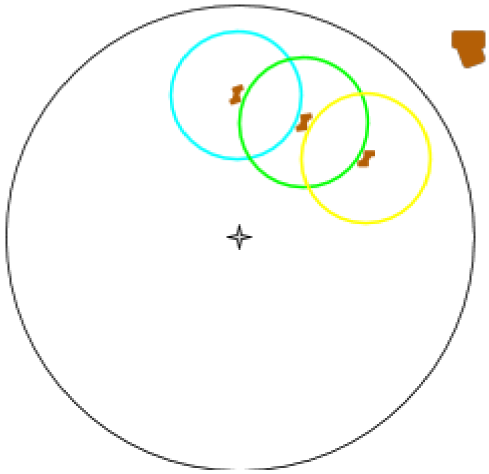
```
function [ output_args ] = RadarFinal( input_args )
    %RadarFinal
    %   Matlab code for my ELEG 492: Introduction to RADAR Systems course.

    % Parameters
    R = 10^10;                      % Range in meters
    L = 5;                       % Lambda in meters
    D = 1:1:10^7;                   % Diameter in meters

    Sa = 2*R*sin((1/2)*asin(L./D)); % -3-dB Beamwidth in meters

    figure
    loglog(D,Sa)
    grid on
    title('Plot of -3-dB Beamwidth Versus Antenna Diameter')
    xlabel('Antenna Diameter (m)')
    ylabel('-3-dB Beamwidth (m)')

end
```



This graph represents the -3-dB beamwidth, S_A, as a function of range, λ, and the antenna diameter. It shows the impact of using interferometry. The largest single dish antenna has a diameter of 305 meters (Arecibo Observatory), which still has a terrible -3-dB beamwidth when targeting relatively small asteroids (a few meters to a few kilometers in diameter). Thus, an interferometer design will help greatly.

The wavelength range is about from 10 centimeters to 10 meters, therefore the parabolic dish must have a diameter of at least 10 meters. The diameter for the antenna will be 20 meters to be safe.

In the illustration below, the dark background represents the noisy background which is space, the yellow, green, and blue circles represent S_A at various instances, and the brown-rotating shape is an asteroid. Notice that the asteroid should always be centered in this circle if the tracking algorithm is correct and most importantly that the radar returns vary on each reading because of the noise. After many rapid trials, the desired signal will be filtered out of the noise. The face of the asteroid which is facing us is also changing, so our reading will be affected slightly, thus our classifications will be general to the entire body of the asteroid (including whatever is floating around it).



Section 3b: Circulator or T/R Switch

Knowing the time it should take for the signal hit the target and bounce back with the tracking algorithm, the circulator will match this period in transmitting and receiving. It will transmit at the start of this period , wait for just before the signal should be back, then receive for a very short amount time in order to minimize the noise. This process repeats until the asteroid is calculated to no longer be viably targeted (i.e. out of range, out of view, etc.).

Section 3c: Transmitter/Receiver

Using the received signal energy formula,

$$S_R = P_T * \frac{4\pi A}{\lambda^2} * \frac{G_T}{4\pi R^2} * \frac{1}{L} * \sigma * \frac{G_R}{4\pi R^2} * A * \tau$$

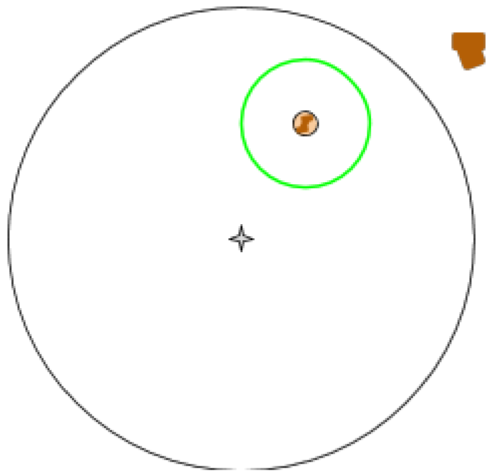
Convert L to all of its subcomponents and assume a monostatic radar.

$$S_R = \frac{P_T G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L_t L_r^2 L_{ch}^2}$$

The maximum range can also be calculated in meters,

$$R_{max} = \left[\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{min} L^2}\right]^{1/4}$$

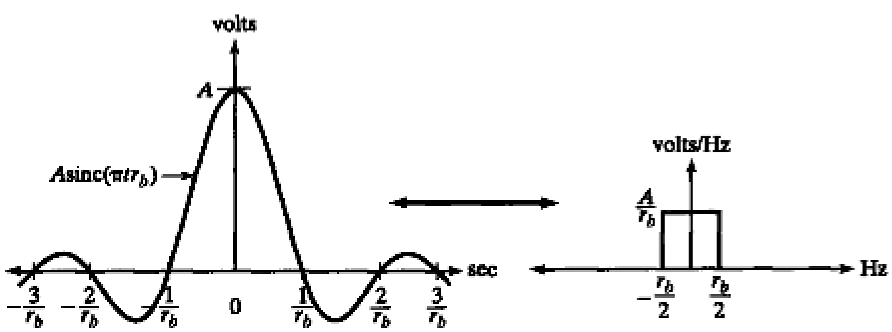
With a -3-dB beamwidth of 10^8 meters and asteroids varying from 3 to 100 meters at the smallest, roughly speaking, this creates a rough plot that can be used to calculate the signal-to-noise ratio. Recall this old drawing,



This time I added a circle around the asteroid which can be approximated to be it's shape with a diameter equal to that of the asteroid. At worst case the Signal-to-Noise ratio (SNR) is $\frac{\pi(3)^2}{\pi(5*10^7)^2} \approx 10^{-15}$ (diameter of 3 meters) and at best case it is $\frac{\pi(1000)^2}{\pi(5*10^7)^2} = 10^{-10}$ (diameter of 1 kilometer). This is an extremely low SNR, but it will be handled in the Signal Processing back end.

The setup of this radar system ensures no probability of false alarms (we know precisely where our target is, there's no missing). From first appearance the returned signal will look just like noise (no CFAR threshold). After many of the iterations (trials), the noise should follow its Gaussian distribution and desired signal will be become apparent. This will be discussed more thoroughly in the back-end sections.

The signal waveform generator for this radar needs to be very advanced. It needs to accurately produce all frequencies within VHF and UHF. This requires a relatively rectangular frequency response, which is a sinc function in the time domain. The rectangular frequency response is centered on the origin as below,



In this case, I can calculate $r_b = 3GHz - 30MHz = 2.97GHz$. There also needs to a frequency shift in the frequency domain by 30MHz. The amplitude should be large, but it directly affects the amount of power the antenna is transmitting (P_t). The power of a sinc function is $A\int_{-\infty}^{+\infty}\left|\frac{sin(x)}{x}\right|dx = A\pi$, where A is the amplitude of the sinc function in volts. I will choose P_t to be 10 kilowatts, making the amplitude of the signal $\pi * 10^4 V \approx 31.4 * 10^3 V$. This is too high of power for any waveform to produce without power amplifiers. The signal could also be a chirp signal, which also would cover the desired band of frequencies, although this is not necessary.

The first power amplifier has the most impact on increasing the noise figure (NF), therefore the most money needs to be spent on this amplifier to make sure it is produces low-noise. The subsequent amplifiers have less and less of an impact on the NF, therefore they can be cheaper.

Section 3d: Transmission Lines

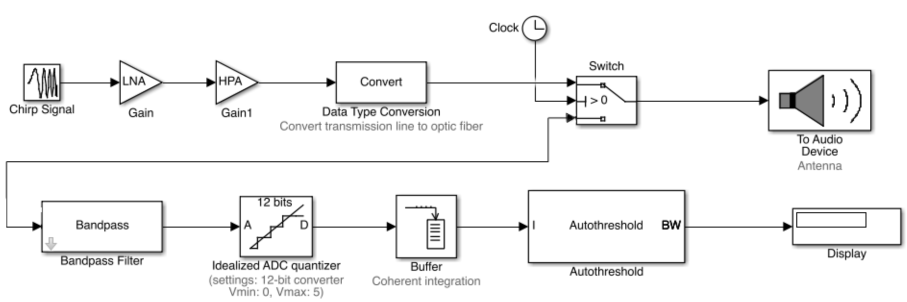
In order to minimize the signal loss due to the transmission line, I will use optic fibers. Optic fibers work well in the VHF and UHF bands. There will need to be couplers at the waveform generator for converting the voltage signal into a light source in the optic fiber and at the circulator for converting the light source into a voltage signal.

Section 4: Back End

Section 4a: Radar Control

A comprehensive computer system needs to be built that acts near-autonomously. It needs to have the features of a web server. It is constantly reading new information from many different sources that are telling what possible targets it has. If there are more than one, it needs a hierarchal approach to selecting its target. Once selecting a target it calculates the asteroid position at all points in the near future, these values will be updated real time, but they act as a best estimate for its location. From this point, a complicated algorithm needs to calculate how the antenna should be angled in order to lock on to this point in space.

Now the radar enters a pulse train phase of a broadband of signals in the range of frequencies of VHF and UHF. The radar then receives the signal precisely when it calls the RTT should be for the signal, since we know exactly where the asteroid is and the speed of the signal (the speed of light).



Simulink schematic of my radar system.

Section 4b: Signal Processing

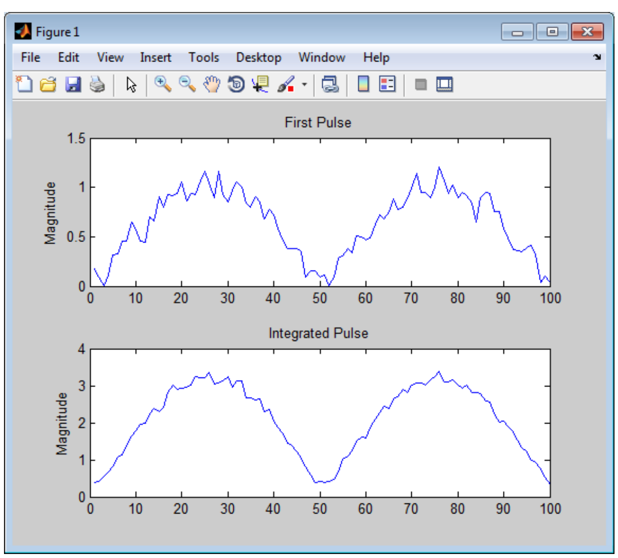
The received signal, after passing through the circulator, enters the bandpass filter which filters out all of the frequencies not in the VHF and UHF band. After that, it enters an analog-to-digital converter, then it enters the coherent integration stage.

Coherent integration is crucial in this project. The signal-to-noise ratio is outstandingly bad, but building up our trails will show the desired signal. It involves buffering many recordings and averaging over the buffer to recover a single signal. Averaging over *M* measurements yields,

$$y = \frac{1}{M}\sum_{i}^{M} y_i = \frac{1}{M}\sum_{i}^{M}(V_0 + m_i) = V_0 + \frac{1}{M}\sum_{i}^{M} m_i$$

y represents the final signal after M buffered readings, V_0 represents the returned signal from the asteroid, and $\frac{1}{M}\sum_{i}^{M} m_i$ represents the random noise which should decrease when the number of *M* measurements in the buffer increases. A simple example of this is show below,

```
function [ output_args ] = CoherentIntegration( input_args )
%COHERENTINTEGRATION Simple example of pulse integration (coherent integration)
%   Example of a two-step pulse integration.

 f = repmat(sin(2*pi*(0:99)'/100),1,10)+0.1*randn(100,10); % Signal with noise
 y = pulsint(f);                     % Integrated pulse
 subplot(211), plot(abs(f(:,1)));    % Noncoherent integration
 ylabel('Magnitude');
 title('First Pulse');
 subplot(212), plot(abs(y));         % Coherent integration
 ylabel('Magnitude');
 title('Integrated Pulse');

end
```



It’s is important to notice the that function starts with the absolute value of the sine function that is superimposed with pseudo-random noise. Because the noise should follow a Gaussian distribution, the coherent integration looks more like the actual absolute value of the sine function.

At this stage the frequency response of the asteroid should be apparent that some frequencies drop in amplitude (Fraunhofer lines). The processor can now point out what frequencies seem to be lacking and pass that on to a display.

Section 4c: Data Storage

A web server will need to be setup that communicates with other sources of data storage. There will also need to be lots of data on the current target when the antenna is activated, as well as a large buffer to hold signal data before being coherently integrated.

Section 4d: Power

The transmitter is the brunt of power consumption for this radar system. It uses 1 kW of power per pulse. This will create tremendous heat which needs to be cooled (i.e. water cooling) in order to minimize thermal noise $N = kTB$ where Boltzmann's constant $k \approx 1.38 * 10^{-23} \frac{J}{K}$, the temperature can be assumed to be $T = 300K$, and $B = 3GHz - 30MHz = 2.97GHz$. Therefore the the thermal noise is roughly $N \approx 1.23 * 10^{-11} W$ at 300K.

Section 4e: Displays

A display will show what frequencies are being detected to be Fraunhofer lines and which frequencies are not being absorbed by the asteroid.

Section 5: Conclusion

Section 5a: Final Remarks

The number of readings for the coherent integration to get any meaningful data back may be too large for this radar system to be practical. I would need to do more research on the actual number of readings that would be needed in order to get an accurate classification of an asteroid. In the preliminary trials of the antenna, it would test itself out on already well classified asteroids in order to see what it predicts. I’d be very interested to see how accurate it’d be in action.