AUTONOMOUS DETECTION, NAVIGATION, AND PROPULSION FOR SATELLITES

by

STANLEY BADGER

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Approved by:

Major Professor
William Kuhn Ph.D.

Abstract

With the increasing number of satellites and space debris in all orbits the need for individual satellites to be able to autonomously detect and determine methods to navigate around them is increasing. Even with continued input and control from a ground station, the ability for a satellite to act to save itself from obstacles not visible from ground stations, or if communications were temporarily lost could be key to saving millions of dollars in hardware as well as improving overall performance and operational lifetimes.

Table of Contents

List of Figures.......v
Introduction.......1
  Document Outline.......1
Location and Detection by Radio Signals.......3
  GPS.......3
  Active Detection.......4
  Orbital Velocity.......7
    Transceiver Design.......9
    Object Tracking.......12
Propulsion Methods.......14
  Chemical Propulsion Methods.......14
    Solid Rocket.......14
    Chemical Rocket.......15
    Hybrid Rocket.......16
    Monopropellant Rocket.......17
  Electric Propulsion.......18
  Ion thrusters:.......19
    Hall effect.......19
    Electric Grid.......21
  Other Emerging and Theoretical propulsion methods:.......22
    Reaction Wheel and Control Moment Gyroscopes.......22
    Solar Sails.......23
    Magnetic Sail.......24
    Magnetic Tether.......24
Calculations of acceleration.......26
Conclusions and Future Work.......30
References.......31
Matlab Code.......34
  Generate Sphere and Ellipsoid.......34

Calculate distance traveled by satellite during the round trip compared to range....................35
    Calculate the escape velocity versus orbital height..35
    Calculating the acceleration due to the different thrusters...36

List of Figures

Figure 1: Sphere with a radius of 200 km generated in Matlab..4
Figure 2: Arbitrary three dimensional ellipsoid generated in Matlab..5
Figure 3: Distance traveled at a speed of 10 km a second generated in Matlab.............................6
Figure 4: Orbital velocity vs. Orbital Height generated in Matlab...8
Figure 5: Solid Rocket image from Wikipedia[16]...14
Figure 6: Chemical rocket[17]..15
Figure 7: Hybrid rocket[18]..16
Figure 8: Monopropellant system on MRO[19]...17
Figure 9: Operation of a Pulsed Plasma Thruster (1) Energy storage unit (2) Igniter (3)Fuel Rod (4)Plasma Acceleration[20]..18
Figure 10: Hall Effect thruster[22]...20
Figure 11: Gridded Ion Thruster[21]..21
Figure 12: Solar Sail [26]...23
Figure 13: Tethered Satellite System deployment[28]...25
Figure 14: Comparison of displacement over a set time in Matlab...27
Figure 15: Comparison of displacement to a set distance created in Matlab...............................28
Figure 16: Direct comparison of displacement versus time for several thrusters created in Matlab 29

Introduction

How do we determine satellite lifetimes? We have made great strides in trying to maximize the lifespan of the electronics through radiation shielding and radiation hardening techniques. Unfortunately for the most part these gains become irrelevant. The only thing we can say with certainty is that the circuitry has been tested and shielded to the best of our ability, and that baring some unknown failure the lifespan of the electronics will exceed the actual limiting factor of satellite life spans.

This limiting factor is the amount of propellant the satellite can carry. While it makes up a significant portion of the launch weight, there is a limit to how long it can last. Propellant is critical for navigation and station keeping. How efficiently it used is critical to extending the lifespan of satellites to the point where the electronics lifespan can actually be tested.

Collisions are another critical thing to consider in satellite operational life spans as more objects enter space. As the recent crash between an Iridium satellite and a defunct Russian satellite illustrates, while it is possible to track objects in space not always does the information get from those who are doing the tracking to those who need the information.

There are quite a few methods that can be used to improve the efficiency of propellant use. The best researched and developed is to use a more efficient propulsion system. Another method just getting started is using autonomous guidance systems on the satellites themselves. What this paper proposes to explore is to combine this with onboard detection systems using radio signals to detect objects in space around the satellite.

Document Outline

In satellites a significant portion of the launch weight and the major determining factor in life span estimates is the amount of propellant that is used for navigation and station keeping. Many different methods can be employed to improve this. In this paper we will explore autonomous detection of objects and navigation. Many applications in remote operation employ this to improve efficiency, or for the sake of continued operations if the remote vehicle is out of communication with its human controllers. This functionality is becoming more and more critical as the number of satellites in non-stationary low earth orbit increases.

The largest amount of research appears to be in visual detection by miniature cameras. This works fine for ground based rovers or even unmanned aerial vehicles, but it is of limited use in space based applications. [1]

For satellites it is preferable to use radio wave based detection methods rather than light as the equipment for detection can be made more simple and robust. Less information is needed for detection of objects using radio waves as it is simply a matter of if the signal returns something is there. Instead of needing cameras that must to be aimed, simple non-directional antennas can be used. The first section deals with detection by radio signals and comparing the operation of a unidirectional radio transponder system with GPS to a follow up section on how orbital speeds are affected by altitude.

Once an object has been located its velocity can be determined by simply tracking its change in position over time. With the relative position and velocity information for other objects in space there are a number of methods that can be used to calculate if a course correction is needed to avoid this particular object as well as any others in nearby space. The second section will discuss methods to simplify the processing.

The third consideration is the actual methods of propulsion used for navigation and station keeping. The most widely used propulsion systems in satellites are called chemical rockets with reaction mass in the form of liquid propellants reacting to decompose into gases or small rocket motors, because of their simple design and well known thrust characteristics. They are simple, but at the cost of poor fuel conservation. The third section will deal with this while being divided into several subsections.

The three subsections for propulsion will be chemical propulsion, electrical propulsion, and emerging and theoretical propulsion methods.

The fourth section will calculate the thrust several systems currently available are able to generate and compare them to find the best combination for efficiency.

The fifth section will give the conclusions of this paper, and be followed by a references and the appendix giving all the code used to generate the Matlab simulations and images.

Location and Detection by Radio Signals

A radio location method that many people may be familiar with is passively detecting a signal source by triangulation. The first example that comes to mind from popular media, at least for fans of the TV show MacGyver, is in the episode titled “Ugly Duckling” where the hero demonstrated locating a radio signal source using a hand held radio with a simple extended antenna, a car radio antenna a certain distance away, and two analog dial watches to determine the angle to the source. This works fine if you have an antenna that can be turned towards a source.

GPS

In a situation where the antenna is either largely unidirectional or has its position fixed, as would be likely the case on a satellite, a different method has to be employed. In the case of a GPS receiver, where you can be certain it is well below the signal source in elevation, the method employed is called trilateration. With line of sight distance to the GPS satellites being within 12,900 miles [2] or 20,760 km.

Each GPS satellite transmits its own time and position data in all directions creating a sphere. With data from two satellites you find the intersection of two spheres which forms a circle. This is why a third satellite’s information is required because the new sphere will intersect the surface of the circle in only two points, with only one being on earth’s surface and the other being out in space. This is the basics of how the position is determined with GPS. It does however neglect that the position estimates of the satellites have a certain amount of error. By having information for more satellites this error can be marginalized to obtain the resolution we enjoy with our handheld GPS devices. [2]

That is the essence of passive detection. The first problem trying to use this for object detection in space is that with the exception of the GPS satellites almost all other satellites aim their signals towards the earth. As illustrated by the recent destructive collision between Iridium 33 and the out of service Russian satellite Kosmos 2251, there are other objects in space that do not give off any form of signal to identify their presence. [3] However the fact that GPS signals do broadcast into space allows for the satellite to passively use this to determine its own position.

Active Detection

With passive detection only to determine an objects position in three dimensional spaces, such as low earth orbit, you would need a minimum of four or more antennas. With active detection this number can be reduced. The critical thing is that the antennas will have to transmit a signal with the system's current time encoded to determine round trip time. Because of the relatively small distance between the individual antennas, we can assume that all of the individual antenna would receive the return signal at almost the same instant as a method of differentiation of reflected signals.

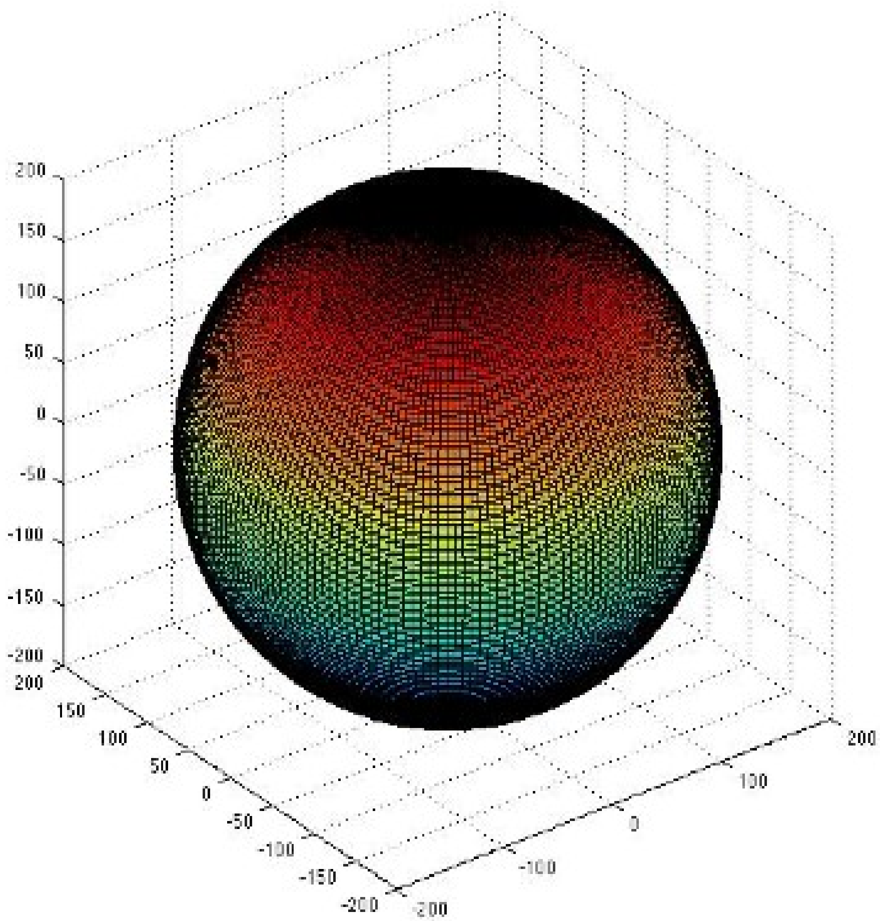

Figure 1: Sphere with a radius of 200 km generated in Matlab

Let's consider the situation with a single antenna transmitting and receiving. When the signal reflects from another object in space and returns, the only information we can be certain of is the round trip time. If the satellite was not in motion, this would give us that the object lies somewhere in a spherical shell with radius R, defined as half the elapsed time, times the speed of light in a vacuum. Since the satellite is in motion it becomes a three dimensional ellipsoid defined by all the possible intersecting circles of a sphere of arbitrary radius (r), centered at the transmit location, and a second sphere of radius (2R - r) centered at the receiving position.

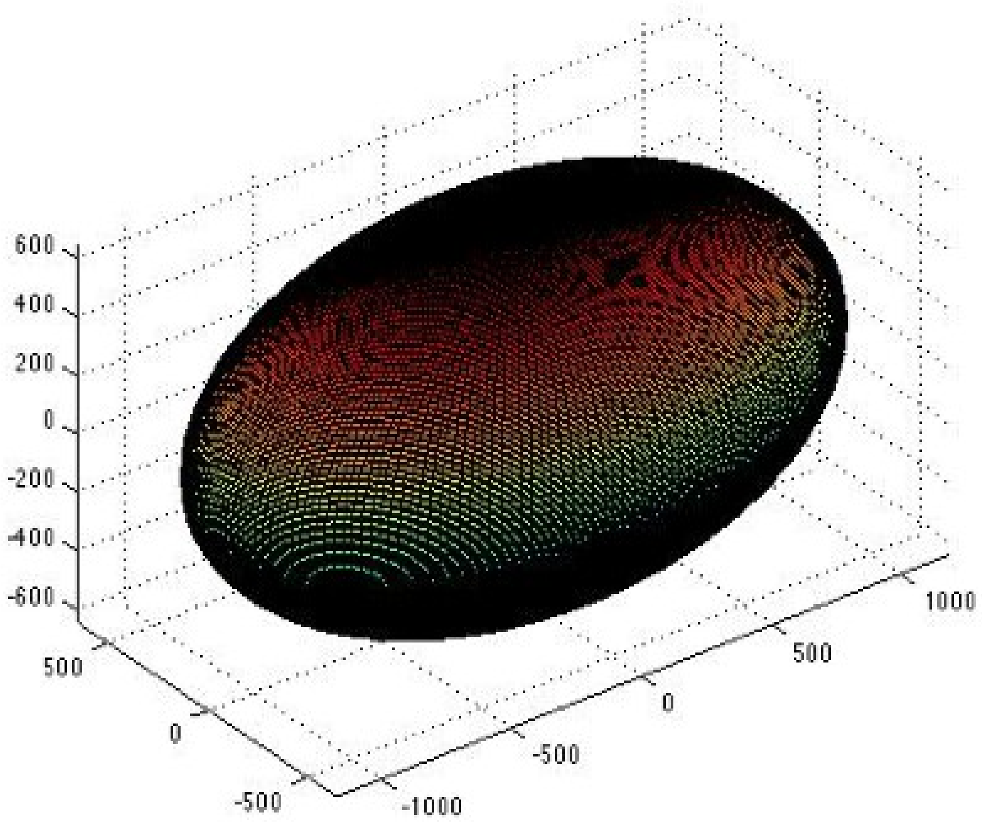

Figure 2: Arbitrary three dimensional ellipsoid generated in Matlab

This brings us to a question of scale. How much distortion will this actually create? When we have an object moving through space, there is a difference in the position between where it transmitted from and where the return signal is received. While this is true there is a difference in scale. Even at orbital velocities for LEO the orbital or escape velocity is on the order of ten kilometers per second. When that is compared to the speed of light, approximately three hundred thousand kilometers a second, we can see that for a range of detection of one hundred to two hundred kilometers the satellite will move very little even when we consider the total travel time.

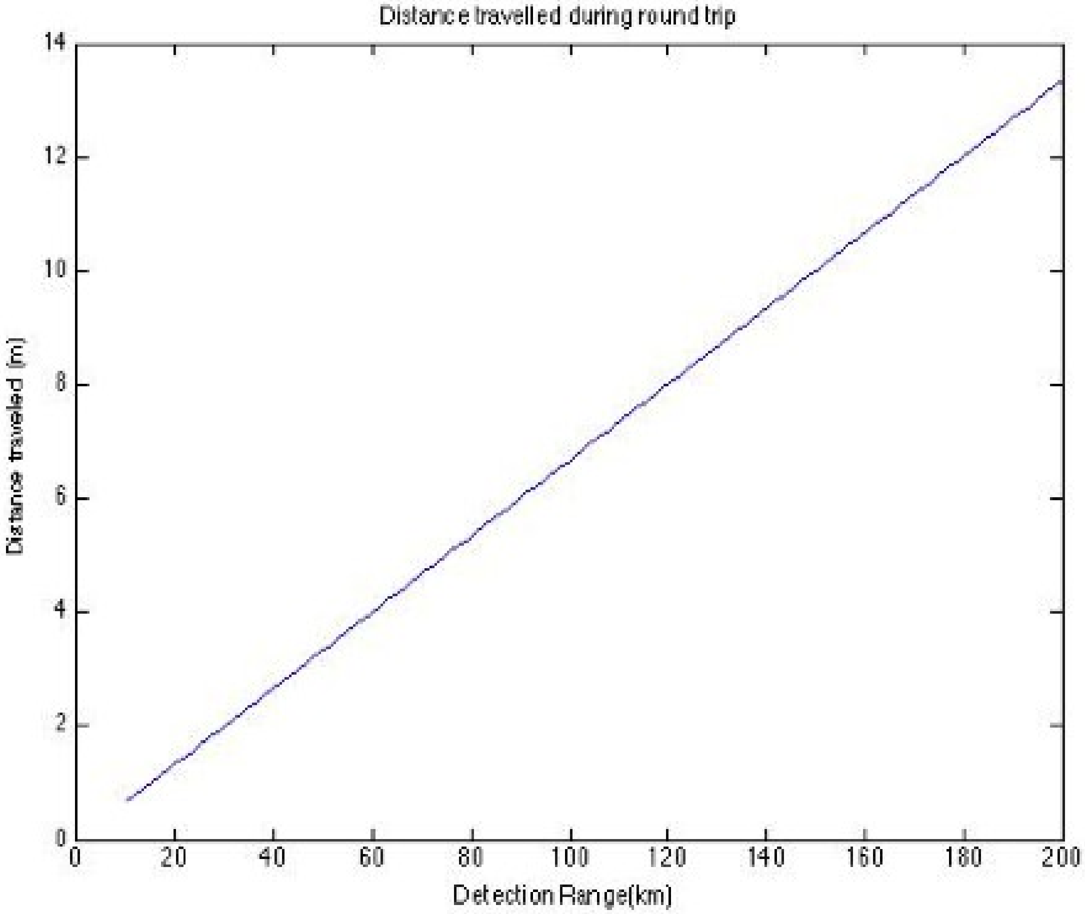

Figure 3: Distance traveled at a speed of 10 km a second generated in Matlab

Given that the satellite moves much less then one percent of the detection range of hundreds of kilometers the shape of the detection surface is still a very close approximation of a sphere. This is actually helpful as it simplifies the calculations. Even if we are able to separate the antenna by ten to twenty meters, by putting them at opposite ends of solar panel arrays, the result is still a close approximation to a sphere with a different center allowing for the same intersection calculations as are used in GPS.

If we add a second antenna as a receiver the result is the position can be narrowed down to approximately a planer circle. This is still inadequate to our needs; even if the satellite itself uses spin stabilization the difference in position of the antenna would only make minor changes to the sphere shape. Adding a third receiver antenna could, dependent on error, result in refining the position to two points in space, but would be just as likely to simply reduce the width of the circular plane.

Returning to the case of only two antennas, If we make both antennas transmit and receive, on different frequencies to avoid interference, then the result will be that we end up with two approximately planer ellipsoids that, depending on error and distortion, could have one intersection point to four or more.

When we add a third antenna only as a receiver, if it is positioned to be perpendicular to the line formed by the other two antennas, we begin to theoretically have the ability to isolate an objects position in three dimensional spaces. This is dependent on how much the error can be minimized in determining the intersection between the six three-dimensional position spheres the two transmitted signals generate.

We conclude that having three antennas set to transmit and receive signals would likely be the minimum hardware baseline for this purpose. Although as with GPS the more data you have to work with the better error can be minimized and resolution improved.

Orbital Velocity

The calculation of orbital velocities can be done simply by considering the mass of the earth, and the distance from the earth's center of mass. [6, 7]

$$v = \sqrt{\frac{\mu}{r}}$$

$$\mu = GM$$

Where G is the gravitation constant [8], M is the mass of the earth, 5.9736×10^{24}, and R is the mean radius of the earth, 6,371.0 km, plus the altitude above sea level. [9]

$$G = (6.67428 \pm 0.00067) \times 10^{-11}\ \mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{s}^{-2}.$$

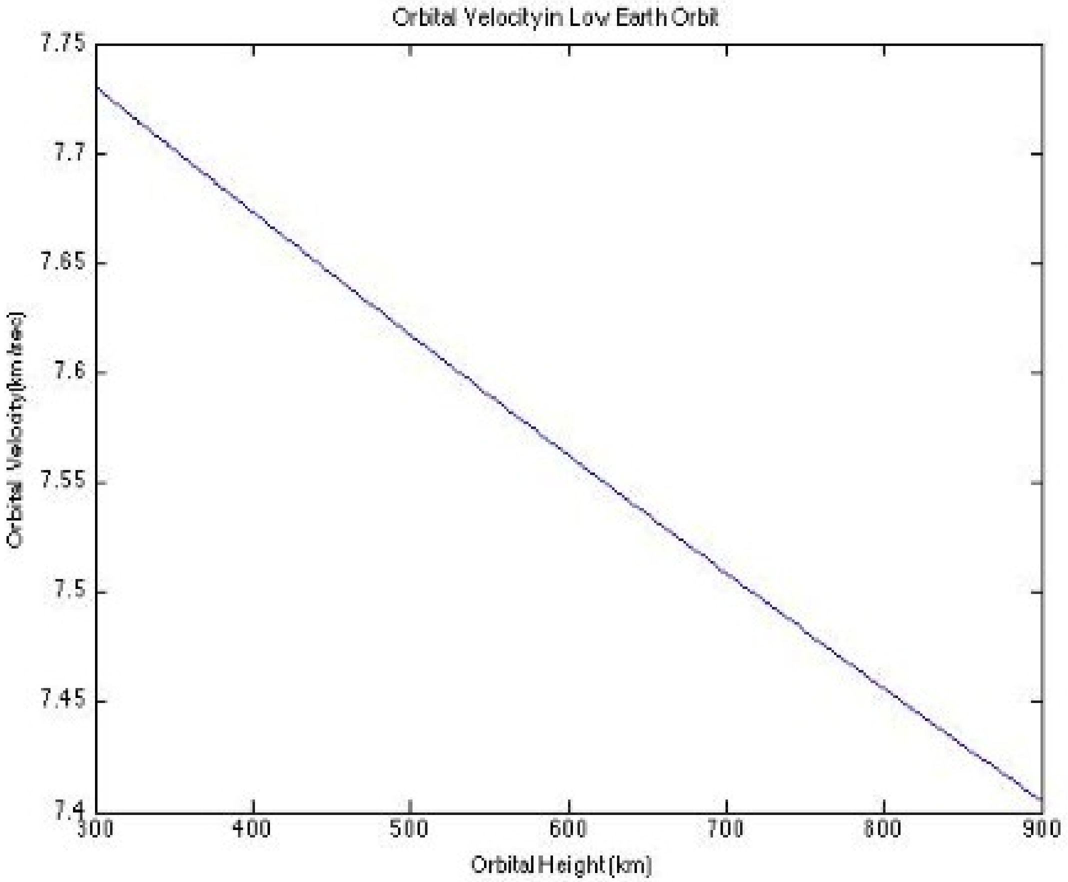

Figure 4: Orbital velocity vs. Orbital Height generated in Matlab

As we can see here the speed to maintain or leave an orbit is impressively fast but still much less then the speed of light.

Autonomous Tracking System:

At present if position information is needed by a satellite's internal system it is calculated at the ground control station and transmitted to it along with other command and control signals. For autonomous navigation it is critical to make this an internal system calculation, while keeping position and velocity calculations from a ground tracking system for use as an error check and backup.

Currently research is being done on using visual telemetry data, such as the position of the earth, sun and moon, along with information from internal gyros. While this shows promise it requires introducing additional equipment for processing [1].

An option that is also begin explored and would integrate better with active detection of obstacles through radio waves is using the readily available GPS signals. At any time on earth's surface anywhere from four to twelve GPS satellites are visible. With this many signals available it is quite possible for it to be used to establish a reasonable position and velocity estimate that the system can use in navigation between information updates from a ground station.[4][5]

With the satellite's own course information as well as the relative position and velocity information for nearby objects many methods can be employed to calculate if any course corrections need to be implemented.

Orbital tracking and trajectories can quickly become a very complex problem. The cost of computing power is always going to be cheaper on the ground, so it is imperative that the autonomous system is designed to work with the minimum computing power possible, to save on cost and power consumption. To that end a beginning autonomous navigation system would be best as a very low power system that would simply check itself against a planned course sent from the ground and maintain the route regardless of whether it is able to communicate with the ground station or not.

The detection system will have a minimum requirement for processing power. We will start with the design of the transponder.

Transceiver Design

In designing radio frequency systems we need to consider the transmission power required, to determine that we first need to know the noise floor level, from there we can calculate the attenuation factor over our range. Since we have a unidirectional antenna the attenuation factor is simply spreading the energy over the surface of a sphere the size of our range in one direction. So for a range of 200 km

$$4*pi*r^2 = 4*pi*(200e3)^2 = 5x10\ m\hat{}2$$

Our attenuation factor for a range of 200 km can almost be treated as one over this number squared, but a few multipliers need to be included to account for the Radar Cross Section [10]. To make it easier to understand I also will convert this to the power decibel scale (dB) [11].

$$P_r = \frac{P_t G_t}{4\pi r^2}\sigma\frac{1}{4\pi r^2}A_{eff}$$

Where

P_t = power transmitted by the radar (Watts)
G_t = gain of the radar transmit antenna (dimensionless)
r = distance from the radar to the target (meters)
σ = radar cross section of the target (meters squared)
A_{eff} = effective area of the radar receiving antenna (meters squared)
P_r = power received back from the target by the radar (Watts)
Source [10]

So to solve this equation for the power transmitted we need values for the effective area of the antenna, the antenna gain of the transmitter, and the radar cross section of the target.

σ is a value in meters squared generally determined through testing [10]. A suggested value for a 1 cm^2 object is 10 or 100 cm^2, because it something this size will likely be junk and therefore tumbling presenting flat surfaces to the satellite creating a much larger RCS[12]. So for a target of 1 cm squared then .001m^2 is the value to use. Next we can use this formula for the effective area of the antenna [13].

$$A_{\text{eff}} = \frac{\lambda^2}{4\pi}G$$

So is we go with a signal in the range of 400 MHz the wavelength is .75 meters. if we use a dipole antenna with a total length of 1.5 meters then Gt = 2.3. [14] Now that we have a gain and a wavelength we can now calculate A_{eff} = .102 m^2.

So now we can solve the original equation for the transmission power. The last value we are lacking is the receiving power that we require which is defined by the sensitivity of the receiver. The limit on this is what is our baseline noise level, which in space (1Hz bandwidth, 4 Kelvin) is -192.5 dBm (decibel referenced to a milliwatt) [11]. We need a margin above this level called the Signal to Noise Ratio if we have a sensitivity set at -182.5 dBm we have a 10 dB

SNR. or our received signal is ten times more powerful then the radio frequency noise in the environment.

((4*pi*r2)2 / (Aeff * σ*Gt)) dB = ((4*pi*(200e3)2)2 / (.102* .001*3.5)) dB = 270.3 dB

Solving for (Pt) dB = (Pr) dB + ((4*pi*r2)2 / (Aeff * σ*Gt)) dB
= -182.5 dBm + 270.3 dB = 87.8 dBm.
Which converted back to watts: .001 Watt *(10^(.1*87.8 dBm) = 605 kilowatt.

This value is far larger then can be sourced by a satellite, so we need to consider methods to increase the apparent power of the signal. There is however another consideration that needs to be included that will help us with this. To assist with differentiating between signals rebounding off of different targets it is better to turn the signals into pulses. This also results in an amplification of the apparent power of the received signal known as Pulse Compression[15]. And Matched Filtering which is a part of this is also required in order to protect the receiver from the original signal. We can calculate the gain in power by using these four equations[15].

$$T' \approx 1/\Delta f$$

$$P \times T = P' \times T'$$

$$T/T' = T\Delta f$$

$$P' = P \times T/T'$$

P is the power of the signal before compression and P' is the power of the signal after compression. So the multiplier becomes the period of the original signal, T, divided by the half period of the signal pulse, T'. To make this easier to understand it could also be seen as the period of the signal multiplied by the frequency of the pulse.

So going back to our 400 MHz signal we can subtract the amplification in decibels. If we turn it into a series of pulses at 100 Hz we get a power gain of 36 dB.

T= 1/f, Gain = P'/P = 400e3/100 = 4000. Converting this back to decibel: 10*log(4000) = 36 dB
(Pt)dB = -182.5 dBm + 270.3 dB – 36 dB = 51.8 dBm.
Converting this back to Watts: .001 Watt *(10^(.1*51.8 dBm) = 151.4 watts

This is a much more reasonable value to use for designing the transceiver, making it possible to power the system. There is another reason for the use of pulse compression. The bandwidth of the signal noise calculation is assumed to be 1 Hz. Therefore we need a one second integration time in detection.

Without pulse compression, a 1 Hz detection time implies a 1 second pulse which has horrible accuracy in range due to the amount the object will move in that period. Pulse compression uses modulation of the pulses with bit periods on the order 10 ns, which results in a broader bandwidth[12].

Object Tracking

Now the calculation of the other objects trajectories relative to earth would require a massive amount of computing power. This problem is not the concern of the onboard systems of the satellite. It would only be concerned with trajectories relative to it, which simplifies the situation to three classes of problems: objects that are stationary in relation to the satellite, objects that are moving away from the satellite, and objects moving towards the satellite.

A stationary object relative to the satellite is only possible if it is traveling at exactly the same speed and in a parallel path, quite possibly another satellite in a constellation. Since this is unlikely to result in a collision it can be removed as a concern.

An object moving away from the satellite would not be an immediate issue, but if it is an unknown object it could be an issue in the future, the information on its relative trajectory could be stored and relayed to a ground control station along with the satellites position information when convenient.

The last class, of objects moving towards the satellite, would be our primary concern. The tracking system would need to determine if the relative position, acceleration, and trajectory is likely to intercept the satellite. If they are not likely to do so within a certain probability the system could then ignore them and mark data on any unknowns to be transmitted back to the ground station for further tracking. Once these objects are eliminated the higher probability targets can be tracked and an estimate of time until possible collision can be determined.

Given the huge amount of volume in space the probability of a high speed collision is low. The relative velocities of other objects will rarely be near to that of escape velocities unless it is a head on collision. If the system can estimate there is enough time to do so, the most efficient method would be to send a collision alert to the ground station and have it calculate the course correction. If a collision is imminent then the best solution would be to calculate a direction to move in that would keep it from coming into the path of any other high collision probability objects and alert the ground station with the amount of course change to calculate the best method of returning to a preferred orbit.

Propulsion Methods

The most simplistic method of propulsion in space would be to use jets of compressed air. While this is very simple to control it has minimal energy and is incredible mass inefficient. The most common form of propulsion for space flight is in the form of chemical rockets.

Chemical Propulsion Methods

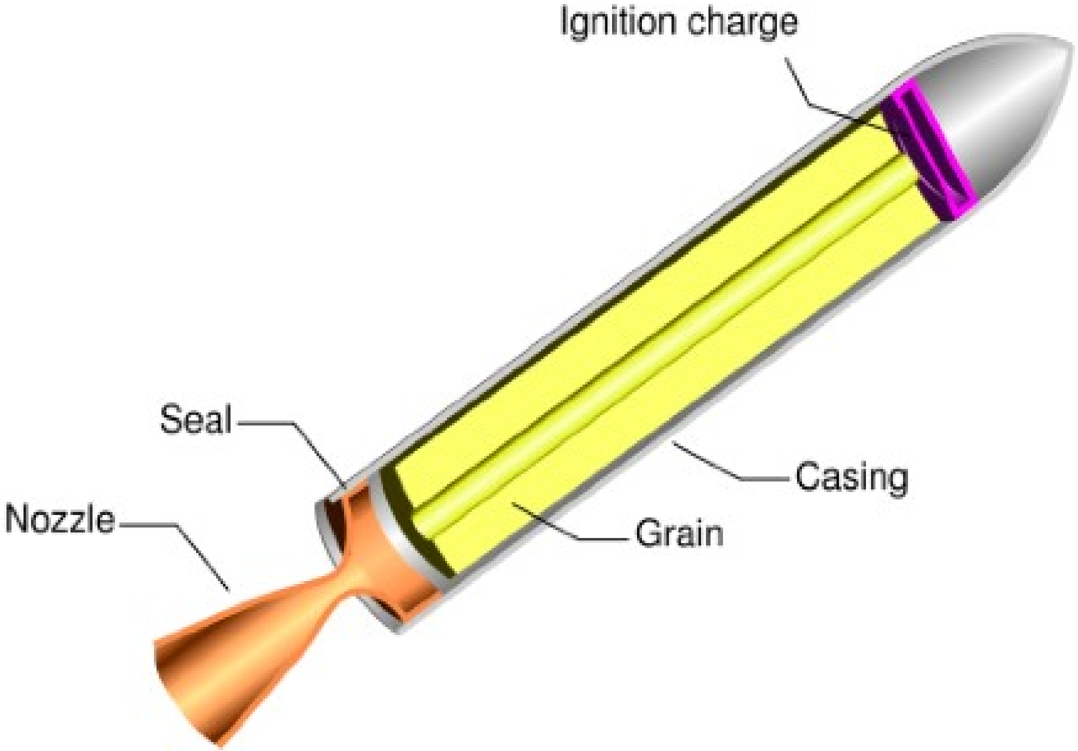

Figure 5: Solid Rocket image from Wikipedia[16]

Solid Rocket

The most basic form of chemical rocket is the solid rocket. This is the first type that was developed after the invention of gunpowder and is still commonly used in fireworks. The two smaller boosters on the sides of space shuttle are also a type of solid rocket. They provide a high amount of thrust in a very small amount of space by combining the fuel with a solid oxygen bearing compound called an oxidizer.[16]

This is the advantage of the solid rocket in that the combustion reaction continues without the need for external oxygen and gives it an advantage in the heavy lift operation to move space vehicles into orbit. It is also its limitation for long term usage in orbital navigation and station keeping. Once the combustion reaction begins it is very difficult to stop, not to mention dangerous to attempt.

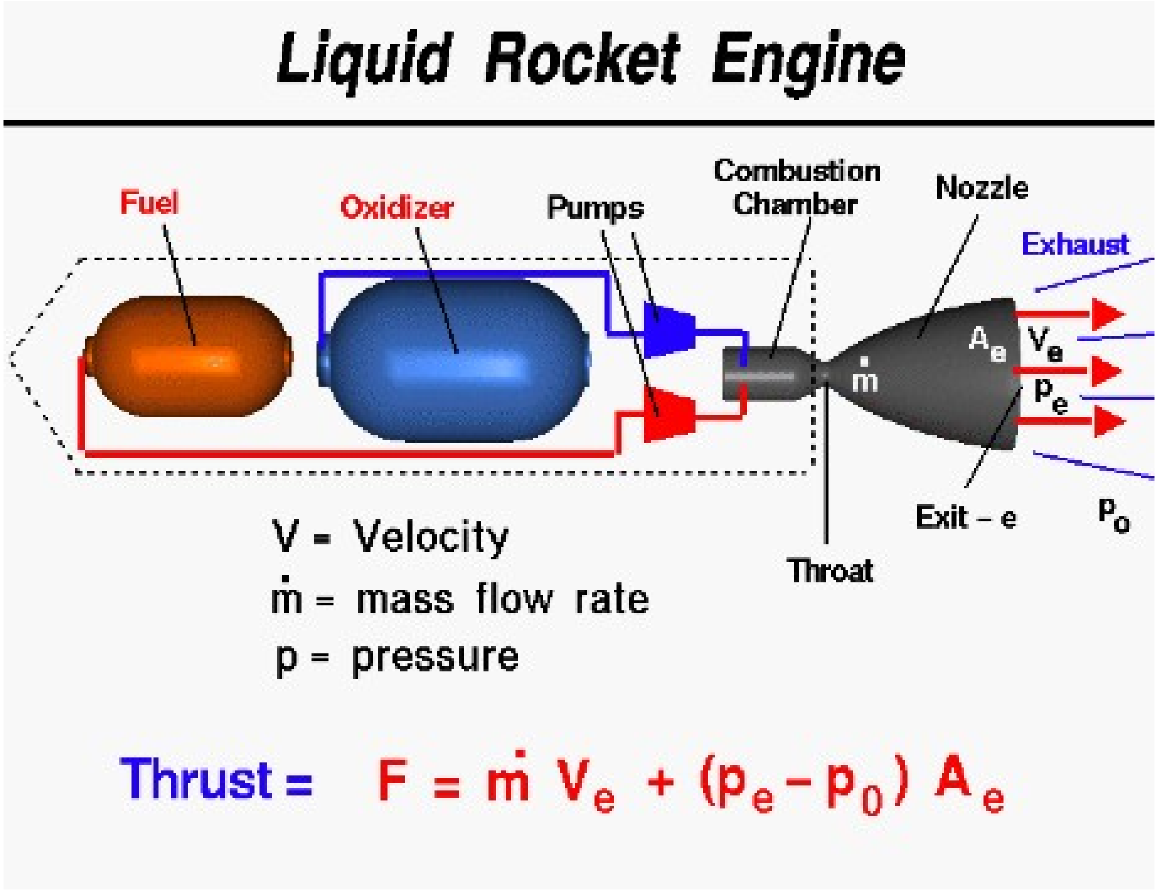

Figure 6: Chemical rocket[17]

Chemical Rocket

The other end of this is the bipropellant rocket in which a liquid fuel and a liquid oxidizer are stored in separate tanks until combined in a reaction chamber. In some cases these are called liquid only because they are gases kept under very high pressure until they liquefy. Compressed gases are used in this application because they inherently mix quickly in the reaction chamber before ignition. In other setups the fuel and oxidizer are liquids that can be turned into a fine mist or vaporize easily at room temperature, like alcohols. The bipropellant Rocket is also noted for having a higher thrust capability then comparable solid rockets

Because the fuel and oxidizer are separated the combustion reaction can be cut off and restarted almost at will, as well as controlling the actual combustion rate. The penalties for this are several. The design of a liquid rocket is far more complex when compared to a solid rocket. If compressed gases are used then they increase the mass for the storage tanks. The gases also have a potential to leak or even rupture the tanks. If liquids are used then more energy will be expended before combustion since have to be vaporized and mixed. This again is most often employed in lifting objects into space.[17]

Hybrid Rocket

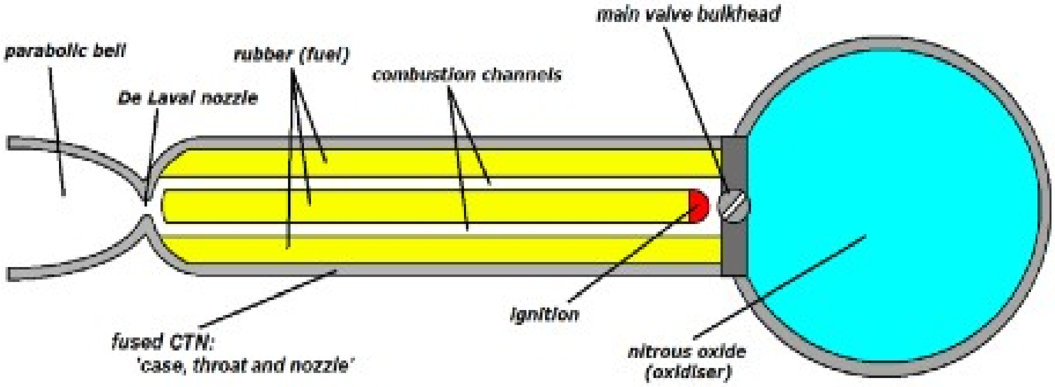

Figure 7: Hybrid rocket[18]

A better possible solution is what is known as a hybrid rocket. This design employs a solid fuel source and a liquid oxidizing agent. The combustion reaction can be halted in space simply by cutting off the flow of the oxidizer. This way only the individually non-burning oxidizer has a potential to leak and the fuel itself is tightly contained. To date this has not been employed for guidance or station keeping.[18]

Figure 8: Monopropellant system on MRO[19]

Monopropellant Rocket

The final type of chemical rocket uses what is called a monopropellant. This is a relatively stable liquid or gas, that when introduced into a reaction chamber with a catalyst decomposes. This reaction releases heat causing the now gaseous vapor to exit the chamber under much greater pressure then when it entered producing more thrust then would have otherwise been available.

This also has the advantage in that the propellant does not have to be stored under high pressure and there is not an actual combustion reaction. This method does come at the cost of lower thrust by comparison to the other chemical rockets. The Mars Reconnaissance Orbiter used six of this type of thruster, each capable of generating 170 Newton of force for the orbital breaking maneuver, as this consumed over 70 percent of the available propellant it would be best to consider the more reasonably sized 22 Newton thruster of the same type used for trajectory corrections in calculations[19]

All of the chemical rockets have relatively poor mass efficiency. More recently in space flight designers have used very high energy plasma or Ion emission to improve the mass efficiency of rocket propulsion.

Electric Propulsion

The first type of electric thruster, and still in use on current NASA projects is the Pulsed Plasma Thruster. Used by both the USSR and the United States during the space race it was first put into use on the Soviet Zond 2 spacecraft in 1964. More recently it was used on the Earth Observing 1 (EO-1).

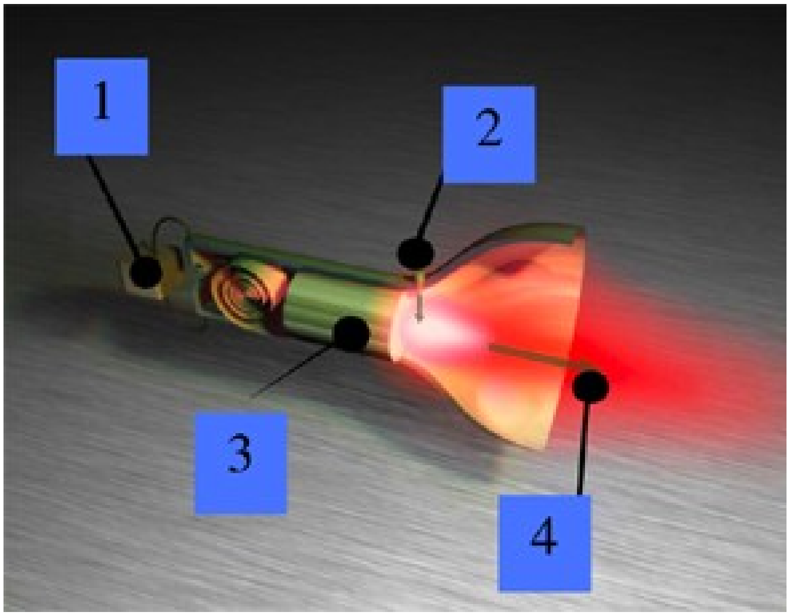

Figure 9: Operation of a Pulsed Plasma Thruster (1) Energy storage unit (2) Igniter (3)Fuel Rod (4)Plasma Acceleration[20]

The thruster operates in a two stage process, first a capacitor called the energy storage device, discharges between electrodes close to a solid propellant. This spreads across the surface of the propellant ionizing it. A magnetic field accelerates this new plasma away from the electrodes and the current between the electrodes from an external power source continues ionizing the solid propellant. A simple spring put pressure on the solid fuel rod to keep the surface close to the electrodes. The whole system on the EO-1 consumes 70 watts of power but is only capable of producing 860 micronewtons of force, equivalent to holding a two inch by two inch piece of paper in your hand. [20]

Ion thrusters:

Ion thrusters are a form of propulsion that uses electricity either from solar cells or a nuclear reaction to create thrust by accelerating ions. While they are very mass efficient the thrust they generate is very small when compared to chemical rockets. This makes them operate on longer time scales.

They fall into two major type categories, dependent on the method they use to accelerate the ions, Electrostatic and Electromagnetic.

Electromagnetic or plasma thrusters are largely still theoretical or experimental. They use an electric field to create the plasma. Acceleration is created by a combination of the electric field and an additional magnetic field interacting with each other.

There are several working types of Electrostatic thrusters in current use. As the name implies the use a static electric field to ionize and accelerate the propellant. The former USSR developed systems based on the Hall effect thruster[22]. While NASA developed a grid type propulsion system using Xenon gas known as the NASA Evolutionary Xenon Thruster (NEXT) system[24].

Hall effect

The Hall effect is simply the deflection force observed on a conductive material in the presence of a magnetic field. The basic design of a Hall effect thruster uses a solid circular anode and a magnetic coil to create a containment field for the hot plasma. This is then pushed away from the positive anode. A stream of electrons is shot into the expelled gas to neutralize the ions and serve as the cathode.[23]

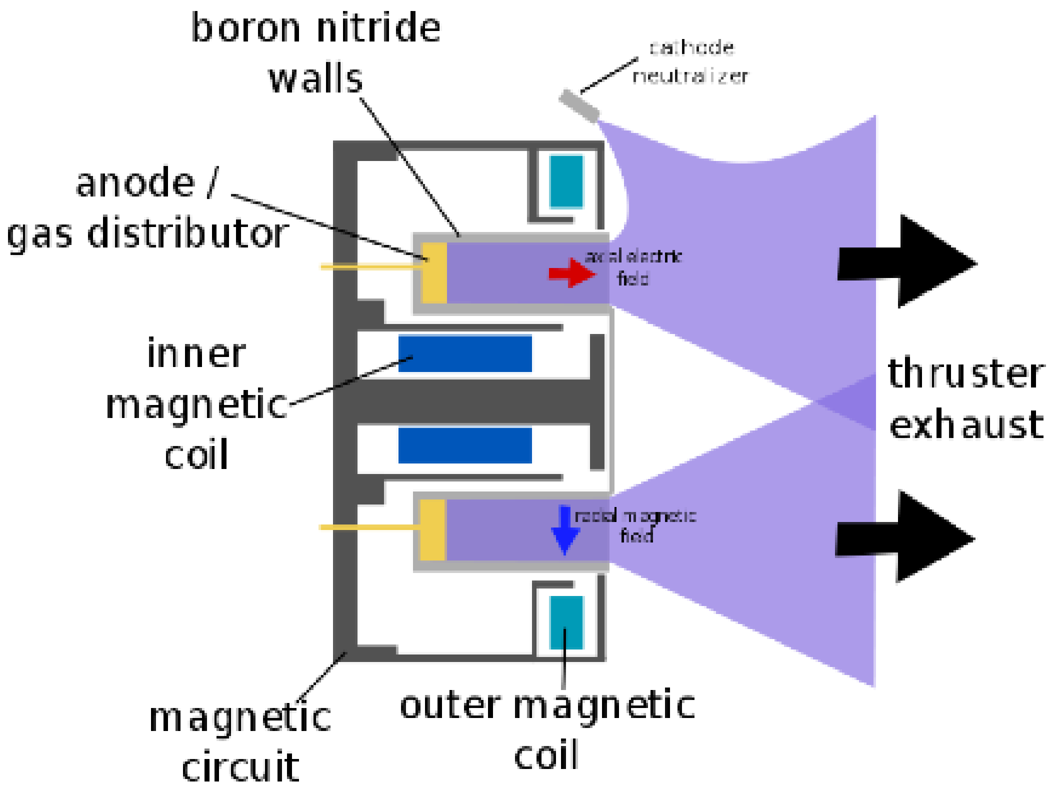

Figure 10: Hall Effect thruster[22]

The Hall effect is simply the deflection force observed on a conductive material in the presence of a magnetic field. The basic design of a Hall effect thruster uses a solid circular anode and a magnetic coil to create a containment field for the hot plasma. This is then pushed away from the positive anode. A stream of electrons is shot into the expelled gas to neutralize the ions and serve as the cathode.[23]

The preferred propellant is Xenon gas because of its high molecular weight and how easily it is ionized. The gas is fed into the thruster through holes in the anode and is ionized by the circulation of high energy electrons within the circular magnetic field created by the coil. Once ionized the propellant is driven away from the anode by the voltage between the anode and negative cathode, typically around three hundred volts. Current research at NASA lists this type of thruster as being able to drive a spacecraft up to fifty kilometers per second, and generate a sustained thrust of three Newton.[22]

Electric Grid

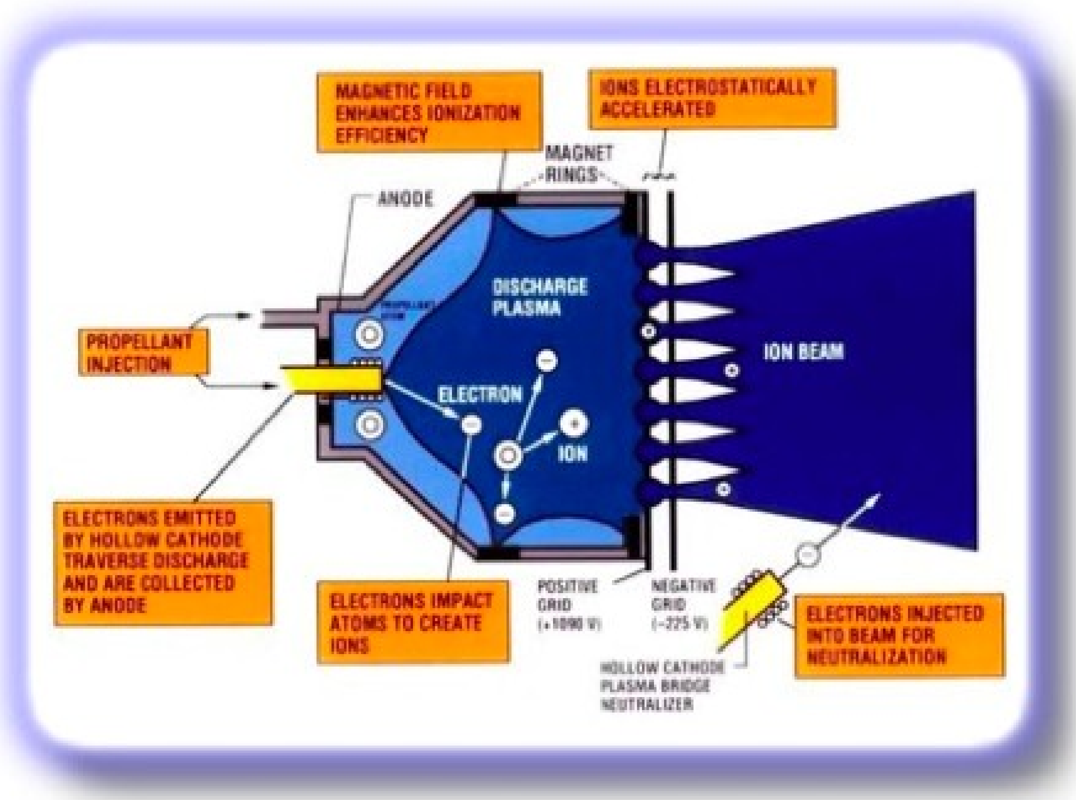

Figure 11: Gridded Ion Thruster[21]

The way a grid type thruster works is a propellant is released into a chamber around an electron gun, just like in the cathode ray tube in older television sets, is used to ionize the gas. By diffusion the now positively charged ions then move through a grid that has a positive electrical potential. Once passed the first grid the ions are accelerated past another grid with a negative electrical potential.

Any free electrons in the chamber would be absorbed by the positive potential grid. A second electron gun is fired into the stream of Ionized gas to neutralize it and prevent the ship from taking on an overall negative charge.

Because the charged grids are bombarded by the ionized gas they erode over time, reducing engine efficiency and life. NASA has demonstrated continuous operation of one of its engines for more than 16,000 hours using Xenon gas, and tests for longer times are ongoing.[24] According to current research at NASA the grid ion thruster can accelerate a spaceship up to ninety kilometers a second, but only creates a maximum thrust of one half a Newton[21].

While there are other electromagnetic propulsion technologies that are considered feasible almost all are in theoretical to experimental stages with a large number of technical issues to overcome. So far because of the high efficiency and highest thrust capability the Hall Effect thruster sounds like the best option with the monopropellant as an emergency backup

Other Emerging and Theoretical propulsion methods:

Reaction Wheel and Control Moment Gyroscopes

The first on the list of possible propulsion methods is what are called reaction wheels. These are very similar in function to the gyroscopic stabilizers, called control moment gyroscopes (CMG), already in use. Both make use of a spinning flywheel. Reaction wheels change the momentum of the wheel to cause movement of the satellite or space station. CMG keep the speed constant and change the angle of the wheel in order to create a resistive torque. Both use no fuel and are very efficient at changing the orientation of the space vehicle. However they are unable to have any effect on the actual heading or velocity of the vehicle[25].

The next group to consider all could be classified under the heading of sails. These use various methods to in essence capture reaction mass already available in space, or make use of the electromagnetic energy present.

Solar Sails

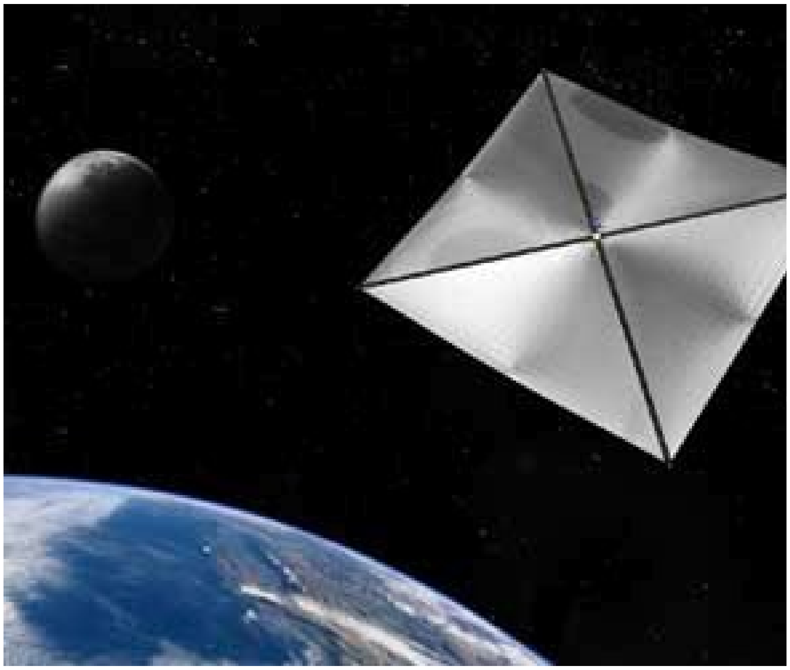

Figure 12: Solar Sail [26]

The most well known method is referred to as the solar sail. These have been theorized about for many years, the idea even thought of by the astronomer Johannes Kepler 400 years ago after observing comet tails. There has been testing of small solar sails, but the sail area is many times larger then the ship itself before any benefit of thrust is found. Due to drag and wear Solar sails could not be used below 800 km of the earth's surface. NASA has within the last decade launched what they call micro-solar sails at a size of twenty meters across for testing purposes[26].

Solar sails work by capturing energy from light or to a lesser extent the solar wind. Because no reaction mass is required this could work well if implemented with reaction wheels and gyroscopes to orient the ship so that the thrust provided is in the desired direction. However the large size and profile would be detrimental to most commercial satellite applications. One thing that could off set the large size is since the sail blocks or deflects incoming radiation, it could reduce the shielding required by the craft if the sail was always placed between the craft and the largest source of incoming radiation. Another possibility for autonomous satellites would be if object detection antennas were placed at the farthest points of the sail, a wider field of detection could be achieved.

There is theoretical work on light based propulsion systems with using a ground based laser to propel a solar sail based craft in orbit but that would not work for an autonomous system.

Magnetic Sail

Still in the theoretical stages is a similar device that operates by extending out a loop of conductive wire. By sending a current through the wire a magnetic field is created that can interact with the environment. The magnetic field interactions also work to allow the loop to maintain its extended shape as the current flowing in only one direction would try to stay as far from the other parts of the loop as possible. Multiple loops could be deployed and kept separated using this same principle.

The effective surface area of this sail is determined by the magnetic field surrounding the cable and not the width of the cable itself.

Because of its much smaller surface area it is less prone to being worn down. At lower altitudes it can be used in conjunction with earth's own magnetic field for propulsion. In higher orbits it can interact with solar wind[27].

Magnetic Tether

Another type of propulsion method that has been explored by NASA is called the Electrodynamic tether. this essentially makes use of a guided micro-satellite launched from a larger vehicle. This is strictly designed for use in conjunction with earth's magnetic field. In the one test done by NASA from the space shuttle to explore feasibility of this method a micro-satellite was released and sixteen kilometers of tether were let out without being powered to test the magnetic field potential. A surge of electricity caused the cable to snap and the micro-satellite was lost[28].

Related to this we have what is called an electric sail that can function similarly to a magnetic sail by sending out multiple tethers. This creates a sail area equal to the magnetic field of each tether. While this sounds good in theory this also creates multiple points of failure, each tether could snap[29].

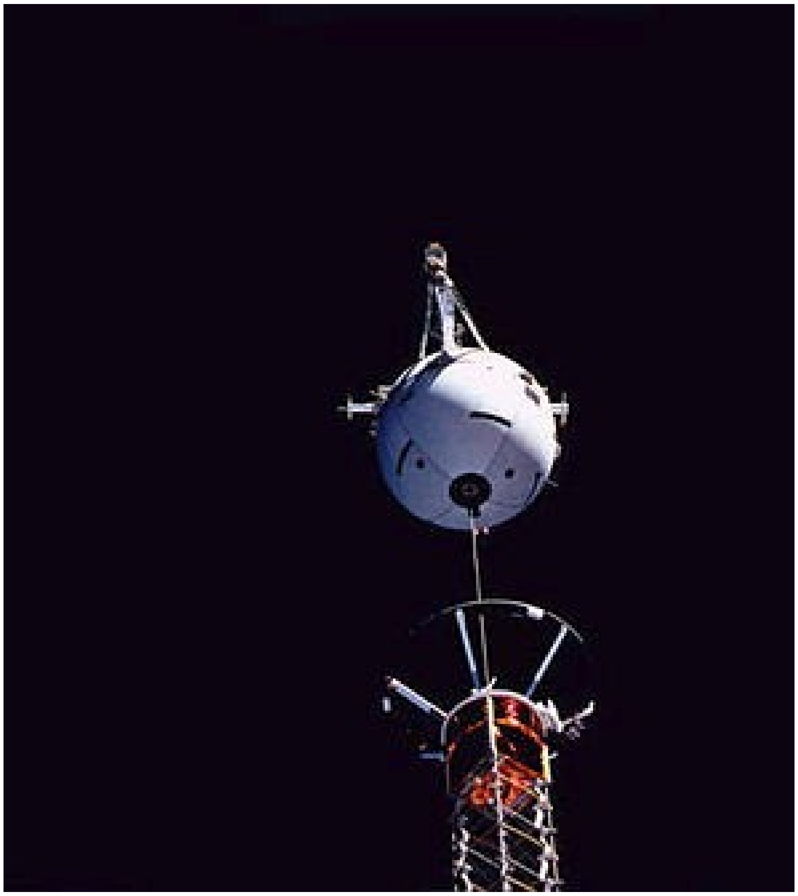

Figure 13: Tethered Satellite System deployment[28]

As with the solar sail concept there is a theory that a particle or plasma beam could be used to drive them from a remote location. This would achieve propulsion for the vehicle, but leaves many questions about safety as well as negating autonomous operation.

Of all of the types currently in development the most useful and practical sounding one is the magnetic sail. multiple loops can be extended out from the craft from motorized drums. If the cable should snap then the two ends can be brought back into the vehicle and, depending on the material type, repaired on board the vehicle after which, it can be redeployed easily.

Calculations of acceleration

Now we come to the heart of the problem. For any propulsion system to be effective for avoidance maneuvering it has to successfully move the craft out of the way of a collision. Even a difference of a few meters can spell the difference between a collision and a miss. The question is can the propulsion system achieve that from the time of detection or not. Now we compare the different propulsion methods by the actual acceleration they provide.

Since we have no real numbers to work with the theoretical propulsion methods will not be considered. The same goes for systems that are not used such as simple compressed gas.

We have to consider several different situations on avoiding a collision. In the end all of them can be reduced all of them have a different amount of time until collision. In space the worst case scenario and the most unlikely situation is the classic head on collision. This is the situation where we have the absolute least amount of time. if we have two satellites traveling at escape velocities, for simplicity say 10 kilometers a second, traveling on the same orbital path towards one another then at a range of two hundred kilometers. As the relative velocity with then be 20 kilometers a second we have a total of ten seconds to adjust the trajectory for our satellite. This is a hypothetical situation, the satellite crash was estimated to be around half this relative velocity between the two craft that crashed earlier this year[3].

We can begin with the basic equation of Force = Mass x Acceleration. If we set a standard mass of 2000 Kilograms we can solve the equation of a given force for acceleration on the craft. For this example let's use the 170 Newton given for one of the large monopropellant thrusters on the Mars Reconnaissance Orbiter.

$$A = F/M = 170\text{N}/2000\text{ Kg} = .085\text{ m}/(\text{s}^2)$$

Now if we treat the satellite as the origin and all other velocities are relative to it the satellite's initial velocity is considered to be zero. The physics equation relating position as the second integral of acceleration just becomes a direct relationship to acceleration times the square of time, $S = 1/2At^2$.

Therefore in ten seconds the position difference from initial vector can be found.

$S = 1/2At^2 = 1/2(.085)(10)^2 = 4.25$ m

As we can see by the numbers here if the solar panels have even a ten meter spread from the center then the craft will not survive. Fortunately the only likely situation where this would happen is if a satellite killer missile is targeting the satellite in question, and then you're basically out of luck anyway. Also the thrust value is more then what even the Mars Reconnaissance Orbiter used for more then orbital braking maneuvers. For that reason we will use the value of 22 N given for the altering of trajectory on the same craft. This will be compared with 3 N for the max of the Hall Thruster, .5 N for the max on the Grid Ion thruster, and 860 micronewtons for the pulsed plasma thruster.

The first way we can compare the thrusters is simply to use there acceleration on the same 2000 kg satellite and see how far they can change the trajectory over a range of time.

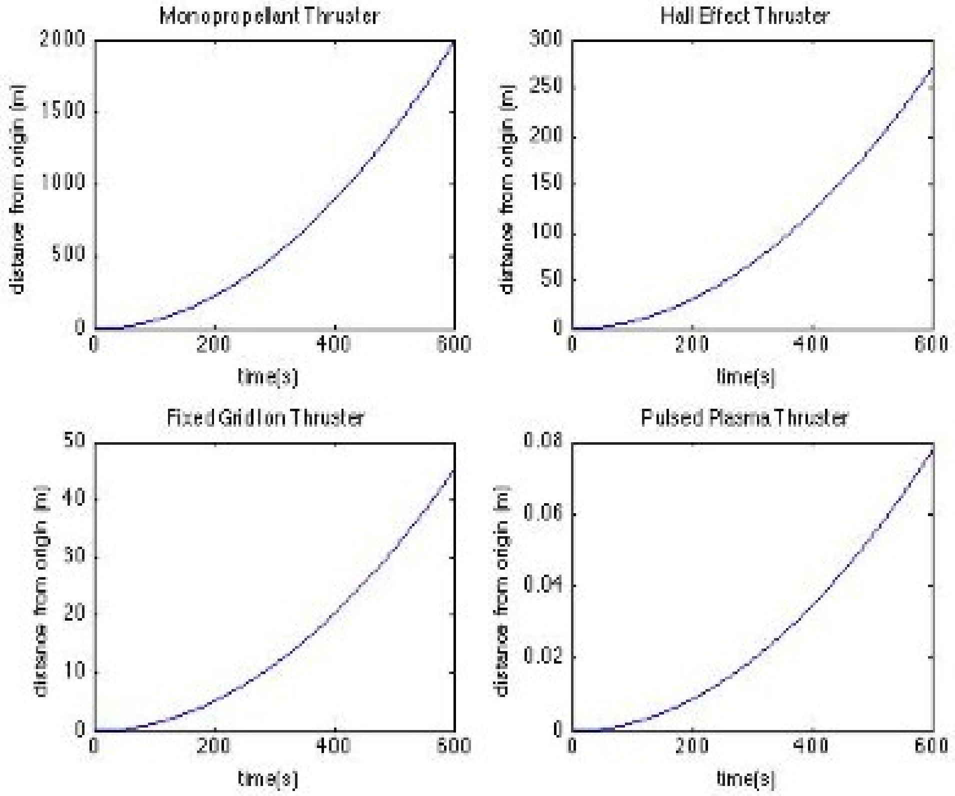

Figure 14: Comparison of displacement over a set time in Matlab

While this helps us get a sense for the distance we can move it is more important to know how much time it would take to move a certain distance so we can know how much time will be needed if a move has to be made. For this let’s find the times it takes to change the satellites trajectory twenty meters from the original, assuming for the moment that our satellite has a radius of 10 meters from the center to the tips of its solar panels and is facing an object of similar size.

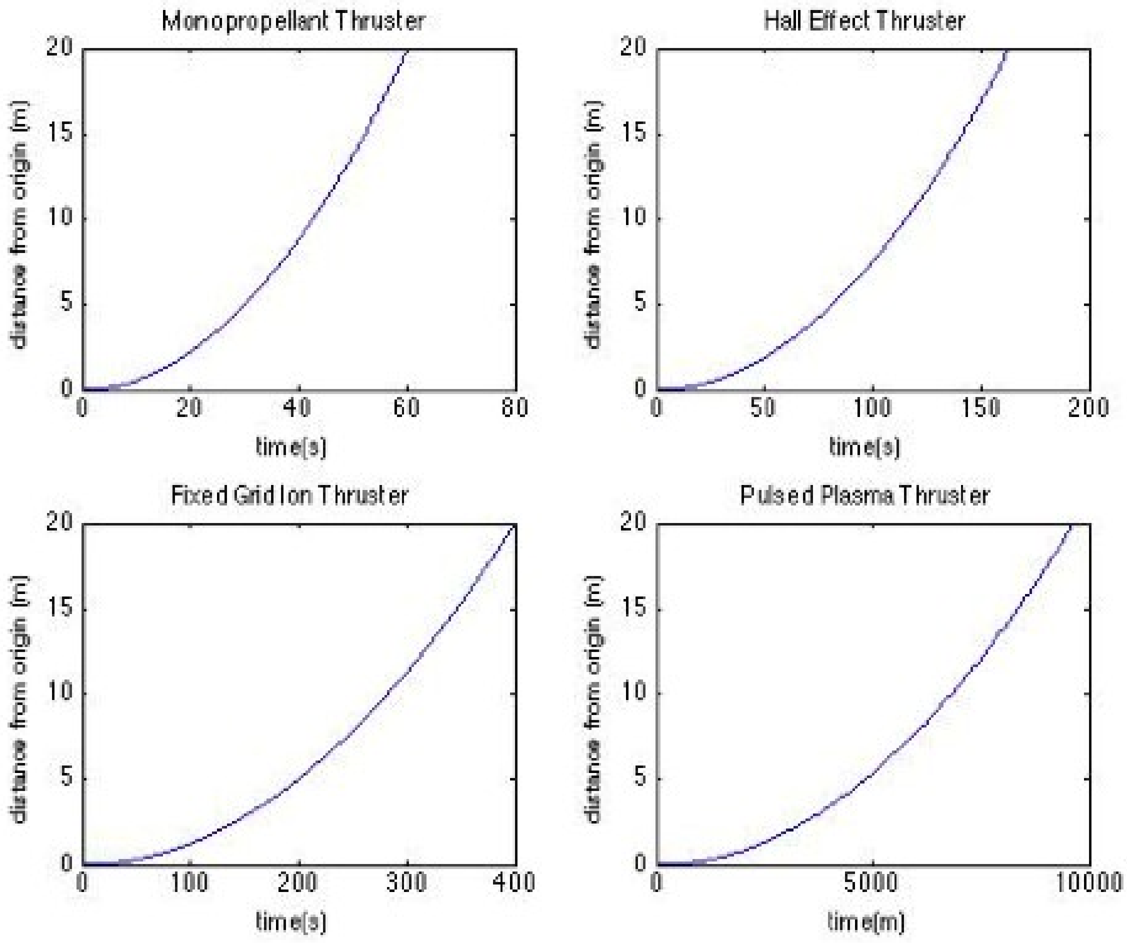

Figure 15: Comparison of displacement to a set distance created in Matlab

With this we can see that the monopropellant thruster was able to move the satellite to a safe distance in less then a minute. The Hall thruster was able to accomplish the same result in under three minutes. The Grid Ion thruster was close to seven minutes. While the Pulsed Plasma thruster is measured in days. Lastly let’s compare the first three side by side.

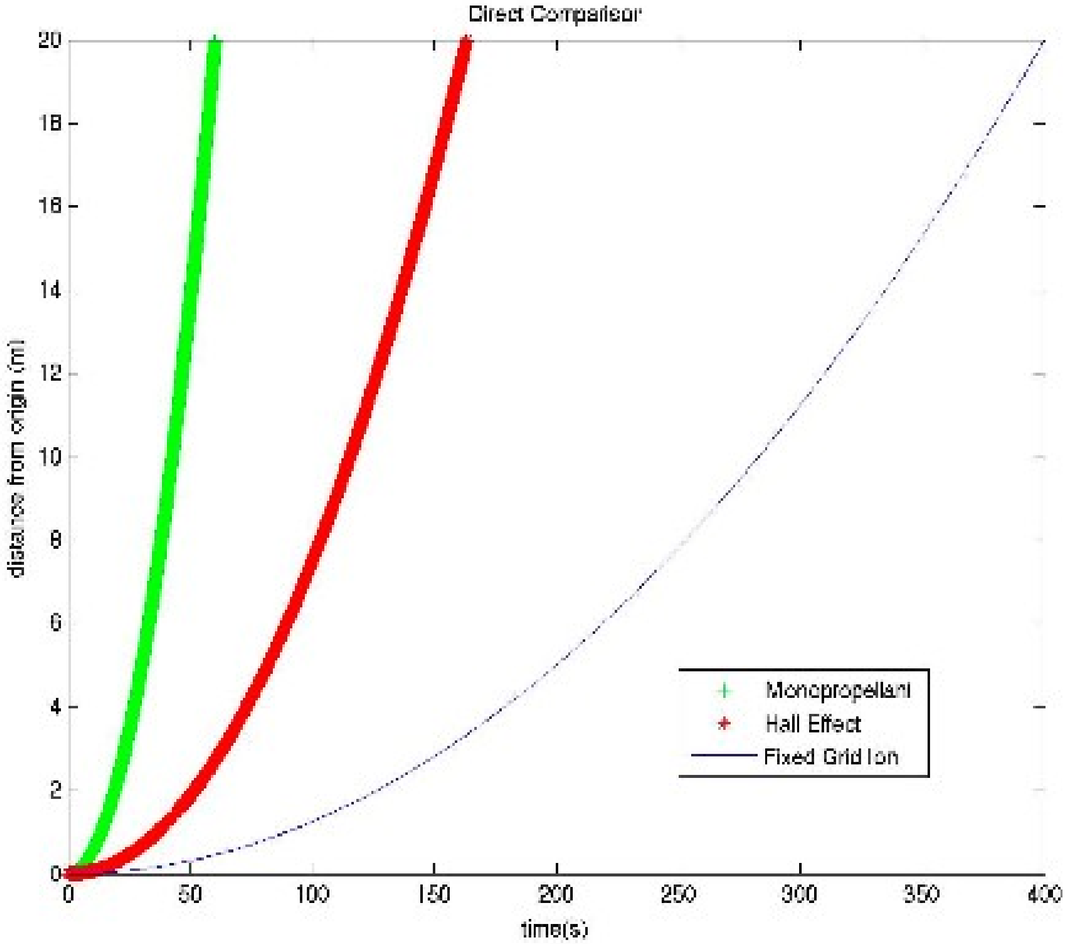

Figure 16: Direct comparison of displacement versus time for several thrusters created in Matlab

Now we can definitely see that if there is an emergency situation the monopropellant thruster is the best one to use, followed by the hall thruster.

Conclusions and Future Work

A basic navigation system is the best short term solution. One that can simply receive a pre-planed course and make sure it is following it based on GPS tracking information. Add in the additional ability to make an emergency course correction and report it to the ground station for calculation of the best return to the desired flight path.

A detection system that uses unidirectional antennas transmitting a transmission time stamp is feasible. The computing power required can be minimized by concentrating on the highest probability targets and relaying all other information back to the ground station for further processing.

The propulsion system that would seem to be best to work with this system would be Hall Effect thrusters with Monopropellant thrusters for emergency backup.

There are several things that would need to be considered before this system could be implemented. The first is that a one second pulse would require very high power expenditure. The other critical issue would be the accuracy of the detection system would need to be studied to verify if object positions could be determined reliably enough for the system to be a trusted to decide if a course correction is needed.

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Matlab Code

Appendices must be identified by letters (Appendix A, Appendix B, etc.) rather than by numbers. For this reason, there are different style headings to use with appendices. For example, the style at the top of this page is “Appendix A - Heading 6.”

Generate Sphere and Ellipsoid

```
clear all
close all
clc

n = 200;

figure(1)

[X,Y,Z] = sphere(200);
X1 = n*X;
Y1 = n*Y;
Z1 = n*Z;
h1 = surf(X1,Y1,Z1);
axis equal

figure(2)
[x, y, z] = ellipsoid(0,0,0,5.9,3.25,3.25,200);
X2 = n*x;
Y2 = n*y;
Z2 = n*z;
h2 = surf(X2,Y2,Z2);
axis equal
```

Calculate distance traveled by satellite during the round trip compared to range.

```
clear all
close all
clc

c = 299792458;% speed of light in a vacuum in meters/sec

R = 10e3:1e3:200e3;

d = 10e3*2*R/c;%how far can our satellite travel during
%the round trip

figure
plot(.001*R,d)%plot distance versus range in Kilometers
title('Distance travelled during round trip')
xlabel('Detection Range(km)')
ylabel('Distance traveled (m)')
```

Calculate the escape velocity versus orbital height

```
clear all
close all
clc

r = 6371;
r1 = (r+300):1:(r+900);
X = 300:1:900;

Ve = .001*sqrt(5.9736e24)*(6.67428e-11)./(1000*r1));

figure
plot(X,Ve)
title('Orbital Velocity in Low Earth Orbit')
```

```
xlabel('Orbital Height (km)')
ylabel('Orbital Velocity(km/sec)')
```

Calculating the acceleration due to the different thrusters

```
clear all
close all
clc

t = 0:.01:600; %range of time to ten minutes

F = [22; 3; .5; 860e-6]; %force thruster is able to produce

A = F/2000;

S = .5*A*(t.*t);

figure(1)
subplot(2,2,1)
plot(t,S(1,:));
title('Monopropellant Thruster')
xlabel('time(s)')
ylabel('distance from origin (m)')

subplot(2,2,2)
plot(t,S(2,:));
title('Hall Effect Thruster')
xlabel('time(s)')
ylabel('distance from origin (m)')

subplot(2,2,3)
plot(t,S(3,:));
title('Fixed Grid Ion Thruster')
xlabel('time(s)')
ylabel('distance from origin (m)')
```

```
subplot(2,2,4)
plot(t,S(4,:));
title('Pulsed Plasma Thruster')
xlabel('time(s)')
ylabel('distance from origin (m)')

%to make this more usefull let`s set a safe distance.
%Perhaps 20 meters to calculate this we simply solve the
%distance equation for time t = sqrt(2*S/A)

T = sqrt(20./(.5*A));

t1 = 0:.01:T(1,1);
t2 = 0:.1:T(2,1);
t3 = 0:.1:T(3,1);
t4 = 0:60:T(4,1);

s1 = .5*A(1,1)*(t1.*t1);
s2 = .5*A(2,1)*(t2.*t2);
s3 = .5*A(3,1)*(t3.*t3);
s4 = .5*A(4,1)*(t4.*t4);

figure(2)
subplot(2,2,1)
plot(t1,s1);
title('Monopropellant Thruster')
xlabel('time(s)')
ylabel('distance from origin (m)')

subplot(2,2,2)
plot(t2,s2);
title('Hall Effect Thruster')
xlabel('time(s)')
ylabel('distance from origin (m)')

subplot(2,2,3)
```

```
plot(t3,s3);
title('Fixed Grid Ion Thruster')
xlabel('time(s)')
ylabel('distance from origin (m)')

subplot(2,2,4)
plot(t4,s4);
title('Pulsed Plasma Thruster')
xlabel('time(m)')
ylabel('distance from origin (m)')

figure(3)
plot(t1,s1,'g+');
hold on
plot(t2,s2,'r*');
plot(t3,s3);
title('Fixed Grid Ion Thruster')
xlabel('time(s)')
ylabel('distance from origin (m)')
legend('mono','hall','ion')
```