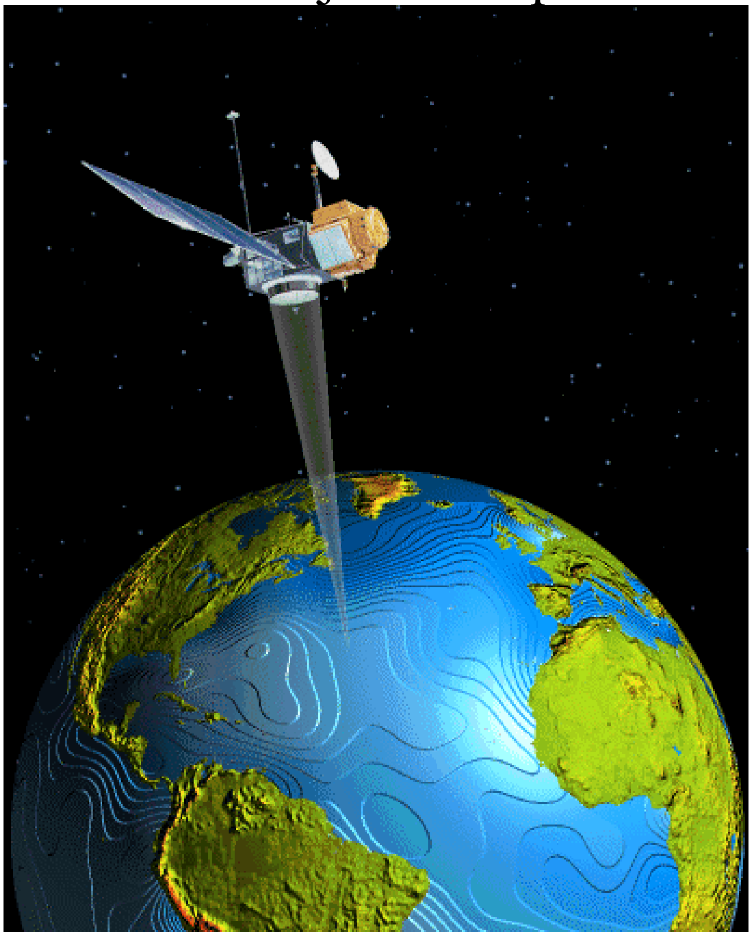
ECE 6390: Satellite Communications
Final Project: "Kepler"



[Source: http://www.ccpo.odu.edu/~arnoldo/ocean405/ocean_405_lecture_supp.html]

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Introduction

Space is the final frontier challenging the technological prowess of man and stimulating his curiosity. As we venture further into space we learn more about our own existence and find answers to the fundamental questions surrounding our own habitat. Although the majority of space exploration is limited to the inner planets of the Solar System (Mercury, Venus, Earth and Mars), unmanned crafts have gone beyond to the outer planets. The success of Galileo and more recently the Cassini project have made scientists sure of their ability to send spacecrafts successfully into deep space. A project to Neptune is being planned with in the next decade that will seek to study the atmosphere of Neptune. Before going onto the details of the project, here is a brief overview of the planet Neptune.

Neptune is the eighth planet in our Solar System with only Pluto being further away from the Sun. It is similar to Jupiter, Saturn and Uranus because it is a gas giant like the other three. However, the fastest winds in the Solar system have been observed at Neptune, an amazing 2000 km/hr.[1] Neptune also has an internal heat source as it dissipates twice the amount of heat it absorbs from the Sun. Neptune also has rings. Table 1, summarizes some information on Neptune:

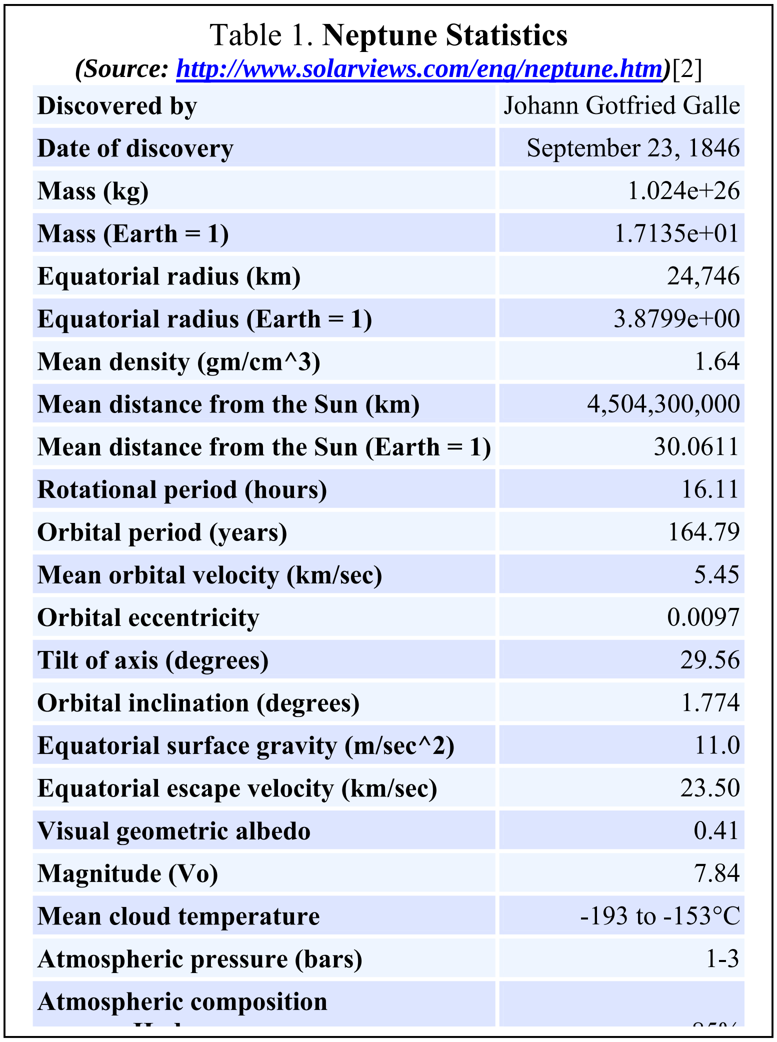

Table 1. **Neptune Statistics**

(Source: http://www.solarviews.com/eng/neptune.htm)[2]

Discovered by	Johann Gotfried Galle
Date of discovery	September 23, 1846
Mass (kg)	1.024e+26
Mass (Earth = 1)	1.7135e+01
Equatorial radius (km)	24,746
Equatorial radius (Earth = 1)	3.8799e+00
Mean density (gm/cm^3)	1.64
Mean distance from the Sun (km)	4,504,300,000
Mean distance from the Sun (Earth = 1)	30.0611
Rotational period (hours)	16.11
Orbital period (years)	164.79
Mean orbital velocity (km/sec)	5.45
Orbital eccentricity	0.0097
Tilt of axis (degrees)	29.56
Orbital inclination (degrees)	1.774
Equatorial surface gravity (m/sec^2)	11.0
Equatorial escape velocity (km/sec)	23.50
Visual geometric albedo	0.41
Magnitude (Vo)	7.84
Mean cloud temperature	-193 to -153°C
Atmospheric pressure (bars)	1-3
Atmospheric composition	

The sheer distance from Earth has meant that only Voyager 2 has visited Neptune on 25th of August 1985. This is set to change since a mission to explore Neptune is in the pipeline. The primary goal of this mission will be to insert probes into Neptunian atmosphere and obtain data from them. The following report presents the design of the satellite system that collects the probe data and sends it real time back to the Earth. This deep space mission will be referred to as the Kepler project. It will involve three probes that will be inserted into the Neptunian atmosphere at specific points. They will then relay the data they collect to the relay satellite using Code Division Multiple Access (CDMA). The data received from the three satellites will then be processed and combined into a single data stream and will then be sent to the Earth where the Deep Space Network will receive the transmission. Figure 1 explains the basic layout of the Kepler project.

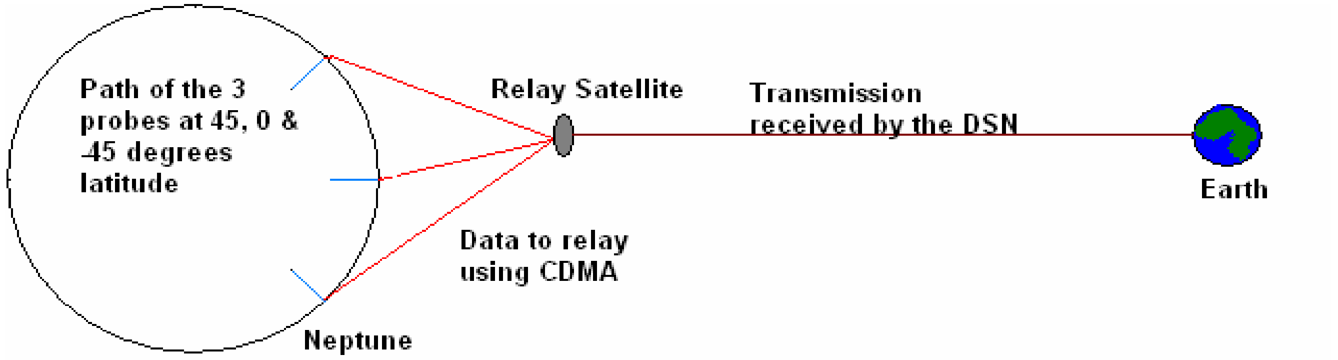

Figure 1. Basic layout of the Kepler project.

The three probes will enter the Neptunian atmosphere at 45°, 0° and -45° latitudes. They will then descend further into the atmosphere till the atmospheric pressure is about 500 bars, about 420 km, over a period of 50 hours while gathering data and transmitting it to the relay satellite. The relay satellite will be orbiting around Neptune and will be in the field of view of all the three probes and Earth at all times. The relay satellite will be in "Neptune Synchronous Orbit" (NSO) meaning that its period of revolution around Neptune will be as long as a Neptunian day (approximately 16 hours). The relay satellite's orbit will be inclined to the equator of Neptune so that it can maintain a communication link with Earth at all times and is never hidden from Earth behind Neptune's shadow. It is assumed that if the satellite can maintain a direct line of sight with the Earth, then the DSN can communicate with the relay satellite.

The success of the Galileo and Cassini mission serves as a good starting point for this project. Although this project is much bigger in magnitude and it is going much further than either of the earlier two missions there is still a lot that can be incorporated from those projects. Hence, these two projects will often be used as a basis for consideration of a design or methodology.

Launch Vehicles, Rockets and Engines

For a space mission of this magnitude and distance, the inability to send such a significant mass all the way to Neptune is a big hindrance. However, the success of deep space missions such as Galileo (to Jupiter) and Cassini (to Saturn) have shown that it is possible. As seen in Table 2, both these missions employed a roundabout trajectory and used gravity assists to reach the respective final destinations.[3],[4] There is no launch vehicle currently available that can send a load of that size to such a significant distance. Using these two missions as an example, the Kepler mission will also involve the use of Gravity Assists to help the spacecraft reach its eventual destination of Neptune's orbit.

Orientation for Cassini was maintained with the help of three reaction wheels and 16 0.5 N hydrazine powered thrusters. These thrusters are also used for minute alterations in spacecraft trajectory but larger changes in spacecraft trajectory are carried out by two main engines that burn nitrogen tetroxide and monomethyl hydrazine.[5] However, NASA has been conducting extensive research in engines and considers Ion Propulsion to be a viable solution for Deep Space Projects. Glenn Research Center has designed an ion propulsion-based engine that was used successfully aboard Deep Space 1 (DS1).[6] An ion propulsion system provides thrust by converting the power from a spacecraft power system into an ionized jet of gas that exits the spacecraft propelling it in the opposite direction.[7] Xenon was used as the fuel in the engine on DS1. Figure 2 explains the overall ion engine workings.

Table 2. Statistics On the Galileo and Cassini Missions

	Galileo	**Cassini**
Launch Date	October 18, 1989	October 15, 1997
Mission	Jupiter	Saturn
On-Orbit Dry Mass	2380 kg	2523 kg
Average Distance from Earth	4.2 AU	8.5 AU
Launch Vehicle	Shuttle - Inertial Upper Stage	Titan IV - Centaur
Trajectory	Venus-Earth-Earth-Gravity-Assist (VEEGA)	Venus-Venus-Earth-Jupiter-Gravity-Assist (VVEJGA)
Arrival Date	December 7, 1995	July 1, 2004

Ion engines are 10 times more efficient than chemical engines in using fuel and, thus, a smaller amount of fuel can provide a constant thrust resulting in constant acceleration over a longer period of time. Thus, the use of ion engines means that lower fuel load and shorter travel times can be realized. However, there is little information and research done to justify the use of such a new technology to drive a project of this magnitude. Many more tests like the DS1 need to be done to further validate the workings of ion engines.

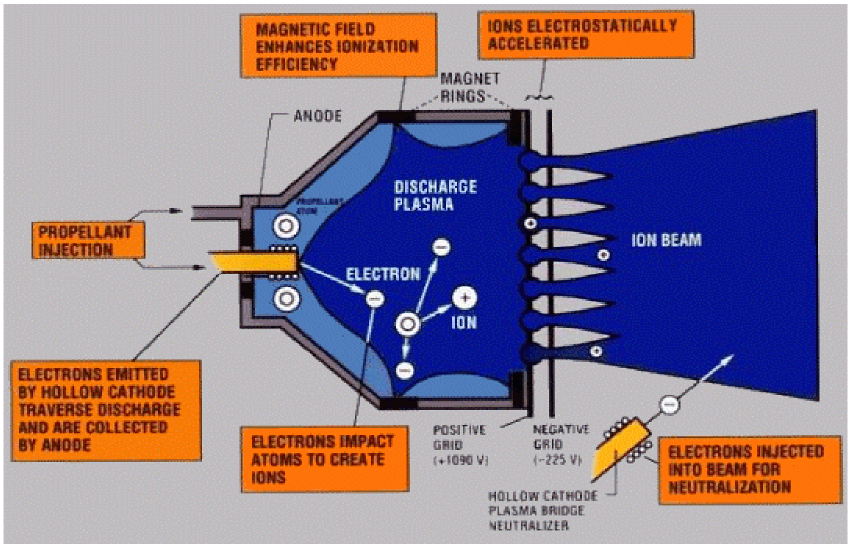

Figure 2. The working of an ion engine.
(Source: http://www.grc.nasa.gov/WWW/PAO/PAIS/fs08grc.htm)[8]

The Kepler mission will involve the combination of many technologies to overcome the sheer distance that needs to be traveled. Although the missions to Saturn and Jupiter (Cassini & Galileo) serve as good examples, they are still much closer than Neptune, which is at an average 28 AU away from the Earth. As seen from Table 2, Saturn is only 8.5 AU away, in comparison. Moreover, the equipment aboard Kepler and the three attached probes will make it significantly heavier than either of the Galileo or Cassini projects. Thus, a combination of all the viable technologies and scientific innovation will be required for Kepler to enter Neptunian orbit.

At Neptune, the relay satellite will probably have to come close to the surface of Neptune and drop the probes, allowing them to descend to the surface while the relay satellite settles in orbit. Then once the relay satellite is set in Neptune Synchronous orbit and the three probes have started their descent into the Neptunian atmosphere, the communication process can initiate. However, once communication is established between the relay satellite and the probes, all the data can be relayed back to Earth in real time.

Power Sources

A spacecraft can either be powered by stored energy or from the energy it creates during its journey. There are primarily four sources of energy that can be considered for powering the Kepler mission: [9]

1. **Batteries**: They have stored energy, which is utilized by the spacecraft when required. Although this technology is well understood, reliable and consistent; it is just not powerful enough to meet the needs of a space mission. However, batteries can be used to store the energy created by some other means. Extremely powerful batteries can also be used aboard the three probes that descend into Neptune. These probes will have a significantly less power demand and their intended function is for 50 hours only. Hence, batteries can be used for storing excess power on the relay satellite and for powering the three probes during their descent into Neptune.
2. **Fuel Cells**: These devices store hydrogen and oxygen in separate chambers. These two elements are then combined to form water and the resulting chemical reaction expends energy, which is harnessed into electrical energy. Fuel cells are used in several near-Earth missions and are similar to batteries except that they can be refueled and have a longer lifespan than batteries. However, they would require too much fuel for a project like Kepler. Moreover, they release a lot of heat in operation, which creates the added overhead of managing that heat. Thus, batteries will be preferred over fuel cells for this project.
3. **Solar Panels**: They convert solar radiation into electricity and are extremely successful for missions close to the Sun. However, they are rendered useless when a spacecraft travels beyond the orbit of Mars and, hence, cannot be a viable source of energy near Neptune. Solar panels are large constructions and are extremely fragile. They are also very expensive. The costs do not justify the use of solar panels for the part of the mission where they can be used to produce electricity. Hence, solar panels will not be used in the Kepler mission.
4. **Radioisotope Thermal Generators (RTGs)**: These devices have radioactive materials as fuel that decays and releases heat energy, which is converted into electricity by the use of thermocouples. An RTG does not give out a huge amount of energy like fission and fusion reactions, but it does give a small amount of energy steadily over a long period of time. RTGs were used to power both the Cassini and the Galileo missions, and are extremely reliable and consistent. The high expense for building RTGs is justified because this is the only viable technology that can be used to power the Kepler mission.

The following tables, Table 3 and Table 4, give some statistics on the power usage and generation aboard the Cassini and Galileo orbiters.[3,4,10] This shows that RTGs can be used to provide power for such large spacecrafts over long periods of time. Given the risk of launching radioactive material, NASA takes extreme precaution to ensure that even in the event of a failure, such as a crash, the radioactive material will not release into the atmosphere. The radioactive fuel is typically inside thick metallic casing to ensure safety and will not release into the air unless some specific accident has compromised the integrity of the RTGs[11].

Table 3. Statistics On Power Usage and Generation Aboard the Cassini and Galileo Orbiters

	Galileo	**Cassini**
Nominal Power Output	570 Watts	640 Watts
Power Source	2 RTGs	3 RTGs
Fuel	Plutonium (238) dioxide	Plutonium (238) dioxide
Amount	15.6 Kg (7.8 kg per RTG)	32.8 kg (10.9 kg per RTG)
Length of Mission	14 years	11 years

At least 3 RTGs will be required aboard Kepler to power its mission. The length and the capabilities of the earlier missions are similar to the one being planned now. However, the real challenge is in the probe, since this is a much more elaborate and longer mission than either the Galileo or Cassini (Huygens probe).[12,13]

Table 4. Statictics On Power Usage and Generation in the Huygens and Galileo Probe

	Galileo Probe	**Huygens**
Nominal Power Output	580 Watts	250 Watts
Power Source	1 $LiSO_2$ battery	5 $LiSO_2$ batteries
Length of mission	48-75 minutes	3-3.5 hours

The insertion of 3 probes into specific parts of the Neptunian atmosphere will be a challenge, and an equally challenging part is to get these probes to slowly descend into the atmosphere for 50 hours. We will need to come up with power supplies that can supply such high power over such a long period of time. At the same time, we can build better equipment to lower power consumption allowing more efficient use of power. Also different methodologies will be required to slow the probes' descent into the atmosphere, giving them ample time to capture data and send it to the relay satellite.

Temperature Control

It is essential to regulate the temperature onboard a satellite. In space, satellites and their components are subjected not only to extreme temperatures but also to quick changes. Thus, the temperature needs to be regulated on board by creating, trapping and dissipating heat into space. This allows a spacecraft and all its components to run at maximum efficiency with all of its components at optimal temperatures. A combination of special hardware and special handling procedures need to be applied to regulate temperature. The biggest source of heat in the solar system is the sun and, thus, while the spacecraft is close to the Sun it needs to be shielded from the radiation of the Sun, but once its far away it needs to generate heat to keep all of its components at operating temperature. While Kepler is close to the Sun, roughly till the orbit of Mars, it should not use its High Gain antennas for communication. Like Cassini, it can use those large dishes like an umbrella and shield the spacecraft from the Sun's radiation. While the antenna is oriented towards the Sun, another low gain antenna will have to be used for communication.[14]

Throughout the mission, Kepler will require a lot of temperature control hardware such as thermal blankets for insulation, thermal shields to provide cover from Sun's radiation, louvers to dissipate heat and heaters to raise the temperature of the devices to operating temperatures. The heat generated by the RTGs can also be used to heat the devices. This was used on the Cassini mission as well. The probes are subjected to even more severe conditions.

The probes will enter the Neptunian atmosphere at high speeds and will experience extremely high pressure and temperature. The Galileo probe that entered the Jovian atmosphere was expected to experience temperatures as high as 14,000 K and dynamic pressures of over 6000 N/sqm, because of which this probe was expected to lose over 60% of its forward shield.[12] Neptune is a similar gas giant and the environment inside its atmosphere will be as unfriendly for the probes. Thus, extremely good materials and engineering is required to make the probes survive in the atmosphere for 50 hours.

Orbits

There are three probes and one relay satellite orbiting around Neptune while maintaining communication with the Earth. The probes have a relatively simple orbit as they orbit at specific latitudes around Neptune. The relay satellite, however, has to be in the field of vision of the probes and also maintain a line of sight with the Earth to allow continuous transmission of data.

The probes have to be inserted at 45°, 0° and -45° latitudes with respect to the Neptunian equator. Upon entering the atmosphere they will descend towards the center of the planet, thus maintaining the angle at which they entered the planet's atmosphere. They will only go a fraction of the way into the Neptunian atmosphere as part of the project. Beyond that, communication will depend on the state of the batteries on the probe and on the probe's ability to withstand the increasing pressure and temperature. Given that the radius of Neptune is 24,476 km, descending 420 km into Neptune is only going to take us roughly 1.7% below the surface of Neptune.

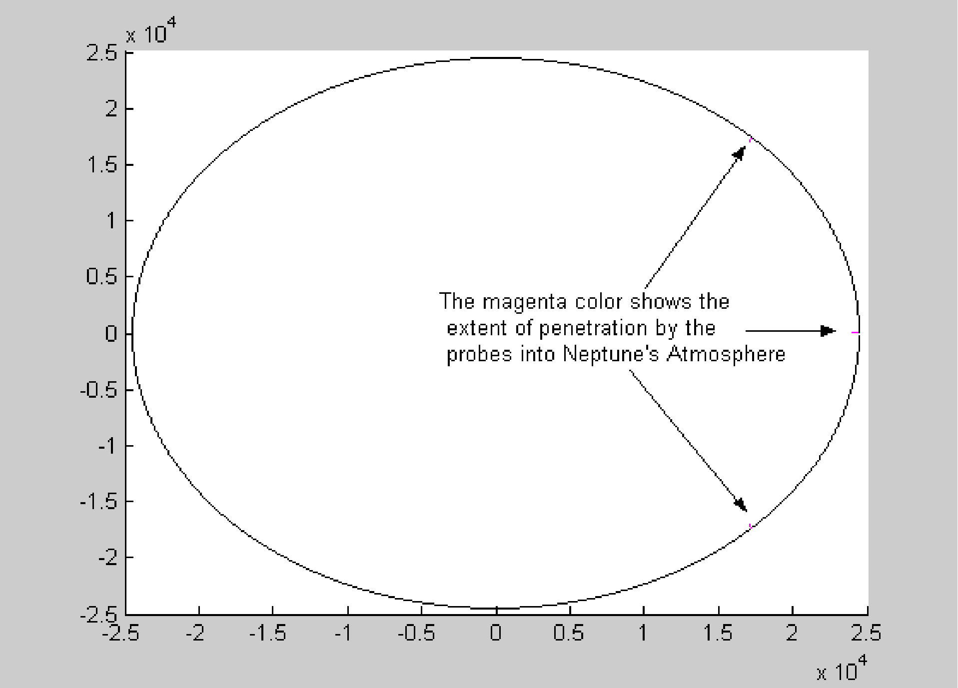

Figure 3. Illustrating the extent of penetration of Neptune's atmosphere

The MATLAB plot in figure 3 illustrates how far into Neptune the probes will actually descend. As they descend into the surface, the probes will just rotate along with Neptune's planetary motion. Thus, the amount of time taken for one probe to complete a revolution will be equal to the length of a single Neptunian day, which is considered to be 16 hours in this design. The relay satellite will be going around Neptune in a synchronous orbit while maintaining constant contact with Earth and the probes at Neptune.

In order for the relay satellite to maintain contact with the probes, it has to stay in the field of vision of all the three probes, which simply means that the angle of elevation always has to greater than 0° and less than 180°. At the same time in order to remain in contact with Earth, the relay satellite has to be in constant field of view of the DSN. In order to maintain contact with DSN, the satellite always has to have Earth in its line of sight and cannot afford to be hidden in Neptune's shadow. This will occur if the relay satellite, Neptune and Earth fall on the same plane with Neptune in between the Earth and the satellite. The satellite will, thus, have to maintain an orbit at an incline to the plane of Neptune's equator. Considering the worst case scenario where the plane in which Neptune's equator lies will also contain the Earth, the relay satellite's orbit will have the maximum inclination to maintain a direct line of sight with the Earth. This maximum inclination, given the worst-case scenario, will be 17.13°.

The following MATLAB plot is a simulation of the satellite's orbit around Neptune. This simulation is from the perspective of a plane perpendicular to the plane of Neptune's Equator. This simulation shows the worst-case scenario in which the Earth is assumed to lie on the same plane as Neptune's equator. This figure shows that the relay satellite will never be in Neptune's shadow and will maintain a direct line of sight with the Earth.

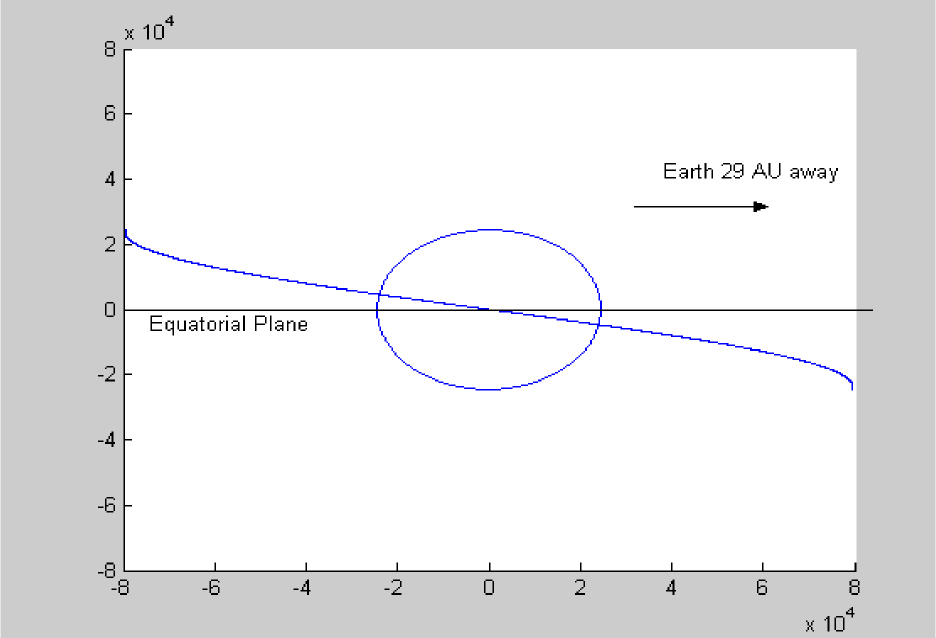

Figure 4. Illustrating the satellite's orbit around Neptune.

This resolves the issue of maintaining contact with Earth, but now the relay satellite will not remain at one point in the sky as far as the probes are concerned. As the probes and the relay satellite revolve around Neptune, the look angles will constantly change. This is acceptable as long as the relay satellite can always remain in the probes' field of vision. The following MATLAB plot shows the look angles, azimuth and elevation over the course of one revolution around Neptune. From this we can see that Azimuth does not change over the course of the orbit. This is because the relay satellite will always be at the same longitude as the three probes. Thus, the azimuth is always 0° (or 180° when the elevation is greater than 90°).

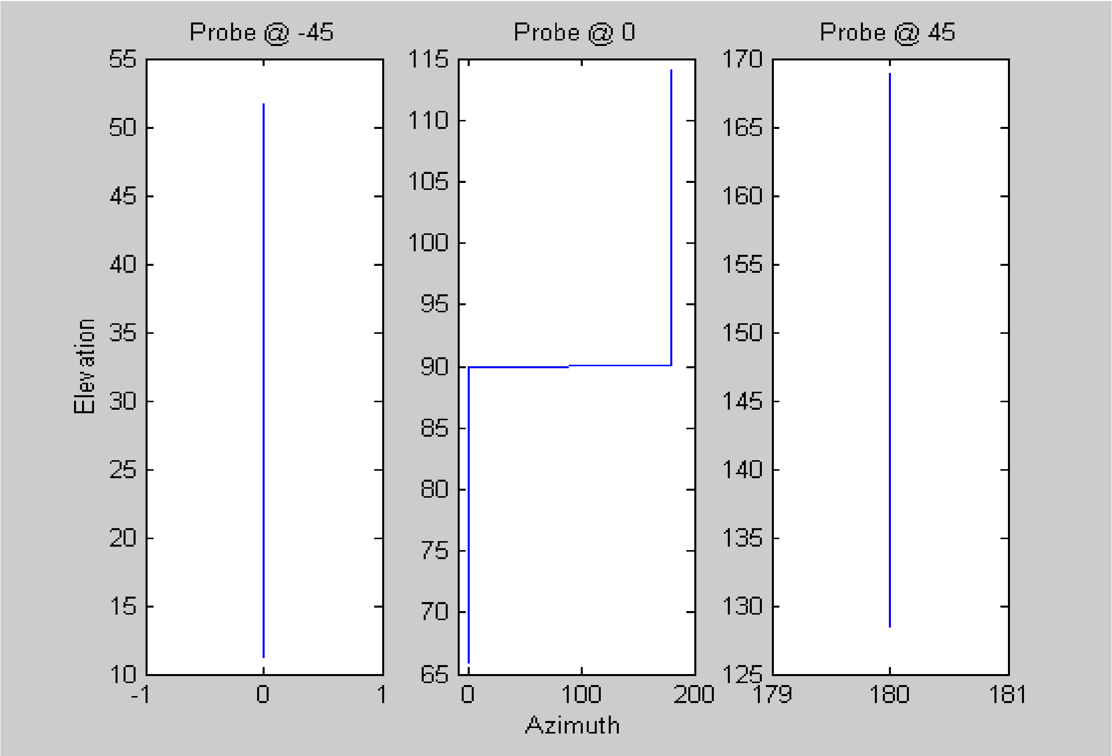

Figure 5. The look angles for all three probes.

The central probe has the greatest range of elevation angles ranging from just under 66° to just over 114°, a range of over 48°. The outer probes have identical ranges and angles with respect to the horizon, with a range of over 40°. Although the range of angles is higher for the center probe, it has a shorter effective path length through the atmosphere of Neptune because the angles for the outer probes with respect to the horizon are much more acute as compared to the center probe. This will affect the antenna design because we will need an antenna with a wider beamwidth for the center probe but with higher gain for the outer probes.

Although the probes will send the data back about the Neptunian atmosphere and its composition, we have a fairly good idea to characterize its behavior for our telecommunications link. Neptune's atmosphere is composed primarily of hydrogen, helium and methane with traces of water vapor, hydrogen sulfide, ammonia and phosphine. As far as telecommunication links are concerned, the atmosphere is extremely lossy and will attenuate the signal further as the probes descend into the atmosphere. The attenuation increases as a function of frequency. This behavior has been characterized by Priscilla Mohammed, whose work has been used to calculate the attenuation in the communications link.[15]

The Neptunian atmosphere has been divided into 2 km wide bands, starting from the surface down to 420 km. For each band, the attenuation caused by every gas component in the atmosphere has been recorded in units of dB/km. Thus, adding the attenuation of all the individual gases in each band at the relevant frequency gives the total attenuation in dB/km for the signal at the chosen frequency. By multiplying the attenuation by the effective path length of the signal through the atmosphere, a good estimate of the actual signal degradation can be made. Since the attenuation increases considerably as a function of frequency, the signal will be transmitted at a frequency of 500 MHz to experience lesser attenuation. Since the CDMA technique will be used to send the data from all three probes, the final signal will have a bandwidth of 28 MHz. Thus, considering the worst case scenario by using the highest frequency of the broadband spectrum (514 MHz) and the longest path length through the atmosphere gives an attenuation of 23.33 dB for the probes at 45° and -45° latitudes and a much smaller one of 5.18 dB for the central probe. This huge difference in the total attenuation is because of the very acute angle of 11° at which the outer probes have to transmit, whereas the most acute angle for the central probe is only 65.99°. The following table shows the large variation in attenuation at the different look angles and frequencies.

Table 5. The best and worse case attenuations at uplink and downlink frequencies

	Outer Probes		**Center Probe**	
Attenuation	**Maximum**	**Minimum**	**Maximum**	**Minimum**
F = 100 MHz	1.579 dB	0.269 dB	0.230 dB	0.210 dB
F = 500 MHz	23.33 dB	5.925 dB	5.215 dB	4.647 dB

This large difference between the attenuation of the outer probes and the central probe, make it necessary to design the antennas and link budgets separately. Finally, we want the signals that reach the relay satellite to have similar power because they share the bandwidth, and, a stronger signal from the central probe will make it difficult to obtain the signals from the outer probes. To overcome this problem, the antenna for the central probe is different from the antenna for the outer probes. Moreover, the transmitted power of the central probe will be less than the transmitted power of the outer probes. However, since all three signals are bound for the same destination, they have been encoded the same way with the use of the same error encoder and spread spectrum modulator.

Antenna Design

The three probes will all have a single low gain antenna; while the relay satellite will have two antennas, one for communicating with the probes and another for maintaining contact with Earth. The relay satellite may also have a low gain antenna for communication while close to the Sun for telemetry control. However, it is not critical for the link from Neptune to Earth, and its design will not be considered. Here, the design of the antenna on the probes and the two antennas on the relay satellite that are used for the link from Neptune are presented.

Central Probe:

This probe experiences less attenuation than the outer probes and also has to travel a smaller path length in free space while heading towards the relay satellite. Although the difference in path lengths is extremely significant while in the atmosphere of Neptune, it provides only a marginal advantage in free space. However, the beamwidth needs to be much wider in order to keep the relay satellite in its view. The requirements for a wide beam and a low gain antenna are met by a simple half-wave dipole antenna. It has a half power beamwidth of 78° and a gain of 1.64, which is equivalent to 2.15 dB. This is sufficient for the central probe. The extra beamwidth makes it easier to keep the antenna pointed towards the relay satellite. Its wider field of vision ensures that the attitude control for this antenna does not have to be extremely accurate or sophisticated.

Outer Probes:

Both the outer probes will have identical antennas because they both are essentially mirror images of each other and face exactly the same attenuation & path length. Not only will these probes need a higher transmitted power, they will also require a more powerful antenna. It can also have a more focused beam, as the range of elevation angles is around 40° as compared to 48° for the central probe. Thus, for these probes 4 half-length dipoles are arranged in a 2 × 2 formation to create an array antenna. The dipoles will be half a wavelength apart so that antenna coupling does not occur. Such a formation will provide a gain of 10.07 or 10.03 dB with a half power beamwidth of 51°. Such a design provides a wider beamwidth than required, making it easier to keep the relay satellite in its field of view. In addition to attitude control systems, it can use phase shifters to steer the beam.

Relay Satellite:

The relay satellite will have two antennas: One for the probes, and one for the Earth. The antenna that will communicate with the probe will be a 2.5 m parabolic dish antenna. Assuming an aperture efficiency of 0.8, this antenna will have a gain of 22.42 dB at 500 MHz. This will provide sufficient gain for the probe signals. Given the wide signal beamwidth of all the three probes, the relay satellite will just need to orient its antenna towards its sub-satellite point and should be able to receive signals from all the three probes. This completes the antenna design for the communication link between the probes and the relay satellite.

The link between the relay satellite and Earth will require a high gain antenna both on the satellite and on the Earth. The frequency being used for this link is 8 GHz. At this frequency, the 34 m DSN dish antenna provides an extremely fine half-power beamwidth of 0.064°. It also provides an enormous gain of 68.82 dB at 8 GHz, assuming an aperture efficiency of 0.94. This will be required as the signal travels through 29 AU of deep space to reach Earth. The antenna on the relay satellite will be a 5.6 m dish, which assuming an aperture efficiency of 0.8, will provide a gain of 53 dB. The Cassini orbiter transmitted data to Earth using only 20 W of transmitted power.[18] However, the Kepler relay satellite will be over three times further away from Earth than the Cassini orbiter and, hence, will require a much higher transmit power of 60 W (17.78 dBW).

Communication System Design

In this section of the report a system level design is presented for all the communication modules on the satellites. Overall the probes will send data to the relay satellite using CDMA at 500 MHz. The relay satellite will be able to communicate with the probes by sending a narrow band signal at 100 MHz. The relay satellite will send the data to Earth using a narrowband signal centered at 8 GHz whereas the DSN will use 8.5 GHz carrier frequency to send commands or information to the relay satellite.

The following figure is a block level design of the communication system that will transmit a signal from the probes to the relay satellite. Except for the Power Amplifiers and the antennas at the end of the block design both the outer probes and the central probe have the exact same design and use the same components. A different amplifier and antenna has been used on the central probe because it experiences much lesser attenuation from the Neptunian atmosphere as compared to the outer probes. Using this design similar powers are received at the relay satellite thus minimizing interference with each other. This will be further illustrated when the link budget is discussed.

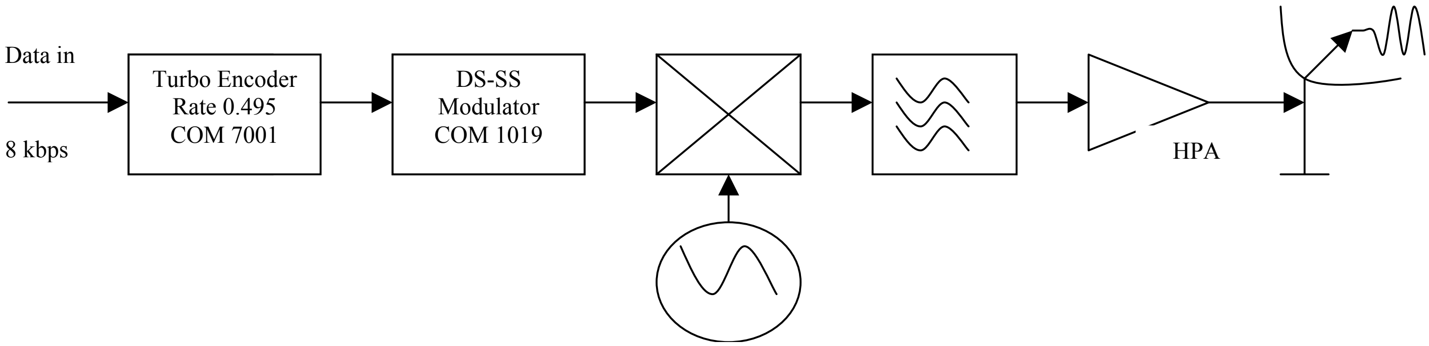

Figure 6. Block diagram of transmitter on the probe.

The 8kbps data stream is encoded using a COM 7001 turbo encoder/decoder device. This device can work both as an encoder and decoder but for this link only the encoding function is used. Different code rates can be chosen ranging from 0.97 to 0.25 rate encoding.[19] For this link a rate 0.495 encoding scheme is used. This results in a 16.16kbps encoded data stream which is then fed into COM 1019 which is a direct sequence spread spectrum modulator. This outputs the data at a rate of 20Mcps and can implement a various different chipping sequences such as gold codes or even GPS chipping sequences.[20] Since only 3 long sequences need to be used, they should be carefully selected so that they exhibit almost ideal sequence behavior. This component also modulates the signals with a roll-off factor of 0.4 and behaves also does the job of a raised root cosine (RRC) filter. This baseband analog signal is now modulated up to a 500 MHz carrier frequency with the help of a local oscillator and mixer. These components and processing is common to all the three probes. However, the amplifier and the antenna for the outer probes are different than the amplifier and antenna for the central probe. The outer probe uses a high power amplifier (HPA) that provides an output power of 17dB. The HD17987 is an example of such an amplifier.[22] The central probe uses a smaller amplifier that provides an output power of around 7dB such as the HD18858. The antenna for the central probe as explained earlier is a half wave dipole whereas the outer probes use a 2 by 2 array of half wave dipoles.

The signal sent out by this setup is received by the 2.5 m dish on the relay satellite. The block diagram representation of the receiver on the relay satellite is shown in the next figure. These two systems combined form the communication uplink from the probe to the satellite. The link budget calculation for this link is summarized in Table 6 and is presented in detail in Appendix A. Although this is a very optimistic calculation, without accounting for all the miscellaneous losses, it still proves the validity of the design because it exaggerates losses and attenuation.

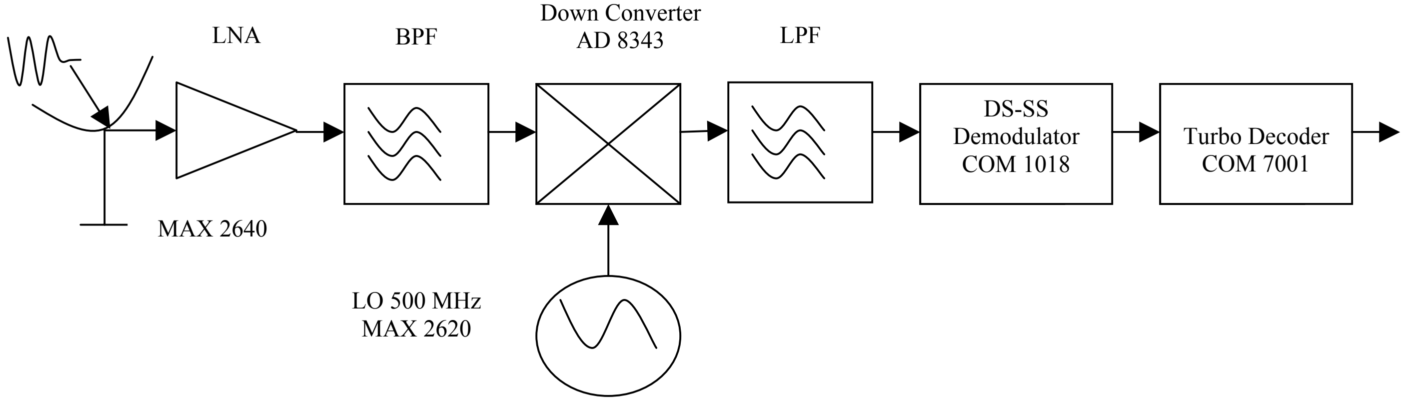

Figure 7. Receiver on relay satellite

This setup of this system is almost the mirror image of the one discussed previously. The signal is received by the relay satellite and is extremely weak and noisy. Hence, it is amplified with a low noise amplifier. The MAX 2640 manufactured by Maxim has a noise figure of only 0.9 dB and provides sufficient gain.[23] It is then filtered before being downconverted to a baseband signal using a local oscillator at 500 MHz and AD 8343 which is an active mixer.[24] This analog signal is then demodulated using COM 1018.[25] This spread spectrum modulator performs the exact opposite operation as the COM 1019 by converting the analog signal to digital and by despreading the wideband signal using the chipping sequence. This signal is then fed into COM 7001 which is used as a turbo decoder this time to extract the original 8kbps data stream. Although the design should work, but as with all satellite links, it is the power that is the limiting factor. The link budget summary below validates that for this link the power is sufficient to have virtually error free communication.

Table 6. Link Budget Calculation from Probe to Relay Satellite

	Outer Probe (-45°, 45°)	Center Probe (0°)	Units	Source/Component
Initial Data rate	8	8	Kbps	Project Statement
Encoded Data	16.1616	16.1616	Kbps	Com7001 Rate 0.495 Turbo Encoder
Spread Spectrum	20	20	Mcps	Com1019 CDMA SS Modulator (BPSK) $\alpha = 0.4$
Signal Bandwidth	28	28	MHz	
EIRP	27.03	9.15	dBW	Pt + Gt
Atmospheric Attenuation Worst case (A)	23.33	5.215	dB	[15]
Path loss in free space	181.74	181.74	dB	$20*\log(4*\pi*R/\lambda)$
Antenna Gain (Gr) **Relay satellite**	22.42	22.42	dB	Dish antenna d = 2.5m $\eta = 0.8$
Rx signal power (Pr)	-155.62	-155.35	dB	Pr = Pt + Gt – A – Pl + Gr
Noise Power (N)	-129.57	-129.57	dBW	N = 10*log(kTsB)
Interference (I)	-138.12	-135.71	dBW	I = Pr of the other two signals
Total Noise (N + I)	-129.003	-128.522	dBW	N+I = 10*log(10^(N/10) + 10^(I/10))
SINR	-26.347	-27.098	dB	SINR = Pr – (N+I)
(C/N)despread	4.583	3.832	dB	(C/N)despread = SINR + Gproc Gproc = chips/bit = 10*log(20e6/16.16e3)
Coding Gain (Gc)	8.1	8.1	dB	Coding gain at BER of 10e-6 Com 7001 Data Sheet
Final Signal to Noise Ratio	12.683	11.932	dB	
Required SNR	10.4	10.4	dB	SNR for BPSK for a BER of 10e-6 [16]

As seen from the last row of Table 5, the required signal to noise ratio for a BPSK signal, in order to maintain a bit error rate of 10^{-6}, is 10.4 dB.[16] This already provides an additional 1 dB for implementation losses and miscellaneous losses. Moreover, a system temperature of 400 K is an exaggerated value that more than compensates for any noise that may be inserted into the system by any of the devices. The system temperature for an antenna pointing to Neptune is estimated to be 345 K by extrapolating the values from the graph in David DeBoer's PhD thesis.[17] Thus, ample implementation margins and extra buffers are available for this link to work properly. Moreover, the atmospheric attenuation included in this link budget calculation is the worst possible and so is the path loss in free space. Actually, the link will experience such severe attenuation for only a fraction of the time and will experience a much higher received power. The increase in received power will still not adversely affect the transmission from other signals. The interference considered is the worst-case scenario and will normally be less than the value that has been used for calculations. The interference values used in this link budget calculation are the sum of the maximum possible received power from the other two probes. Thus, by using the minimum received power from one probe and the maximum power from the interfering signal, we are still able to resolve a signal error free. The actual BER for this link will be much smaller than 10^{-6}. The Voyager spacecraft uses a 16,384 interleaver and 10 iterations on a rate ½ turbo code that requires an S/N ratio of 0.7 dB only.[16] If such a coding scheme is used on this link, then the despread C/N ratio is already over 2.5 dB more than the required value of 0.7. This further increases the margin and makes the link stronger.

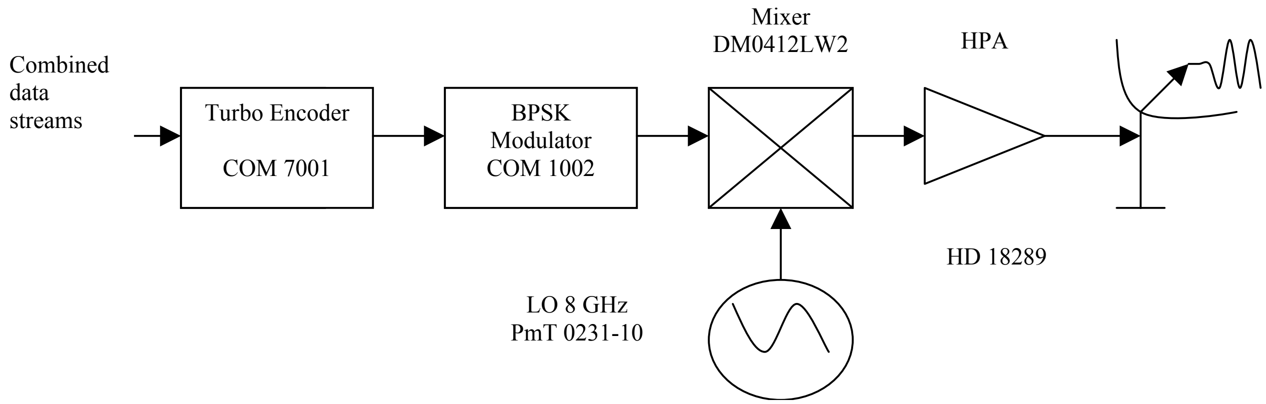

Figure 8. Block diagram of receiver for probe signal on the relay satellite.

The other critical link in the Kepler project is the downlink from the relay satellite to the Earth Station. The data that is received from the three probes is first merged together into a single data stream so that it can be relayed back to Earth without the use of any multiple access schemes. There is an overhead involved with merging data streams and so the resultant stream will be have higher bit rate than just 24 kbps which is the sum of the three individual streams. For this design an overhead of 6kb has been added. Thus, the data will have to be relayed back to Earth at a rate of 30 kbps. This data will first be encoded using the same COM 7001 turbo encoder at rate 0.495. This will then be modulated using a COM 1002 baseband modulator with a roll-off factor of 0.4.[25] It is then modulated up to its 8 GHz carrier frequency and then amplified with a HPA to a final transmit power of 17.78 dB.[26,27] Then it is transmitted using the satellite's 5.6 m dish high gain antenna. This signal will then reach the Earth over four hours later after traveling through four billion three hundred and thirty eight million kilometers of free space. Although the signal is virtually undetectable when it reaches the Earth it is still much stronger than the noise present in its frequency band. The link budget for the downlink from the relay satellite to the DSN on the Earth is summarized in the table below and it is even stronger than the probe to relay satellite link.

Table 6. Link Budget Calculation from Relay Satellite to Earth Station

Item	Value	Unit	Source
Data rate	30	Kbps	3 * 8Kbps and assumed overhead
Encoded data	60.61	Kbps	Rate 0.495 Turbo encoder Com 7001
Signal Bandwidth	84.854	KHz	Com1019 Modulator (BPSK) $\alpha = 0.4$
Noise Bandwidth	60.61	KHz	Bn = Symbol rate
Transmitted Power Pr	17.78	dBW	LNA configuration
Antenna Gain Gt	53	dB	D = 5.6m
EIRP	73	dBW	
Wavelength (λ)	.0375	m	$\lambda = c/f_c$
Path Loss (Pl)	303.25	dB	$20*\log(4*\pi*R/\lambda)$
Antenna Gain (Gr) DSN	68.82	dB	d = 34m eta = 0.94
Received Power (Pr)	-163.65	dBW	Pr = Pr + Gt + Gr – Pl
Noise Power (Pn)	-167.77	dBW	Pn = 10*log(k*Tsys*Bn)
C/N	4.12	dB	Pr-Pn

The signal is extremely narrowband as it is only 84.85 KHz wide. The received signal to noise ratio, without the coding gain, is 4.12 dB. This is an extremely good ratio as some of the turbo code devices require much less than that to decode the signal without any errors. Jet Propulsion Lab had planned to use rate 1/6 turbo code on board the Cassini. This code is so powerful that a C/N of 0 dB is required for error-free recovery of data.[16] If such an encoding scheme is used, we can see that an implementation margin of over 4 dB is available for miscellaneous losses including attenuation caused by rain. With the critical power limiting links functional, it is much simpler to see the working of the return links. Their designs look almost identical to their corresponding links except that they operate at different frequencies and are not as severely power limited.

First considering the uplink from the DSN based Earth station to the relay satellite. The carrier frequency for this link is 9 GHz. The DSN can transmit as high as 500,000 Watts. Considering such a high transmit power with almost the same constraints as the downlink the uplink is extremely strong. Here is a block diagram of the receiver on the relay satellite to receive this signal.

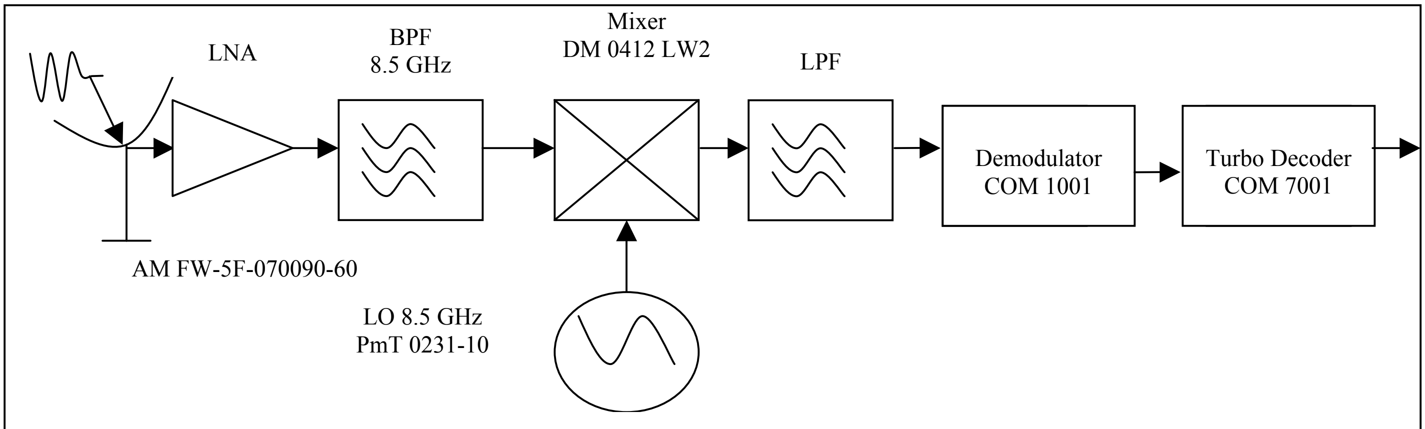

Figure 9. Block diagram of receiver for Earth signal on the relay satellite.

The link budget calculation for this link can be seen in the appendix. Only the communication link from the relay satellite to the probe has not been considered. This link will employ a frequency of 100 MHz so that it experiences extremely low attenuation from Neptune's atmosphere.[15] Moreover, this signal need not employ any kind of multiple access technique and hence will be an extremely narrow band signal. A block diagram illustrates the main components of this link. The details of the link budget calculations can be found in the appendix. Along with the receiving systems, the three probes will need to have different antennas for this link. This is because the half wave dipoles for 500 MHz will be too long for this wavelength. Thus a single half wave dipole for a frequency of 100 MHz will have to be mounted on each of the three probes as a receiving antenna for this link. After the exaggerated losses and by considering the worst case attenuation that is only faced by the outer probes for a very short period of time, the link is still virtually lossless. A signal bandwidth of 1 MHz is assumed.

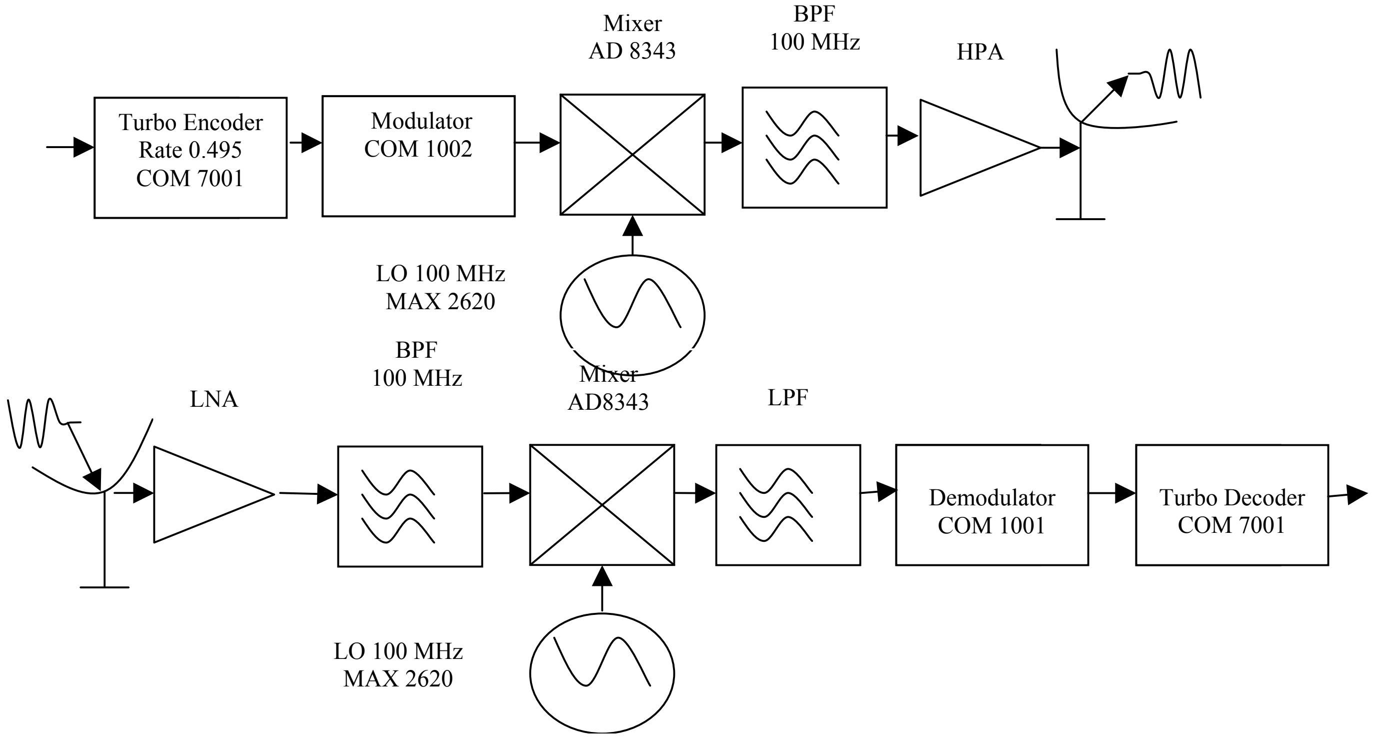

Figure 10. The transmitter and receiver design for relay satellite to probe link.

Cost, Reliability and Performance of components

All the components used in these system level designs are off the shelf components that are widely available for use and not really applicable for use on a satellite. Not only are they not space certified but they are not sophisticated enough to provide the awesome performance that is required on space crafts. These devices are used to help serve as an example and illustrate the feasibility of the design. Thus, none of the parts used are actually worthy of being on the Kepler mission and a more sophisticated device will have to be made that will have the same functionality or behavior and in addition will dissipate less energy and will be space certified. Thus, the cost of these parts will not provide an accurate estimate of the cost. However, the cost of these components can be used to come up with a ball park figure for the cost of the communication systems. Table 7 lists the prices of some of the products used while comparable devices are used as a guide to guess prices for the products that are not readily available

Table 7. Cost of devices used.

Component	Price per unit	Quantity used	Total Cost
COM 7001 (Error coder/decoder)	$375	10	$3,750
COM 1002 Modulator	$295	2	$590
COM 1001 Demodulator	$295	4	$1180
COM 1019 SS Modulator	$295	3	$885
COM 1018 SS Demodulator	$295	1	$295
Mixers	$4.36	8	$34.88
High Power Amplifier	$2000	5	$10,000
LNA	$0.80	5	$4.00
Oscillators	$1.98	10	$19.80
Filters	$1.35	8	$10.80
Total cost			**$16,769.48**

This table has summarized the cost of the components only. It would cost a lot more when trying to interface them correctly. The additional cost of wires, passives and other setup devices such as batteries will drive up the cost further. Considering a 100% overhead such a system would cost $33,539. However, this is only when looking at the retail prices available. All the parts on the Kepler mission will have to be made on special order using the best of the materials and processes. This will drive up the cost significantly and choosing a factor of 1000 to estimate the increase in cost, the final communication system will cost 33.54 million dollars. However, this ignores the cost of the antennas which will be a very significant cost. Moreover, the antennas will have to have attitude control which will be expensive as well. The Cassini mission is estimated to have a cost of $3.4 billion already and the Kepler mission is on a larger magnitude than the Cassini it will cost significantly more than that as well.[28]

5 billion dollars can easily be allotted to this mission and it may require more because of the length of the mission. However, this endeavor deep in space can help us find answers about the creation of life on our planet. Moreover, the cost of this mission can also be justified easily. The three probes going into the Neptunian atmosphere will send data at 8kbps for 50 hours. Thus, after 50 hours 4.32 gigabits of data would have been sent by the probes alone. Considering that this is the only scientific data that the Kepler project ever returns the cost per bit of this project is only $1.157. It is however, impossible that the relay satellite will not send back data gathered through its own scientific instruments. Imagining a project length of 15 years, even if the relay satellite collects and sends back data at an unbelievably slow rate of 50 bits per second 23.65 gigabits of data will be received at Earth. Now the cost per bit of information is only 17.7 cents. A lot more data will actually be received since the satellite has the capability to transmit at a higher rate and also will have data to send back that no one on Earth has ever seen. Thus, when the cost is measured up against the benefit, sending the Kepler mission to Neptune seems a logical choice especially since it has such an efficient and well designed communications system.

Appendix A

Satellite Link Budgets Calculations

Link from Probe to Relay Satellite

Note: Although the center probe and outer probe have different link budget calculations they are shown simultaneously here.

Data = 8kbps Encoded with rate 0.495 rate encoder

$datarate = \frac{8\times10^3}{0.495} = 16.16kbps$ This encoded data is now put into a SS modulator (20 Mchips/sec)

$$G_{proc} = \frac{chips}{bit} = 10\log\left(\frac{20\bullet10^6}{16.16\bullet10^3}\right) = 1237.5chips/bit = 30.93dB$$

$$f_c = 500MHz$$

$$\therefore \lambda = \frac{3\times10^8}{500\times10^6} = 0.6m \qquad \lambda = \frac{c}{f_c} \quad R = 58361km$$

$$Pl = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 58361\times10^3}{0.6}\right) = 181.74$$

$$G_R = \eta\left(\frac{\pi d}{\lambda}\right)^2 = 0.9\left(\frac{\pi\times2.5}{0.6}\right)^2 = 174.582 = 22.42dB$$

For the center probe worst case attenuation $A = 5.215dB, Pt = 7dB, Gt = 2.15dB$

For the outer probes worst case attenuation $A = 23.33dB, Pt = 17dB, Gt = 10.03dB$

$\mathrm{Pr} = Pt + Gt - A - P1 + Gr$

For center probe: $\mathrm{Pr} = 7 + 2.15 - 5.215 - 181.74 + 22.42 = -155.35dB$

For outer probes: $\mathrm{Pr} = 17 + 10.03 - 23.33 - 181.74 + 22.42 = -155.62dB$

$N = 10\log(KT_sB), K = 1.38\times10^{-23}, T_s = 400K, B = 20MHz$

$N = 1.104\times10^{-13}Watts = -129.57dB$

Interference (I) is the received power of the other two signals. The worst case scenario is considered in which the other two signals are received at the highest power possible and the signal to be decoded is the weakest. Since all things remain virtually the same only the attenuation changes. Using the least attenuation experienced

I for center probe = $-155.62 + 23.33 - 5.925 + 10\log(2) = -135.21$ dB

I for outer probes = $10\log(10^{-13.82} + 10^{-15.485}) = -138.122dB$

$N + I = 10\log\left(10^{\frac{N}{10}} + 10^{\frac{I}{10}}\right)$= -128.522dB for center probe and -129.003dB for the outer ones

$SinR = \mathrm{Pr} - (N + I)$

$= -155.35 - (-129.003) = -26.347dB$ for the outer probe

$= -155.62 - (-128.522) = -27.098dB$

$$\left(\frac{C}{N}\right)_{despread} = SinR + G_{proc}$$

For outer probes $\left(\frac{C}{N}\right)_{despread}$ = -26.347dB + 30.93 dB = 4.583dB

For the center probe $\left(\frac{C}{N}\right)_{despread}$ = -27.098dB + 30.93 dB = 3.832dB

Coding gain for rate 0.495 Turbo code for BPSK = 8.1dB

Final $\left(\frac{C}{N}\right)_{BPSK}$ = 4.583dB + 8.1 dB = **12.683dB** for outer probes

Final $\left(\frac{C}{N}\right)_{BPSK}$ = 3.832dB + 8.1 dB = **11.932dB** for center probe

Link from Relay Satellite to Probe

This link uses 100 MHz frequency with a bandwidth of 1 MHz. All the three probes have a half wave dipole to receive this signal and the relay satellite transmits using its 2.5m dish. This data is also turbo coded which gives the signal an 8.1dB coding gain.

$$G_T = \eta\left(\frac{\pi d}{\lambda}\right)^2 = 0.9\left(\frac{\pi \times 2.5}{0.6}\right)^2 = 6.169 = 7.902dB$$

$$G_R = 2.15dB, A = 1.58, Pt = 17dB$$

Path loss $Pl = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 58361\times 10^3}{3}\right) = 167.76$

$$\mathrm{Pr} = Pt + Gt - A - Pl + Gr = 17 + 7.902 - 1.58 - 167.76 + 2.15 = -142.29\,\mathrm{dB}$$

Assuming a system temperature of 150 Kelvin at a bandwidth of 1Mhz

$$N = 10\log(KT_sB), K = 1.38\times 10^{-23}, T_s = 150K, B = 1MHz$$

$$N = 2.07\times 10^{-15}Watts = -146.84dB$$

$$\left(\frac{C}{N}\right) = -142.29 - (-146.84) = 4.5503dB$$

$\left(\frac{C}{N}\right)_{BPSK}$ = 4.5503 + 8.1 = **12.65dB**

Thus, the return link also is a virtually loss less transmission. Since the worst case attenuation for the outer probe is considered the link will automatically work for the central probe since its link will be less lossy and so need not be considered separately.

Downlink from Relay Satellite to Earth

This link uses 8 GHz frequency and sends out a very narrow band signal of . All the three probes have a half wave dipole to receive this signal and the relay satellite transmits using its 5.6m dish. This data is also turbo coded which gives the signal an 8.1dB coding gain. The signal is received at the DSN using their 34 m dish antennas

$$G_T = \eta\left(\frac{\pi d}{\lambda}\right)^2 = 0.9\left(\frac{\pi \times 5.6}{0.0375}\right)^2 = 198087 = 52.97dB$$

$$G_T = \eta\left(\frac{\pi d}{\lambda}\right)^2 = 0.94\left(\frac{\pi \times 34}{0.0375}\right)^2 = 7.62646 \times 10^6 = 68.82dB$$

$$Pt = 17.78dBW \;\; R = 29AU = 29 \times 149{,}598{,}000{,}000 = 4.33834 \times 10^{12}$$

Path loss $Pl = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 4.33834 \times 10^{12}}{.0375}\right) = 303.25dB$

$$\Pr = Pt + Gt - P1 + Gr = 17.78 + 52.97 - 303.25 + 68.82 = -163.68\,\text{dB}$$

Assuming a system temperature of 20 Kelvin

B=symbol rate = $\left(\frac{30 \times 10^3}{0.495}\right) = 60.6061 \times 10^3$

$$N = 10\log(KT_s B), K = 1.38 \times 10^{-23}, T_s = 20K, B = 60.61 \times 10^3$$

$$N = 1.67 \times 10^{-17} Watts = -167.77dB$$

$$\left(\frac{C}{N}\right) = -163.68 - (-167.77) = 4.12dB$$

$$\left(\frac{C}{N}\right)_{BPSK} = 4.12 + 8.1 = \mathbf{12.22dB}$$

Uplink from Earth to Relay Satellite

This link uses 8.5 GHz frequency. Since this link is not power limited, it can use a much wider bandwidth for data transmission. The DSN is capable of transmitting upto 500,000 WattsAll the three probes have a half wave dipole to receive this signal and the relay satellite transmits using its 5.6m dish. This data is also turbo coded which gives the signal an 8.1dB coding gain. The signal is received at the DSN using their 34 m dish antennas

$$G_T = \eta\left(\frac{\pi d}{\lambda}\right)^2 = 0.94\left(\frac{\pi \times 34}{0.0353}\right)^2 = 8.6096\times10^6 = 69.35dB$$

$$G_R = \eta\left(\frac{\pi d}{\lambda}\right)^2 = 0.9\left(\frac{\pi \times 5.6}{0.0353}\right)^2 = 223623.039 = 53.50dB$$

$$Pt = 500{,}000 = 56.99dBW \quad R = 29AU = 29\times149{,}598{,}000{,}000 = 4.33834\times10^{12}$$

Path loss $Pl = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 4.33834\times10^{12}}{.0353}\right) = 303.78dB$

$$\Pr = Pt + Gt - P1 + Gr = 56.99 + 69.35 - 303.78 + 53.50 = -123.94\ \text{dB}$$

Since this is a very strong signal with a lot of transmitted power lets assume that 100 MHz of bandwidth is being used. At the same time an estimation of the system temperature also needs to be done. The antenna at Neptune will only see the Earth as a little speck in its entire field of vision, while the rest of it will the dark cold deep space. However, lets assume a system temperature of 150 Kelvin so that it incorporates a noisy LNA as well.

$$N = 10\log(KT_sB), K = 1.38\times10^{-23}, T_s = 150K, B = 100\times10^6$$

$$N = 2.07\times10^{-13}Watts = -126.84dB$$

$$\left(\frac{C}{N}\right) = -123.94 - (-126.84) = 2.9003dB$$

$$\left(\frac{C}{N}\right)_{BPSK} = 2.9003 + 8.1 = \mathbf{11.00dB}$$

Thus a health and stable signal exists even after considering an extremely high system temperature and a wideband signal.

Appendix B

MATLAB Code

```
%Ranit Windlass ECE 6390 Final Project
%Illustrates the extent of penetration in Neptunian atmosphere
r = 24476;
theta = 0:.001:2*pi;
theta = [0,theta,2*pi];
pr=24056:.5:24476;
hold on
plot(r*cos(theta),r*sin(theta),'b');
plot(pr*cos(45*pi/180),pr*sin(45*pi/180),'r');
plot(pr*cos(0*pi/180),pr*sin(0*pi/180),'r');
plot(pr*cos(-45*pi/180),pr*sin(-45*pi/180),'r');
hold off
```

Figure B1. MATLAB code to show the extent of Neptunian atmospheric penetration

```
r = 24476;
theta = 0:.001:2*pi;
theta = [0,theta,2*pi];
r1 = 83107;
phi = [-17.1283:.0109:17.1283,17.1283:-.0109:-17.1283];
phi = phi*pi/180;
hold on
plot(r*cos(theta),r*sin(theta));
plot(r1*cos(theta).*cos(phi),r1*sin(phi));
hold off
```

Figure B2 Shows the orbit of the relay satellite around Neptune

```
function el = orbit(Le,delt)
%Ranit Windlass Project Look angles calculation
%a = initial Latitude
%b = initial longitude
%c = Vlatitude
%d = Vlongtiude
%e = delta t
%Le = Latitude of probe (-45,0,45)
Ls(1) = -17.1283*pi/180; %initial latitude
Le = Le*pi/180; %latitude of satellite remains same
re = 24476*1000; %radius of neptune in meters
rs = 83107*1000; %radius of neptune synchronous orbit
lon(1)=0; %longitude of satellite and probe
dellat =(34.2566*pi)/(180*16.11*1800)*delt; %rate of change of latitude (for satellite)
dellon =(2*pi/(16.11*3600))*delt; %rate of change of longitude(for satellite and probe)
deltalat(1) = Ls(1) - Le; %for azimuth (180 or 0)
gam = Ls(1) - Le;
el(1) = acosd(sin(gam)/sqrt(1+(re/rs)^2 - 2*(re/rs)*cos(gam)));
if deltalat(1) >=0
   az(1) = 0;
else
   az(1) = 180;
end
i=1;
while (lon(i) < 2*pi) & (i < 40000)
   Ls(i+1)=Ls(i)+dellat;
   lon(i+1)=lon(i)+dellon;
   deltalat(i+1)= Ls(i+1) - Le;
   gam = Ls(i+1)-Le;
   el(i+1) = acosd(sin(gam)/(sqrt(1+(re/rs)^2 - 2*(re/rs)*cos(gam))));
   if deltalat(i+1) >=0
      az(i+1) = 0;
   else
      az(i+1) = 180;
   end
   i=i+1;
   if (lon(i) >= pi) & (dellat > 0)
      dellat = -dellat;
   end
end
length(az);
plot(az,el);
```

Figure B3. MATLAB code that plots the look angles for the 3 probes

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