LINK ANALYSIS FOR THE NEAR EARTH ASTEROID PROSPECTOR

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ABSTRACT

The Near Earth Asteroid Prospector (NEAP) has a scheduled launch date between mid-1999 and mid-2000, and will encounter a yet to be determined near Earth asteroid (1.1 - 2.2 AU distance from Earth) some ten months later [2]. The purpose of this mission is not only to collect valuable scientific and geological data, but to also determine the value of the asteroid's materials for possible mining and exploitation [2], [3]. The purpose of this paper is to detail frequency allocation issues and to determine possible return (space to Earth) data rates associated with deep space communications with the NEAP spacecraft.

KEYWORDS

Deep Space Network (DSN), National Aeronautics and Space Administration (NASA), Near Earth Asteroid Prospector (NEAP), Near Earth Asteroid Rendezvous (NEAR), National Telecommunications and Information Administration (NTIA), Astronomical Unit (AU).

INTRODUCTION

NEAP will be the first privately funded spacecraft to ever leave the Earth's sphere of influence [2]. Mirroring NASA's $300 million Near Earth Asteroid Rendezvous (NEAR) mission, NEAP will accomplish most of it's counterparts objectives but at an expected cost of only $50 million [2].

NASA's Deep Space Network (DSN) provides the capabilities for spacecraft command and control. It also provides the capabilities for the reception of spacecraft telemetry data as well. The network is composed of three strategically located deep space facilities that are located at Goldstone, California; near Madrid Spain; and near Canberra, Australia [4].

These locations are approximately 120 degrees apart to insure constant observation of spacecraft as the Earth rotates [4]. Each facility is equipped with at least one 26-meter antenna, one 34-meter antenna, and one 70-meter antenna.

In designing a telecommunications system for the NEAP mission, two questions immediately come to mind. What are the possible frequency allocations for deep space communications with the NEAP spacecraft? What return data rates can be achieved without exceeding spacecraft power limitations? The first question can be answered by comparing the frequency allocations as dictated by the NTIA to those frequencies that are supported by DSN. The second question can be answered by performing a return link budget analysis.

FREQUENCY ALLOCATION

Before the actual communications design can proceed, the forward and return frequency ranges must first be determined. Comparisons must be made between the non-government frequency allocations as dictated by the NTIA frequency allocation tables to those frequencies that are supported by DSN. Deep space is defined by DSN as spacecraft distances greater than two million Km from Earth [5]. The deep-space frequency bands supported by DSN [5] are described in table 1.

Table 1. Frequencies Supported by DSN

Band	(Earth to Space)	(Space to Earth)
S	2110-2120 MHz	2290-2300 MHz
X	7145-7190 MHz	8450-8500 MHz

Table 2 illustrates the NTIA US non-government frequency allocation bands [6]. Note that a “ * ” indicates a footnotes presented by NTIA. These footnotes each consist of the letters US followed by one or more digits denote stipulations applicable to both government and non-government stations [6]. **US252**—The bands 2110-2120 and 7145-7190 MHz, 34.2-34.7 GHz are also allocated for Earth-to-space transmissions in the Space Research Service, limited to deep space communications at Goldstone, California [6]. Therefore as long as NEAP is classified as a “Space Research” mission, the frequency bands listed in table 2 can be applied.

Table 2. NTIA Non-government Frequency Allocations

Band (MHz)	**Earth to Space (MHz)**	**Space to EArth (MHz)**	**U S Non-Government Allocation**
2110-2150 (S-Band)	2110-2120		US252 *
2290-2300 (S-Band)		2290-2300	Space Research (Space to Earth) (Deep Space Only)
7125-7190 (X-Band)	7145-7190		US252 *
8400-8450 (X-Band)	None	None	Government Allocation Only
8450-8500 (X-Band)		8450-8500	Space Research (Space to Earth) (Deep Space Only)

* Indicates US footnotes presented by NTIA.

Table 3 illustrates the overlaps that occur between the non-government frequency allocations dictated by the NTIA (table 2) to those frequencies that are supported by DSN (table 1).

Table 3. Overlaps between DSN and NTIA

Band	(Earth to Space)	(Space to Earth)
S	2110-2120 MHz	2290-2300 MHz
X	7145-7190 MHz	8450-8500 MHz

RETURN LINK BUDGET ANALYSIS

For all deep-space-missions, spacecraft communications must be maintained while assuring that spacecraft power is conserved. A link budget analysis provides such assurance. In a link budget analysis, all of the positive and negative power contributions are summed [7]. The resulting value should be equal to or slightly greater than some predetermined positive performance margin (usually 3 dB).

When performing a link budget analysis, there are two different cases to consider. The uplink and the downlink (sometimes referred to as forward and return link respectively). The uplink describes the transmission from Earth to the spacecraft, while the downlink describes the transmission from the spacecraft to Earth [7]. Because of spacecraft power limitations, the downlink power budget is generally more critical than the uplink power budget [7].

The downlink Link budget consists of the following subregions: **transmitter parameters, path parameters, receiver parameters, total power summary, carrier performance, and channel performance** [7]. Note that all parameters are expressed in dB.

The **transmitter parameters** include parameters through the antenna at the transmitter side (S/C) of a communications link [7]. The downlink transmitter parameters include the following:

1. Total transmitter power
2. Spacecraft antenna gain
3. Antenna pointing loss
4. Transmitter lumped circuit loss
5. Effective Isotropic Radiated Power (EIRP)

The **total transmitter power** is just the actual spacecraft transmit power expressed in dB.

The **spacecraft antenna gain** [8] is directly proportional to frequency as shown by the ***Universal Gain Equation***:

$$G_{dB} = \frac{10\log\left(4\pi A_e f^2\right)}{c^2}$$

Where c is the speed of light (3.0×10^8 m/s) and A_e is the effective antenna aperture defined by [8]:

$$A_e = \eta_{ap} A_p$$

where A_p is the antenna's physical aperture and ($_{ap}$ is the aperture efficiency (typically between 45 and 65 %) [8]. The **Antenna pointing loss** is set to 3 dB, which is the worst case scenario [7]. The **Transmitter lumped circuit losses** are just the path losses between the power amplifier and the transmit antenna (typically −1 dB) [7]. The **Effective Isotropic Radiated Power** (EIRP) can then be defined as follows [7]:

*EIRP = Total Transmitter Power + Spacecraft Antenna Gain +
Antenna Pointing Loss + Transmitter Lumped Circuit Loss*

The **path parameters** include space loss and loss due to atmospheric attenuation. The **Space loss** is defined by the following formula [8]:

$$L_{sdB} = 20\log\left(\frac{4\pi Rf}{c}\right)$$

Where R is the distance from the spacecraft to Earth. It is easy to see that space loss increases with both distance and frequency. Losses due to **atmospheric attenuation** are a function of the distance the signal travels through the Earth's atmosphere. It typically has a value of −0.1 dB [7]. The **total power received at Earth** can then be defined as follows:

Total Power Received @ Earth = EIRP + Space Loss + Atmospheric Attenuation

The **receiver parameters** include the following:

6. Receiving antenna polarization loss
7. DSN antenna pointing loss
8. DSN antenna gain
9. Receiver circuit loss

The **polarization loss** [7] is the loss that is introduced to the link budget due to the polarization of the signals. The polarization loss is set to 0.10 dB as described by the DSN 810-5 handbook. [5]. The DSN **antenna pointing loss** [7] is the loss attributed to the misalignment of the DSN antenna with respect to the spacecraft antenna. A value of 0.10 dB is typically used. The **DSN antenna gain** is dependent upon which of the three DSN sub networks is being used (26-m, 34-m, 70-m). Table 4 lists the respective DSN antenna gains [5].

Table 4. DSN Antenna Gains

DSN Sub Network	DSN Antenna Gain (dB)
26-m	52.50
34-m	68.10
70-m	74.10

The **receiver circuit** loss is set to a value of 0.1dB [5]. The **total power summary** includes the following:

10. Received Power
11. Noise Spectral Density
12. System Noise Temperature
13. Received P_t/N_o.

The **total received power** is calculated as follows [7]:

Total Received Power = Total Power Received at Earth + Polarization Loss + DSN Antenna Pointing Loss + DSN Antenna Gain + Receiver Circuit Loss

Noise Spectral Density = $10\log(1000kT_{sys})$

The **noise spectral density** is a function of the **DSN antenna system noise temperature** [7].

K = Boltzman's constant = 1.38×10^{-23}
T_{sys} *= The system noise temperature in Kelvin*

The **system noise** is composed of two basic sources: environmental noise picked up by the receiving antenna and electronic noise produced in the receiving electronics. The electronic noise produced by the transmitting electronics isn't considered in the computations [7]. The system noise temperature varies with DSN antenna size and elevation (see table 5) [5].

Table 5. Antenna Noise Temperature

DSN Antenna	Antenna Noise Temperature (Kelvin) (10 degree antenna elevation)
26-m subnet	145
34-m subnet	40
70-m subnet	50

The received $\mathbf{P_t/N_o}$ [7] is the ratio between received signal power and the noise power. Pt/No is calculated as the total received power in dB minus the noise spectral density in dB.

$P_t N_o$ *(dB) = Total Received Power (dB) - Noise Spectral Density (dB)*

When a digital signal is modulated onto a carrier, some loss will be introduced. Some threshold is required for the receiver to be able to lock onto the received carrier. This loss occurs because some of the power contained in the digital signal will be lost outside the bandwidth of the channel [7]. **The carrier performance parameters** include the following:

14. Telemetry Carrier Suppression
15. Received Carrier Power
16. Carrier Noise Bandwidth
17. Threshold CNR
18. Carrier Threshold Power
19. CNR Margin

The **telemetry carrier suppression** [7] can be determined from the following equation:

$$10\log[Cos^2 (\quad + 0.01(x - 1))]$$

Where (is the modulation index that is assigned a value of 0.35. *X* is assigned a value of 73 [5].

The r**eceived carrier power** [7] is the total power in the carrier when the carrier arrives at the receiver. The received carrier power is defined as follows:

P_C *= Total Received Power + Telemetry Carrier Suppression + Ranging Carrier Suppression + DOR Tone Carrier Suppression*

$2B_{lo} = 10\log(BW)$

The **carrier noise bandwidth (2B$_{lo}$)** [7] is the loss due to the limited bandwidth of the receiver loop. It is determined from the following equation:

Where BW is the bandwidth of the receiver loop. The **carrier to noise threshold** is the necessary ratio between the received signal power to the received noise power. This ratio must be above a minimum threshold for the receiver to be able to lock onto the signal [7]. We will use a value of 10 dB. The **carrier threshold power** is the amount of excess power contained in the signal, than what is required for the receiver to lock onto the signal. It is defined by the following equation [7]:

Carrier Threshold Power = Noise Spectral Density + Carrier Noise BW + Threshold CNR

The carrier to noise ratio margin is defined as the [7]:

CNR Margin = Received Carrier Power - Carrier Threshold Power

The **channel performance** is concerned with the losses incurred by the digital signal when it is passed through the channel. Some threshold value is required for the receiver to be able to recover the signal received through the channel [7]. The channel performance parameters include:

20 Telemetry Modulation Loss
21 Data Power to the Receiver
22 Data raw
23 Radio Loss
24 System Loss
25 E_b/N_o
26 Threshold E_b/N_o
27 Performance Margin

The **telemetry modulation loss** can be determined from the following formula [7]:

$$10 \log [\sin^2 (\quad + 0.01(x - 1))]$$

Where (is the modulation index that is assigned a value of 0.35 [5]. *X* is assigned a value of 73 [5]. The **data power to the receiver (Pd)** is defined by the following [7]:

P_d *= Total Received Power + Telemetry Modulation Loss + Range Data Suppression + DOR Tone Data Suppression*

Note that both Range Data Suppression and DOR Tone Data Suppression are set to zero for this analysis. The data rate will obviously effect the link margin. The higher the data rate the higher the required power. The data rate is represented as a loss in the link budget:

Data Rate = 10 log*(data rate)*

Radio and system losses result from imperfect RF carrier tracking. This leads to higher bit error rates of the recovered telemetry data than would be obtained if perfect tracking were to take place. The amount of loss is determined by the statistical properties of the phase error in the receiver carrier tracking loop and by the bit-detection process being used. Both of these values are determined empirically. Radio losses will be set equal to −0.7 dB and system losses will be set equal to −1.0 dB [7].

E_b/N_o is the ratio of the bit energy to the noise power spectral density, at the detector input [7].

E_b/N_o = Data Power to the Receiver + Data Rate + Radio Loss + System Loss - Noise Spectral Density

In order for the receiver to be able to decode the incoming signals, the signal has to be above the **threshold E_b/N_o**. For a BER of 10^{-6} and PSK modulation, the required thresholds [91, [10] are illustrated in table 6 for the different forward error correcting schemes:

Table 6. FEC Performance

Forward Error Correcting Scheme	**Threshold E_b/N_o (dB)**
No FEC	9.6 (BER = 10^{-5})
Reed-Solomon/Convolutional (k = 7, r = _)	2.9 (BER = 10^{-6})
Turbo Codes (2 + 32 states, R _, m = 18)	0.8 (BER = 10^{-6})

The performance margin is the amount of power that is left over after the required thresholds have been subtracted. It is defined by the following equation [7]:
Performance Margin = E_b/N_o ! Threshold E_b/N_o

For this analysis, a 3 dB minimum performance margin is maintained.

Figure 1 illustrates bit rate versus spacecraft transmit power for various spacecraft antenna gains. The analysis was performed at S-band, using the concatenated Reed-Solomon /convolutional coding forward error correction technique and the 34-meter DSN receive antenna.

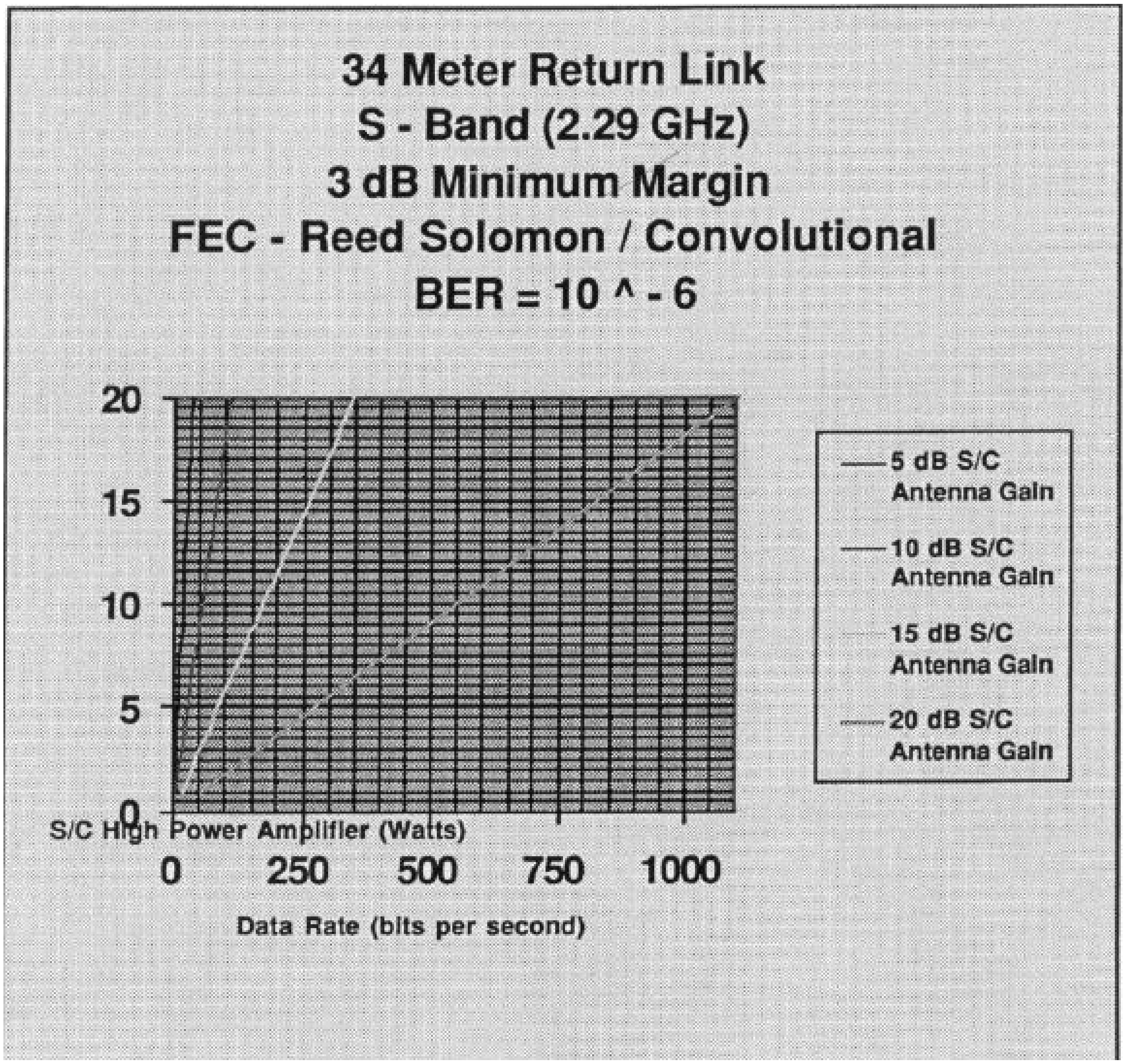

Figure 1. Bit rate versus S/C transmit power for 5, 10, 15, 20 dB S/C antennas

Figure 1 clearly illustrates that the return data rate increases with both spacecraft antenna gain and spacecraft transmit power.

CONCLUSION

Before the design of a deep space communications system can proceed, the forward and return frequency bands must first be determined. Overlaps were found between the non-government frequency allocations as dictated by the NTIA frequency allocation tables to those frequencies that are supported by DSN. Table 3 illustrates these overlaps for both the forward and return paths. It should be mentioned that one might be tempted to simply choose X-band over S-band since antenna gain is directly proportional to frequency (by the Universal Gain Equation). However, one needs to keep in mind that any gain due to the increase in frequency is offset by the increase in space loss, which is directly proportional to frequency as well.

In a link budget analysis, all of the positive and negative power contributions are summed [7]. The resulting value should be equal to or slightly greater than some predetermined positive performance margin (usually 3 dB). The higher the return data rate the greater the consumption of spacecraft power. The goal is to acquire a maximum data rate without exceeding the 3 dB performance margin. Figure 1 illustrates bit rate versus spacecraft transmit power for various spacecraft antenna gains. The analysis was performed at S-band, using the concatenated Reed-Solomon /convolutional coding forward error correction technique. Figure 1 clearly illustrates that the return data rate increases with both spacecraft antenna gain and spacecraft transmit power. It should be mentioned that the Reed-Solomon /convolutional coding forward error correction technique was chosen because of it's good performance (Threshold E_b/N_o= 2.9 dB) and its proven flight legacy.

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