Emergency Communications for NASA's Deep Space Missions

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Abstract—The ability to communicate with spacecraft during emergencies is a vital service that NASA's Deep Space Network (DSN) provides to all deep space missions. Emergency communications is characterized by low data rates (typically ∼10 bps) with the spacecraft using either a low-gain antenna (LGA, including omnidirectional antennas) or, in some cases, a medium-gain antenna (MGA). Because of the use of LGAs/MGAs for emergency communications, the transmitted power requirements both on the spacecraft and on the ground are substantially greater than those required for normal operations on the high-gain antenna (HGA) despite the lower data rates. In this paper, we look at current and future emergency communications capabilities available to NASA's deep-space missions and discuss their limitations in the context of emergency mode operations requirements. These discussions include the use of the DSN 70-m diameter antennas, the use of the 34-m diameter antennas either alone or arrayed both for the uplink (Earth-to-spacecraft) and the downlink (spacecraft-to-Earth), upgrades to the ground transmitters, and spacecraft power requirements both with unity gain (0 dB) LGAs and with antennas with directivity ($>$ 0 dB gain, either LGA or MGA, depending on the gain). Also discussed are the requirements for forward-error-correcting codes for both the uplink and the downlink. In additional, we introduce a methodology for proper selection of a directional LGA/MGA for emergency communications.

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[1] 978-1-4244-7351-9/11/$26.00 ©2011 IEEE.
[2] IEEEAC Paper #1734, Final Version 1.0, Updated 11/16/2010.

1. Introduction

Among the services offered by NASA's Deep Space Network (DSN) are communications services during spacecraft emergencies [1]. While these services are not used very often, practically all deep-space missions have experienced anomalies which have led to the use of emergency mode communications. Therefore, the ability to communicate with the spacecraft during emergencies has often meant the difference between the success and the failure of the mission.

What differentiates emergency mode communications from normal communications operations is the assumption that, during an emergency, the spacecraft may have limited or no pointing capability, and therefore, the high-gain antenna (HGA) on the spacecraft cannot be used for communications. This assumption means that during emergencies, the communication to and from the spacecraft will have to take place through a broad-beam low-gain antenna (LGA) or a medium-gain antenna (MGA).

Another consequence of this assumption about the lack of pointing capability during an emergency is that the spacecraft may be communicating with Earth intermittently due to tumbling. Because of this, long block length channel codes such as Reed-Solomon codes concatenated with convolutional codes or turbo codes cannot be used. This in turn means that the emergency link has to operate at a higher bit signal-to-noise ratio (E_b/N_0) than a link used for nominal operations.

Given these constraints, we need to know at what distance we can communicate with a spacecraft during an emergency. For the uplink, this is done by calculating the link margin as the distance varies. For the downlink, this is done by calculating the amount of transmitted RF power required on the spacecraft to close the emergency link as a function of distance.

It should be noted that the assumption about the loss of pointing capability and attitude control by the spacecraft during an emergency is not absolute and in many cases does not apply. For example, solar powered spacecraft require the spacecraft to be sun-pointed during an emergency so that the spacecraft solar panels can receive solar radiation, thus providing power

to the spacecraft. In such cases, antennas with gains could be used with the understanding that the spacecraft will be sun-pointed (as opposed to Earth-pointed) during the emergency. Therefore, part of the analysis presented in this paper will focus on the use of directional antennas for emergency communications.

The analysis in this paper will focus on the use of X-band frequencies (8.42 GHz band for downlink and 7.17 GHz band for uplink) for emergency communications. Although we are beginning to investigate the possible use of Ka-band (32-GHz) frequencies, we expect X-band to be used for the foreseeable future for emergency communications. Not only is there a substantial amount of infrastructure for supporting these frequencies at the DSN, X-band is far less susceptible to adverse weather than Ka-band, thus providing a more reliable means of communications during an emergency. In Section 2, we will discuss the current and future types of assets and capabilities that are or could become available to the DSN at X-band for emergency communications. These capabilities are those of the DSN 70-m diameter antennas with different levels of uplink transmission power and those of the 34-m diameter Beam-Waveguide (BWG) antennas used either as stand alone assets or in arrays for both the uplink and the downlink.

This paper is organized as follows. In Section 2, the assumptions used in this analysis are discussed, including performance models for directional LGAs/MGAs, capabilities of the DSN assets used for emergency communications, and the link design parameters for both the uplink and the downlink. In Section 3, these assumptions are used to analyze the uplink performance during an emergency both for when an omnidirectional antenna is used and for when a directional antenna is used on the spacecraft. In Section 4, the same kind of analysis is presented for the downlink. In Section 5, we apply the methodology presented in Sections 3 and 4 to a Mars mission and to a Saturn mission. In Section 6, we discuss caveats and possible future work in this area. In Section 7 conclusions are discussed.

2. ASSUMPTIONS

The Emergency Link Design

As mentioned before both the uplink and the downlink communications during an emergency are characterized by low data rates. However, the requirements in terms of error rates and the type of errors that can be tolerated substantially differ for the uplink and the downlink emergency channel.

For the downlink, higher error rates could be tolerated than on the uplink since, during an emergency, the downlink contains only engineering data that provides information about the status of the spacecraft. Therefore, the downlink can tolerate errors as long as some of the engineering information (which is typically repeated because usually the status of the spacecraft does not change significantl over time even during an emergency) is received correctly. The only caveat is that the information has to be decoded quickly in case the spacecraft has lost attitude control. For this reason for downlink we assume that the NASA standard (7,1/2) convolutional code [2] is used with a bit signal-to-noise ratio (E_b/N_0) of 4.12 dB. This code could be quickly decoded and provides a bit error rate of 10^{-5} at 4.12 dB E_b/N_0 threshold.

During an emergency, the uplink channel is used to command the spacecraft. Since erroneous commands could endanger the mission, not only the channel error rate must be very low, but also errors that are not correctable should be detected. For this reason a (63,56) BCH channel code is used that corrects all single bit errors and detects all three-bit errors. We assume that this code operates at an E_b/N_0 of 10 dB which provides a bit error rate of 10^{-8} and an undetected codeword error rate of 10^{-10}.

We assume that the emergency mode data rate both for the uplink and downlink is 10 bps and that residual carrier modulation with subcarrier is used in both cases [2]. For residual carrier modulation a minimum carrier loop signal-to-noise ratio (SNR) of 11 dB is needed in order for a receiver to lock on to the carrier. The radio losses with 11 dB carrier loop SNR are approximately 0.5 dB for both the uplink and the downlink since the low-rate radio loss model is applicable [2].

For the downlink analysis, the required transmitted RF power from the spacecraft that will close the link is calculated. Assuming a 10 Hz carrier loop bandwidth for the ground receiver[3] the required total power-to-noise ratio (P_t/N_0) for the link is 21.9 dB-Hz.

For the uplink analysis we evaluate the E_b/N_0 margin for the link as a function of distance. Since the uplink has a fi ed amount of transmitted power (see below), we vary the modulation index by firs assigning enough power to the carrier so that the carrier loop on the spacecraft has the necessary 11 dB loop SNR. We then allocate the rest of the power to the data and calculate the link margin. This, of course, requires assumptions about the spacecraft carrier loop bandwidth and the spacecraft system noise temperature. For this analysis we use a carrier loop bandwidth of 100 Hz and a system noise temperature of 400 K. These values are similar to those for NASA's Mars Reconnaissance Orbiter. Note that for most spacecraft the loop bandwidth is narrower than 100 Hz and this value was picked in this analysis to represent an upper bound.

All links will be designed for a tracking elevation of 20 degrees in 99% weather (i.e., only 1% of the time the link will not close due to bad weather) at Canberra Deep Space Communications Complex. The calculations for the ground antenna G/T and equivalent isotropic radiated power (EIRP) are

[3] Although typically narrower loop bandwidths are used for ground receivers, we have chosen the 10-Hz loop bandwidth value in order to account for the possible use of higher phase noise axillary oscillators for emergency mode operations.

all made under these criteria.

We assume that when an omni antenna is used on the spacecraft for emergency communications, it has unity gain (0 dB) and the orientation of the spacecraft relative to Earth has no effect on the gain. This is a simplifying assumption since most spacecraft have several LGAs. These, combined with the structure of the spacecraft, create blind spots and exclusion zones where communication from their directions is not possible. Use of directional LGAs/MGAs is treated in more detail below.

Finally, we do not analyze the performance of the emergency link during superior solar conjunctions. Even though some of the analysis in this paper assumes an Earth-Sun-Probe (ESP) angle of 180 degrees which corresponds to periods of superior solar conjunction, the analysis presented here does not take into account the solar scintillation effects on the link caused by the RF signal traveling through the solar corona. It should be noted that in practice, spacecraft scientifi operations are suspended and no maneuvers are scheduled during periods of solar conjunction in order to minimize the probability of an emergency event. In the unlikely event that the spacecraft does experience an emergency during a period of solar conjunction, because of the unreliability of communications due to solar scintillation, the best chance for recovery of the spacecraft is assumed to occur after the solar conjunction is over and recovery efforts take place on a best effort basis during solar conjunctions without any guarantees.

DSN Assets and Capabilities for Emergency Mode Operations

For the emergency mode communications we consider the use of both the 70-m antennas and the 34-m antennas. The 70-m antennas will be used by themselves while the 34-m antennas could be used either as stand-alone antennas or in arrays both for uplink and downlink.

The 70-m antennas are currently equipped with a 20-KW transmitter at X-band. Operating under 99% weather conditions at 20 degrees elevation, this provides an EIRP of 115.7 dB-W [3]. In this analysis we also investigate the uplink performance of the 70-m antenna equipped with the 80-KW transmitter that is being developed for the 34-m antennas as well as the uplink performance with a 500-KW transmitter (possibly based on the design used for Goldstone Solar System Radar) on the 70-m. The gain-to-temperature ratio (G/T) for the 70-m for 99% weather at 20-deg elevation is 58.0 dB-K^{-1} [3].

The 34-m antennas are currently equipped with a 20-KW X-band transmitter with the plans to implement 80-KW transmitters. It is expected that the 80-KW transmitters will provide the 34-m antennas with the same uplink capabilities as a 70-m with a 20-KW transmitter, thus providing the means of replacing the 70-m antennas for uplink operations. With the 20-KW transmitter the EIRP for the 34-m antenna at 99% weather and 20-deg elevation is 109.5 dB-W and with the 80-KW transmitter the EIRP is 115.6 dB-W [4]. Note that with the 80-KW transmitter, the performance of the 34-m antenna is nearly identical to that of the 70-m antenna with a 20-KW transmitter. The G/T for a single 34-m antenna with 99% weather at 20-deg elevation is 51.5 dB-K^{-1} [4].

The 34-m antennas could be used in arrays to receive signal from the spacecraft [5] and there have been experiments that have demonstrated that these antennas could also be arrayed for uplink transmissions [6][7]. Arraying options need to be considered because there are plans to decommission the 70-m antennas at the DSN. When n identical antennas are arrayed together for downlink reception, the G/T is increased by a factor of n with some arraying losses. When n identical antennas (each with its own transmitter) are arrayed for uplink, the EIRP is increased by a factor of n^2 plus some arraying losses. In our analysis we assume an arraying loss of 1 dB for both the uplink and the downlink.

Spacecraft Antenna Gain and Beamwidth Models

In our analysis, we assume that a circular antenna (either horn or parabolic) is used for the emergency communications' directional LGA/MGA antenna. The main beam pattern is assumed to be symmetric and is approximated by a Gaussian function given by

$$G(\psi) = G_0 \exp\left(-\alpha\psi^2\right) \tag{1}$$

where G_0 is the boresight gain, ψ is the off-boresight angle, and α is related to the half-power beamwidth, B_{HP}, by

$$\alpha = \frac{4\ln(2)}{B_{HP}^2} \tag{2}$$

Equation (1) is assumed to be valid when the off-boresight loss is less than 8 dB, i.e., the equation is valid for $\psi \leq \psi_{max}$ such that $10\log\left[\exp\left(-\alpha\psi_{max}^2\right)\right] = -8$. Beyond ψ_{max} the formula in equation (1) overestimates the off-boresight losses.

The half-power beamwidth, B_{HP} and the boresight gain, G_0, are both functions of the diameter of the antenna (D) and the wavelength (λ) at which the antenna is used. G_0 is a quadratic function of D/λ and is given by

$$G_0(D) = \eta\left(\frac{\pi D}{\lambda}\right)^2 \tag{3}$$

where η is the antenna's efficien y. For this analysis η is set to 0.5 although for horn type antennas efficien y could exceed 0.7.

B_{HP} is a linear function of λ/D. Its value in degrees is given by:

$$B_{HP} = \frac{62\lambda}{D} \tag{4}$$

Note that while the actual equations for half-power beamwidth and gain of parabolic and horn antennas are

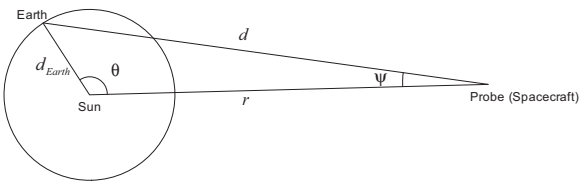

Figure 1. Geometry of a sun-pointed spacecraft

slightly different from eqs. (3) and (4), we use eqs. (3) and (4) as good approximations for the performance of both in order to preserve continuity in our analysis.

Selection of the directional LGA/MGA for a Sun-Pointing Spacecraft

The analysis of a spacecraft to the inner solar system where the spacecraft operates inside the orbit of the Earth around the sun is not considered here because when such a spacecraft is sun-pointed, Earth could either be behind the spacecraft (opposite side of the spacecraft from the sun) or in front of the spacecraft (same side of the spacecraft as the sun). To analyze the emergency communications needs of such a spacecraft a complete mission trajectory is need. For missions where the spacecraft operates outside of the orbit of Earth around the sun, the requirements for the directional LGA/MGA could be determined as follows.

The Earth-Sun-Probe geometry of a sun-pointed spacecraft in the plane of ecliptic whose distance from the sun is greater than Earth's distance from the sun is illustrated in Figure 1. As seen from this figure at distance r from the sun, when the ESP angle is equal to θ and the spacecraft is sun-pointed, the spacecraft needs to communicate over a distance d with an off-boresight angle ψ which is equal to the Earth-Probe-Sun (EPS) angle. Using the law of cosines we have

$$d = \sqrt{r^2 + d_{Earth}^2 - 2rd_{Earth}\cos(\theta)} \tag{5}$$

where d_{Earth} is Earth's distance to the sun.

We also have

$$\psi = \arctan\left(\frac{d_{Earth}\sin(\theta)}{r - d_{Earth}\cos(\theta)}\right) \tag{6}$$

Using eqs. (1) through (6) along with the equation for the free-space path loss, we obtain the total path attenuation between Earth and the receiver of a sun-pointed spacecraft through

$$\gamma(D,\theta,r) = \frac{\eta D^2 \exp\left[-\ln(2)\left(\frac{D}{31\lambda}\arctan\left(\frac{d_{Earth}\sin(\theta)}{r-d_{Earth}\cos(\theta)}\right)\right)^2\right]}{r^2+d_{Earth}^2-2rd_{Earth}\cos(\theta)} \tag{7}$$

At distance r, the best antenna is the one whose worst performance over the entire range of ESP angles is better than

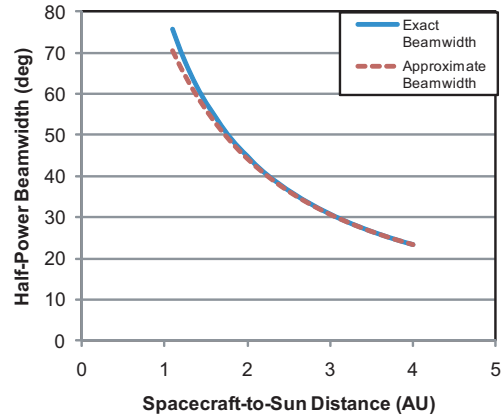

Figure 2. Approximate and Exact Half-Power Beamwidths vs. Distance

the worst performance of any other antenna over that range. Therefore, findin the optimum LGA/MGA is akin to solving a max-min problem, i.e.,

$$D_{opt}(r) = \max_D\left[\min_\theta \gamma(D,\theta,r)\right] \tag{8}$$

When trying to select the right size antenna for a mission whose trajectory is define by $\mathcal{T} = \{(\theta(t), r(t))\}$ the max-min problem becomes:

$$D_{opt}(\mathcal{T}) = \max_D\left[\min_t \gamma(D,\theta(t),r(t))\right] \tag{9}$$

Although $D_{opt}(r)$ in equation (8) can be calculated easily through a combination of differential calculus and numerical techniques, for sake of simplicity we use a very close approximation for it by letting

$$\hat{D}_{opt}(r) = \frac{31\lambda}{\sqrt{\ln(2)}\arctan(d_{Earth}/r)} \tag{10}$$

and assuming that the worst path attenuation in this case takes place when $\theta = 90$ degrees. This approximation is tight both in terms of estimating the beamwidth of the antenna and determining the worst-case path attenuation. These are illustrated in Figs. 2 and 3.

Note that as r becomes large, $\arctan(d_{Earth}/r) \approx d_{Earth}/r$. Using this approximation in equation (10) we have

$$D_{opt}(r) \approx \hat{D}_{opt}(r) \approx \frac{31r\lambda}{\sqrt{\ln(2)}d_{Earth}} \quad r >> d_{Earth} \tag{11}$$

This relationship is demonstrated in Figure 4. Note that the difference between the uplink and downlink antenna diameters is due to the difference between the uplink frequency and the downlink frequency.

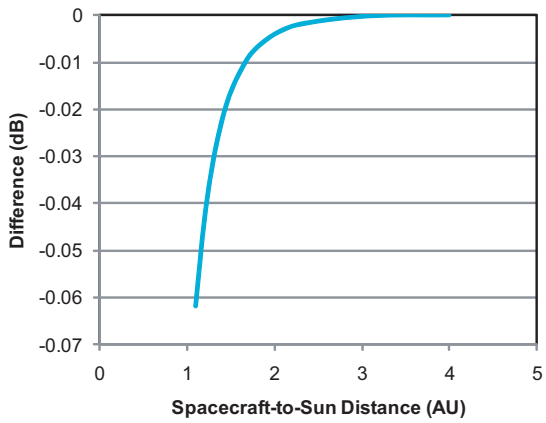

Figure 3. The Difference between Approximate and Exact Worst-Case Scenario Link Budgets vs. Distance

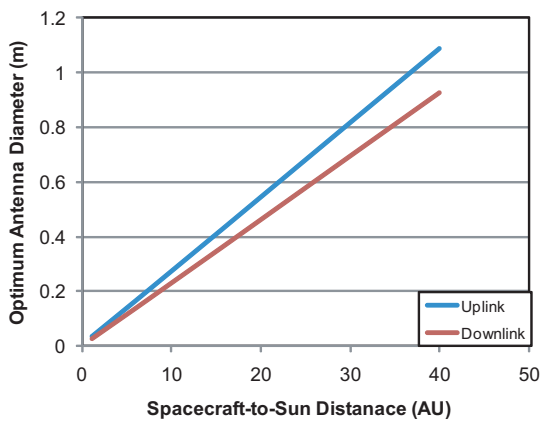

Figure 4. Optimum Spacecraft directional LGA/MGA Diameter for Uplink and Downlink vs. Distance.

Considering that for large r, $r^2 + d_{Earth}^2 \approx r^2$, using the $D_{opt}(r)$ value obtained through equation (11), and assuming $\theta = 90$ degrees for equation (7), we have

$$\gamma\left(D_{opt}(r), r, 90\right) \approx \frac{961\eta\lambda^2 e^{-1}}{d_{Earth}^2 \ln(2)} \quad r >> d_{Earth} \qquad (12)$$

which is invariant with respect to r. This means that at long distances, if the LGA/MGA has a diameter of $D_{opt}(r)$, the amount of required transmitted power for the worst-case emergency link does not vary and that the uplink margin for the worst-case emergency link will remain constant.

3. Uplink Analysis

The margin on the uplink for emergency communication through an omnidirectional LGA as a function of spacecraft-to-Earth distance is shown in Figs. 5 and 6 for single antennas and arrayed antennas respectively. The maximum spacecraft-to-Earth distance at which we can communicate through an omni with the spacecraft is given in Table 1.

Table 1. Maximum Distance for Uplink Communications through an Omnidirectional Antenna for Different Uplink Assets Configuration

Uplink Assets Configuratio	Maximum S/C-Earth Distance (AU)
Single 34-m, 20-KW	2.4
Two 34-m, 20-KW	4.3
Single 34-m, 80-KW	4.8
70-m, 20-KW	4.9
Three 34-m, 20-KW	6.4
Two 34-m, 80-KW	8.6
70-m, 80-KW	9.9
Three 34-m, 80-KW	12.9
70-m, 500-KW	24.6

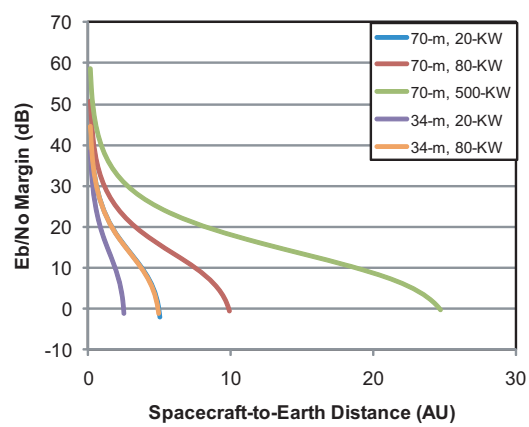

Figure 5. Uplink E_b/N_0 Margin for Omni LGA vs. Spacecraft-to-Earth Distance, Single Antennas

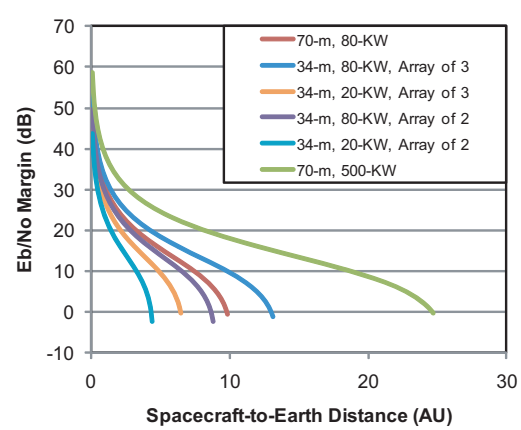

Figure 6. Uplink E_b/N_0 Margin for Omni LGA vs. Spacecraft-to-Earth Distance, Arrayed Antennas

Looking at Figs. 5 & 6 and Table 1, we make the following observations:

- The uplink margin, when communicating through an omni, does not decrease as the inverse square of the spacecraft-to-Earth Distance. This is due to the fact that we have to maintain a constant carrier loop SNR of 11 dB. For a spacecraft loop bandwidth of 100 Hz, this corresponds to a constant carrier power-to-noise ratio (P_c/N_0) of 31 dB.
- Because they have nearly identical EIRPs, a 70-m antenna with a 20-KW transmitter and a 34-m antenna with a 80-KW transmitter perform nearly identically.
- Except for an array of three 34-m antennas with 80-KW transmitters, a 70-m equipped with a 80-KW transmitter outperforms all other considered configuration that use the 34-m antennas. Since the use of three 34-m antennas at the same time because of an emergency could substantially disrupt the operations at a DSN complex (not to mention the fact that at this time Canberra complex has only two 34-m antennas) equipping DSN's 70-m assets with 80-KW transmitters should be seriously considered.
- No configuratio that is considered can outperform the 70-m equipped with a 500-KW transmitter. Adding a 500-KW transmitter based on the current radar transmitter could substantially increase the reach of the DSN during spacecraft emergencies.
- For inner planet missions where a directional antenna cannot be used due to geometry and the distances will not exceed 2 AU, emergency uplink communications can be supported adequately through an omni even with a 34-m antenna with a 20-KW transmitter.

In Figs. 7 through 14 we investigate the use of directional LGAs/MGAs for missions that go beyond the orbit of Earth around the sun. Each figur has three types of curves: one type shows the worst-case uplink margin for an omni antenna; the second type shows the worst-case uplink margin for a directional antenna that is optimized for the specifi spacecraft-to-sun distance, and the third type shows the worst-case uplink margin for a fi ed size directional LGA/MGA. The fi ed size LGA/MGA is selected such that at the distance that the omni margin falls below zero, the maximum off-boresight loss of the antenna when the spacecraft is sun-pointed does not exceed 8 dB. The motivation for using such an antenna is to see whether or not a single antenna size could adequately meet the needs of emergency uplink communications when communications through an omni antenna becomes impossible. Table 2 shows the maximum distances at which these LGAs/MGAs could be used to close the link. Note that for the case of a single 34-m antenna with a 20-KW transmitter, curves for two such LGA/MGA antennas are plotted. In this case, the second antenna is selected such that its off-boresight loss when sun-pointed will not exceed 8 dB at the distance where the firs directional LGA/MGA no longer can be used to close the link.

Looking at Figs. 7 through 14 and Table 2 we make the following observations

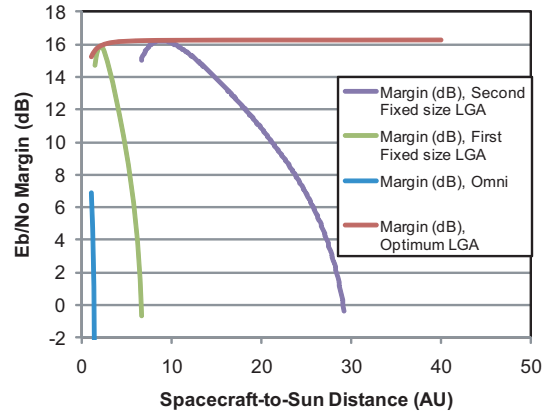

Figure 7. Uplink E_b/N_0 Margin for Worst-Case Link for Omni, Optimum LGA/MGA and Fixed Size LGAs/MGAs vs. Spacecraft-to-Sun Distance, Single 34-m Antenna, 20-KW Transmitter

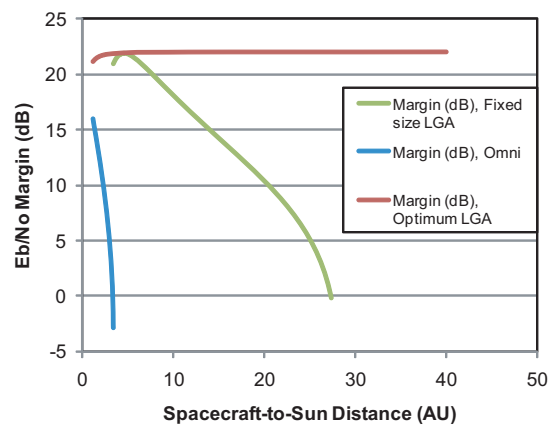

Figure 8. Uplink E_b/N_0 Margin for Worst-Case Link for Omni, Optimum LGA/MGA and Fixed Size LGA/MGA vs. Spacecraft-to-Sun Distance, Array of Two 34-m Antennas, 20-KW Transmitters

- As expected, in all cases under considerations, the link margin for the optimum LGA/MGA becomes constant as the spacecraft-to-sun distance increases. This result is explained in the derivation of equation (12).
- Both the 70-m antenna with a 20-KW transmitter and the 34-m antenna with a 80-KW transmitter can support uplink emergency communications to a sun-pointed spacecraft with a directional LGA/MGA beyond the orbit of Neptune ($\sim$ 30 AU).
- Without using directional LGAs/MGAs, none of the uplink configuration under considerations can provide uplink emergency communications through an omni for the entire solar system.

4. Downlink Analysis

As mentioned before, for our emergency downlink analysis we consider the required spacecraft downlink RF power. The

Table 2. Maximum Distance for Uplink Communications through a Fixed-Size LGA/MGA for Different Uplink Assets Configuration and LGA/MGA Diameter and Half-Power Beamwidth

Uplink Assets Configuratio	Maximum S/C-SUN Distance (AU)	LGA/MGA Diameter (m)	Half-Power Beamwidth (deg.)
Single 34-m, 20-KW, 1st LGA/MGA	6.5	0.059	44.2
Single 34-m, 20-KW, 2nd LGA/MGA	29	0.238	10.9
Two 34-m, 20-KW	27.3	0.124	21.0
Single 34-m, 80-KW	34.4	0.138	18.9
70-m, 20-KW	36.8	0.145	17.9
Three 34-m, 20-KW	>40	0.198	13.1
Two 34-m, 80-KW	>40	0.278	9.35
70-m, 80-KW	>40	0.321	8.09
Three 34-m, 80-KW	>40	0.433	5.99
70-m, 500-KW	>40	0.857	3.03

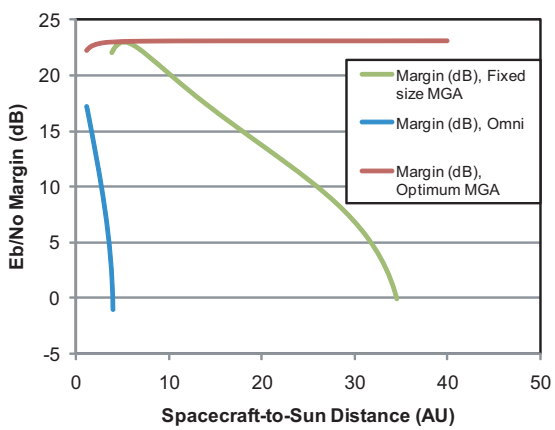

Figure 9. Uplink E_b/N_0 Margin for Worst-Case Link for Omni, Optimum LGA/MGA and Fixed Size LGA/MGA vs. Spacecraft-to-Sun Distance, Single 34-m Antenna, 80-KW Transmitter

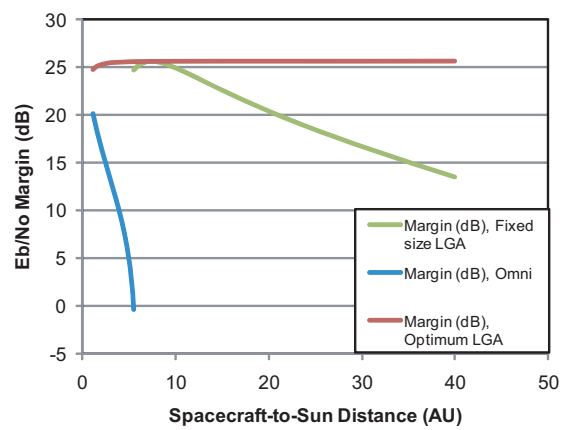

Figure 11. Uplink E_b/N_0 Margin for Worst-Case Link for Omni, Optimum LGA/MGA and Fixed Size LGA/MGA vs. Spacecraft-to-Sun Distance, Array of Three 34-m Antennas, 20-KW Transmitters

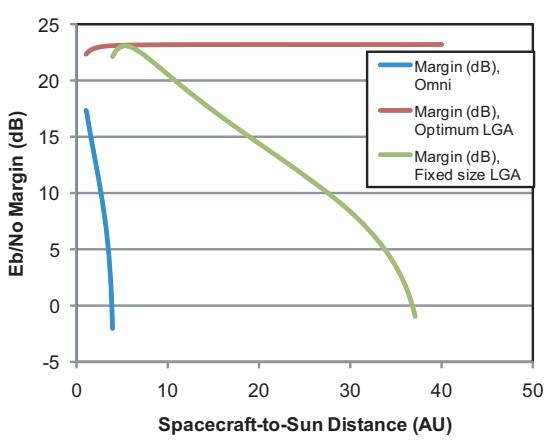

Figure 10. Uplink E_b/N_0 Margin for Worst-Case Link for Omni, Optimum LGA/MGA and Fixed Size LGA/MGA vs. Spacecraft-to-Sun Distance, Single 70-m Antenna, 20-KW Transmitter

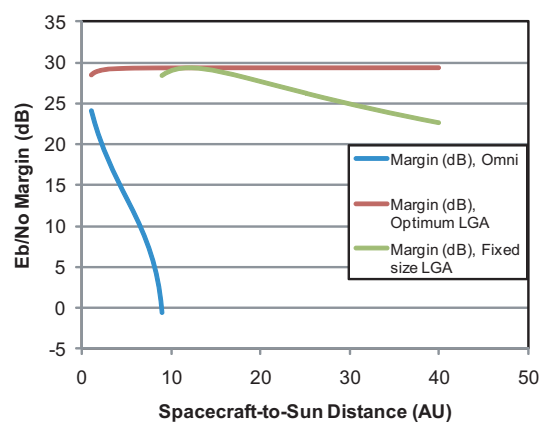

Figure 12. Uplink E_b/N_0 Margin for Worst-Case Link for Omni, Optimum LGA/MGA and Fixed Size LGA/MGA vs. Spacecraft-to-Sun Distance, Single 70-m Antenna, 80-KW Transmitter

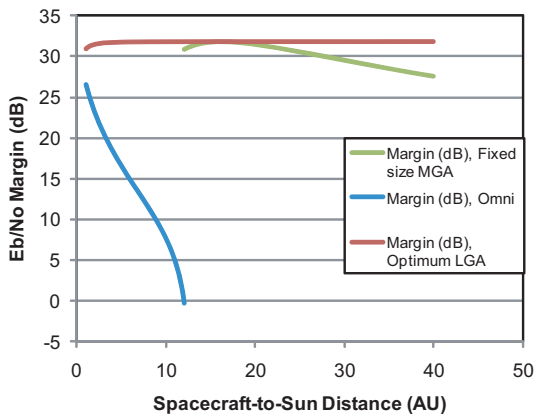

Figure 13. Uplink E_b/N_0 Margin for Worst-Case Link for Omni, Optimum LGA/MGAand Fixed Size LGA/MGA vs. Spacecraft-to-Sun Distance, Array of Three 34-m Antennas, 80-KW Transmitters

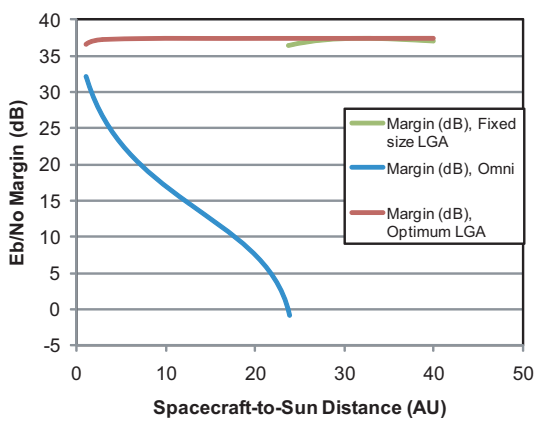

Figure 14. Uplink E_b/N_0 Margin for Worst-Case Link for Omni, Optimum LGA/MGA and Fixed Size LGA/MGA vs. Spacecraft-to-Sun Distance, Single 70-m Antenna, 500-KW Transmitter

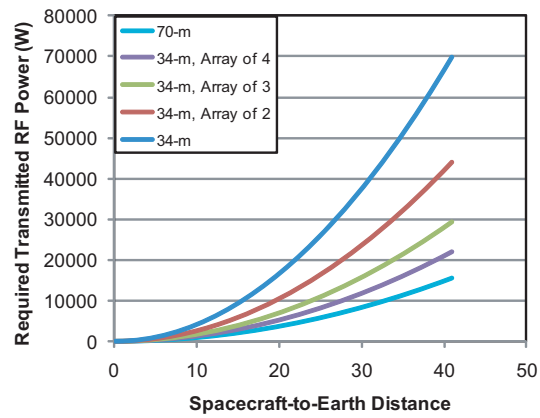

Figure 15. Required Spacecraft RF Power for Emergency Downlink Communications through an Omni Antenna vs. Spacecraft-to-Earth Distance for Different Ground Assets Configuration

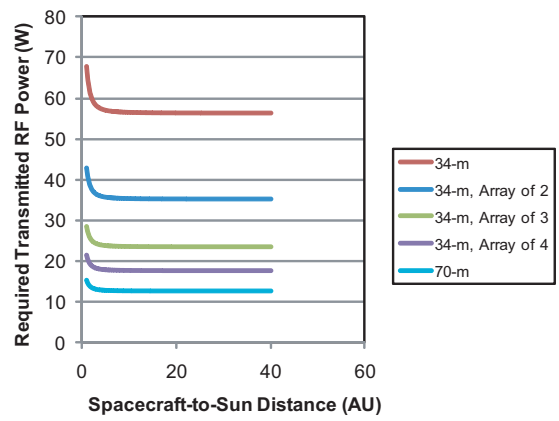

Figure 16. Required Spacecraft RF Power for Emergency Downlink Communications through the Optimum Directional LGA/MGA vs. Spacecraft-to-Sun Distance for Different Ground Assets Configuration

results of this analysis for omnidirectional LGAs are shown in Figs. 15 & 16, and Table 3. First we note that the required RF power for downlink communications through an omni increases as a square of the spacecraft-to-Earth distance. Depending on the ground assets used for tracking the spacecraft, the RF power coefficien varies. These RF coefficient are shown in the second column of Table 3. This fact means that even at Mars, substantial amount of downlink RF power is required to close the emergency link through an omni antenna (see Table 3). Therefore, a directional LGA/MGA is almost mandatory for spacecraft that operate beyond the orbit of Earth around the sun.

As Figure 16 shows, the amount of required RF power is reasonable when an optimum LGA/MGA is used. As the distance increases, this power approaches a constant. Again this phenomenon is explained by the derivation of equation (12).

Finally, note that even an array of four 34-m antennas cannot match the receive performance of a 70-m antenna during an emergency. This means that the DSN should carefully weigh its options for 70-m replacement by considering the future deep-space mission set.

5. Case Studies

In the previous two sections we have shown that at a given distance from the sun, there is an optimum size for directional LGAs/MGAs that supports emergency communications with adequate uplink margin and reasonable spacecraft downlink RF power. However, since all missions have a cruise phase, the emergency communications requirements during the cruise should also be considered. In this section we show how the results from the previous two sections could be used to design a reliable emergency communications system for entire duration of the mission using the mission's trajec-

Table 3. Required Spacecraft RF Power Coefficien for Downlink Communications through and Omni and Required Spacecraft RF Power for Downlink Communications at Maximum Mars-Earth Distance for Different Ground Assets Configuration

Ground Assets Configuratio	RF Power Coefficien (W/AU^2)	Req. RF Power at Max. Mars Dist. (W)
Single 34-m	41.6	297
34-m, Array of 2	26.2	187
34-m, Array of 3	17.5	124
34-m, Array of 4	13.1	93.3
70-m	9.34	66.6

tory. We illustrate our approach for two cases: a mission to Mars, and a mission to Saturn.

Approach

We assume that during an emergency the spacecraft is sun-pointed and that the spacecraft has both an omni LGA and a directional LGA/MGA. The omni LGA is used only when the off-boresight losses of the directional LGA/MGA on the downlink are greater than its gain.

As our firs cut we use the optimum directional LGA and the downlink RF power that is calculated for when the spacecraft reaches its destination. Since the downlink operations put a greater constraint on the emergency link design, we assume that the LGA/MGA is optimized for the downlink frequency at its destination. If this design closes the emergency link throughout the cruise then the design is adequate and no further work is needed.

If the design is not adequate, then we have to consider changing both the antenna size and the required RF power. Since the required spacecraft RF power puts a greater constraint on the overall emergency link design, we typically broaden the antenna beam and increase the RF power to close the link over the entire cruise phase.

Once we achieve a design that works for the cruise phase, we analyze the uplink and the downlink performance of the design at the mission destination. If the design has too much downlink margin at the destination, we reduce the RF power and decrease the antenna beamwidth until we achieve a design that just meets the margin requirements both at the destination and during the cruise.

Emergency Communications System Design for a Mars Mission

Mars missions use a minimum energy transfer orbit during cruise. Figure 17 illustrates the EPS angle and spacecraft-to-Earth distance for such a trajectory. Using the approach in the previous section for selecting the optimum LGA/MGA

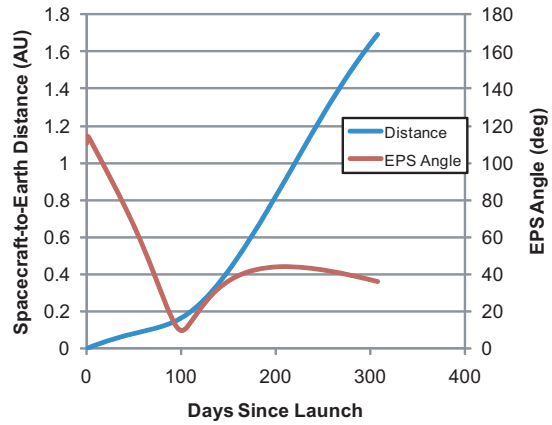

Figure 17. Spacecraft-to-Earth Distance and EPS Angle for a Mars Mission during Cruise

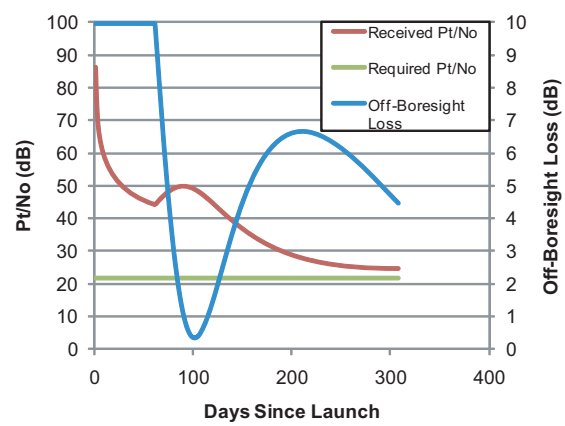

Figure 18. Downlink P_t/N_0 at a 34-m Antenna and LGA/MGA Off-Boresight Loss During Cruise for a Mars Mission

at Mars, the optimum beamwidth for the LGA/MGA is calculated to be 59.97 degrees. If a 34-m antenna is used for the downlink, the required spacecraft downlink RF power is 64.27 W. Using these parameters we calculated the downlink performance over a 34-m antenna and the uplink performance for a 34-m antenna with a 20-KW transmitter. The results are shown in Figs. 18 & 19. As seen from these figure the optimum LGA/MGA design for Mars provides a downlink P_t/N_0 that is above the required P_t/N_0 and an uplink margin that is positive for the entire cruise. Therefore, the optimum LGA/MGA design for Mars satisfie both the cruise phase and science phase requirements. Note that in this particular case, for the firs 62 days of cruise, because of the large EPS angles, the spacecraft uses its omni antenna for emergency communication and hence the constant off-boresight loss which is equivalent to the directional LGA's gain.

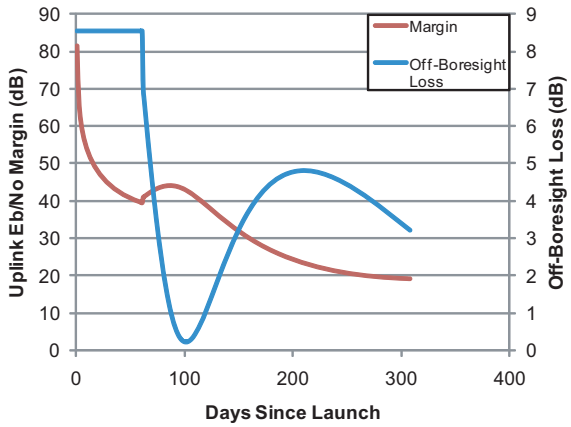

Figure 19. Uplink E_b/N_0 Margin from a 34-m Antenna with a 20-KW Transmitter and LGA/MGA Off-Boresight Loss During Cruise for a Mars Mission

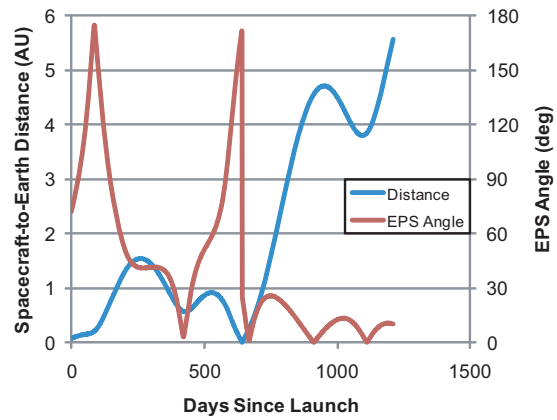

Figure 20. Spacecraft-to-Earth Distance and EPS Angle for a Mission to Saturn during Cruise

Emergency Communications System Design for a Mission to Saturn

Unlike missions to Mars, missions to the gas giants use complicated gravity assist trajectories to reach their destinations. In this analysis we use Cassini's Venus-Earth-Earth gravity assist (VEEGA) trajectory during its cruise as a representative cruise trajectory for a mission to Saturn. This trajectory is shown in Figure 20. Assuming that a 70-m antenna with a 20-KW transmitter is used for both uplink and downlink emergency communications, our initial system design results in a LGA/MGA with a beamwidth of 10.24 degrees and a required spacecraft downlink RF power of 12.6 W. Using these parameters, we calculated the downlink and the uplink performance during the cruise. These are illustrated in Figs. 21 and 22. As seen from these figures while the uplink always has a positive margin during the cruise, the initial design fails to support downlink emergency communications during the cruise for extended periods of time. Note that this design produces three distinct periods during which the spacecraft has to use the omni LGA (these periods are characterized by constant off-boresight losses that correspond to the gain of the directional LGA/MGA).

If we want to simply increase the spacecraft RF power to compensate for the inadequate P_t/N_0 on the downlink during the cruise, we need a 120-W RF amplifie which in turn results in having a very large margin of approximately 10 dB on the downlink once the spacecraft reaches Saturn. By using the approach described in this section, we reached a fina design with 31.1 W spacecraft RF transmitted power and a LGA/MGA with a beamwidth of 22.32 degrees. The performance of this system during cruise is shown in Figs. 23 and 24. As seen from these figures this design produces adequate downlink P_t/N_0 and positive margin on the uplink for the entire cruise period under considerations. At Saturn, this design has a minimum P_t/N_0 equal to the required P_t/N_0 of 21.9 dB on the downlink and has an uplink E_b/N_0 margin of at least 17.9 dB. Note that this design completely eliminates

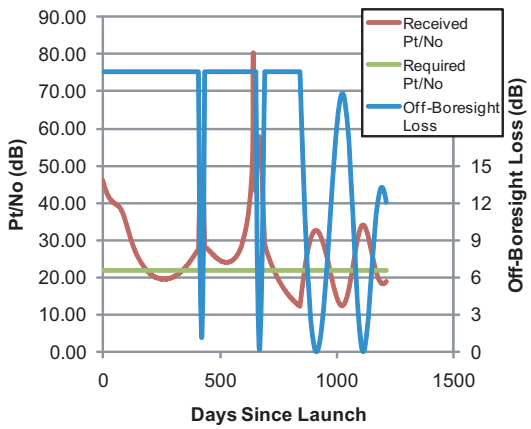

Figure 21. Downlink P_t/N_0 at a 70-m Antenna and LGA/MGA Off-Boresight Loss During Cruise for a Mission to Saturn, Initial Design

the last period when the omni was used with the initial design. This is logical because this last period in the original design corresponds to a period where the spacecraft-to-Earth distance rapidly increases (see Figure 20).

6. Caveats and Future Work

Caveats

The analysis presented here is necessarily theoretical and is meant as a guideline for designing the end-to-end emergency communications systems for deep-space missions. For design of the actual end-to-end communications systems, actual antenna beam patterns, spacecraft exclusion zones/blind spots for LGA/MGA/omni coverage as well as the dynamic behavior of the spacecraft such as dead-banding should be taken into account. In addition, the theoretical analysis here is done in the plane of the ecliptic. However, no planet lies exactly in the plane of the ecliptic. Therefore, actual planetary trajectories should be considered when designing the emergency communications system. The same is true for missions that

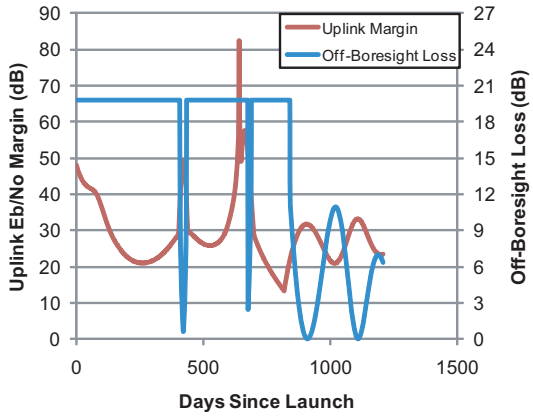

Figure 22. Uplink E_b/N_0 Margin from a 70-m Antenna with a 20-KW Transmitter and LGA/MGA Off-Boresight Loss During Cruise for a Mission to Saturn, Initial Design

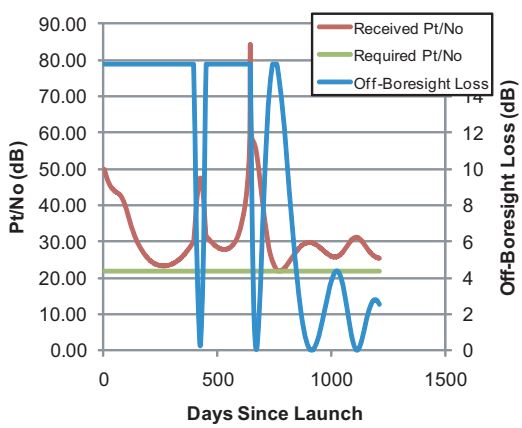

Figure 23. Downlink P_t/N_0 at a 70-m Antenna and LGA/MGA Off-Boresight Loss During Cruise for a Mission to Saturn, Final Design

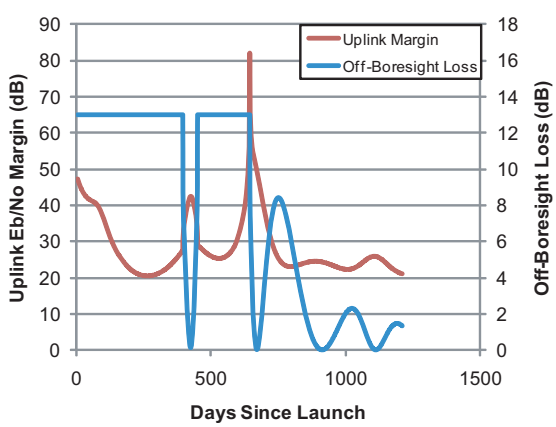

Figure 24. Uplink E_b/N_0 Margin from a 70-m Antenna with a 20-KW Transmitter and LGA/MGA Off-Boresight Loss During Cruise for a Mission to Saturn, Final Design

go outside of the ecliptic such as missions to Pluto and those to astroids whose orbit lies outside of the ecliptic. Furthermore, this analysis does not adequately address the issue of emergency communications for missions that operate inside the orbit of Earth around the sun.

Our analysis also assumed that the highest off-boresight losses occur only when the spacecraft is sun-pointed during an emergency. This is not strictly true. Spacecraft emergency telecommunications systems are used during critical events such as orbit insertions (OIs) and trajectory correction maneuvers (TCMs) when the spacecraft orientation can produce off-boresight losses that are greater than any observed during the mission when the spacecraft is simply sun-pointed. Therefore, this analysis does not provide any guidelines as to the design of the telecom system during such events.

As mentioned before, the values chosen in this analysis for the spacecraft carrier loop bandwidth and system noise temperature are representative and designs for specifi spacecraft should consider the actual measurements of the spacecraft equipment. Furthermore, the system noise temperature on the spacecraft could be higher than the 400 K assumed in this analysis because of solar background noise when the spacecraft is sun-pointed. In addition, a weather reliability of 99% may not be adequate for some missions. In such cases, depending on the desired level of link reliability, the performance could be siginificantl reduced. For example, a desired link reliability that will require 6 dBs of margin over the 99% weather performance would reduce the maximum supportable distances on the uplink by a factor of two and increase the required spacecraft power values on the downlink by a factor of four. Finally, this is a firs cut at the end-to-end emergency telecommunications system design, and actual spacecraft operational experiences have not been considered in this analysis.

Future Work

This analysis should be expanded to use actual LGA/MGA beam patterns as well as actual planetary trajectories for the link design. The issue of missions that operate inside Earth's orbit around the sun as well as issues concerning OIs and TCMs should also be addressed. In addition, the increase in the spacecraft system noise temperature because of solar background noise should be dealt with. Furthermore, we need to consider the use of antenna technologies that could change the beamwidth of a LGA/MGA as the spacecraft's distance relative to the sun increases. Such technologies could take the form of antennas with unfolding petals or phased-array antennas. The analysis also needs to consider advances in channel coding that could substantially reduce the required SNR on the emergency link, thus extending the range of the DSN during emergencies. Finally, this analysis should be modifie to take into account actual spacecraft dynamics and the operational experience of NASA's deep-space missions.

7. CONCLUSIONS

In this paper we analyzed the end-to-end emergency communications system for NASA's deep-space missions. This analysis indicates that most planetary missions require a directional LGA/MGA for emergency communications and the ability to sun-point the spacecraft during an emergency in order to reduce the amount of the emergency downlink RF power that the spacecraft needs. Our analysis also provides a guideline as to how to best select the LGA/MGA for operations at a particular distance from the sun and how to modify this design in order to meet the cruise phase emergency requirements.

This paper also shows that even though equipping the DSN's 34-m antennas with 80-KW transmitters provides a capability equivalent to those currently offered by the 70-m antennas with a 20-KW transmitter, putting 80-KW transmitters on the 70-m antennas could substantially increase the reach of the DSN during spacecraft emergencies.

Finally, we note that even an array of four 34-m antennas does not have the same receive performance as a 70-m antenna. Therefore, since NASA is contemplating replacing the 70-m antennas, it should carefully consider its options for replacing the 70-m.

ACKNOWLEDGMENTS

This work was performed at Jet Propulsion Laboratory, California Institute of Technology (Caltech), under a contract with National Aeronautics and Space Administration.

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BIOGRAPHY

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David Morabito (M'80) was born in Los Angeles, California. Since 1973, he has worked at Caltech's Jet Propulsion Laboratory in Pasadena, California, on several engineering and scientifi research projects. Among the areas he has worked on are spacecraft navigation, Very Long Baseline Interferometry (VLBI), Radio Science experiments on the Voyager 2, Ulysses, and Galileo spacecraft, performance characterization of beam-waveguide antennas, media propagation effects on spacecraft telecommunication links, and telecommunications systems design for proposed future space missions. His most recent project is studying the use of Ka-band (32 GHz) as a telecommunications link frequency for spacecraft communications. He has over 120 publications in several professional journals, and conference proceedings. He is a member of the International Astronomical Union, the American Astronomical Society, and the American Geophysical Union.

Robert Cesarone is with the Jet Propulsion Laboratory, California Institute of Technology. He is currently involved in program management, strategy development and long range planning. His activities specificall involve telecommunications and mission operations, including development of architectural options for the Deep Space Network, NASA's network for tracking interplanetary spacecraft. He has held his present position since September 1991 and has been employed at JPL since 1977. Prior to his current assignment he has held a number of positions within the Voyager Navigation Team, in particular that of lead trajectory and maneuver engineer for the Voyager 2 flyby of Uranus and Neptune. Prior to his arrival at JPL, he attended the University of Illinois, where he received a B. S. in Mathematics in 1975 and an M. S. in Aeronautical and Astronautical Engineering in 1977. Mr. Cesarone has authored 50 technical and popular articles covering the Voyager Mission, trajectory design, gravity-assist and space navigation and telecommunications. He is an associate fellow of the American Institute of Aeronautics and Astronautics, a member of the World Space Foundation and a recipient of the NASA Exceptional Service Medal.

Douglas Abraham is a Senior Systems Engineer within the Architecture, Strategic Planning, and Systems Engineering Offic of JPL's Interplanetary Network Directorate. In this capacity, he oversees efforts to forecast future mission customer requirements and trends, assesses their implications for Deep Space Network evolution, and assists in the development of the roadmaps and plans needed to guide this evolution. Doug also supports NASA's Space Communications and Navigation (SCaN) Offic in the study and planning of future, integrated space communications architectures.

Prior to his current assignment, Doug worked on the Galileo, Ulysses, and Cassini fligh projects. He has also worked on several pre-project formulation activities, including Pluto Fast Flyby and the "Fire and Ice" collaboration with Russia. Doug began his career as a graduate student intern in the International Space Station Program Offic (1988). He graduated Magna Cum Laude from Texas A&M University in Physics (1986) and earned an M.S. in Technology and Science Policy, with specialization in technology assessment and electrical engineering, from Georgia Tech (1990).