Deep Space Mission Emergency Mode Downlink

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Abstract: This paper investigates telecommunications between a deep space mission satellite and the ground station during an emergency mode. Once emergency is detected, spacecraft is put into a safe mode, i.e., antenna to be used for emergency mode communications is pointed towards the sun and use total available power to transmit. There are many parameters affecting communications in this mode and these should be properly balanced to produce desired results. This paper explores the effectiveness of spacecraft antenna gain pattern in the emergency mode with respect to positions of the spacecraft, earth, Sun Earth Probe (SEP) angle at the receiving antenna, and the range of the spacecraft with respect to the ground station. The paper also provides parabolic reflector antenna diameter that should be used for emergency mode as a function of the satellite to sun range in the solar system.

1. Theory: Usually for a NASA planetary mission, a link budget analysis is done at the maximum earth to spacecraft range of the mission and the gain of the antenna needed is computed to provide acceptable margins at the downlink receiving station. The same procedure is followed for the emergency link with minimum SEP angle predicted for the trajectory. This analysis usually provides a reasonable value of the gain necessary to sustain the telemetry and emergency downlinks with reasonable data and carrier margins. As mentioned above, there are many parameters to be considered in this procedure, a method is shown in this paper to optimize the antenna gain necessary to produce the desired results for the emergency links.

First, we will assume a mission with minimum sun to spacecraft distance of 1 astronomical unit (AU) or more, basically sending the spacecraft towards Mars and the outer planets. Fig. 1 shows the involved geometry. Let d_{ES} be the distance from the Earth to Sun in AU. This distance is usually taken to be 1 AU. The distance d_{SS} is between spacecraft and the Sun in AU and finally, R is the distance (range) between the spacecraft and the Earth in AU. θ_{SEP} is the Sun Probe Earth (SEP) angle in degrees, and θ_{Ant} is the angle between the sun pointed spacecraft antenna bore sight and the earth in degrees.

Next, the emergency mode of the spacecraft needs to be defined. In general, emergency can include severe situations such as the spacecraft tumbling, turning, rotating uncontrollably etc. However, for this analysis we will consider a much less severe case as an example in which, the spacecraft has detected some fault in any one of its major subsystems and on-board algorithm or the ground station control forces the spacecraft to go into a safe mode. In this mode the spacecraft is sun pointed, i.e., the emergency mode communications antenna is sun pointed and then spacecraft solar panels being usually gimbaled are also pointed to the sun. This can be done because the sun sensors installed on the spacecraft are usually very reliable and their input can be used by the antenna pointing system to point the antenna to the sun. Earth position is variable with respect to the spacecraft hence it is generally not possible to point emergency mode spacecraft antenna to earth in a safe mode. Fig. 1 shows a possible geometry of the emergency condition when the spacecraft antenna is pointed to the sun with the angles involved in that geometry.

Three issues need to be examined to see how a communications link may be effected in the emergency mode. First, the range R shown in Fig. 1 from spacecraft to earth receiving station will naturally affect the link performance.

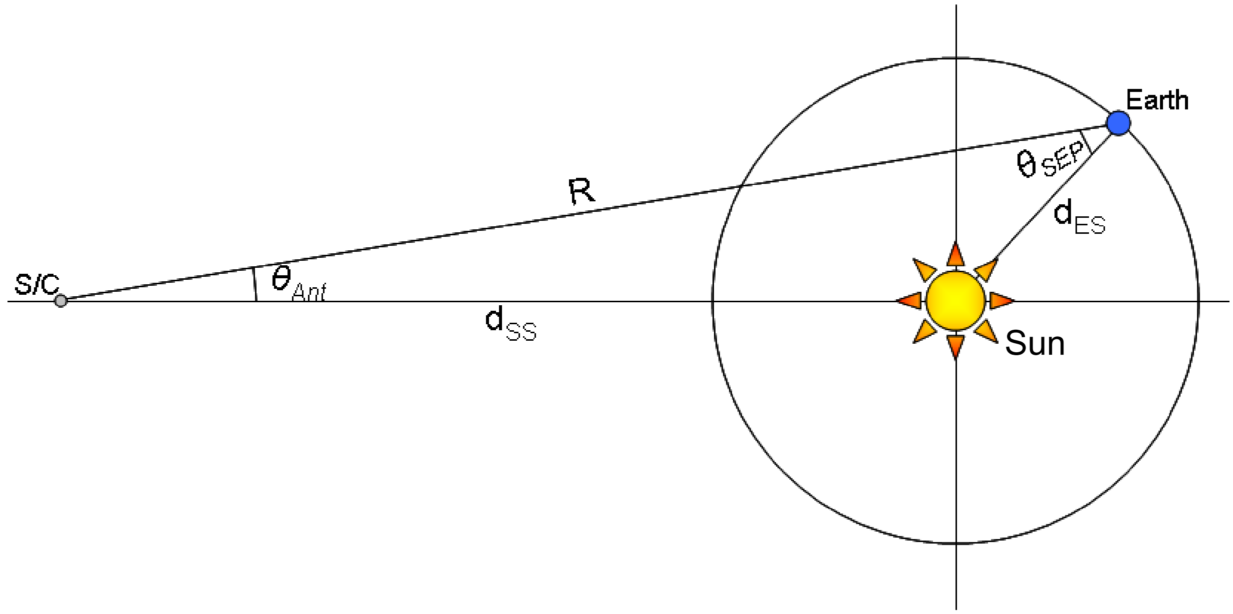

Figure 1. Geometry for the Emergency Link

Second parameter of interest is the actual gain of the spacecraft emergency mode antenna, $G(\theta_{Ant})$ directed towards the earth, and finally, the SEP angle, θ_{SEP} , that determines how much noise the sun adds to the signal received at the receiver. The combined effect of all these three will decide how good the emergency mode telecom link performs. Each of these parameters and their effects will be examined below. We will assume that range d_{ES} is equal to 1 AU, and range d_{SS}, the distance between the spacecraft and the Sun in AU is known (i.e. the position of the spacecraft is known to the ground station).

2. The Range R: Since the basic geometry involves a triangle, angle θ_{SEP} may be made as the independent variable of the analysis. Since the position of the earth in its orbit around the sun changes, the Range R will be changing and it needs to be expressed in terms of the angle θ_{SEP}. Using the cosine law of the triangles this is easily derived to be:

$$\mathrm{R} = d_{ES}\left[Cos(\theta_{SEP}) + \sqrt{\left(\frac{d_{SS}}{d_{ES}}\right)^2 - (Sin(\theta_{SEP}))^2} \right] \tag{1}$$

R is then used to compute the propagation loss, L_p from the spacecraft antenna to the ground station receiving antenna focal point. The loss is also called space loss or the wave spreading loss, expressed in dB is given by the well known formula given in Eq. (2), where λ is the wavelength of the link frequency and is given by 300/Freq (m) with Freq as the frequency of the link in Mega Hertz (MHz). Eq. (2) provides the propagation loss in dB. Fig. 2 shows the propagation loss for an X-Band frequency of 8450 MHz and the spacecraft to sun distance d_{SS} is 1.5 AU (the average distance from Mars to the sun).

$$L_p = 10\,\mathrm{Log}_{10}\left(\frac{\lambda}{4\,\pi\,\mathrm{R}}\right)^2 = 10\,\mathrm{Log}_{10}\left\{\frac{\lambda}{4\,\pi\,d_{ES}\left[Cos(\theta_{SEP}) + \sqrt{\left(\frac{d_{SS}}{d_{ES}}\right)^2 - (Sin(\theta_{SEP}))^2}\right]}\right\}^2 \tag{2}$$

3. Spacecraft Antenna Gain Towards Earth: The gain that is being used by the link is the gain of the sun pointed spacecraft antenna towards earth. To compute this quantity one needs to define an antenna, as an example,

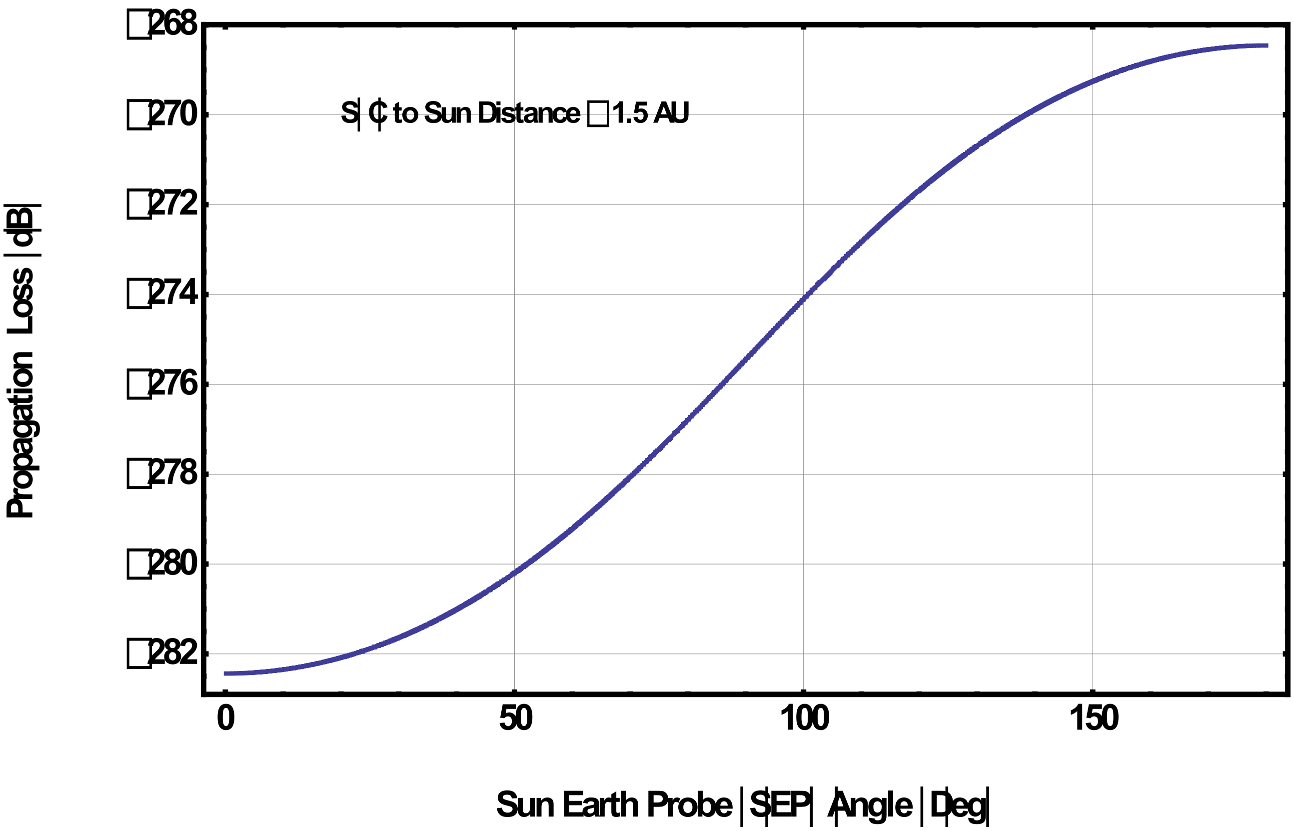

Figure 2. Propagation loss in dB computed as a function of SEP angle

we will consider a parabolic reflector antenna whose gain is known in every direction around the antenna. In the absence of that, actual measured antenna pattern may also be used. We will use a parabolic reflector antenna with the following well known gain pattern in dB.

$$G_T = 10\,\mathrm{Log}_{10}\left[G(\theta_{Ant})\right] = 10\,\mathrm{Log}_{10}\left\{\eta\left[\frac{2\,J_1\left(\frac{\pi\, d}{\lambda}\,\mathrm{Sin}(\theta_{Ant})\right)}{\mathrm{Sin}(\theta_{Ant})}\right]^2\right\}$$

$$= 10\,\mathrm{Log}_{10}\left\{\eta\left[\frac{2\,J_1\left(\frac{\pi\, d}{\lambda}\,\left(\frac{d_{ES}}{d_{MS}}\right)\mathrm{Sin}(\theta_{SEP})\right)}{\left(\frac{d_{ES}}{d_{MS}}\right)\mathrm{Sin}(\theta_{SEP})}\right]^2\right\} \quad (3)$$

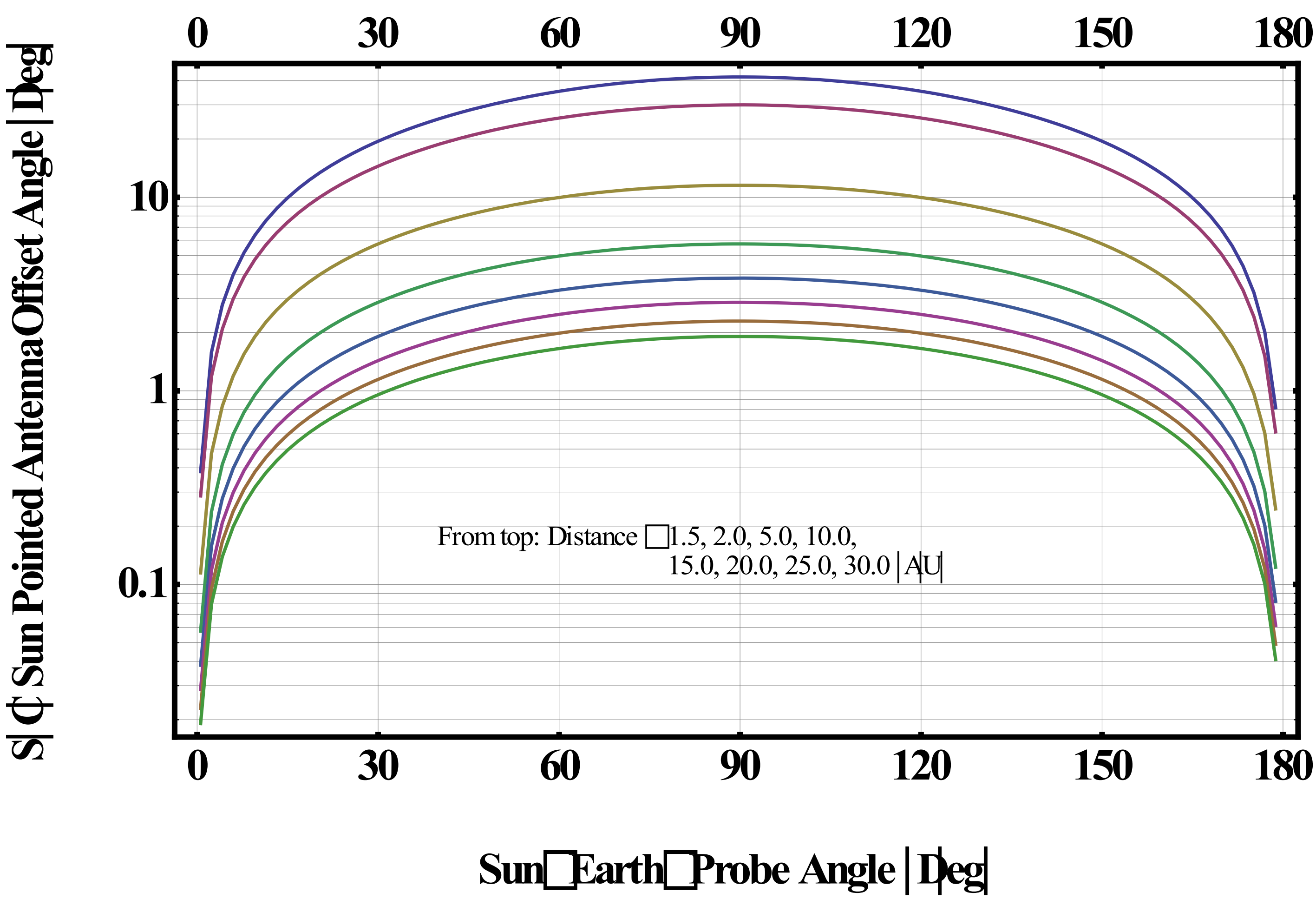

Figure 3. S/C antenna offset angle as a function of the Sun-Earth-Probe angle.

Where θ_{Ant} is the angle defined in Fig. 1 for the spacecraft antenna, d is the spacecraft parabolic reflector antenna aperture diameter in meters, λ is the wavelength of the link frequency in meters, and finally η is the efficiency of the spacecraft antenna. Since θ_{SEP} is the angle of overall interest, θ_{Ant} must be expressed in terms of θ_{SEP} which is quite straight forward. Fig. 3 shows a plot of θ_{Ant} as a function of θ_{SEP} and the parameter is the distance d_{SS}, the sun to spacecraft distance.

Fig. 3 shows that as the θ_{SEP} angle changes from 0 degrees to 180 degrees, the offset angle of sun pointed spacecraft antenna varies from 0 degrees to a maximum value. The geometry shown in Fig. 1 shows this also. It should be noted that the maximum offset angle naturally depends upon distance of the spacecraft from sun center, larger the distance, smaller is the variation of the offset angle. The second part of the Eq. (3) expresses the antenna gain in terms of θ_{SEP} angle. For the frequency of 8450 MHz as before, and with a parabolic reflector antenna of 0.5 meter diameter as an example, the spacecraft antenna gain directed towards Earth as a function of the θ_{SEP} is drawn in Fig. 4.

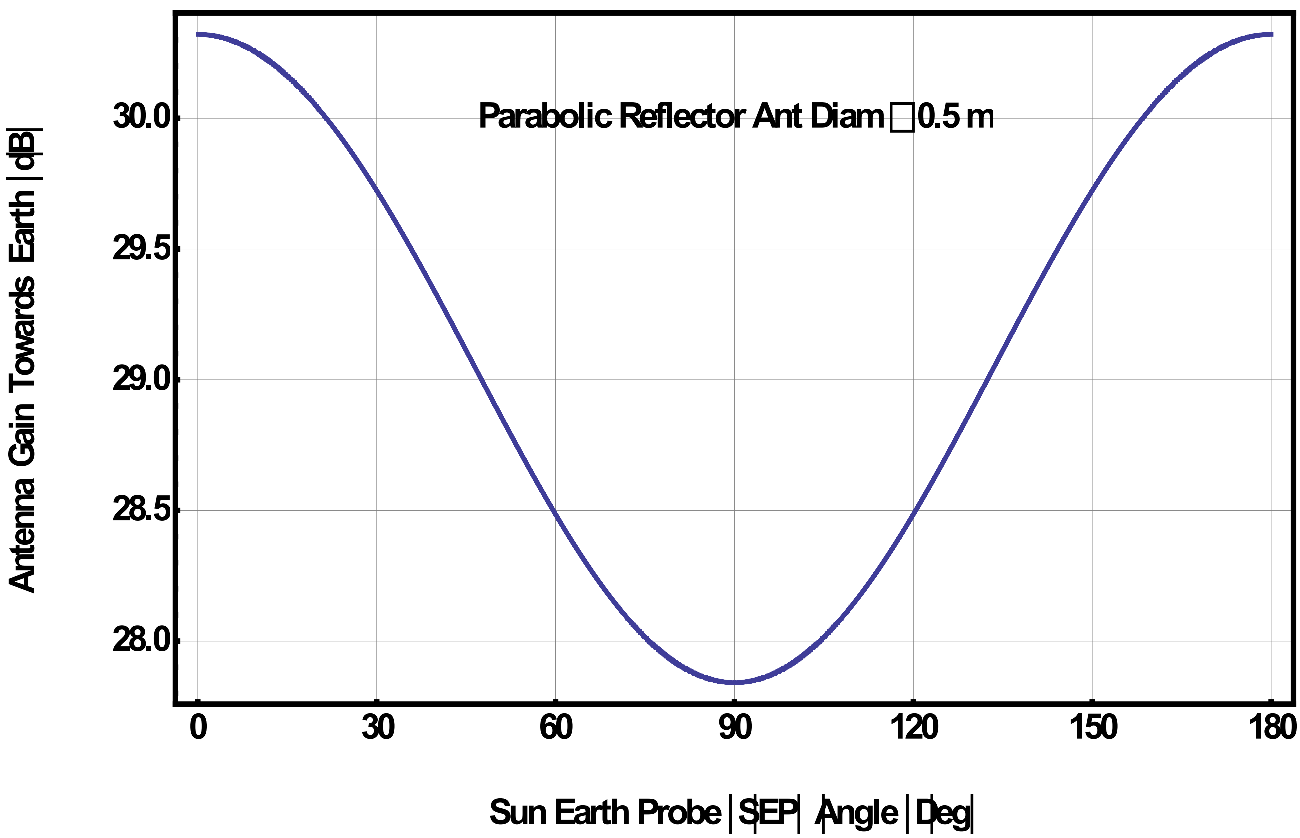

Fig. 4 Spacecraft antenna gain directed towards Earth as a function of the θ_{SEP}

4. Noise Spectral Density At the receiver: To compute the link performance, one naturally needs the ground station receiving antenna gain and noise contribution of various sources to the signal received by the receiver antenna that produces the noise spectral density. To compute a number, one needs to fix the receiver station and the antenna that will be used by the link. Because this is an emergency link, as it is usually done, we will use the highest gain antenna NASA stations have, i.e., the Deep Space Network (DSN) 70 meter diameter parabolic reflector antenna. Total system noise temperature is an aggregate of various sources temperature such as receiver operating temperature, weather induced temperature, physical antenna temperature, background noise temperature and hot body induced temperature. All temperatures are obtained from DSN 70 m antenna station document (JPL Document 810-005). Hot body noise temperature increase, usually due to the sun (sometimes due to the planets in the antenna beam width) depends upon the angle θ_{SEP} shown in Fig. 1. JPL Document 810-005 mentioned above also provides this temperature increase for the 70 m antenna. Using these data provided in that document Fig. 5 was generated. It should be noted that the total system noise temperature is measured in Kelvins. As expected, noise temperature is very high when θ_{SEP} is small, then it rapidly decreases and achieves a final steady value. This steady value embodies noise temperature increase due to all the entities except for the hot body noise due to sun. It is well known

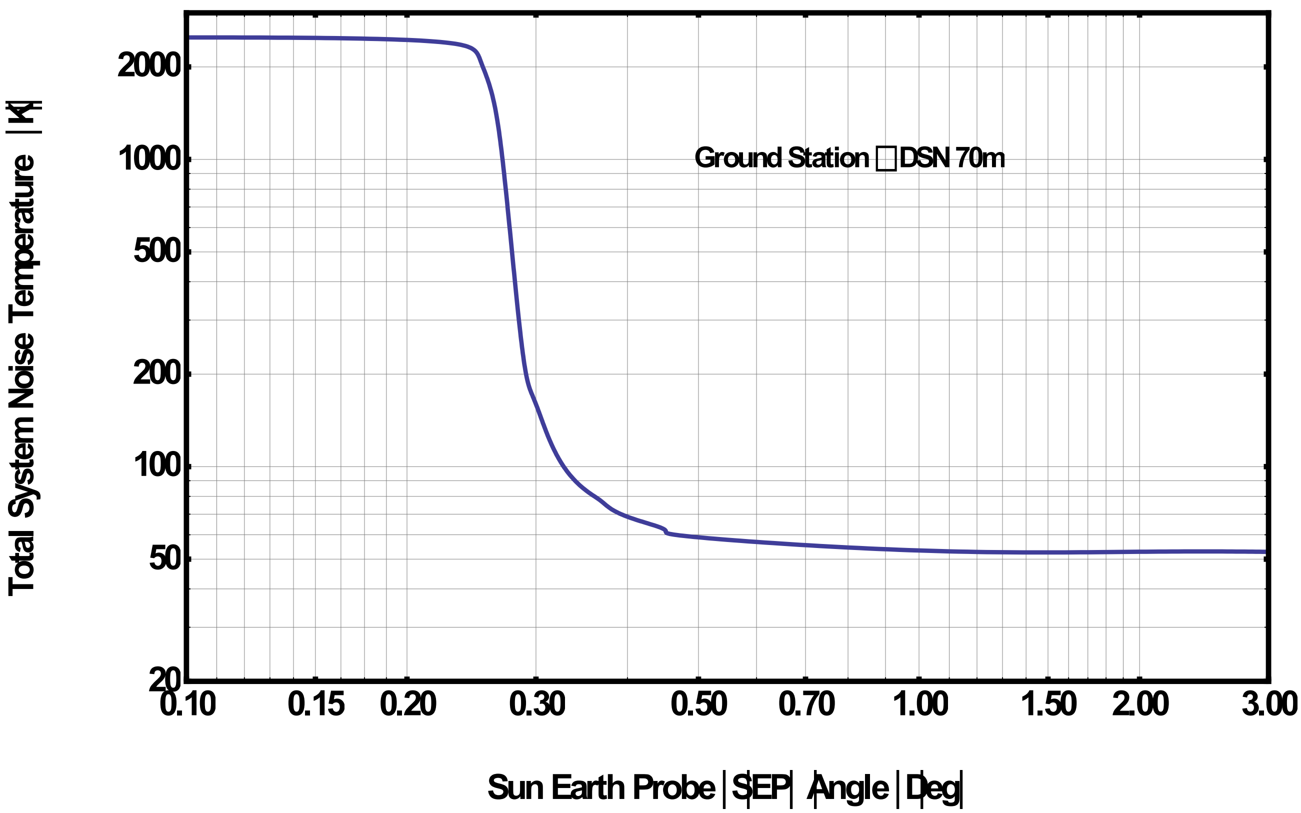

Figure 5. Total system noise temperature increase for DSN 70 m antenna station

that total noise temperature multiplied by Boltzmann's constant (-228.6 dB/W/Hz) produces single sided noise spectral density of noise that is added to the signal.

Next, we will use the signal and noise powers received by receiver antenna to compute bit energy to noise density ratio, otherwise known as E_b / N_0 for the link at hand. To make this conversion one needs some other parameter values of the link. The aggregate of losses on the spacecraft after the transmitter (power amplifier), L_{SC} will be assumed to be -2 dB, that includes the line/cable/waveguide losses, switches, filters, circulators etc. encountered before antenna focal point. Channel loss aggregate, L_C will be assumed to be -1 dB that includes the Ionospheric loss, Tropospheric loss, clouds, rain, dust particulars, etc. for the X-Band link with a frequency of 8450 MHz. This loss seems to be rather large; however, rain can produce a severe loss for the propagating wave. Finally, receiver system losses, L_{Syst} that include the antenna waveguide losses, polarization losses, receiver system losses including the carrier tracking phase jitter losses, waveform distortion losses, demodulation losses etc. will be assumed to be -1 dB.

There are still four more parameter values needed to proceed further. Power transmitted by spacecraft, P_T (W) the bit rate of the link, R_b (BPS), coding gain, G_{Code} (dB) due to inclusion of error correction coding for transmission and finally receiving station antenna gain, G_{Rcv} (70 m antenna gain at an appropriate elevation angle and weather distribution given in the JPL document 810-005). Power transmitted will generally be the full rating of the power amplifier; here we will assume that 50 Watts are available for the spacecraft. Now remembering that this is an emergency mode link, bit rate will be relatively small compared to usual telemetry bit rate of spacecraft. Bit rate of link R_b was assumed to be only 10 bits per second, with BPSK transmission. The coding gain of 5 dB was assumed. Final the 70 m antenna has a gain of 74.02 dB including all degradations mentioned above. Using these data the E_b / N_0 as a function of θ_{SEP} was computed according to the following formula.

$$\left(\frac{E_b}{N_0}\right)_{dB} = G_T + L_{SC} + \mathrm{L_C} + \mathrm{G_{Rcv}} + \mathrm{L_{Syst}} - \mathrm{L_{Code}} - 10\,\mathrm{Log}_{10}\left(R_b\right) - 10\,\mathrm{Log}_{10}\left(T_{Eq}\right) + 228.6 \tag{4}$$

Where, the equivalent system noise temperature, T_{Eq} (K) was computed as a function of θ_{SEP} using data for Fig. 4. Thus, as the position of earth changes in its orbit, E_b / N_0 received by ground station will change. Fig. 6 shows received E_b / N_0 in dB at the ground station as a function of θ_{SEP}. Fig. 6 shows the received E_b / N_0 for two cases, one for transmitting spacecraft antenna having a gain of -0.74 dB (almost an omni) and the other with antenna gain 14.4 dB. Fig. 6 also has the E_b / N_0 required to have a Bit Error Rate of 10^{-5} for the link. It is seen from Fig.6 that the larger gain antenna on the spacecraft has significant portion of the curve below the 10^{-5} BER line while the smaller gain antenna is consistently above the 10^{-5} line throughout the θ_{SEP} range, except very near θ_{SEP} =0 degrees where the noise added by the sun becomes overwhelming and the link breaks. Larger gain antenna curve has significant portions below the 10^{-5} line indicating that if the emergency on the spacecraft occurred when the θ_{SEP} is such that the graph is below the 10^{-5} line then the bits will be received with a BER worse than 10^{-5} with 0 dB data margin. Since emergencies occur with total randomness, it is better to have an antenna of gain -0.74 dB for the emergency communications where the data reception with a BER of 10^{-5} with 0 dB margin is guaranteed. It must be noted that doing the analysis for a minimally accepted θ_{SEP} does not serve the purpose because as Fig. 6 shows, the larger gain antenna does satisfy the BER of 10^{-5} requirement in some regions of θ_{SEP} but at other places this requirement is not satisfied. It should be noted that the results seen above were predicated on the parameter values used for computations. One of the major parameter is the spacecraft to sun distance, d_{SS}. For the above graph the d_{SS} was 1.5 AU (the average distance between sun and the spacecraft), if this value is changed, the result would also vary.

Fig. 7 shows the optimal antenna diameter using the method described above when it was applied to NASA's Mars reconnaissance Orbiter (MRO) spacecraft parameters where the received BER is smaller than or equal to 10^{-5} with a 0 dB data margin for a data rate of 10 bps at an X-band frequency of 8450 MHz.

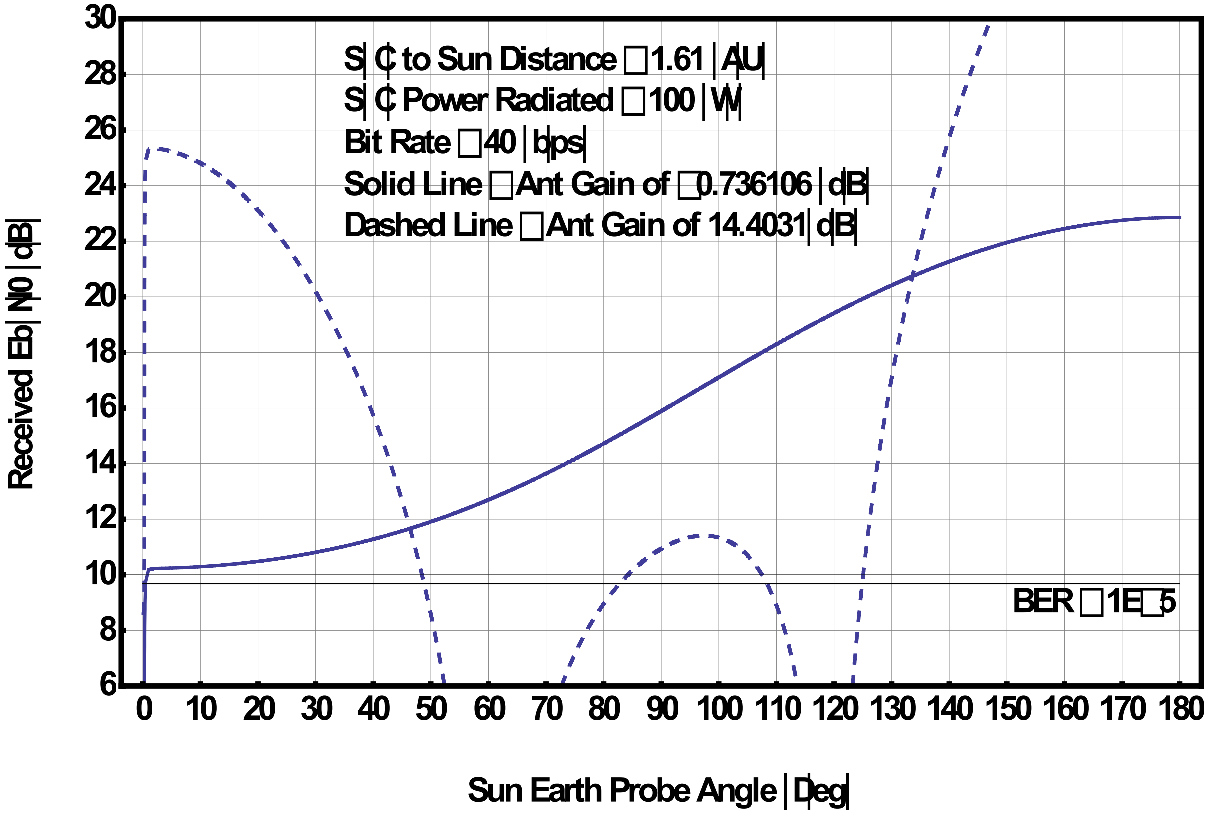

Figure 6. Received E_b / N_0 as a function of θ_{SEP}

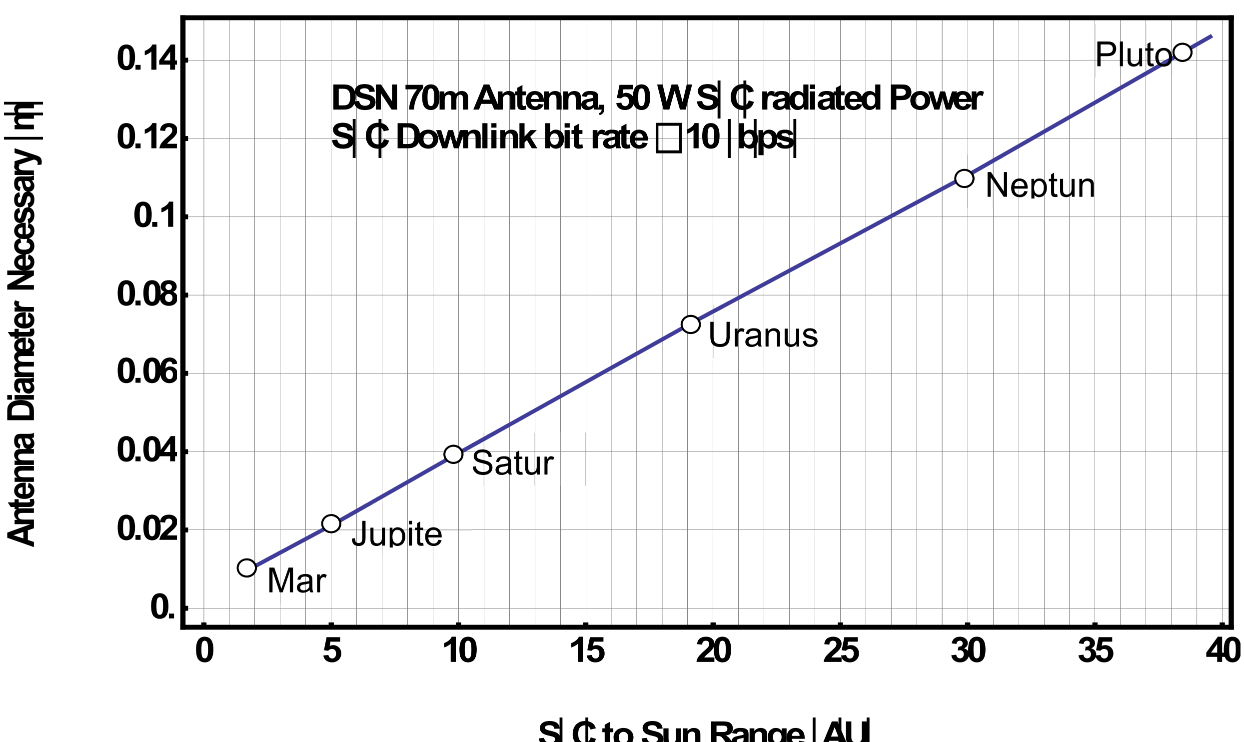

Figure 7. Antenna diameter necessary as a function of spacecraft to sun range

Conclusion: This paper presents a methodology for analyzing the performance of emergency mode downlink factoring into it the effects of gain, SEP and the range. The analysis presented here shows the effect of spacecraft antenna pattern on the emergency mode communications when the antenna is sun pointed. The analysis was done for a parabolic reflector antenna using the Bessel function approximation for the power pattern; however, the same can be done for any antenna with a known antenna pattern such as for the horn antenna, dipole antenna, patch antenna etc. used for the emergency mode. Even measured pattern values can be used for this analysis if sufficient data is available.

It should be noted that more often than not the spacecraft does not have a special antenna to be used for the emergency mode, it in fact uses the LGA for this mode. In this case, the margin may become significantly larger than 0 dB because the LGA is generally designed for transmission of data at a higher bit rate than that for the emergency mode and with at least a 3 dB margin at the ground station. The margin afforded by the LGA will be variable with respect to θ_{SEP}. If LGA is to be used and not a specially designed emergency mode antenna for the emergency mode, then the above plot must be created to see if E_b / N_0 dips below the 1E-5 line indicating a negative data margin.

The analysis was done for a particular set of relevant parameter values, if a parameter value is different from what is considered in this paper, then the results must be computed by running the whole computation again and not by scaling the results shown in the paper. This is due to the fact that the zeroes of the antenna do not scale appropriately. Fig 7 shows the spacecraft antenna diameter for any distance from the sun in the range of 1 AU to 40 AU (includes Mars to Pluto range) that will provide a consistent 0 dB margin with a BER of 10^{-5}.

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References

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