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Radio Astronomy Use of Space Research (Deep-Space) Bands in the Shielded Zone of the Moon

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The effects of deep-space probes on future radio-astronomy observations from the shielded zone of the Moon (SZM) are quantified by means of the radio-frequency power densities produced at the lunar surface in those deep-space exploration frequency bands with primary status in the International Telecommunications Union Table of Frequency Allocations. A worst-case approximation is used to determine the maximum number of deep-space probes that would be needed to produce harmful interference to the radio-astronomy observations in those bands.

I. Introduction

The shielded zone of the Moon (SZM) has been defined in the International Telecommunication Union (ITU) Radio Regulations (RR29-Section VI) [1], and this definition is related to the protection of future radio-astronomy observations from that portion of the Moon never facing the Earth and, therefore, naturally shielded from most of the electromagnetic radiation artificially generated at the Earth and its surrounding space. In summary, the "SZM comprises the area of the Moon's surface and adjacent volume of space which are shielded from emissions originating within a distance of 100,000 km from the center of the Earth."[1] In this zone, "emissions causing harmful interference to radio astronomy observations and to other users of passive services shall be prohibited in the entire frequency spectrum."[2] Exceptions to this are the frequency bands allocated to the space research service using active sensors, to the space operations service, and to other space research transmissions.

The Space Frequency Coordination Group (SFCG) [4] decided in Resolution A12-2R3 "to study the technical and operational questions relative to the radio links of scientific information transmission from probes exploring planets and the Moon; to study Agencies' future space exploration program spectrum and communications requirements and to make recommendations to member agencies on the actions to be taken to provide the additional spectrum allocations."[3]

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[1] *International Telecommunication Union Radio Regulations*, International Telecommunication Union, ISBN 92-61-04141-8, RR no. 2632.1, Geneva, Switzerland, p. RR-29-5, 1990.

[2] Ibid., RR no. 2632.

[3] *Handbook of the Space Frequency Coordination Group (SFCG)*, European Space Agency, Executive Secretariat, Paris, France, Resolution A12-2R3, p. 2, December 15, 1995.

This article will quantify the expected levels of radio-frequency power densities in the SZM produced by deep-space probes exploring the solar system and utilizing the ITU's primary allocations for space research (deep-space) bands: 2290–2300 MHz (S-band), 8400–8450 MHz (X-band), and 31,800–32,300 MHz (Ka-band). Table 1 provides some of the characteristics of the major solar system bodies that are applicable to this subject.

Table 1. Solar system parameters applicable to deep-space exploration–SZM interaction.

Parameter	Sun	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Equatorial diameter, km	1,392,000	4878	12,104	12,756	3476	6787	142,796	120,000	50,800	48,600	2302
Rotation period, Earth days	25.38	58.65	243[a]	23 h 56 m 4 s	27.32	1.03	0.414	0.438	−0.65[a]	0.77	−6.39[a]
Year length, Earth days or years	—	88 days	224.7 days	365.26 days	—	687 days	11.86 yr	29.46 yr	84.01 yr	164.8 yr	247.7 yr
Mean distance from the Sun, 10^6 km	—	57.9	108.2	149.6	—	227.9	778.3	1427	2870	4497	5900
Mean orbital velocity, km/s	—	47.9	35.0	29.8	—	24.1	13.1	9.6	6.8	5.4	4.7
Inclination of axis, deg	7.25	0.0	177.3	23.45	6.68	25.19	3.12	26.73	97.86	29.56	122
Inclination of orbit to ecliptic, deg	—	7.01	3.39	0	5.15	1.85	1.30	2.48	0.77	1.77	17.13

[a] Retrograde.

II. The Scenario

This article considers deep-space probes exploring the solar system at a distance from the Earth as far as, or farther than, Venus. Also, the probes considered will be mainly in the ecliptic plane or at a maximum of ±20 deg from the ecliptic plane; therefore, Pluto's exploration will be covered.

It is convenient, as a way of simplifying the analysis, to consider first a hypothetical single deep-space probe transmitting and fully occupying the allocated deep-space bandwidths of 10 MHz at S-band, 50 MHz at X-band, and 500 MHz at Ka-band. This situation is a worst case, probably only to be approached in an aggressive manned exploration of Mars. In this way, the spectral power flux densities (SPFDs) produced at the Moon's surface by the deep-space probe will be readily comparable with the radio-astronomy SPFD harmful interference levels given in Table 4 of [2]. The more realistic case of a limited number of deep-space probes, each with a reduced effective transmitting bandwidth, will also be considered.

The Moon orbits the Earth in approximately 4 weeks at a mean distance of 3.84×10^5 km. From Table 1, it may be deduced that deep-space probes at the nearest planet to the Earth (Venus) will produce very similar electromagnetic power densities at the Earth and Moon surfaces, since the associated space transmission losses differ by a very small amount. This difference of a few hundredths of a dB increases to almost 2 dB when the deep-space probe is at the near edge of the deep-space region. The deep-space region, as defined by the ITU, starts at a distance of 2×10^6 km from the Earth. Space research probes at shorter distances (near-Earth) are not addressed in this article.

Figure 1 is a representation (not to scale) of the Moon orbiting the Earth, with approximate parameters as given in Table 1. The Sun is assumed to be at the left side of the figure. A given point on the surface of the shielded zone of the Moon will have approximately 14 days of sun illumination followed by another 14 days of total darkness.

A deep-space probe exploring the space between the Sun and the Earth's orbit is customarily referred to as an inner deep-space probe. All the other space probes are usually known as outer deep-space probes. In Fig. 1, the wave fronts of these two types of deep-space probes have been represented. As the Earth–Moon system orbits around the Sun, it may be deduced that the inner deep-space probe wave front will reach the SZM when it is illuminated by the Sun, or approximately 26 weeks out of an Earth year. The remaining 26 weeks of the Earth year, the SZM will effectively be shielded from the line-of-sight propagation of the Sun's emissions. Also note that an outer deep-space probe wave front will reach the SZM half of the time when it is illuminated by the Sun and the other half when it is in shade.

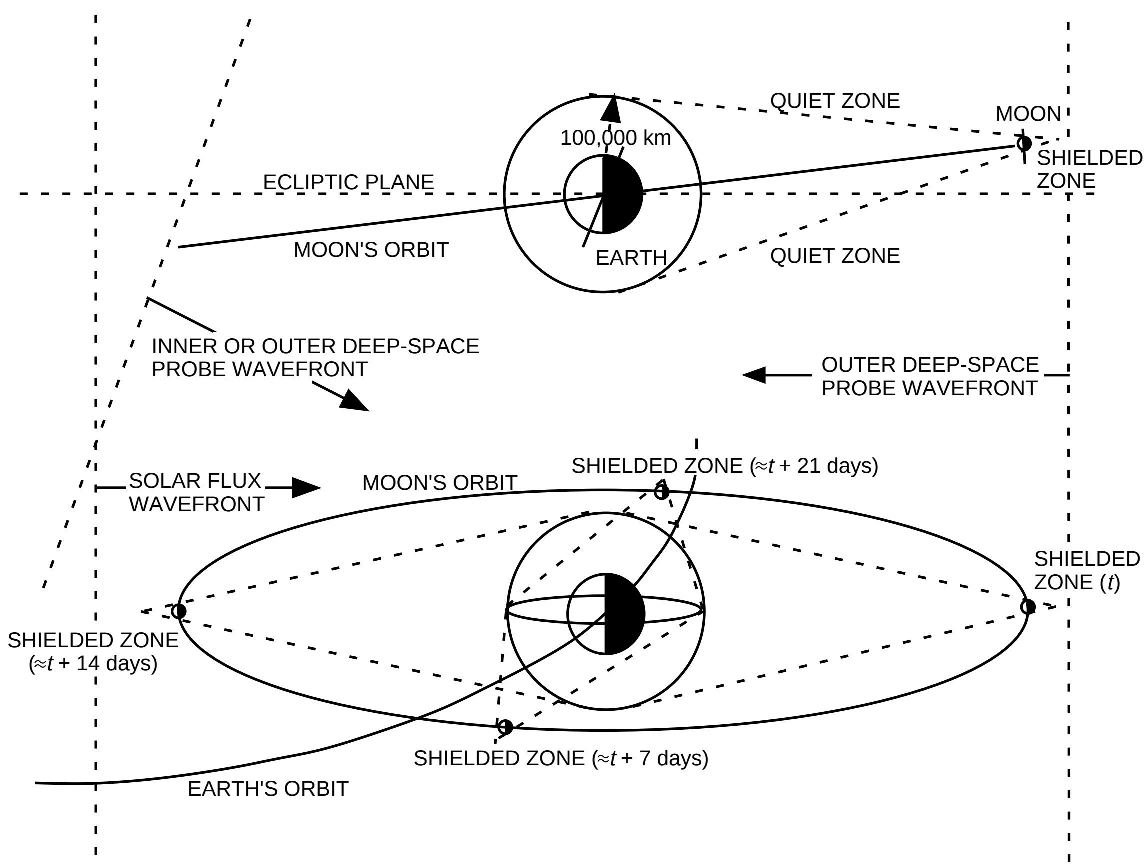

Fig. 1. Deep-space probe Sun–Earth–Moon interference scenario (not to scale).

III. Spectral Power Flux Densities Due to Deep-Space Exploration Probes

Deep-space exploration telecommunication transmissions are achieved at the Earth's surface by high-efficiency antennas with low-noise amplifiers. In the Appendix, it is shown that, given a data symbol signal-to-noise ratio (SSNR) at the deep-space Earth station's demodulation process, the SPFD, W/(m^2 Hz), at the Earth's surface may be considered to be approximately independent of the symbol rate and only dependent on the frequency band and the antenna gain-to-system noise temperature ratio of the Earth station in use.

The deep-space telecommunication link may be used, apart from its telemetry function, for several scientific purposes, such as the performance of Doppler measurements on the carrier; ranging measurements with a ranging modulation; radio science, usually on the carrier frequency without modulation; differential one-way ranging (DOR) with tones further apart from the carrier, etc. From the point of view of radio-astronomy continuum observations, the telemetry function is considered to be the most common emission source and will be the one to be analyzed in this article.

Deep-space missions usually are operated near the coded telemetry threshold of $SSNR = 4$ dB or lower (see the Appendix). Because of variations as large as 3 dB in the antenna gain-to-system operating noise temperature ratio, G/T_{op}, with antenna elevation and the potential noise contribution from the planet being explored, as well as the fact that as the mission progresses the symbol rate usually is changed by factors of 2, an SSNR of 9 dB will be considered to be the maximum to be maintained at the Earth antenna's telemetry decoding process. The minimum SSNR to be considered will be 4 dB. Receiver system losses are assumed to be negligible.

The use of these baseline limits allows us to consider the SPFD at the Earth's surface as a function of the deep-space antenna in use for each particular mission or phase of the mission. Therefore, and as shown in the Appendix, the maximum SPFD at the Earth's surface will change with the frequency band, the SSNR, and the Earth station G/T_{op} considered. Approximate maximum and minimum results for the SPFDs are shown in Table 2 for typical 70-m- and 34-m-diameter antennas. These values were obtained from Eq. (A-5) of the Appendix as the performance of the most significant Earth station parameters were changed from the minimum to the maximum values considered in Table 2. The equivalent power spectral densities (PSDs), W/Hz, at the output of an isotropic antenna (0-dBi gain) have been included for consistency with the present Earth-based radio-astronomy harmful levels provided in [2].

Table 2. Approximate power densities at the Earth's surface for a minimum/maximum SSNRs of 4/9 dB.

Antenna diameter, m	Frequency band[a]	ε_{ap} max/min	G max/min, dBi	T_{op} min/max, K	G/T_{op} max/min, dB/K	A_{iso} $\lambda^2/4\pi$, dBm^2	SPFD min/max, dB(W/(m^2 Hz))	PSD[b] min/max, dB(W/Hz)
34	S	0.60/0.55	56.1/55.7	16/59	44/38	−28.7	−239.9/−228.9	−268.6/−257.6
	X	0.71/0.65	68.2/67.8	26/60	54/50	−40.1	−238.5/−229.5	−278.6/−269.6
	Ka	0.49/0.19	78.0/74.0	50/199	61/51	−51.5	−234.1/−219.1	−285.6/−270.6
70	S	0.75/0.70	63.3/63.0	17/31	51/48	−28.7	−246.9/−238.9	−275.6/−267.6
	X	0.67/0.64	74.2/74.0	26/63	60/56	−40.1	−244.5/−235.5	−284.6/−275.6

[a] S-band is 2290–2300 MHz; X-band is 8400–8450 MHz; and Ka-band is 31,800–32,300 MHz.

[b] Isotropic antenna.

IV. Effects of Deep-Space Probes on the SZM

Harmful interference levels for the SZM have not yet been defined. Therefore, those levels shown in [2] for protection of radio-astronomy observatories at the Earth's surface will be considered first.

Figure 2 shows the present harmful interference levels for radio-astronomy observations (continuum and spectral line) at the Earth's surface [2]. Only frequencies above 1 GHz have been considered. The most probable maximum and minimum SPFDs produced by deep-space probes also have been plotted. The maximum SPFD plotted in Table 2 corresponds to probes tracked by 34-m-diameter deep-space Earth stations with worst-case parameters (maximum T_{op}, minimum gain, and a maximum SSNR of 9 dB). The minimum SPFD plotted corresponds to probes tracked by 70-m-diameter deep-space Earth stations with best-case parameters (minimum T_{op}, maximum gain, and a minimum SSNR of 4 dB).

From Fig. 2, it may be deduced that a single hypothetical deep-space probe fully occupying the ITU-allocated deep-space bands will most likely exceed the radio astronomy-desired maximum levels for Earth-based radio-astronomy continuum observations.

The conclusions drawn above from Fig. 2 apply to the case when the deep-space research-allocated bands are fully occupied. It will now be assumed that typical deep-space missions producing the SPFDs represented by the large dots in Fig. 2 will most likely be transmitting in a maximum effective bandwidth that is 1 percent of the radio-astronomy observing bandwidth (0.1 MHz for S-band, 1 MHz for X-band, and 5 MHz for Ka-band). This situation will reduce the effective interference power level [see Eq. (A-8) of the Appendix] from the deep-space probe into the radio-astronomy observing bandwidth by approximately 20 dB ($10 \log(B/(0.01B))$). As a gross approximation, one deep-space probe at S-band with the limited bandwidth considered would not produce harmful interference, allowing for another probe to be simultaneously in view above the lunar horizon. At X-band, the margin would be approximately 9 dB, allowing, therefore, at least 8 probes in view, and finally, at Ka-band the margin would be around 12 dB, allowing 16 probes to be simultaneously in view above the lunar horizon.

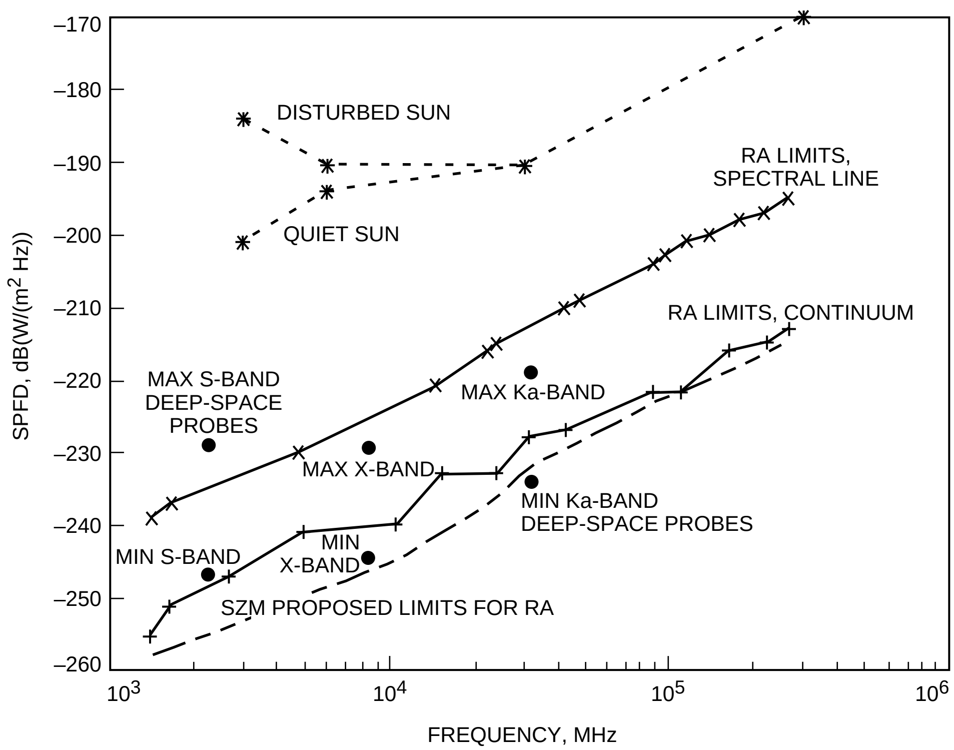

Fig. 2. Deep-space probes' SPFDs and radio astronomy (RA) harmful interference thresholds.

V. Radio-Astronomy Observations in the SZM: Further Considerations

As mentioned, harmful interference levels for radio-astronomy observations in the SZM have yet to be defined. The following subsections consider some of the possible modifications to the radio-astronomy Earth-based observations harmful limits.

A. Observing Bandwidth Considerations

A possible modification to the Earth-based observations radio-astronomy harmful limits may be derived from the probable increase of existing observing bandwidths, Δf_1. Observations in the SZM of the Moon should take advantage of improved technology. Therefore, it may very well be assumed that the total power observations will be effected in bandwidths, Δf_2, of at least 10 percent of the observing center frequency. These new harmful levels, deduced from Eq. (10) of [2], have been represented by the dashed line in Fig. 2 and are even weaker, $10\log(\Delta f_1/\Delta f_2)^{1/2}$, than those previously considered. If the same deep-space probe bandwidths (0.1 MHz in S-band, 1 MHz in X-Band, and 5 MHz in Ka-band) are assumed as those in Section IV, the effective unwanted power level from the deep-space probe into the larger radio-astronomy observing bandwidth will decrease by $10\log(\Delta f_2/\Delta f_1)^{1/2}$.

B. Sun Effects

The approximate SPFD produced by the Sun on the Earth's (or Moon's) surface [3] has been plotted in Fig. 2. Inner deep-space probes, in some instances, will have to be designed taking into consideration the effects of the Sun on the system noise temperature, T_{op}. Therefore, the deep-space probes' SPFD limits represented in Fig. 2 should be considered applicable only to outer deep-space probes. SPFD limits for inner deep-space probes in general will be larger than those corresponding to outer deep-space probes and have to be determined. The same considerations also should apply to the sensitivity of the radio-astronomy observations in the illuminated SZM. Results of an error analysis for the radio-astronomy sensitivity of a highly directive antenna with the Sun as a limiting factor should be made available to correctly assess the implications of the Sun's radiation.

VI. Improving Radio-Astronomy Observations in the SZM

Control of the number of deep-space probes or, in general, imposing limitations on the operation of deep-space probes for space research in the deep-space allocated bands should be avoided by all means. Efforts should be directed to the implementation in any future SZM radio-astronomy observatory of observation, data-processing, and instrumentation techniques designed to reduce the effects of the deep-space probes' radio-frequency levels, improving, therefore, the prospects of radio astronomy's successful use of these relatively narrow bands allocated on a primary basis to the space research service.

The constant power levels delivered by the deep-space probes, as well as the precise knowledge of their frequency, timing, and position (most probably orbiting a natural radiating body such as a planet), will also contribute to the success of the radio-astronomy observations in the allocated deep-space bands.

VI. Conclusions

It should be made clear that, due to the primary allocation status of the space research bands, there should not be any need of coordination with radio-astronomy observations effected in these deep-space allocations. Successful radio astronomy observations from the shielded zone of the Moon (SZM) in the S-, X-, and Ka-bands allocated to space research (deep space) seem possible when a limited number of deep-space probes are considered. It has been shown that at least 2 (S-band), 8 (X-band), and 16 (Ka-band) probes, each occupying 0.1 MHz at S-band, 1 MHz at X-band, and 5 MHz at Ka-band, can be active simultaneously and above the SZM radio-astronomy observatory horizon without surpassing the present-day harmful limits specified for Earth-based radio-astronomy observations.

Since future observation bandwidths will most probably be at least 10 percent of the center observing frequency, it is suggested that there be new harmful interference levels for radio-astronomy continuum observations in the SZM. These new limits, although more stringent than the present harmful levels for Earth-based observations, would improve the radio-astronomy observational tolerance to the radio emissions from deep-space probes. This is the case if the number of deep-space probes and the limited transmitting bandwidths previously considered remain unchanged.

Imposing more constraints on deep-space research exploration than those already naturally encountered should be avoided by all means. Therefore, interference-reduction techniques should be considered and implemented for radio-astronomy observatories wishing to effect observations including the space research (deep-space) allocated bands.

Finally, it is suggested that further studies be completed for the inner deep-space probes since this type of probe will radiate into the SZM when it is illuminated by the Sun. Also, it is intended that the potential impact of unwanted emissions (out-of-band and spurious) will be the subject of a future study.

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Appendix

The Relationship Between SPFD and SSNR

Binary phase shift keying (BPSK) modulation generally is utilized for space–Earth data transmissions. For systems using BPSK, a convenient performance measurement is the symbol signal-to-noise ratio (SSNR):

$$SSNR = \frac{ST_s}{N_0} = \frac{ST_s}{kT_{op}} = \frac{ST_s}{k(T_A + T_R)} \quad \text{(A-1)}$$

with

$S =$ received signal (data) power, W

$T_s =$ period of the received binary symbol, s

$N_0 =$ receiver system noise spectral density, W/Hz

$k =$ Boltzmann's constant, 1.38×10^{-23} J/K

$T_{op} =$ total system operating noise temperature, K

$T_A =$ antenna noise temperature, K

$T_R =$ receiver noise temperature, K

where S and N_0 are determined at the same reference point in the receive system.

The above ratio determines the probability of a detected symbol being in error. For BPSK systems, a convenient reference is a probability of 10^{-5} for a symbol being in error; that corresponds to an approximate SSNR of 9 dB for uncoded transmissions. The introduction of coding in the symbols transmitted increases the transmission bandwidth but lowers the required SSNR to approximately 4 dB for a typical (7,1/2) convolutional code with the same error rate of 10^{-5}.

To relate the spectral power flux density (SPFD), W/(m^2 Hz), to the SSNR, it should be noted that

$$S = SPFD \times A_p \times \varepsilon_{ap} \times B = SPFD \times \frac{\pi D^2}{4} \times \varepsilon_{ap} \times B \quad \text{(A-2)}$$

where

$A_p =$ physical aperture, m^2

$\varepsilon_{ap} =$ aperture efficiency

$B =$ transmission bandwidth, Hz

$D =$ aperture diameter, m

The antenna gain may be written as

$$G = \frac{4\pi}{\lambda^2} \times A_p \times \varepsilon_{ap} \quad \text{(A-3)}$$

with

$$\lambda = c/f$$
$$\lambda = \text{propagation wavelength, m}$$
$$c = \text{speed of light, } 3 \times 10^{10} \text{ m/s}$$
$$f = \text{propagation frequency, Hz}$$

Therefore, from Eqs. (A-2) and (A-3),

$$S = \frac{\lambda^2}{4\pi} SPFD \times G \times B \tag{A-4}$$

and from Eqs. (A-1) and (A-4),

$$SPFD = \frac{4\pi}{\lambda^2} \frac{k}{BT_s} SSNR \frac{T_{op}}{G} \tag{A-5}$$

For BPSK signals, $B \times T_s \approx$ constant. The approximation $B \times T_s \approx 1$ will be assumed in the results shown in Table 2. Therefore, for a given SSNR, the SPFD will be approximately independent of the symbol transmission rate and will be dependent in the frequency band in use and the G/T_{op} considered.

It is convenient to relate the SPFD to the power spectral density (PSD), W/Hz, and the power (P_{tot}), W, produced at the output of an isotropic antenna (0-dBi gain). In this way, comparisons may be made directly to the interference levels harmful to radio astronomy that are given in [2].

The effective area of an isotropic antenna, A_{iso} (m^2), is

$$A_{iso} = \frac{c^2}{4\pi f^2} = \frac{\lambda^2}{4\pi} \tag{A-6}$$

Therefore,

$$PSD = SPFD \times A_{iso} = SPFD \frac{\lambda^2}{4\pi} \tag{A-7}$$

Sometimes it is more convenient to relate the total power, p_{tot}, produced by the deep-space probe at the radio astronomy antenna to the harmful interference input power, ΔP_H [2]. This total power is related to the PSD by

$$P_{tot} = PSD \times B \tag{A-8}$$