COMPLIANCE WITH HIGH-INTENSITY RADIATED FIELDS REGULATIONS – EMITTER'S PERSPECTIVE

Joseph Statman[1], Vahraz Jamnejad[1] and Lee Nguyen[2]

ABSTRACT[3]

NASA's Deep Space Network (DSN) uses high-power transmitters on its large antennas to communicate with spacecraft of NASA and its partner agencies. The prime reflectors of the DSN antennas are parabolic, at 34m and 70m in diameter. The DSN transmitters radiate Continuous Wave (CW) signals at 20 kW - 500 kW at X-band and S-band frequencies. The combination of antenna reflector size and high frequency results in a very narrow beam with extensive oscillating near-field pattern. Another unique feature of the DSN antennas is that they (and the radiated beam) move mostly at very slow sidereal rate, essentially identical in magnitude and at the opposite direction of Earth rotation.

The DSN is in the process of revamping its documentation to provide analysis of the High Intensity Radiation Fields (HIRF) environment resulting from radio frequency radiation from DSN antennas for comparison to FAA regulations regarding certification of HIRF protection as outlined in the FAA regulations on HIRF protection for aircraft electrical and electronic systems (Title 14, Code of Federal Regulations (14 CFR) §§ 23.1308, 25.1317, 27.1317, and 29.1317).

This paper presents work done at JPL, in consultation with the FAA. The work includes analysis of the radiated field structure created by the unique DSN emitters (combination of transmitters and antennas) and comparing it to the fields defined in the environments in the FAA regulations. The paper identifies areas that required special attention, including the implications of the very narrow beam of the DSN emitters and the sidereal rate motion. The paper derives the maximum emitter power allowed without mitigation and the mitigation zones, where required.

Finally, the paper presents summary of the results of the analyses of the DSN emitters and the resulting DSN process documentation.

1. INTRODUCTION

NASA established in 1963 the Deep Space Network (DSN) to provide communications and navigation support to missions of NASA and its partner agencies in the USA and internationally. As shown in Figure 1, the DSN has facilities in the USA (GDSCC, near Goldstone, California), Spain (MDSCC, near Madrid) and Australia (CDSCC, near Canberra). Each of these facilities has large steerable antennas, 34m to 70m in diameter and extensive signal processing capabilities. The antennas are equipped with high sensitivity low-noise amplifiers and high-power transmitters – these are required due to the extreme distances needed for communications with missions at deep space.

---

[1] Jet Propulsion Laboratory, California Institute of Technology, (JPL/CIT), 4800 Oak Grove Drive, Pasadena, CA 91109
[2] Federal Aviation Administration, Avionics Systems Branch, 470 L'Enfant Plaza, SW, Washington, DC 20024
[3] The work reported in this paper was partially conducted at the JPL/CIT under contract with the National Aeronautics and Space Administration and at NASA HQ. Copyright 2012. All rights reserved

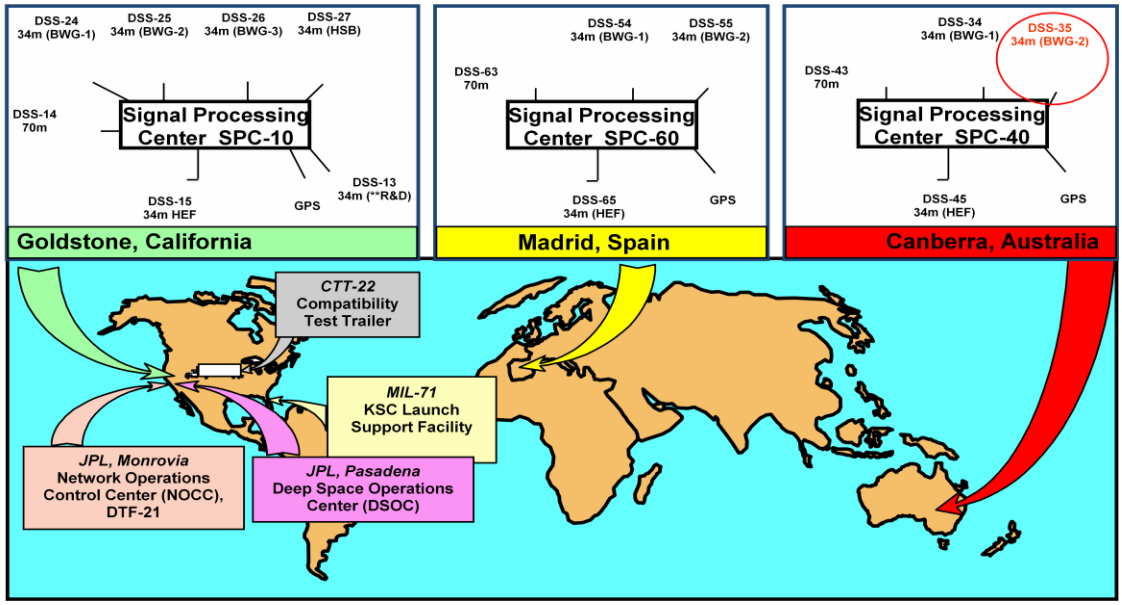

Figure 1 – Configuration of the Deep Space Network (DSN)

The FAA established regulations in 14 CFR §§ 23.1308, 25.1317, 27.1317, and 29.1317, High-intensity Radiated Fields (HIRF) protection for Aircraft Electrical and Electronic Systems (Federal Register Vol. 72, No. 150, dated 8/6/2007) for protection of the operation of these aircraft systems when the aircraft is exposed to external HIRF environments. While the FAA does not regulate DSN antennas and transmitters, the process the DSN undergoes with spectrum agencies to obtain emitter certification involves a validation that the DSN emitters do not exceed the environment specified by the FAA or, if the DSN radiation exceeds that environment, appropriate mitigation (e.g. aircraft exclusion zones and/or coordination) is taken. Note that the specific rules are country- and agency-dependent, but the HIRF environments in the FAA regulations are harmonized with other national airworthiness authorities.

The DSN radiation environment is unique. It is characterized by large antennas (34m and 70m in diameter) that move very slowly, large transmitters (up to 500 kW) and very narrow beams, mechanically (not electronically) steered, that are fixed with respect to the antennas.

This paper describes the FAA regulations (Section 2), the analysis required to characterize the DSN environment (Section 3), followed by a brief description of the resulting process and documentation upgrades incorporated in the DSN (Section 4). Section 3 provides a sample analysis, for a single combination of antenna and transmitter – specifically, for the case of a 34m beam waveguide antenna, 80 kW transmitter, and comparison to FAA HIRF Environment I. As part of the process, this analysis is repeated for each combination of DSN antenna and transmitter and for each FAA HIRF Environment.

2. FAA REGULATIONS

The FAA established Radio Frequency (RF) field strengths for certification of aircraft and their parts in a HIRF Environment. The criteria define the radiation environment the aircraft electrical and electronic systems have to withstand in HIRF Environment I (Certification HIRF

Environment), HIRF Environment II (Normal HIRF Environment), and HIRF Environment III (Rotorcraft Severe Environment). Table 1 shows the FAA certification limits for Environment 1.

While these are FAA standards, they are harmonized with other national airworthiness authorities. In fact, the process to develop these environments consisted of collecting data in the US and Europe to establish the governing criteria. Unfortunately, the process did not identify the CDSCC and MDSCC emitters and assumed that the GDSCC emitters are protected by an aircraft exclusion zone.

In general, the FAA regulations assume that emitters are of the pulsed radar type and are characterized by a high-energy pulse followed by no transmission. Thus, the three environments are characterized by "Peak" field value, during the pulse, and "average" field value, over the period of the pulsed radar. Such transmitters have two types of effects on electrical and electronic equipment:

1. "Upsets" of memory cells, e.g. zeros to ones or the reverse, caused by the "peak" radiations.

2. Thermal effects, or malfunctions caused by increase in the temperature of electronic junctions, as a function of radiation over time (the FAA standard uses 1 second for fixed-wing aircraft and 3 seconds for rotorcraft).

The DOT/FAA/AR-98/69, NAWCADPAX--98-156-TM prepared by the Naval Air Warfare Center, December 1998 report [Ref. 1], and SAE International (SAE) Aerospace Recommended Practice (ARP)5583a / European Organization for Civil Aviation Equipment (EUROCAE) ED-107a "Guide to Certification of Aircraft in a High-Intensity Radiated Field (HIRF) Environment," June 2010 [Ref. 5] assumes that averaging is computed over time, using many cycles of the periodic /pulsed emitter. Because the DSN transmitters are CW transmitters, but impact the aircraft only during the short time it crosses the narrow beam, the main adjustment in the DSN procedure is that it allows for spatial averaging – averaging the field over the path that the aircraft passes through the beam.

FREQUENCY	FIELD STRENGTH (V/m)	
	PEAK	AVERAGE
10 kHz - 2 MHz	50	50
2 MHz - 30 MHz	100	100
30 MHz - 100 MHz	50	50
100 MHz - 400 MHz	100	100
400 MHz - 700 MHz	700	50
700 MHz - 1 GHz	700	100
1 GHz - 2 GHz	2,000	200
2 GHz - 6 GHz	3,000	200
6 GHz - 8 GHz	1,000	200
8 GHz - 12 GHz	3,000	300
12 GHz - 18 GHz	2,000	200
18 GHz - 40 GHz	600	200
In this table, the higher field strength applies at the frequency band edges.		

Table 1 – FAA HIRF Environment I (Certification HIRF Environment)

Appendix A compares the assumptions in NAWC report to the assumptions used in this paper.

3. ANALYSIS TO EVALUATE DSN RADIATED FIELDS

Figure 2 shows the model of radiation from a DSN antenna. There are three zones: a near-field zone, modeled as a cylinder with diameter equal to antenna diameter, a far-field zone, modeled as a cone centered at the antenna, and a transition zone between the near-field and far-field zones. The detailed structure of the field is quite complex and varies as a function of the antenna diameter and transmitter frequency, as will be shown in Figure 3 below.

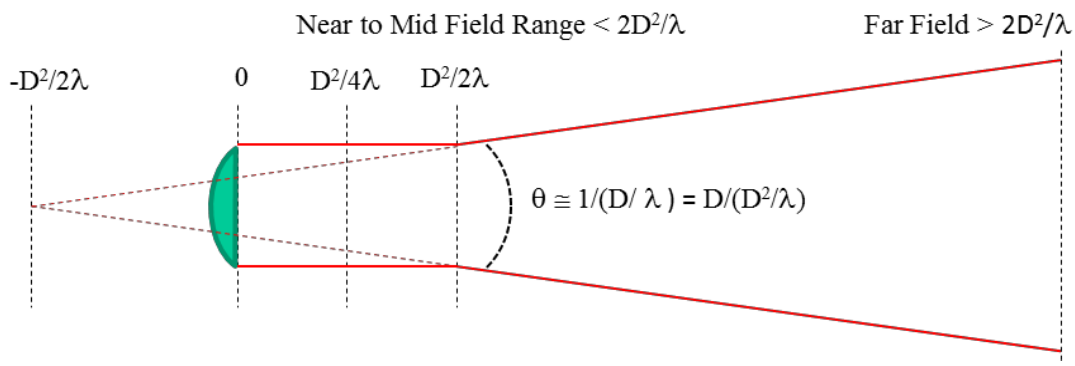

Figure 2 – Model of radiation from a DSN antenna

The simple model of the near-field is a cylinder, with the diameter of the antenna and centered on the antenna. Figure 3 shows the finer structure of the field, normalized to the average field strength level for Environment I. The horizontal axes plot the distance along the cylinder, while the vertical axes plot the distance from the antenna from the center of the cylinder outward. As expected, as the distance from the center of the cylinder reaches 17m, the radius of the cylinder, the field drops sharply. Notice further how the field is quite complex, fluctuating from point to point, in this case drawn to 30 km, well beyond the near field. Nevertheless, at no point does the field strength exceed the FAA "Peak" value, 1000 V/m for Environment I, 6-8 GHz.

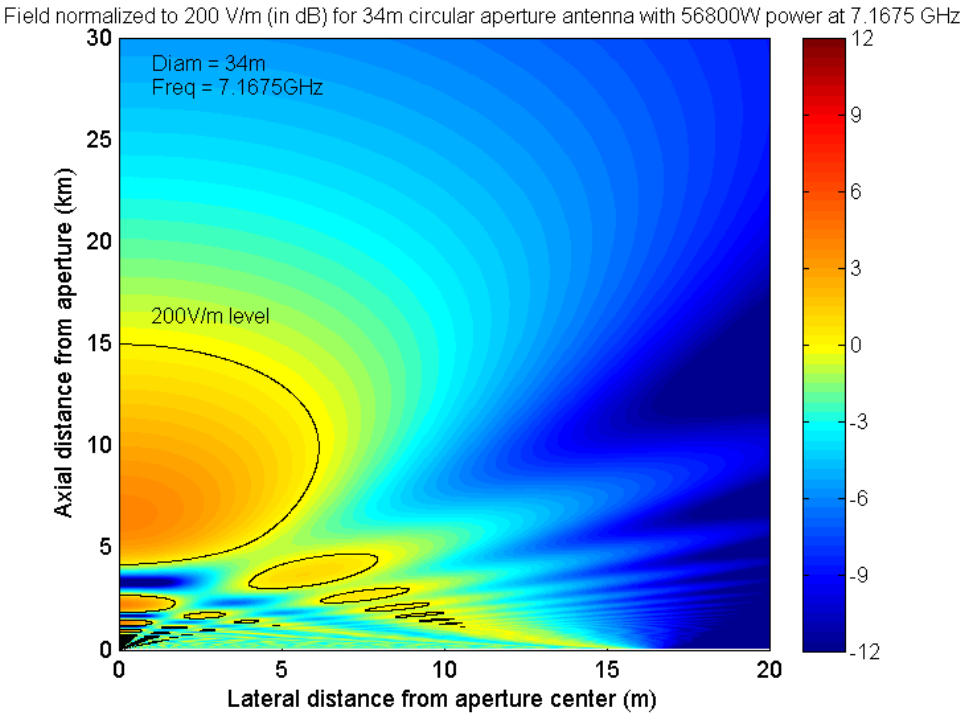

Figure 3 – Example of Detailed Field Strength

How Figure 3 is derived. First, it is important to distinguish between the "nominal power" of a transmitter and the "effective power". "Nominal power", for the DSN, is the power as measured in the last measuring point in the uplink chain (for the 80 kW transmitter, "nominal power" is at the switch between the horn feed and the water load). "Effective power" is the power radiated out of the antenna aperture, accounting for losses after the measuring point (load switch) which include losses from the switch to the feed horn and those after feed through sub and main reflectors (including Ohmic, leakage, blockage, surface errors, etc.) losses to aperture which account for the efficiency of the antenna. Table 2 shows these values. Thus, the "effective power" for the 80 kW transmitter is determined to be 56.8 kW.

Component	Efficiency/loss factor
Loss, load switch to Feed Horn	0.85 (~0.7 dB)
S/X dichroic: spill loss Ohmic loss VSWR (reflection) loss	0.9992 0.9986 0.99
Upper BWG mirrors (4): spill loss Ohmic loss RMS surface error loss	0.9950 0.9981 0.9960
Lower BWG mirrors (2): spill loss Ohmic loss RMS surface error loss	0.9984 0.99903 0.9970

Main reflector panel & gap leak Ohmic loss RMS surface error loss	0.99812 0.99954 0.9770
Support structure blockage	0.8746
Total Post Feed Horn loss	0.8283 (~0.8 dB)
Total Loss Factor/Efficiency	~0.71 (~1.5 dB)
Input Power: 80000 W Beam Output power: 56800 W	

Table 2 – Losses for 34m/80kW, Reference to Power Load Switch

Next we need to compute the average field. We take the conservative approach – averaging over the minimum of 1 sec and the time required for crossing the beam. Because that time varies depending on the aircraft speed and antenna elevation angle, the "average field" plotted here for each elevation angle is the maximum over aircraft speed range (100-350 knots for fixed wing aircraft).

Table 3 shows the beam crossing time for a 34m antenna, for a variety of aircraft speed and antenna elevation. Note that unless there is a combination of low speed and low elevation, the crossing time is less than 1 second. This table assumes that aircraft fly horizontally since aircraft usually operate in level flight, and that the aircraft crosses through the center of the antenna beam, resulting in the longest crossing time. During ascent/descent, aircraft are restricted to 3 degrees slope except for emergencies (for example 14 CFR sec. 171.317 — Approach elevation performance requirements). The DSN complies with the ITU regulatory limit to assure that no transmission below 10 degrees and horizon mask occurs.

		Speed (knots)					
		100	**150**	**200**	**250**	**300**	**350**
Antenna Elevation (deg)	**10**	*3.81*	*2.54*	*1.90*	*1.52*	*1.27*	*1.09*
	20	*1.93*	*1.29*	*0.97*	*0.77*	*0.64*	*0.55*
	30	*1.32*	*0.88*	*0.66*	*0.53*	*0.44*	*0.38*
	40	*1.03*	*0.69*	*0.51*	*0.41*	*0.34*	*0.29*
	50	*0.86*	*0.58*	*0.43*	*0.35*	*0.29*	*0.25*
	60	*0.76*	*0.51*	*0.38*	*0.31*	*0.25*	*0.22*
	70	*0.70*	*0.47*	*0.35*	*0.28*	*0.23*	*0.20*
	80	*0.67*	*0.45*	*0.34*	*0.27*	*0.22*	*0.19*
	90	*0.66*	*0.44*	*0.33*	*0.26*	*0.22*	*0.19*

Table 3 – Maximum Beam-crossing Times for the 34m Near-field Beam

Figure 4 shows the resulting average field. For this case, we conclude that no mitigation is required if the antenna operates at elevations over 30 degrees or higher, and limited mitigation (e.g. exclusion zone and/or coordination) is required for lower elevation angles.

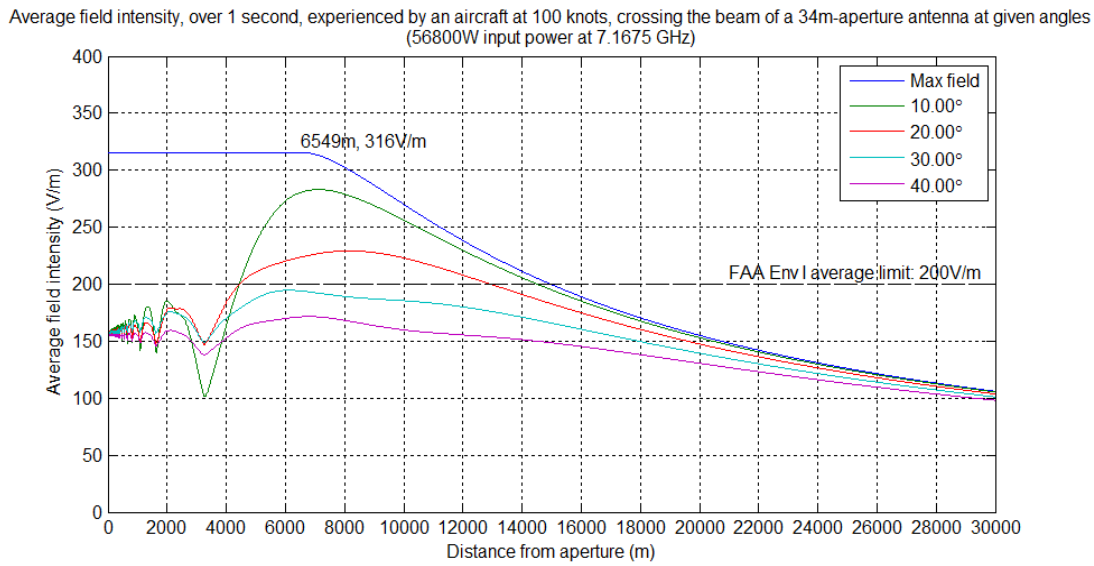

Figure 4 – Peak and Average Field, 80 kW/X-band/34m, referenced to Environment I

4. CONCLUDING REMARKS

The paper presents summary of the results of the analyses of the DSN emitters. The methodology and the assumptions used in the DSN emitter analyses are consistent with the HIRF environment evaluation and assumptions used the NAWCADPAX--98-156-TM, with spatial averaging utilized for comparison to the average field strength levels.

The DSN procedure has extended the analysis presented here to other combinations of transmitter and antenna.

ACKWOWLEDGEMENT

The authors thank Mr. Dave Walen, FAA Chief Scientific and Technical Advisor, Aircraft Electromagnetic Compatibility (EMC) for his support throughout this effort, in particular with his insights regarding the FAA regulatory role and processes, and Ms. Wendy Hodgin of the Deep Space Network for her helpful review and comments.

REFERENCES

[1] "High Intensity Radiated Field External Environments For Civil Aircraft Operating In The United States of America," Naval Air Warfare Center, Aircraft Division, Patuxent River, Maryland, Report No: NAWCADPAX--98-156-TM, .

[2] R. W. Bickmore and R. C. Hansen, "Antenna Power Densities in the Fresnel Region," Proc. IRE, vol. 47, pp. 2119-2120, December 1959.

[3] M. M. Rabello and S. L. G. Nobili, "Radiating Near-Field Power Density and Dierectivity Reduction of Tapered Circular Apertures," Radio Science, vol. 8, N0. 7, pp. 677-680, July 1973.

[4] V. Jamnejad, "A Study of Near to Far Fields of JPL Deep Space Network (DSN) Antennas for RFI Analysis," IEEE Aerospace Conference, Big Sky, Montana, March 6-13, 2004.

[5] "Guide to Certification of Aircraft in a High-Intensity Radiated Field (HIRF) Environment," SAE ARP5583a/EUROCAE ED-107a, June 2010.

APPENDIX A
Comparison of Assumption in NAWC Study to Assumptions in this paper

In general, the DSN procedure follows the assumptions and procedures used in report NAWCADPAX--98-156-TM, prepared by the Naval Air Warfare Center, Aircraft Division, Paxtuxent River, Maryland, published December 1998 [Ref. 1]. There are few exceptions listed below. Primarily, these are to reflect the use of spatial averaging to compute "DSN Average" values.

The NAWC report generally assumes pulsed radar type transmitters, sending a train of short, powerful pulses. Such transmitters have two types of effects on electrical and electronic equipment:

1. "Upsets" of memory cells, e.g. zeros to ones or the reverse, caused by the "peak" radiations.

2. Thermal effects, or malfunctions caused by increase in the temperature of electronic junctions, as a function of radiation over time (the FAA standard uses 1 sec for fixed-wing aircraft and 3 sec for rotorcraft).

The NAWC report assumes that averaging is computed over time, using the duty cycle of the periodic /pulsed emitter. Instead, for the DSN (that has CW transmitters) spatial averaging is used. The main adjustment in the DSN procedure is that it allows for spatial averaging – averaging the field over the path that the aircraft passes through the beam. For the DSN procedure, extensive analyses were performed of the complex field structure, especially in the near field and mid-field.

The following are differences/adjustments used for the DSN case, relative to the NAWC report.

Obtaining the actual detailed fields of these antennas using rigorous Physical Optics, method of moments or other EM analysis techniques is very time consuming and subject of other studies. There are a number of reports and papers on the subject of calculating the on-axis near field of large circular aperture antennas [Refs. 1-3]. These provide maximum field values along main/boresight axis of the antenna. An internal JPL report has generalized the analysis for a variety of antennas including the circular aperture antennas which again provide a good summary of the on-axis field. However, as can be shown the field strength away from main axis becomes weaker. We have made a fairly rigorous but still approximate formulation in [Ref. 4] to provide a more accurate representation of the field on and about the main beam of the antenna. The following simplifying assumptions are used in obtaining the field strengths. Details of the calculation are given in that reference.

i) The pattern is circularly symmetric.

ii) A scalar formulation for the field is used. The actual field is of a vectorial nature.

iii) The field on the aperture is assumed to be uniform in amplitude. This is approximately valid, since the DSN dual reflector antenna systems are shaped to produce a uniform phase and a fairly uniform amplitude distribution on the aperture with drop-off at the edges to reduce diffraction. We have used an effective uniformly illuminated aperture which is slightly smaller than the actual antenna (specifically, 33.09 for the 34m antenna and 68.22 for 70m antenna).

iv) The reflector is designed to produce uniform phase on the aperture. However, the surface errors, misalignments, gravity and wind pressure effects will distort this uniform phase front. For the purpose of this study we ignore these effects, although, they can be included at a later stage.

v) The Fresnel approximation is made to the exponential kernel in the radiation integral such that the distance from observation point to a point on the aperture, r, is approximated by a linear term of the vertical distance to the aperture and a quadratic term of vertical distance to the central axis.

vi) No blockage effects due to sub-reflector, support struts, etc. are directly included (but only through a lump-sum efficiency factor). They should have minimal effects.

vii) No surface errors and tolerance are directly included in the computation process (but only through a lump-sum efficiency factor). These, in general, tend to reduce the peaks and partially fill the nulls in the field distribution.

The results provided in Section 3 are thus obtained. It should be mentioned that they agree with those of the internal JPL report along the main axis. That paper suggests an efficiency factor of 0.55. In producing our results, we have actually used an efficiency factor of 0.71 which is more accurate for DSN antenna considered. This indeed provides a more conservative set of results.

Field averaging

Although the peak value of the field might be of interest in some special cases (e.g., a hovering helicopter), for most cases of interest an aircraft is moving with a certain speed through the antenna beam, and the average field over a given period of time and the corresponding travelled distance may be of greater significance. The worst case scenario involves crossing the beam through its center. The angle of the direction of travel with the direction of the beam axis must also be taken into account for the distance travelled. Notice that for a given period of time, time averaging and space averaging are equivalent.

In performing averaging of the field, initially we compute the average field normal to the main axis and across the center of the beam to a width of D (diameter of the antenna) for any given distance from aperture. Due to relatively slow field variation along the beam (in units of beam diameter D), this averaging is reasonable even for non-normal angles of crossing the beam.