Radiation Hazard Analysis
High Performance Phased Array Fixed Earth Station

Introduction

This analysis calculates the non-ionizing radiation levels for a SpaceX Services, Inc. ("SpaceX Services") high-performance phased array earth station ("HP terminal"). The calculations performed in this analysis comply with the methods described in FCC Office of Engineering and Technology Bulletin, Number 65 (Edition 97-01) ("Bulletin 65").[1] This analysis demonstrates that SpaceX Services HP terminals are compliant and will not result in exposure levels exceeding the applicable radiation hazard limits.

Bulletin 65 and Section 1.1310 of the Commission's rules specify two separate tiers of exposure limits: one for Occupational/Controlled Exposures and one for General Population/Uncontrolled Exposures. Limits for Occupational/Controlled Exposures apply in situations where persons are exposed as a consequence of their employment and are fully aware of and can control their exposure. These limits also apply in situations where a person is transient through a location where such limits would otherwise apply provided the person is made aware of the potential for exposure. The limits for General Population/Uncontrolled Exposure apply in situations in which the general public may be exposed, or in which persons that are exposed as a consequence of their employment may not be fully aware of the potential for exposure or cannot exercise control over their exposure.

SpaceX Services will ensure installation of HP terminals at customer premises by qualified installers who have an understanding of the antenna's radiation environment and the measures best suited to maximize protection of the general public and persons operating the equipment. Some HP terminals will be deployed in Occupational/Controlled Environments, especially for enterprise customers. In addition, many installations will be made in areas that are inaccessible to the public. However, some HP terminals will likely be deployed in General Population/Uncontrolled Environments as well. Accordingly, SpaceX Services will deploy two versions of these terminals that differ only in the software that determines their maximum duty cycle, and will ensure that the higher duty cycle is only deployed in areas that are not accessible to the general public. As a result, this analysis discusses the Maximum Permissible Exposure ("MPE") limit for both the

[1] SpaceX Services has learned that the IEEE International Committee on Electromagnetic Safety recently updated a standard that Bulletin 65 had relied upon in part. *See* IEEE Std C95.3-2021, *IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 300 GHz*, IEEE Standards Association (approved Mar. 25, 2021) ("Updated IEEE Standard"). Among other things, that update revised its recommended methodology for calculating power density in the near field region. Bulletin 65 states that it "is not intended to establish mandatory procedures, and other methods and procedures may be acceptable if based on sound engineering." Bulletin 65 at 1. Moreover, the bulletin recognizes that "[i]n some cases, . . . measurements or a more detailed analysis may be required." *Id.* In this case, a fundamental assumption of the IEEE analysis may not apply to the flat planar nature of the SpaceX Services HP terminal. Specifically, the SpaceX Services phased array HP terminal consists of a large number of identical radiating elements (over 1000 small patch antennas) distributed uniformly over the physical aperture, and each antenna element is excited with the same RF power. As a result, the aperture illumination is uniform and the illumination efficiency is 100% (i.e., illumination efficiency is 1). By contrast, the antennas discussed in the new IEEE Standard assume a circular aperture with non-uniform illumination (i.e., illumination efficiency less than 1), which reduces the effective area of the antenna and thereby increases power density in the near field. *See* Updated IEEE Standard, Section D.4.4.

Occupational/Controlled exposures and for General Population/Uncontrolled exposures, which for the Ku-band frequencies used by these HP terminals is a power density equal to 5 mW/cm^2 averaged over a six-minute period and 1 mW/cm^2 averaged over a thirty-minute period, respectively.[2]

As described in the definitional section below, this report analyzes the maximum power density levels in the vicinity of an HP antenna in three regions: (1) the far field, (2) the near field, and (3) near the main reflector surface. These radiation regions were analyzed using the definitions and formulas in Bulletin 65 for aperture antennas. Note that the SpaceX Services HP terminal is a flat phased array, such that the other region normally included in analyses for parabolic dishes (*i.e.*, between the main reflector and the feed) is not applicable in this case.[3] The results of this analysis reflecting the current version of Bulletin 65 are summarized in Table 1 (for the General Population/Uncontrolled version) and Table 2 (for the Occupational/Controlled version), each of which identifies the potential exposure under worst-case operating conditions.

The Commission's website indicates that Bulletin 65 is currently under review to reflect updated guidance to applicants.[4] However, in the interest of timely review of this application and in an abundance of caution, the results of an analysis reflecting the Updated IEEE Standard are summarized in Table 3 (for the General Population/Uncontrolled version) and Table 4 (for the Occupational/Controlled version), similarly identifying the potential exposure under worst-case operating conditions. By including these supplemental analyses, however, SpaceX Services does not concede that the new standard is appropriate for phased array antennas and looks forward to engaging with the Commission on a better tailored methodology.

HP Terminal Description

The HP terminal is a flat phased array capable of steering its beams to track NGSO satellites passing within its field of view. As the terminal steers the transmitting beam, it also adjusts the power to maintain a constant level at the receiving antenna of its target satellite to the extent possible, compensating for variations in antenna gain and path loss associated with the steering angle. At the phased array's equivalent of an "antenna flange," the highest transmit power is 4.0 W. There is no difference in transmit power between HP terminals at the center or edge of the spot or between clear sky or heavy rain conditions.

The HP terminal transmits bursts of information at designated times that are assigned to the terminal by the network. The duty cycle of the uplink transmissions is controlled by the network and independently monitored by the software controlling the HP terminal; this ensures that the transmit duty cycle of a terminal cannot exceed a specified level under any circumstances.

2 *See* 47 C.F.R. § 1.1310(e).

3 Bulletin 65 also calls for consideration of the transition region between near field and far field. However, the power density in the transition region will be less than the maximum power density in the near field and more than the minimum power density in the far field for the purpose of evaluating potential exposure. Accordingly, if the analysis demonstrates compliance for both the near field and far field, it necessarily demonstrates compliance for the transition region.

4 *See* Federal Communications Commission, "OET – Bulletins On-line," https://www.fcc.gov/general/oet-bulletins-line (visited January 20, 2022).

Explanation of the Analysis

The "Calculated Values" in Tables 1-4 are the exposure rates calculated using the formulae from Bulletin 65 for a system with continuous (100% transmit duty cycle) transmission. SpaceX Services HP terminals, however, transmit only short bursts of data periodically as instructed by the network and are neither designed for nor capable of continuous transmission. Therefore, in order to compute the effective radiated energy of a SpaceX Services HP terminal, the terminal's maximum possible transmitter duty cycle has been used to adjust the values calculated using the Bulletin 65 methodology. Accordingly, the calculated figures reflect the total potential for human exposure based on the length of time that the HP terminal transmits energy during the relevant period for consideration.

Results of Analysis

This analysis demonstrates that the SpaceX Services HP terminal is not a radiation hazard because the terminal does not exceed (1) the MPE limit of 1 mW/cm^2 averaged over a thirty-minute period when used in general population/uncontrolled environments, and (2) the MPE limit of 5 mW/cm^2 averaged over a six-minute period when used in occupational/controlled environments.

Conclusion

This radiation hazard analysis demonstrates that SpaceX Services HP terminals will not result in exposure levels exceeding the applicable MPE limits.

Definitions

1) Far Field Region

The far field region extends outward from the antenna surface, beginning at a distance of $\frac{0.6D^2}{\lambda}$ meters where the D is the diameter of the antenna. The maximum power density is calculated using the equation recommended in Bulletin 65.

2) Near Field Region

The near field region is a volume co-incident with the direction of the main beam extending outward from the antenna surface the length of the near field $\frac{D^2}{4\lambda}$ meters.

3) Transition Region

The transition region is located between the near field region and the far field region. This region has a power density that decreases with increasing distance. Therefore, the power density in the transition region will be less than the maximum power density in the near field and more than the maximum power density in the far field for the purpose of evaluating potential exposure.

4) Region Near the Antenna Surface

The power density near the antenna surface can be estimated as equal to four times the power divided by the area of the main reflector surface (phased array illumination is uniform).

TABLE 1: RADIATION FROM SPACEX HP PHASED ARRAY EARTH STATION (GENERAL POPULATION/UNCONTROLLED)

Input Parameters

Antenna Dimensions	D_1 = 0.52 m, D_2 = 0.48 m
Frequency	f = 14.25 GHz
Max Power into antenna	P_{max} = 4.0 W
Max EIRP	$EIRP_{max}$ = 6606.9 W $10\log(EIRP_{max}) = 38.2\ dBW$
Aperture efficiency [%]	η = 74.2%
Maximum Transmit Duty Cycle	DTx = 15.5%

Calculated Values

Wavelength	$\lambda = \frac{c}{f} = 0.0211\ m$
Area of Reflector	$A = 0.2496\ m^2$
Max Antenna Gain	$G_{max} = \frac{\eta 4\pi A}{\lambda^2} = 5251$ $10\log(G_{max}) = 37.2\ dBi$
Length of Near Field	$R_{nf} = \frac{D_1^2}{4\lambda} = 3.21\ m$
Beginning of Far Field	$R_{ff} = 0.6\frac{D_1^2}{\lambda} = 7.71\ m$

Maximum Power Density Calculations

Power Density in Far Field	$S_{ff} = DTx\frac{EIRP_{max}}{4\pi R_{ff}^2} = 0.14\ \frac{mW}{cm^2}$
Power Density in Near Field	$S_{nf} = DTx\frac{4\eta P_{max}}{A} = 0.74\ \frac{mW}{cm^2}$
Power Density at Antenna Surface	$S_{ref} = DTx\frac{4P_{max}}{A} = 0.99\ \frac{mW}{cm^2}$

TABLE 2: RADIATION FROM SPACEX HP PHASED ARRAY EARTH STATION (OCCUPATIONAL/CONTROLLED)

Input Parameters

Antenna Dimensions	$D_1 = 0.52$ m, $D_2 = 0.48$ m
Frequency	$f = 14.25$ GHz
Max Power into antenna	$P_{max} = 4.0$ W
Max EIRP	$EIRP_{max} = 6606.9$ W $10\log(EIRP_{max}) = 38.2\ dBW$
Aperture efficiency [%]	$\eta = 74.2\%$
Maximum Transmit Duty Cycle	$DTx = 33\%$

Calculated Values

Wavelength	$\lambda = \frac{c}{f} = 0.0211\ m$
Area of Reflector	$A = 0.2496\ m^2$
Max Antenna Gain	$G_{max} = \frac{\eta 4\pi A}{\lambda^2} = 5251$ $10\log(G_{max}) = 37.2\ dBi$
Length of Near Field	$R_{nf} = \frac{D_1^2}{4\lambda} = 3.21\ m$
Beginning of Far Field	$R_{ff} = 0.6\frac{D_1^2}{\lambda} = 7.71\ m$

Maximum Power Density Calculations

Power Density in Far Field	$S_{ff} = DTx\frac{EIRP_{max}}{4\pi R_{ff}^2} = 0.29\ \frac{mW}{cm^2}$
Power Density in Near Field	$S_{nf} = DTx\frac{4\eta P_{max}}{A} = 1.57\ \frac{mW}{cm^2}$
Power Density Off-axis Near Field (20dB below peak)	$S_{nf,off\ axis} = \frac{S_{nf}}{100} = 0.0157\ \frac{mW}{cm^2}$
Power Density at Antenna Surface	$S_{ref} = DTx\frac{4P_{max}}{A} = 2.12\ \frac{mW}{cm^2}$

Table 3: Radiation from SpaceX HP Phased Array Earth Station Reflecting Updated IEEE Standard (General Population/Uncontrolled)

Input Parameters

Antenna Dimensions	$D_1 = 0.52$ m, $D_2 = 0.48$ m
Frequency	$f = 14.25$ GHz
Max Power into antenna	$P_{max} = 4.0$ W
Max EIRP	$EIRP_{max} = 6606.9$ W $10\log(EIRP_{max}) = 38.2\ dBW$
Aperture efficiency [%]	$\eta = 74.2\%$
Maximum Transmit Duty Cycle	$DTx = 11.5\%$

Calculated Values

Wavelength	$\lambda = \frac{c}{f} = 0.0211\ m$
Area of Reflector	$A = 0.2496\ m^2$
Max Antenna Gain	$G_{max} = \frac{\eta 4\pi A}{\lambda^2} = 5251$ $10\log(G_{max}) = 37.2\ dBi$
Length of Near Field	$R_{nf} = \frac{D_1^2}{4\lambda} = 3.21\ m$
Beginning of Far Field	$R_{ff} = 0.6\frac{D_1^2}{\lambda} = 7.71\ m$

Maximum Power Density Calculations

Power Density in Far Field	$S_{ff} = DTx\frac{EIRP_{max}}{4\pi R_{ff}^2} = 0.10\ \frac{mW}{cm^2}$
Power Density in Near Field	$S_{nf} = DTx\frac{4P_{max}}{\eta A} = 0.99\ \frac{mW}{cm^2}$
Power Density at Antenna Surface	$S_{ref} = DTx\frac{4P_{max}}{A} = 0.74\ \frac{mW}{cm^2}$

TABLE 4: RADIATION FROM SPACEX HP PHASED ARRAY EARTH STATION REFLECTING UPDATED IEEE STANDARD (OCCUPATIONAL/CONTROLLED)

Input Parameters

Antenna Dimensions	D_1 = 0.52 m, D_2 = 0.48 m
Frequency	f = 14.25 GHz
Max Power into antenna	P_{max} = 4.0 W
Max EIRP	$EIRP_{max}$ = 6606.9 W $10\log(EIRP_{max}) = 38.2\ dBW$
Aperture efficiency [%]	η = 74.2%
Maximum Transmit Duty Cycle	DTx = 33%

Calculated Values

Wavelength	$\lambda = \frac{c}{f} = 0.0211\ m$
Area of Reflector	$A = 0.2496\ m^2$
Max Antenna Gain	$G_{max} = \frac{\eta 4\pi A}{\lambda^2} = 5251$ $10\log(G_{max}) = 37.2\ dB\text{i}$
Length of Near Field	$R_{nf} = \frac{D_1^2}{4\lambda} = 3.21\ m$
Beginning of Far Field	$R_{ff} = 0.6\frac{D_1^2}{\lambda} = 7.71\ m$

Maximum Power Density Calculations

Power Density in Far Field	$S_{ff} = DTx\frac{EIRP_{max}}{4\pi R_{ff}^2} = 0.29\ \frac{mW}{cm^2}$
Power Density in Near Field	$S_{nf} = DTx\frac{4P_{max}}{\eta A} = 2.85\ \frac{mW}{cm^2}$
Power Density Off-axis Near Field (20dB below peak)	$S_{nf,off\ axis} = \frac{S_{nf}}{100} = 0.0285\ \frac{mW}{cm^2}$
Power Density at Antenna Surface	$S_{ref} = DTx\frac{4P_{max}}{A} = 2.12\ \frac{mW}{cm^2}$