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Field Exposure Hazard for Space Station
Astronauts During Extravehicular Activity**

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COMPUTER ANALYSIS OF ELECTROMAGNETIC FIELD EXPOSURE HAZARD FOR SPACE STATION ASTRONAUTS DURING EXTRAVEHICULAR ACTIVITY

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Abstract

In order to estimate the RF radiation hazards to astronauts and electronics equipment due to various Space Station transmitters, the electric fields around the various Space Station antennas are computed using the rigorous Computational Electromagnetics (CEM) techniques. The Method of Moments (MoM) was applied to the UHF and S-band low gain antennas. The Aperture Integration (AI) method and the Geometrical Theory of Diffraction (GTD) method were used to compute the electric field intensities for the S- and Ku-band high gain antennas. As a result of this study, The regions in which the electric fields exceed the specified exposure levels for the Extravehicular Mobility Unit (EMU) electronics equipment and Extravehicular Activity (EVA) astronaut are identified for various Space Station transmitters.

I. Introduction

Predicting the near-field intensities (strengths) around an antenna and structures is important in assessing personnel and electronic equipment Radio Frequency (RF) exposure hazards. ¹Griffin experimentally studied the electromagnetic fields in the Space Shuttle payload bay due to the Ku-band antenna. ^{2,3}Murphy analyzed and presented the obtained Space Shuttle flight experiment data for the electromagnetic fields produced by the Space Shuttle S- and Ku-band antennas. No prediction techniques based on the rigorous

Computational Electromagnetics (CEM) techniques were presented in their studies.

There are concerns about the levels of electric field strength produced by the Space Station communication and tracking systems transmitters. Users of the Space Station designing scientific experiment payloads need to know the levels of electromagnetic fields in the Space Station environment. Astronauts are required to assemble and maintain the Space Station. To ensure the astronaut safety and mission success, the electromagnetic fields produced by the Space Station various transmitters need to be quantified. This study is to quantify and analyze the near-field strengths and power densities around the Space Station various UHF, S-, and Ku-band antennas, as shown in Fig.1, based on the rigorous computational electromagnetic methods.

In recent years, due to the advance of computer and computational electromagnetics, rigorous prediction methods have been developed which can be used in the early design stage to complement the costly experiment process. A reliable computational tool provides for the early detection of problems and helps to find the solutions. Predicting the electric field strengths close to an antenna is not trivial. Within the near field, far-field approximations are no longer valid, and hence more rigorous numerical techniques and more complex antenna models have to be applied. In this study, the Method of Moments

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(MoM), the Aperture Integration (AI) method, and the Geometrical Theory of Diffraction (GTD) method were used to compute the electric field intensities.

The regions in which the electric fields exceed the specified maximum permitted RF exposure to the Extravehicular Mobility Unit (EMU) electronic equipment and Extravehicular Activity (EVA) astronaut are identified for the Space Station various UHF, S-, and Ku-band antennas. Contour curves of equal electric field strength are presented at selected field strength levels.

II. Low Gain Antenna Analysis

A technique to predict the near field strengths has been developed by Wilton and Hwu^{4,7}. The electric field integral equation (EFIE) is formulated in the frequency domain using the vector and scalar potential description for an arbitrarily shaped, perfectly conducting structure consisting of surfaces and wires. The surfaces are modeled by planar triangular patches, and thin wires are modeled by piecewise linear segments. The integral equations are formulated via the equivalence principle, and the method of moments is applied to solve for the currents induced on the boundary surfaces of the system. The current distribution on the structure can be obtained for each specified excitation by solving the resulting matrix equation. From these currents, the near field can be obtained.

Let S denote a configuration of an antenna immersed in an incident electromagnetic field. In general, S may consist of a collection of conducting bodies S_B and wires S_W . An electric field E^i , defined to be the field due to an impressed source in the absence of S , is incident on and induces surface current J and total current I on S_B and S_W respectively. A pair of coupled integral equations for the configuration of wires and bodies may be derived by requiring the tangential component of the electric field to vanish on each surface. Thus we have

$$E_{tan}^i = (j\omega A + \nabla\Phi)_{tan} \quad (1)$$

where

$$A = \frac{\mu}{4\pi} \left(\int_{S_B} J \frac{e^{-jkR}}{R} dS' + \int_{S_W} \frac{I}{2\pi a(s')} \frac{e^{-jkR}}{R} dS' \right) \quad (2)$$

$$\Phi = \frac{j}{4\pi\omega\epsilon} \left(\int_{S_B} \nabla' \cdot J \frac{e^{-jkR}}{R} dS' + \int_{S_W} \frac{I}{2\pi a(s')} \frac{dI}{ds'} \frac{e^{-jkR}}{R} dS' \right) \quad (3)$$

and $R=|r-r'|$ is the distance between an arbitrarily located observation point r and a source point r' on S . In (2) and (3), the wavenumber $k=2\pi/\lambda$, where λ is the wavelength, ϵ and μ are the permittivity and permeability, respectively, of the surrounding medium, s' is the arc length along the wire axis, and a is the radius of the wire.

The current is written as a linear combination of subdomain basis functions with unknown expansion coefficients. These unknown coefficients are obtained by applying the method of moments for solving the integral equation,

The vector and scalar potentials A and Φ can be calculated at any point in space according to the formulas (2) and (3). Finite differences were used to approximate the gradient and curl operations, and hence to determine the near electric and magnetic fields at a given point. Detailed procedures may be found in Wilton and Hwu^{4,7}.

II.a. UHF Low Gain Antenna

The Space Station UHF antenna transmit frequency is 413.5 MHz. The electric field strength levels that an EVA astronaut or sensitive electronic equipment might experience from UHF antenna system operation are required to comply with specified RF radiation protection criterion.

A radiated power of 5 watts is used for the UHF quadrifilar helix antenna for the high power communication link between the Space Station and Shuttle Orbiter. The maximum permitted RF exposure to the EMU at the UHF frequencies is 3.16 V/m peak, as shown in Fig. 2. The maximum permitted RF exposure to the EVA astronauts at the UHF frequencies is shown in Fig. 3. The regions in which the electric fields are greater than the maximum permitted RF exposure to the EMU at the UHF frequencies are identified in Fig. 4. For 5 watts radiated power, a cylindrical region of 14 meter diameter and 10 meters in length, extending 9 meters forward and 1 meter backward

from the antenna and centered about the boresight axis, should be avoided to reduce the risk associated with excessive UHF antenna RF exposure to the EMU electronic equipment.

As shown in Fig. 3, the maximum permitted RF exposure to the EVA astronaut is an average power density of 1.378 mW/cm^2 (13.78 W/m^2), which is an electric field intensity of 102 V/m peak (or 72 V/m rms) at the UHF frequency of 413.5 MHz. For 5 watts radiated power, the electric field intensity criterion will not be exceeded by the UHF antenna if the EVA astronaut stays further than 0.5 meter from the antenna.

II.b. S-Band Low Gain Antenna

The Space Station S-band omni antenna transmit frequency is 2.265 GHz. The electric field strength levels that an astronaut or sensitive electronic equipment might experience due to S-band antenna system operation are required to comply with specified RF radiation protection criterion.

Forty watts of maximum radiated power is used in this analysis for the S-band quadrifilar helix antenna. The maximum permitted RF exposure to the EMU at the S-band frequencies is 106 V/m peak as shown in Fig. 1. The regions in which the electric fields are greater than the maximum permitted RF exposure to the EMU at the S-band frequencies are identified in Fig. 5. Based on the results obtained for the 40 watts radiated power, a cylindrical region of 1.1 meter diameter and 0.8 meter in length, extending outward from the antenna and centered about the boresight axis, should be avoided to protect the EMU electronics.

As shown in Fig. 2, the maximum permitted RF exposure to the EVA astronaut at the S-band frequencies is an average power density of 5 mW/cm^2 (50 W/m^2), which is an electric field intensity of 194 V/m peak (or 137 V/m rms). Based on the results obtained for 40 watts maximum radiated power, as shown in Fig. 5, the electric field intensity criterion for the EVA astronaut will not be exceeded by the S-band antenna provided the EVA astronaut stays further than 0.5 meter from the S-band omni antenna.

III. High Gain Antenna Analysis

Traditionally, the AI method has been widely used for calculating aperture antenna patterns in the forward region, which includes the main beam and the near-in sidelobes. The physical optics approximation is used. The approximation fails in the shadow region of the aperture antenna because the currents on the shadow side of the antenna are neglected. For the calculation of these wide-angle sidelobes, the GTD has been found very efficient and accurate. The combination of AI and GTD methods was applied in this study for the numerical analysis of the high gain horn and reflector antennas.

The AI technique has been widely used for calculating aperture antenna patterns in the forward region. The approximations used in this technique are: The current density is zero on the shadow side of the antenna. The discontinuity of the current density over the rim of the antenna is neglected.

The radiation field of an aperture antenna can be computed by integrating the field distribution on the aperture. For an aperture antenna with aperture defined in the X-Y plane and pointed along the Z-axis, the radiation field (E) can be computed by

$$E = \frac{jk}{2\pi} \iint (F_x e_x + F_y e_y) \frac{e^{-jkR}}{R} dx dy, \quad (4)$$

where e_x and e_y are the x- and y-components of the aperture field. F_x and F_y are the modified vector element patterns associated with two Huygen's sources. R is the distance between a field point and a source point. The wavenumber $k = 2\pi/\lambda$, where λ is the wavelength.

In the numerical integration, the aperture is treated as a collection of overlapping subapertures. Each subaperture is square in shape and consists of four adjacent grid squares. The field distribution for each subaperture is triangular which permits a piecewise linear approximation to the overall aperture field distribution. Detailed descriptions of the method can be found in Rudduck⁸.

GTD gives valid results in the shadow region of horn and reflector antennas since the currents on either side of the edge are accounted for implicitly. This method is finding increasing

application to horn and reflector antennas for the antenna patterns in far-out sidelobe and backlobe regions.

At high frequencies the scattering fields depend on the electrical and geometrical properties of the scatterer in the immediate neighborhood of the point of reflection and diffraction. Thus, the total fields (E^{tot}) can be obtained by summing up the individual contributions of the direct field (E^{dir}), reflected field (E^{ref}), and diffracted field (E^{dif}), as follows:

$$E^{tot} = E^{dir} + \sum_{n=1}^N E_n^{ref} + \sum_{m=1}^M E_m^{dif}. \quad (5)$$

The diffracted fields are related to the incident fields by means of diffraction coefficients. In a similar way, the reflected fields are obtained using reflection coefficients. Since the diffracted field is determined solely by the incident field and the local nature of the scattering surface, it is possible to derive a diffraction function relating the incident field to the diffracted field for a certain scatter geometry, a so called canonical configuration. Detailed descriptions of the method can be found in Rudduck⁸ and Kouyoumjian⁹.

III.a. S-Band Steerable High Gain Antenna

The S-band subsystem, also known as the Assembly/Contingency Subsystem (ACS), is a bi-directional RF link utilizing the Tracking and Data Relay Satellite System (TDRSS) S-band Single Access (SSA) service to receive audio, software uploads, and commands from the ground station, and to transmit audio and core element telemetry to the ground station. In addition, the S-band subsystem is utilized to support ground based tracking services for station orbit determination. The transmit frequency for the S-band antenna is 2.265 GHz. The near-field intensity levels around the Space Station produced by the S-band high gain antenna are a real concern because of the high radiated power.

A maximum of 40 watts (16 dBW) and a minimum of 21.4 watts (13.3 dBW) radiated power (P_r) at the antenna aperture were estimated for the S-band high gain steerable horn antenna. These estimates are based on the maximum estimated Effective Isotropic Radiated Power EIRP (29 dBW), the minimum specified EIRP (26.3 dBW)

and the specified minimum antenna gain (13 dBic):

$$P_{r_max}(16\text{dBW})+G(13\text{dBic})=EIRP_{_max}(29\text{dBW})$$

$$P_{r_min}(13.3\text{dBW})+G(13\text{dBic})=EIRP_{_min}(26.3\text{dBW})$$

In the aperture integration, a TE_{11} mode aperture field distribution is assumed for the S-band conical horn antenna. The square grid size was set to be $0.01 \lambda^2$. The results correlate well with that using $0.0025 \lambda^2$ square grid size. To further validate the S-band antenna model used in the computer simulation, experimental measurements were performed in the antenna test range. Good agreement is obtained for the computed and measured antenna radiation patterns. Detailed descriptions and data can be found in Hwu¹⁰.

The maximum permitted RF exposure to the EMU is 106 V/m peak at the S-band frequencies. The regions in which the electric fields are greater than the maximum permitted RF exposure to the EMU at the S-band frequencies are identified in Fig. 6. Based on the results obtained for the maximum radiated power (40 watts or 16 dBW), a cylindrical region of 1 meter diameter and 2.3 meters in length, extending outward from the antenna and centered about the boresight axis, should be avoided to reduce the risk associated with excessive S-band antenna RF exposure to the EMU electronic equipment. The maximum permitted RF exposure to the EVA astronaut is an average power density of 5 mW/cm^2 (50 W/m^2) or an electric field intensity of 194 V/m peak (or 137 V/m rms) at the S-band frequencies. Based on the results obtained for a maximum radiated power (40 watts), the electric field intensity criterion will not be exceeded by the S-band antenna if the EVA astronaut stays outside of a cylindrical region of 0.5 meter diameter and 1.3 meters in length, extending outward from the antenna and centered about the boresight axis.

III.b. Ku-Band Steerable High Gain Antenna

The Ku-band subsystem is a single direction RF link utilizing the TDRSS Ku-band Single Access (KSA) service to transmit payload data and video to the ground station. The transmit frequency for the Ku-band antenna is 15 GHz. The near-field intensity levels around the Space Station produced by the 6-ft. reflector antenna are a matter for concern.

A maximum of 10 watts (10 dBW) and a minimum of 4 watts (6 dBW) radiated power (P_r) at the antenna aperture were estimated for the Ku-band reflector antenna. These estimates are based on the maximum allowable EIRP (56 dBW), the minimum allowable EIRP (52dBW), and the specified minimum antenna gain (46 dBic):

$$P_{r_max}(10\text{dBW})+G(46\text{dBic}) = \text{EIRP}_{_max}(56\text{dBW})$$
$$P_{r_min}(6\text{dBW})+G(46\text{dBic}) = \text{EIRP}_{_min}(52\text{dBW})$$

In the aperture integration process, the square grid size was set to be $1 \lambda^2$. The results agree well with that using $0.25 \lambda^2$ square grid size. In the numerical integration, the aperture field is approximated by a collection of overlapping subapertures with triangular field distribution. As a consequence of this piecewise linear approximation of the aperture field, the grid size can be increased to reduce the field sample number without losing accuracy. The simulations were carried out on a Cray X-MP/EA 464 supercomputer. To further validate the Ku-band antenna model used in the computer simulation, experimental measurements were performed on the antenna test range. Good agreement was obtained for the computed and measured antenna radiation patterns. Detailed descriptions and data can be found in Hwu¹¹.

The maximum permitted RF exposure to the EMU is 20 V/m peak (or 14.14 V/m rms) at the Ku-band frequencies. The regions in which the electric fields are greater than the maximum permitted RF exposure to the EMU at the Ku-band frequencies are identified in Fig. 7. Based on the results obtained for a maximum of 10 watts radiated power, a cylindrical region of 2.5 meters diameter and 230 meters in length, extending outward from the antenna and centered about the boresight axis, should be avoided to protect the EMU electronic equipment and reduce the risk associated with the Ku-band antenna RF exposure.

The RF radiation protection criterion specified for the EVA astronaut is an average power density of 5 mW/cm^2 (50 W/m^2) or an electric field intensity of 194 V/m peak (or 137 V/m rms) at the Ku-band frequencies, same as for the S-band frequencies. Based on the results obtained for a maximum of 10 watts radiated power, the 194 V/m peak (or 137 V/m rms) electric field intensity criterion will not be exceeded by the Ku-band antenna so long as the

EVA astronaut stays outside of a cylindrical region of 2.5 meters diameter and 5 meters in length, extending outward from the antenna and centered about the boresight axis.

IV. Concluding Remarks

In this paper, the electric field strengths due to the Space Station UHF, S-band and Ku-band transmitters was presented. The rigorous method of moments, aperture integration method and the geometrical theory of diffraction method were applied in this study. These computational techniques can be used in the early design stage, when the hardware is not yet available, to identify and solve problems earlier. They can also complement the costly experiment process in the system performance evaluation. As a result of this study, the regions in which the electric fields exceed the specified maximum permitted RF exposure to the EMU electronic equipment and astronaut are determined. This information is important in assessing personnel and electronic equipment RF exposure hazards and is useful for the users of the Space Station designing scientific experiment payloads to be operated in the Space Station environment.

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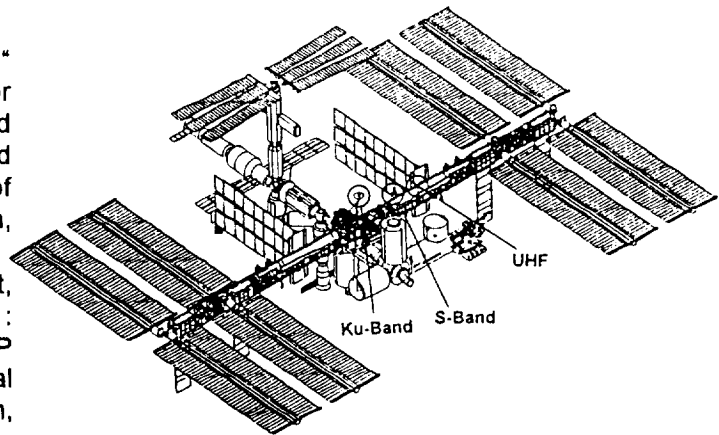


Fig. 1. Space Station various antennas.

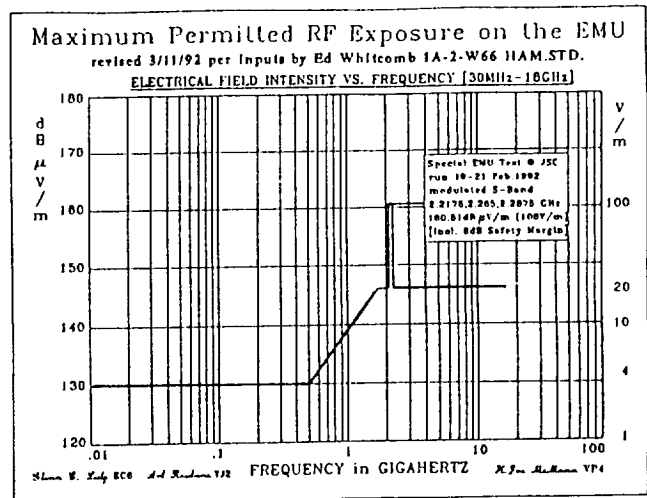


Fig. 2. The maximum permitted RF exposure on EMU electronics.

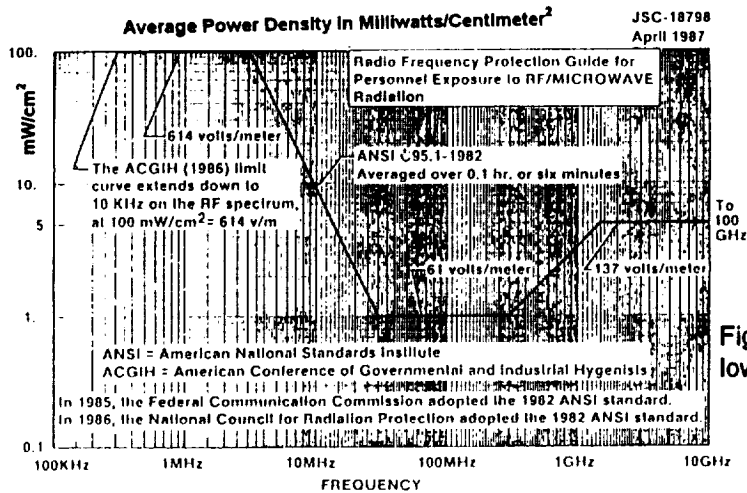


Fig. 3. The maximum permitted RF exposure on EVA astronauts.

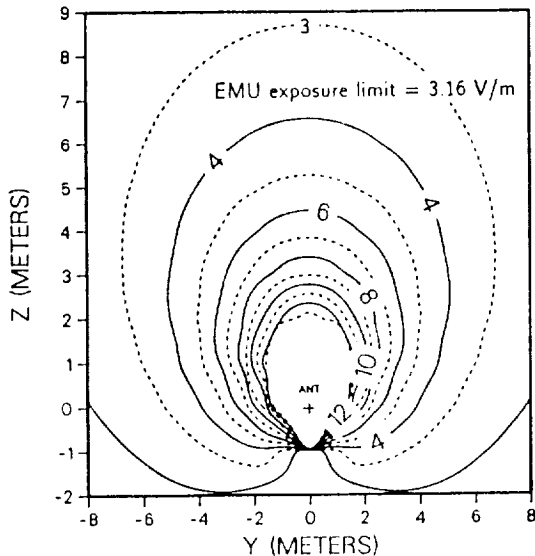


Fig. 4. The electric fields produced by the UHF low gain antenna with 5 watts radiated power.

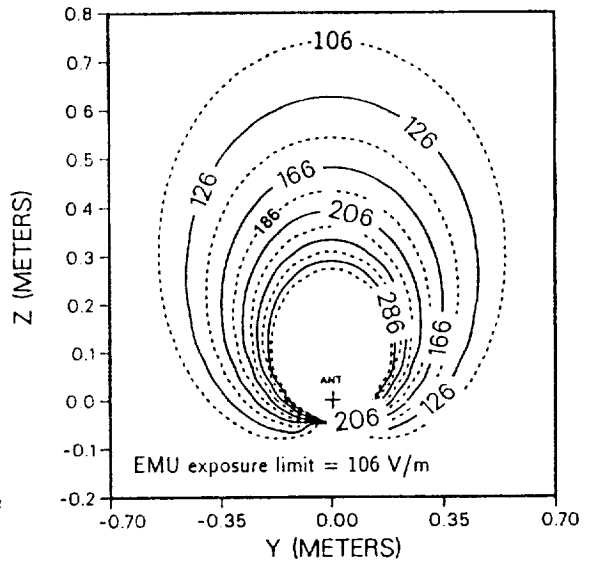


Fig. 5. The electric fields produced by the S-band low gain antenna with 40 watts radiated power.

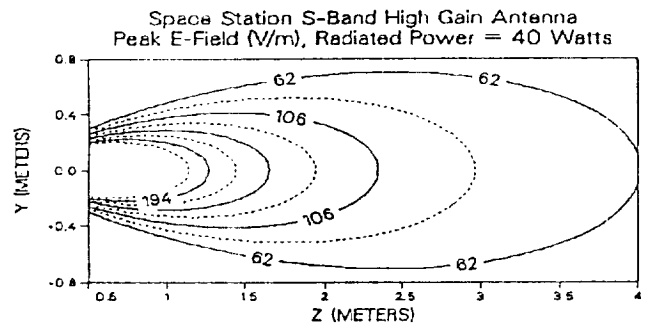


Fig. 6. The electric fields produced by the S-band high gain antenna with 40 watts radiated power.

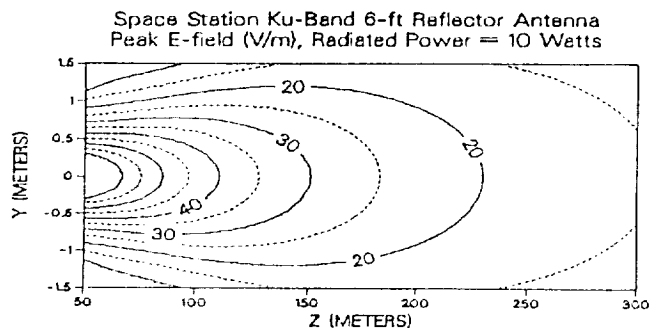


Fig. 7. The electric fields produced by the Ku-band high gain antenna with 10 watts radiated power.