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INTERACTIONS BETWEEN THE SPACE STATION AND THE ENVIRONMENT

A Preliminary Assessment of EMI

G. B. Murphy
H. B. Garrett

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109

ABSTRACT

A review of the interactions between proposed Space Station systems/payloads and the environment that contribute to electromagnetic interference has been performed. Seven prime sources of interference have been identified. These are: The Space Station power system; active experiments such as beam injection; ASTROMAG; ram and wake density gradients; pick up ions produced by vented or offgassed clouds; waves produced by current loops that include the plasma and structure; arcing from high voltage solar arrays (or possible ESD in polar orbit). This review indicates that: minimizing leakage current from the 20 kHz power system to the structure; keeping the surfaces of the Space Station structure, arrays, and radiators non-conducting; minimizing venting of payloads or systems to non-operational periods; careful placement of payloads sensitive to magnetic field perturbations or wake noise; and designing an operational timeline compatible with experiment requirement are the most effective means of minimizing the effects of this interference. High degrees of uncertainty exist in the estimates of magnitudes of gas emission induced EMI, radiation of 20 kHz and harmonics, ASTROMAG induced interference, and arc threshold/frequency of the solar array. These processes demand further attention so that mitigation efforts are properly calibrated.

1.0 INTRODUCTION

The Space Station, as a resource laboratory for a wide range of scientific experimentation, must provide an environment compatible with many (sometimes conflicting) objectives. The purpose of this paper is to summarize an investigation into the major sources of contamination of the external electromagnetic environment. This environment, specified in SSP 30420, limits narrowband and broadband electric fields to levels illustrated in figures 1a and 1b and limits magnetic fields to levels shown in figure 2. The ElectroMagnetic Environment (EME) requirements go beyond that traditionally accepted for space-borne equipment (MIL-STD-461C, part 3). The reasons for this difference are not particularly mysterious; the requirements for the Space Station are driven simply by a need for low background emission for sensitive experiments instead of the receiver interference and electronic compatibility issues encountered in typical military or space hardware.

The Space Station is of unprecedented size, carries experiments that can disturb or interact with the background environment, has a power system much different than has ever been flown on a spacecraft, and outgasses/vents products which affect the environment. All of these factors must be considered in assessing which particular design options, hardware configurations, or operational scenarios may adversely affect the EME, and cause the station to be an unsuitable carrier for certain instrumentation. We have examined possible interactions between the hardware or effluents and the natural environment. From this examination, we have identified seven processes that may adversely alter the EME. These processes are:

a. leakage of 20 kHz and harmonics from the power system,
b. waves induced by ionospheric currents closing through the large Space Station structure,
c. possible plasma trapping and EMI generated by the ASTROMAG superconducting magnet
d. broadband electromagnetic noise from possible arcing of the solar array,
e. Ram/wake plasma density gradients,
f. ionization of effluent clouds,
g. waves induced by particle accelerators (e.g. electron beams)

We shall examine each of these processes in detail, assess the impact of each on EME, and recommend courses of action that minimize the effects.

The specification for Space Station defines field disturbances according to broadband electric, narrowband electric, and narrowband magnetic. Before we begin detailed discussion of each of the physical processes, we shall define more precisely the meaning of these terms. This will allow us to determine which processes impact which specifications.

'Broadband emissions' can be created by two fundamentally different processes. The first is what we shall call impulse noise. That noise is generated by a system producing a pulse of current in a conductor that is short in the time domain (broad in the frequency domain). This noise typically has its highest frequency component inversely proportional to the rise time, and its lowest frequency component inversely proportional to the duration of the pulse. The voltage phase is coherent across the band. This type of noise can be produced by relay closures, arcs, etc. When detected by an 'antenna', the noise voltage will be proportional to the bandwidth (BW) and the noise power proportional to $(BW)^2$.

A second type of broadband emission is continuous in both time and frequency. When observed on an oscilloscope or listened to in the audio frequency domain, it appears as 'white' noise. This emission results from physical processes associated with the thermal motion of electrons in electronic systems, and, as we shall see, from certain plasma processes. The spectrum is not always 'white'; that is, the frequency domain may reveal slopes or cutoffs but the noise is broadband in the sense that the noise frequency components are continuous across the band of interest. This type of noise has the detected voltage proportional to $(BW)^{1/2}$ and detected power proportional to BW and differs from impulse noise in that its phase is random across the band. Broadband noise of this nature is particularly annoying in communication systems because the signal to noise ratio, assuming the desired signal is narrowband, is inversely proportional to BW.

Narrowband emissions, both electric and magnetic, can be regarded as continuous in the time domain and sharply peaked in the frequency domain. Detected voltages add in an RMS manner since different sources are (in general) incoherent. Likewise the signal power, once within the receiver bandwidth, is independent of bandwidth.

It should be noted that the wide variety of signals encountered in nature are not always so easily classified. Many processes produce noise with power spectral density proportional neither to BW or BW^2 but somewhere in between. In examining interactions between Space Station components and the natural environment, it will be necessary to classify sources of interference that fit none of these definitions precisely.

We must further note that although the process of modulating current through a conductor produces both electric and magnetic fields, not all of the processes producing waves in a plasma produce electromagnetic waves. Many produce only 'electrostatic' waves. These are not like free-space electromagnetic waves and, along with having no magnetic component, may have their electric field along the direction of propagation (or at some angle) instead of transverse. An excellent review of plasma waves occurring in nature is given by Shawhan [1985]. Many plasma waves do not propagate at all in the strictest sense but their electric fields must be considered in interference calculations just as one must consider near-field evanescent waves near a dipole antenna. We shall, in our analysis, consider interference fields near the Space Station structure and not concern ourselves with propagation effects unless appropriate.

2.0 RADIATION OF 20 KHZ AND HARMONICS

This radiation, which will be both electric and magnetic, is from two sources. The first source is leakage because of imperfect shielding of the transmission line. The second source of fields are those produced by current that is present in the structure (chassis) and exists because of finite impedance between elements of the power system and structure ground. As we shall see, this chassis current can easily dominate the EME at 20 kHz and harmonics.

2.1 RF Radiation

Let us first consider 20 kHz radiation from the transmission line. A number of studies have focused on the trade-offs required in choosing a power system for Space Station [Hansen, 1987; Rice, 1986; Simon and Nored, 1987; Renz et al, 1983], but few have dealt in more than a qualitative way with the potential for EMI. One study by Pistole [1985] was focused on EMI considerations but used three-phase 200 volt AC for the primary and assumed flat bus bars for distribution in the modules. As with all EMI analyses, the end result is very sensitive to system configuration. The transmission line being considered for 20 kHz primary distribution is a double-sided strip line design [Schmitz and Biess, 1989]. Here we examine the work of Schmitz and Biess [1989], since those measurements reflect most accurately the current system configuration.

The Schmitz and Biess tests were performed in a screen room with the cable driven by a prototype 20 kHz resonant inverter. Electric fields were measured with the source end at 440 V and the load end open. Magnetic fields were measured with a resistive load designed to draw 60 amps. The sensor loop was placed in three planes: one parallel and two perpendicular to the transmission line. Figure 3a shows the average radiated magnetic field (at one meter) along the length of the transmission line and compares it to the current SSP 30237 limit and source current. Figure 3b illustrates the measured narrowband electric field (also at one meter) and compares it to 30237. The harmonic content of the current and voltage may be load dependent, therefore these tests must be used for comparing harmonic content of the emissions to that of the source. Note that, indeed, the radiated field is closely related to the source current and that high frequency emission is somewhat enhanced. Unfortunately, the power system design is not yet firm enough to state that these measurements represent what can be expected in the completed system and only give us a first order estimate.

2.2 Chassis Current

AC currents may also be induced in the chassis by stray capacitance between the cable, converters, etc. and the chassis. These currents must be distinguished from those in the transmission line. Stray currents that traverse the length of the Space Station structure cause the structure to behave like a loop antenna. Whether the structure is insulating on its surface or conducting determines the interaction between this 'antenna' and the plasma.

If the structure is conductive it will have a significant sheath surrounding it due to the v x B motional potential. This sheath has been shown to be capable of conducting noise over large distances very efficiently [Laurin et al, 1989]. Sheath waves are guided waves that are conducted along conductors surrounded by sheaths much like waves in a coaxial cable transmission line. Anywhere sheaths overlap, the waves can propagate. The significance of this is that noise generated locally can be conducted along Space Station structures to other cables which may be sensitive to this frequency. Unless the sheath is forced to collapse, the waves propagate with little attenuation. Therefore, as a worst case scenario, we assume that cables placed anywhere externally on the Space Station may be within a sheath which is "connected" to a source of noise via the "structure-sheath coax transmission line". The electric field and magnetic field within the sheath depend on the size of the sheath, various plasma parameters, and the frequency of interest. Cut-off for this propagation, when the structure and sheath are in a magnetic field, will be somewhere near 1/2 f_e (electron gyrofrequency) or about 500 kHz. This allows propagation of 20 kHz and the principal harmonics. The radial and longitudinal components of the electric field change as the frequency increases but, for 20 kHz and the third harmonic, it will be mostly radial.

It is very difficult to predict the magnitude of the interference. A worst case estimate calculates the electric and magnetic fields near a current loop where the value of the current is chosen to be the expected leakage current. The distance from the loop is chosen to be the sheath size (~10 cm) instead of the actual physical separation. In the case of Space Station, the loop is chosen to include an electrical element, such as the cable or cable tray, and the truss structure. Assuming a worst case loop area of 100 m^2 (2m x 50m) and a measurement distance of 10 cm, the E and H fields in the sheath may be approximated by:

$$E \simeq 40 + 20 \log (I_1/I_0) \text{ dBv/m at 20 kHz}$$

$$E \simeq 50 + 20 \log (I_2/I_0) \text{ dBv/m at 60 kHz}$$

$$H \simeq 200 + 20 \log (I/I_0) \text{ dBpT}$$

where I_0 is 1 amp and I is the assumed leakage current

Thus for an allowed leakage current of 1 ma the worst case fields observed in the sheath would be:

$$E \simeq -20 \text{ dBv/m}$$

$$H \simeq 140 \text{ dBpT}$$

It is suggested that a serious effort be undertaken to determine the affect of geometry, to analyze the effects of insulating the struts to minimize sheaths, and to develop methods for ground test, so that the extent of this problem of narrowband electric/magnetic field interference may be determined and appropriate susceptibility tests be developed. If it is possible to ensure attenuation of sheath waves, much higher leakage currents can be allowed. For example, the field at 1 meter from the ground loop discussed above is down by 40 dB for electric and 60 dB for the magnetic components which, although still an issue when compared to spec, are much more tolerable from an interference standpoint. Making the surface of the struts non-conducting will reduce their sheath and help this problem.

3.0 IONOSPHERIC CURRENT CLOSURE

In addition to AC currents coupled to the structure by the power system, parts of the structure which are uninsulated conductors can couple to the ionosphere causing DC current flow.

The DC current flow is induced by the potential difference (with respect to the plasma rest frame) between different ends of the conductor. This potential is of magnitude

$$\phi = \mathbf{v} \times \mathbf{B} \cdot \mathbf{l}$$

where
- $\mathbf{v}$ = spacecraft velocity vector
- $\mathbf{B}$ = magnetic field vector
- $\mathbf{l}$ = vector distance between points that contact the plasma

If the conductor is exposed along its length, the <u>electric field</u> in the sheath around the conductor can induce <u>lower hybrid waves</u> [Hastings et al, 1988]. The part of the conductor that <u>collects current</u> from the plasma causes the production of <u>Alfven waves</u>.

It is not our purpose in this paper to discuss the physics of how conductive objects moving through a magnetic field in the presence of a plasma produce waves. The reader is referred to Barnett and Olbert, [1986]; Hastings et al, [1988]; for a discussion of the production of lower hybrid waves by AC currents in the structure. Drell et al [1965] is a good source for an introduction to the phenomena of Alfven waves induced by passive current collection. Acuna and Ness [1976] observed these waves in the Jovian environment. Our brief discussion here is based on these and other references in the context of the Space Station.

3.1 <u>Alfven Waves</u>

The Alfven wave is a hydromagnetic wave <u>stationary</u> in the Space Station reference frame. The power loss due to this wave (and thus its magnitude) depends on the conductive area perpendicular to **B** and factors that determine current collection such as surface potential and plasma density. An analysis of the passive DC currents induced by motional EMF in the Space Station system, assuming the solar array surfaces and modules are conductive and the structure is non-conductive, was performed. This is a worst case scenario and the results can be summarized as follows.

Power loss (drag) for Space Station is limited by ion current collection in the ram direction and photoelectron emission in the wake for the altitude range of 200-400 km. If the Space Station solar arrays are conductively coated and bonded to the chassis, the current limit is about 500 ma (eight wings at 60 ma each). This results in a power loss of ~3 watts for a plasma density of 2e5/cm^3 and in an electromagnetic drag which is small compared to the aerodynamic drag.

The magnetic field in the Alfven wing will have an average magnitude (at 2e5/cm^3) of about 5 nT indicating that sensitive magnetometers which typically desire noise levels of .1 nT may be affected and must be carefully placed to avoid the wings.

Although when doppler shifted into the Space Station reference frame, the Alfven wave becomes stationary, the plasma density, current collection area, and magnetic field spatial and temporal variations cause the Alfven wave to have low frequency components. An upper bound for these variations is a DC value of 5 nT. Spatial variations will have a frequency cut-off for values higher than v/L where L is the characteristic array (or current collector) dimension and v is the spacecraft velocity. This is between 50 and 100 Hz for Space Station.

Thus we see that the worst case Alfven wave disturbance creates DC and low frequency components of the magnetic field. This disturbance will most likely be an issue only for sensitive magnetometers that attempt to measure currents in the plasma or map the finely detailed temporal variation of the earth's field. These worst case fields are produced assuming that the solar arrays, placed at each end of the structure, are conductive and tied to chassis. This allows for a large $\mathbf{v} \times \mathbf{B} \cdot \mathbf{l}$ potential and maximum current collection. If the arrays are conductive but <u>not</u> tied to chassis these worst case fields can be reduced by about a factor of 5. If the arrays and structure are insulated from the plasma and the Space Station is grounded to the plasma at a central location (e.g. the pressurized modules), the fields are reduced almost an order of magnitude. Careful placement of magnetometers may avoid the disturbed field in the Alfven wing, but a detailed analysis will need to be performed once the Space Station geometry and conductivity of its many surfaces are determined.

3.2 <u>Lower Hybrid Waves</u>

Lower hybrid waves are electrostatic waves with their electric field approximately perpendicular to the local magnetic field. They can be excited by the components of sheath electric fields perpendicular to B which exist around conductive Space Station structures. Both DC and AC components of the sheaths can excite such waves. Hastings and Wang [1989] analyze this process in detail for the Space Station case and note that the radiation generated (in the far field) depends sensitively on the geometry and conductivity of the structure. Barnett and Olbert, [1986] and Hastings et al [1988] also discuss this wave generation mechanism.

The component of radiation due to the DC sheath (and a DC current flow through the structure) is a continuum emission. That is, it is pseudo-broadband and, in the plasma rest frame, will exist in the frequency range $f_{eh} < f < f_e$ or, for the Space Station

$$5 \times 10^3 \text{ Hz} \leq f \leq 9 \times 10^5 \text{ Hz}$$

Although the references cited above analyze the radiation produced in the far field rest frame and we are interested in the near field moving frame, some of the results can guide us in designing a system which minimizes the generation of these waves.

The power loss (Hastings and Wang [1989]) can be written as:

$$P_{rad} = I^2 Z = \left(\frac{vxB \cdot l}{Z_{rad}+R}\right)^2 Z_{rad}$$

where Z_{rad} = radiation impedance
R = impedance of structure
$vxB \cdot l$ = motional potential
I = ionospheric current closing through structure

This can be minimized by decreasing the current collected from the plasma (decreasing collecting area, decreasing motional potential) and by maximizing the mismatch between the structure impedance and Z_{rad}. Power loss has been calculated by Hastings [1989] to be on the order of a watt for reasonable values of structure resistance and a geometry that has solar arrays with conductive surfaces. This is similar in magnitude to worst case power losses calculated for the Alfven waves.

Since Z_{rad} is very sensitive to geometry and plasma composition, the best approach for minimizing this noise source seems to be to limit, as much as possible, the current collection which is consistent with the recommendations of the previous sections. Calculation of the Doppler shifted spectrum and an estimate of wave magnitudes has not yet been completed and remains to be addressed theoretically.

4.0 ASTROMAG

The large superconducting magnet, ASTROMAG, accepted as an attached payload on Space Station, has been analyzed to determine the levels of electromagnetic disturbance. The DC magnetic field, possible effects of quenching, plasma wave emissions, and helium leakage have all been examined. The former two will be described in more detail in the following paragraphs. It should be noted that it is virtually impossible to predict with an accuracy better than an order of magnitude what wave emission levels may be. The interaction between the ASTROMAG magnet and the ionosphere constitutes a fundamental plasma experiment which has not been performed in the laboratory. Bounds can be placed on the available energy for wave emission but it is not possible to assess how much of the energy is channelled into any particular wave mode without complex model development.

4.1 DC Fields

The magnet is set up for nominal operation as a quadrupole so as to minimize the resultant torque by the earth's field [Sullivan et al, 1989]. The remaining torque is comparable to aerodynamic drag torque assuming a 30-40 meter distance from Space Station center of gravity. The DC fields will, however, obviously affect sensitive magnetometer measurements. The coil's field reaches a level equivalent to the earth's field at a distance of 15-20 meters. Since this field falls off as r^5, at a distance of ~75 meters (which is about as far away as you can get from ASTROMAG), the field contributes ~2.5×10^{-4} G or about .1% to the background. If this interference field were constant, it should be possible to subtract it from any measurement. However, it is important to realize that in order to subtract this interference field one needs to know alignment accurately. For example a 1° alignment error results in a change of several hundred nT at 20 m which is considerably greater than the signals measured by sensitive magnetometers. Additionally, if alignment changes are due to thermal and dynamic effects, there will be a time varying component to this field. If sensitive magnetometers are flown, they should be located as far as possible from ASTROMAG and the magnet may have to be off for their measurements.

4.2 Quench

If the coil should suddenly lose its superconductive properties (e.g., loss of coolant, shorted coil, micrometeroid impact, etc.), the magnet will quench. How a superconducting magnet quenches is part of its design. A probable I(t) during quench has been obtained from the Magnet Lab at MIT for a typical design configuration. The maximum dI/dt is ~1000 amp/s and the characteristic decay time is ~1 s. This quench is quite slow compared to the 10^{10} amps/s dI/dt and nanosecond rise times for ESD events. Radiation from this process would appear to be of low frequency and pose no hazard to Space Station or payload systems. It is very important, however, that this quench be treated carefully during instrument development to assure that no failure modes are introduced that allow faster current rise times. Rise times 10 - 100 times greater may begin to be of concern. The effect of the quench on the plasma confined in its magnetosphere has not been analyzed.

4.3 EMI from Plasma Processes

As discussed above, the ASTROMAG magnet is itself an interesting plasma experiment. We have studied the various mechanisms that could lead to plasma energization and conclude that it is likely that a substantial plasma density can build on the closed field line region and that a significant fraction of electrons will be accelerated to energies high enough to cause molecular excitation and generation of a broad spectrum of waves. Since we cannot explicitly predict the wave energy likely in a specific frequency band, we have estimated the total energy available for excitation processes. The result, assuming a background ionospheric density of 10^5 electrons/cm^3 and 10^8 neutrals/cm^3, is that the two sources of free energy, impinging neutrals and ions, are estimated to contribute 20 - 200 mwatts of energy to waves and optical emissions near the Space Station.

Table I summarizes the possible types of radiation, the frequency ranges, and potential sources of plasma waves. Only the lower hybrid and cyclotron waves can be bounded in magnitude based on analogous measurements of wave energy induced by pick-up ions on the Shuttle [Gurnett et al, 1988]. This magnitude is ~1 mv/m and has been classified as narrowband even though it occurs over a broad frequency range.

No emissions are expected to be at a level high enough to interfere with electronic systems but they may interfere with sensitive instruments by raising the background noise level. Only two precautions can be taken to minimize EMI (and other effects such as glow) from the magnet. First, minimize gas emissions (especially species with low ionization potential and easily excitable metastable states) near the magnet's "magnetosphere" and second, simply turn the magnet off if it creates background noise that is unacceptable to other experiments. Designers of the magnet as well as the operational timeline should be sensitive to these issues.

5.0 ARCS AS A SOURCE OF BROADBAND NOISE

Arcs are transient events that produce true broadband electromagnetic noise. In the low altitude low inclination orbit of Space Station the only serious candidates for environmentally induced arcs are the photovoltaic arrays. A number of experiments, notably the PIX flight experiments [Grier, 1985; Purvis, 1985; Ferguson, 1986] have studied the problem of arcing for negatively biased solar arrays. Two fundamental questions remain unanswered: 1) How does the arc onset voltage depend on cell geometry, and on the background plasma/neutral density/composition? 2) How does arc rate scale with these parameters?

Only two theories known to the authors address these issues. Jongeward [1985] suggests that a contaminant insulating layer on the interconnects interacts with ions collected from the plasma to produce fields strong enough to generate high electron emission currents leading to avalanche ionization. Hastings et al [1989] theorize that gases desorbed from cover glasses by electron bombardment produce a neutral density in the vicinity of the interconnect that is high enough to lead to breakdown. Unfortunately, results of preliminary experiments conducted on Space Station solar cells are not yet available. 160 V was chosen for the operational voltage primarily because no arcing was observed with the PIX array below 200 V. However, since we do not yet know definitively how the phenomena scales with cell geometry and environmental conditions, we can not be certain that -160 V is below arc threshold. Validation must wait until tests are completed under realistic flight conditions.

Experiments with older cell geometries suggest that the arc onset voltage and frequency may be dependent on plasma and/or neutral density [Snyder, 1984]. Both theories suggest that background neutral density as well as plasma density and composition may be critical. The Hastings et al [1989] theory suggests that temperture may be a factor since it affects outgassing. We begin to see an example of a synergistic effect. Thruster operations, local offgassing, and ram surface pressure all act to enhance the local density, as would any environmentally induced outgassing. The worst case envi- ronment is (even without thruster gas effects) expected to show about one order of magnitude increase in plasma density and about two orders increase in neutral density as a result. For the purpose of this paper, we therefore assume by extrapolation of current data [Grier, 1985; Purvis, 1983; Snyder, 1984] that the array could arc and estimate the magnitude of the interference generated. Leung [1983] has conducted experiments in an acrylic anechoic chamber where the arc spectrum and intensity for a given arc current have been measured. We shall use his results to scale to Space Station after calculating the probable arc magnitude.

Kuninaka et al [1986] have suggested that the emission of electrons from the discharge sites is determined by space charge limited current flow. However, the value for area and distance used in the calculation is uncertain. Experiments have shown [Snyder, 1984] that the peak current seems to be related to the value of the capacitance chosen. Up to 50 amp has been measured by Miller [1985] and there was evidence that interconnects showed damage due to melting of the metal surface. A real array, when powered up, will supply approximately 2 amps (~3 amps for short circuit) before limiting. All experimental evidence suggests that an arc, once initiated, will draw the current necessary to bring the bias below the point where the arc will cut off. The limit is probably based on the details of the emission characteristics at the arc site. We therefore assume that for the Space Station array an arc will bring one sector (16 cells at 8 volts and 2 amps) to a cut-off condition.

We can now use Leung's data on radiated emissions to estimate the Space Station electromagnetic environment. Leung's data on EMI were taken for peak currents estimated to be on the order of .1 to .2 amps. Therefore, we shall scale his data by a factor of 10 for worst case Space Station array arcs. Figure 4 scales the laboratory data to Space Station assuming a measurement distance of 20 meters (Leung's was 1 m). Although the radiated levels are not enough to disturb or damage electronics, they will be ~50-90 dB above the Space Station broadband spec. Note also that this noise is electromagnetic and the impulse nature of the arcs can present shielding difficulties for the magnetic component. Even for the very low probability of an individual cell arcing, the number of cells in the Space Station photovoltaic arrays imply a serious source of interference.

A preliminary assessment of conducted emission on the transmission line due to solar array arcs has been done by Stevens et al [1986] and they find no adverse effects. More detailed analysis has been done by Kuniaka and Kiriki [1989] to determine induced circuit transients. They also conclude that arcs of less than 100 V should produce negligible conducted interference. The analysis needs to be repeated, however, once power system models are more mature and verification tests are complete on the Space Station cells.

6.0 WAKE TURBULENCE

Although numerous papers have addressed the physics of the plasma wake at mesosonic velocities, few have discussed the EMI that can be generated. Leung [private communication] has measured Diachotron waves in the laboratory. Ma et al [1987] have reported electrostatic noise generated in the wake of Titan (Voyager observations). Recently Tribble et al [1989] have reported on plasma turbulence and electrostatic noise in the Shuttle wake. Unfortunately, it is very difficult to scale with certainty either the laboratory or space measurements to Space Station. Although Shuttle is close in scale size to the Space Station and flies in a similar orbital environment, it is surrounded by an offgassed cloud which itself generates plasma turbulence and electrostatic noise (see section 7.0). Therefore using the Shuttle data as an upper bound, we obtain figure 5 for the worst case wake-induced noise. It is important to note that this noise is confined to the region near the ion mach cone. Objects on the truss that are tens of meters away from the solar arrays, or other large objects such as the pressurized modules, should see noise of considerably less magnitude and be affected only by smaller wakes of objects more local. Models of wake noise generation and propagation are too immature to refine the estimate further.

7.0 GAS CLOUD EMISSION

Recent Spacelab experiments aboard the Shuttle Orbiter have provided a wealth of heretofore unobtainable information about the interactions between large bodies and the LEO plasma. The Shuttle is not only the largest body flown to date but, as was discovered over a period of time, carries with it a large gas cloud. The discovery of "Shuttle glow" [Banks et al, 1983], broadband electrostatic noise [Shawhan et al, 1984a], heated electron populations [McMahan et al, 1983], a modified ion environment [Hunton and Carlo, 1985], and contaminant ions in the wake [Grebowsky et al, 1987] have begun to fill in pieces in what appears to be a complex puzzle associated with large body induced environments and contaminant interactions. Recent studies of the neutral and ion populations during thruster operations [Wulf and Von Zahn, 1986; Narcisi, 1983; Shawhan et al, 1984b], modification of the plasma during FES operations and H_2O dumps [Pickett et al, 1985; Pickett et al, 1988], the discovery of pick-up ions consistent with chemistry of the H_2O, O^+ interaction [Paterson and Frank, 1989] as well as observations by neutral mass spectrometers [Hunton and Swider, 1988; Wulf and Von Zahn, 1986; Miller, 1983], have helped to sort out the interactions which result from release of contaminants by the Orbiter. Observations by IR, optical, and UV instruments on board the Orbiter [Torr, 1983; Torr and Torr, 1985; Torr et al, 1988; Koch et al, 1987] and by IR on the ground [Witteborn et al, 1987] have provided insight into the effects of both absorption and emission by this contaminant population. Ground observations of shuttle plumes and modeling of their interaction with the background plasma by Bernhardt et al [1988a; 1988b] have given additional insight into the ionization of contaminent clouds. It is now clear, as a result of these pathfinder experiments, that to conduct experiments in plasma physics, provide long-term monitoring and a data base for the ionosphere, observe astronomical targets over a broad range of wavelengths, and provide sensitive remote sensing capability, the Space Station environment must be kept free of neutral gas emission.

The EMI which can result from these gas clouds is related to their ionization by charge exchange, collisions, solar UV, or CIV processes and the currents these ions produce.

Murphy [1988] has examined published data from the Plasma Diagnostic Package on the OSS-1 and Spacelab 2 missions and correlated the level of pseudo-broadband electrostatic noise with emission of water vapor. The water, which easily charge exchanges with the background 0^+ plasma, produces a ring distribution unstable to the growth of electrostatic waves [Hwang et al, 1987; Pickett et al, 1985; Gurnett et al, 1988].

The level of noise at 1 kHz (chosen as typical of the pseudo-broadband noise spectra for these data) is plotted in figure 6 for three different cases of "small" gas cloud releases. The level of uncertainty in the measurement of H_2O density is represented by the vertical error bars. The three cases chosen represent almost 3 orders of magnitude in gas density. In all cases, the dominant gas is H_2O. The first is the H_2O vapor cloud associated with the Orbiter outgassing per se, the second, an operation of the Flash Evaporator System (FES), and the third, a typical operation of a VRCS thruster. In all cases the releases were on the dayside and in an ambient 0^+ plasma of density $\sim 10^5$ cm^{-3}. Note that the data indicate that the noise is linearly proportional to the density of gas released. The best fit to the data is that the intensity (at 1 kHz) of electrostatic noise is proportional to the product of H_2O and 0^+ densities. The constant of proportionality is such that at a 1 g s^{-1} release rate, the measured electric field anywhere within the general interaction region will be ~ 1 mV/m in a 150 Hz bandwidth (150 Hz is the approximate bandwidth at which these measurements were made). This correlation is certainly not perfect but leads one to believe that most of the observed noise can be tied to this contaminant release.

In order to properly scale the data to Space Station, several parameters need to be known:

1) The mass ejection rate and composition of gas leaking from the cabin and released through vents.

2) The ionization rate of the gas.

For purposes of this paper, we shall take the level measured near the Shuttle resulting from the offgassed water as our upper bound. Figure 7, taken from Gurnett et al [1988], shows a typical spectrum of this noise measured several hundred meters from the Orbiter. As can be seen, it is pseudo broadband below about 10^4 Hz and Gurnett et al [1988] indicate its wavelength is ≤ 1 meter. Clearly, this noise can be minimized by assuming that vents or thrusters are not operated during quiescent periods and that seals on pressurized modules have leak rates commensurate with the EME requirements.

8.0 EMISSION FROM ELECTRON BEAMS

The use of electron beams to study the phenomena associated with naturally occurring beams in the auroral region has a rich history in ground and flight experiments as well as in theoretical studies and computer simulation. It is not the purpose of this paper to review this work in any detail. The reader should consult the references for more information. Here we shall draw on data from experiments flown on rockets and the Shuttle to estimate the kind of electrical interference that may be expected when such experiments are conducted.

Beams emitting DC current and pulsed current have been investigated with energies ranging from ~ 50 ev [Koons et al, 1982] to 8 kev [Beghin et al, 1984] and currents less than 1 ma to several hundred milliamps. A wide range of plasma wave types have been observed. Typically, emission at the electron gyrofrequency and plasma frequency has been observed as well as ion and electron whistler waves [Shawhan et al 1984; Neubert et al, 1986; Reeves et al, 1988; Winckler et al, 1985]. Sources of these waves, which serve to scatter the beam and convert some of its kinetic energy into electromagnetic energy have been studied extensively. Farrell et al [1988] and Okuda et al [1988] are excellent sources for this topic. We are concerned here with the final result -- that is, what are the expected field strengths measured by an observer close to the experiment? For the answer we turn to measurements made on three specific Shuttle missions: OSS1, Spacelab 1, and Spacelab 2.

The wave emission depends on the injection pitch angle relative to the magnetic field [Neubert et al, 1986] and, to a certain degree, on the current and energy of the beam. In addition to narrowband emission at the gyro frequency and plasma frequency, strong waves are always observed in the VLF band between about 750 Hz and 10 kHz with an f^{-n} spectral density where n varies from -.7 to 1.5 [Farrell et al, 1988]. Detailed classifications of the spectra have been carried out by Akai [1984]; and Shawhan et al [1984]. We shall use the results from Shawhan et al [1984], Neubert et al [1986], and Reeves et al [1988] to place an envelope on the narrowband electric and magnetic emission. Figures 8a and 8b illustrate the probable upper bound of these emissions assuming a beam current of ~100 ma and a beam energy of 1-5 kev.

Although not directly related to EMI, the issue of charge balance for the Space Station must also be addressed. A recent, two dimensional simulation of this problem by Okuda and Berchem [1988] notes that charging can take place to fairly high potentials during beam operation. This charging is not a problem in itself but its consequences must be studied on a case by case basis. No significant charging was observed on Spacelab when the engine nozzles had access to the ambient plasma. However, charging was observed on Spacelab at comparable beam currents when the engine nozzles were in the wake. (The nozzles con- tribute ~30 m^2 to the conducting surface area of the Shuttle Orbiter and are the primary current return path.)

Keeping the prime conducting area of Space Station near the center of the vehicle and assuring a collecting area ≥ 100 m^2 should accommodate beam currents of several hundred milliamps with charging measured only in 10's of volts. Large current beams (>1 amp) and those with energies greater than a few kilovolts should provide, as part of their experiment, a system to insure charge neutralization. Detailed analysis can be undertaken once such an experiment and the Space Station conductive structure have been defined.

9.0 SUMMARY

Table II presents a summary of the wave source, wave type, and probable frequency ranges based on this review. To minimize sources of EMI from Space Station/ environment interactions, the following actions are recommended.

1) minimize leakage of 20 kHz and harmonic currents to structure by careful design of converters, interfaces, and cable; assure that the current return path does not include the structure but is carried along the 'green wire' to minimize loop area;

2) Study the effects of sheath waves on the propagation of 20 kHz and harmonics as these waves may raise levels of electric and magnetic noise due to leakage currents by several orders of magnitude;

3) minimize contact with the background plasma by making surfaces (e.g. solar arrays, cable trays, etc.) non-conductive; contact with the plasma should be made at one 'point' or area near the center of the station to avoid large **v** x **B** potentials (at least 100 m^2 is appropriate);

4) conduct design studies and laboratory tests under realistic flight conditions to assure that solar arrays can be operated at voltages which do not arc;

5) determine by analysis and test the effect of debris and micrometeroid impact holes on the arc rate of the solar arrays;

6) pay careful attention to the location and look direction of sensors sensitive to DC or low frequency magnetic fields and electric fields from wakes; consider that ASTROMAG operations may need to be scheduled carefully and that long term operation of the magnet may preclude certain other experiments;

7) analyze the ionization of gas leakage and vent products to determine if the broadband emission environmental requirements can be met during quiescent periods; develop a model which incorporates ionization rates, plasma dynamics, and neutral gas dynamics;

8) implement all of the following methods to minimize gaseous contamination which may ultimately affect the EME (this will also affect surface deposition):

a) The Orbiter should be allowed to outgas for ≥ 24 hours before docking with the Station (the Orbiter should be behind the Station).

b) Procedures minimizing thruster activity and plume impingement should be implemented for docking activity.

c) Any plan which includes continuous thrusting for reboost is eliminated based on EME considerations. The noise environment would exceed the specification by several orders of magnitude if the product of the thruster exhaust exceeds $\geq .1$ g/s of H_2O.

d) Brief gaseous releases, either by Station hardware or other equipment, must be minimized, documented, and made available to users on a common data buss.

e) EVA activity should be confined to non-quiescent periods whenever possible. (This assumes a vented suit.)

9) Many investigations sensitive to background noise level, may not be able to schedule simultaneous operation with an electron beam experiment. Experiments that produce beams of ~1 amp of current should provide an additional source of neutralization.

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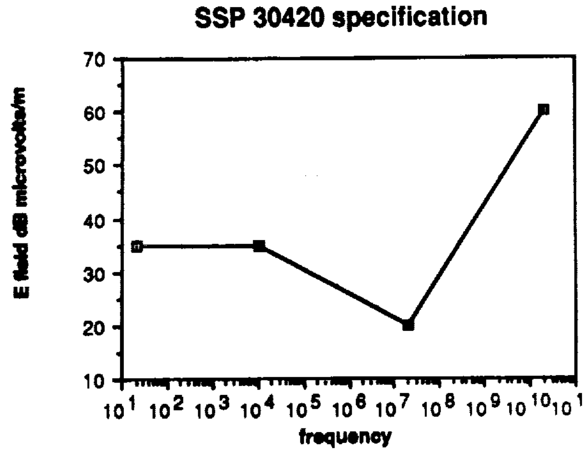

Figure 1a.

The narrowband electric field environment specified 1 meter from structure. (SSP 30420 Oct. 1, 1986).

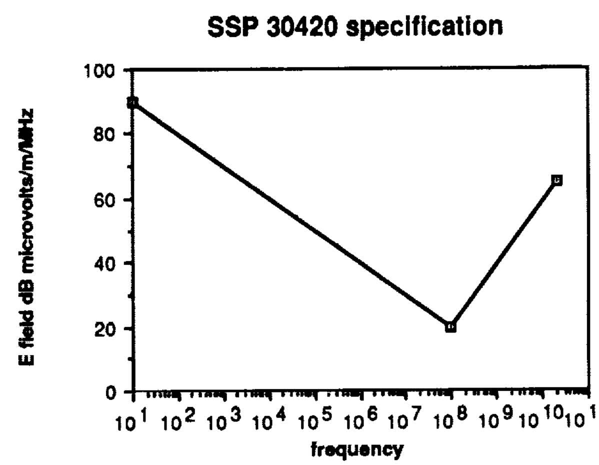

Figure 1b.

The broadband electric field environment at 1 meter from structure. (SSP 30420 Oct. 1, 1986).

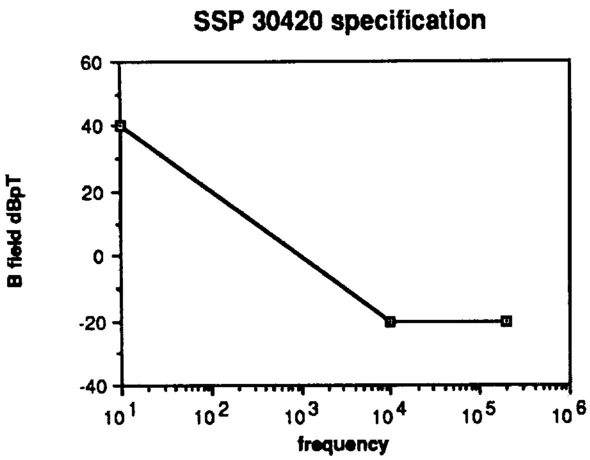

Figure 2.

The narrowband magnetic field environment (SSP 030420 Oct 1, 1986). SSP 30237 indicates a ±10 kHz wide notch around 20 kHz to allow for the 20 kHz power supply noise.

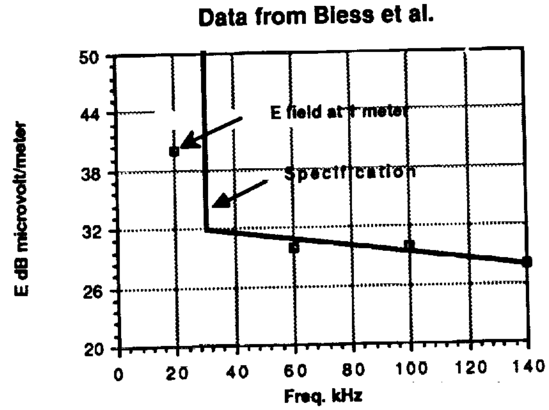

Figure 3b.

The radiated electric field of the transmission line at 1 meter (Biess et al).

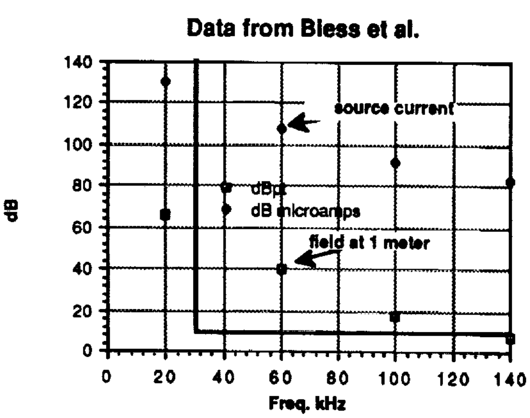

Figure 3a.

The radiated magnetic field of the transmission extrapolated to 1 meter from measurements by Biess et al. Note that the transmission line current at each frequency is also shown.

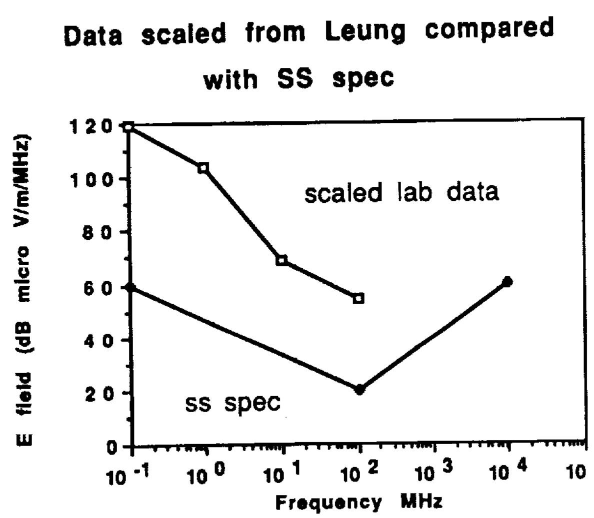

Figure 4.

The probable magnitude of the broadband electric field generated by arcs on the solar array. Measurement distance is assumed to be 20 meters. Data are from Leung [1984].

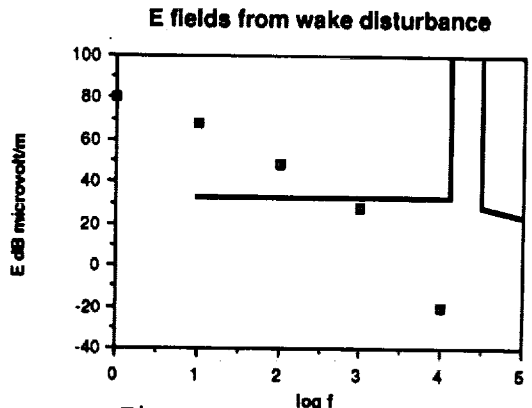

Figure 5.

The probable magnitude of electric field wake noise near the mach cone of an object of characteristic dimension ~10m.

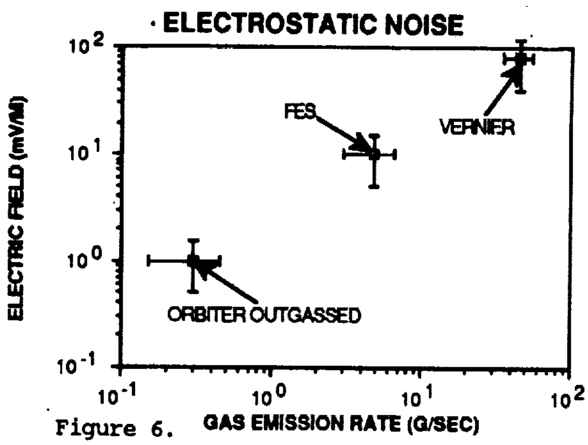

Figure 6.

Electrostatic noise at 1kHz with a ±15% bandwidth is shown for three different levels of gas emission (derived from Pickett et al [1984]).

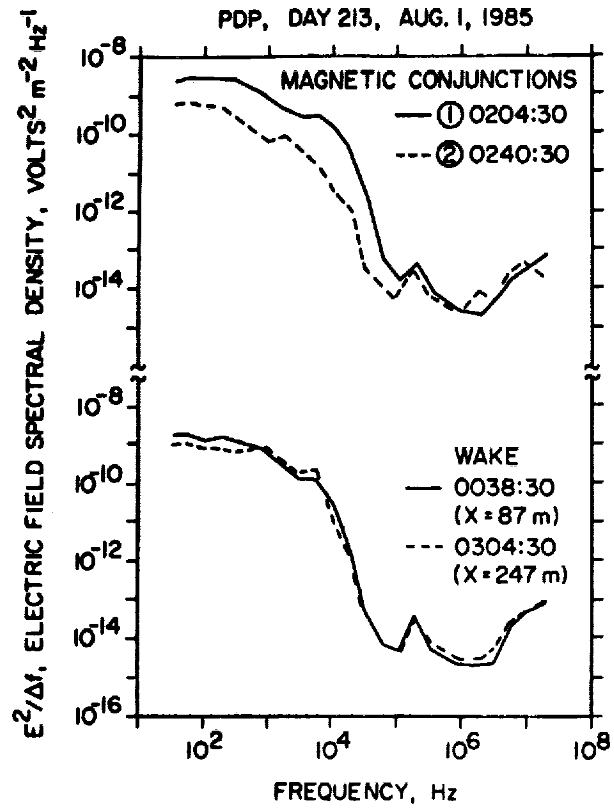

Figure 7.

Graph is from Gurnett et al [1988] and indicates the electric spectrum of noise induced by the ionization of gas clouds (top) and that induced by wakes (bottom).

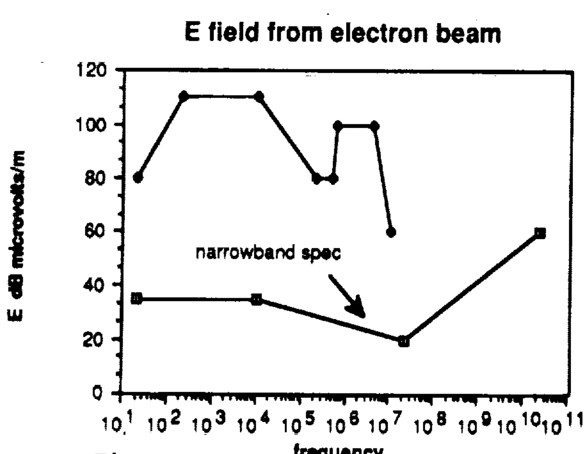

Figure 8a.

The envelope of probable electric field emissions due to a 100ma 1kev electron gun at a distance of ~5 meters. Also shown is the narrowband emission limit of figure 1a.

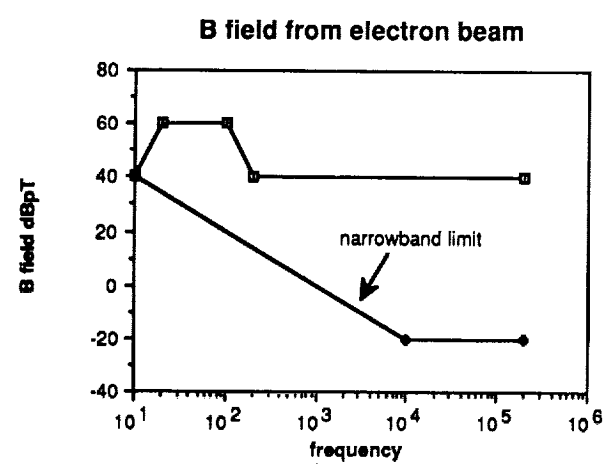

Figure 8b.

The envelope of magnetic field noise induced by the same electron beam is compared to the SSP 30420 specification.

Table I

radiation type	frequency range	source
lower hybrid waves + cyclotron waves	40Hz - 10kHz broadband 40Hz + others	ring distribution ions - primarily the wake region
plasma turbulence	broadband 10Hz < f$\leq$ 6 kHz	plasma wake region
lower hybrid waves	100 - 200 kHz	boundary layer at ion turning pt.
upper hybrid waves	30 MHz	boundary layer
whistler waves	100 kHz - 1 GHz	loss cone (cusp regions)
Alfven waves	stationary but time varying amplitude	generated by ionospheric current collection

Table II

Source	Wave type	Wave Classification: Electric	Wave Classification: Magnetic	Frequency Range	Magnitude Estimate (at 1 meter): Electric	Magnitude Estimate (at 1 meter): Magnetic
Power System						
transmission line	electromagnetic	N	N	20 kHz and harmonics	~40 dBμv/m* at 20 KHz	≤70 dBpT* at 20 KHz
current loops	sheath wave lower hybrid	N N	N	20 kHz and harmonics	100 dBμv/m+ at 20 kHz	140 dBpT+ at 20 kHz
Ionosheric Current	Alfvén wave lower hybrid wave	 PB	N	DC - 100 Hz 20 kHz and harmonics	 unknown in Doppler shifted near field	≤74 dBpT
ASTROMAG	DC magnetic (see Table I)		N	DC <F<100 Hz		>88 dBpT++
ARCS	electromagnetic	B	B	100 kHz<f<100 MHz	110 dBμV/m/MHz at 1 MHz	H = E/120π
WAKE	electrostatic	PB		0<f<10 kHz	≤50 dBμv/m at 100 Hz	
Gas Cloud	electrostatic	DC		0<f<10 kHz at 1 kHz	≤60 dBμv/m**	
Electron Beam	electron gyrofreq. plasma frequency electron whistlers electrostatic ion gyrofrequency	N N PB DC N	N PB N	~1 μHz ~3 μHz 10 kHz<f<1 MHz 10 Hz<f<10 kHz	≤100 dBμv/m ≤100 dBμv/m ≤100 dBμv/m ≤110 dBμv/m ≤120 dBμv/m	unknown unknown ≤40 dBpT ≤40 dBpT ≤60 dBpT

* based on prototype inverter and transmission line
\+ assumes 1 ma leakage current; 2m x 50m loop; 10cm sheath
** 88dBpT at 75 meters
++ assumes 1g/s water emission rate

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