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Summary

Spacecraft in geosynchronous orbit can be charged electrically to high voltages by interaction with the space plasma. Differential charging of spacecraft surfaces leads to arc and blowoff discharging. The discharges are thought to upset interior, computer-level circuitry. In addition to capacitive or electrostatic effects, significant inductive and less significant radiative effects of these discharges exist and can be modeled in a dipole approximation. Flight measurements suggest source frequencies of 5 to 50 MHz. Laboratory tests indicate source current strengths of several amperes. Electrical and magnetic fields at distances of many centimeters from such sources can be as large as tens of volts per meter and meter squared, respectively. Estimates of field attenuation by spacecraft walls and structures suggest that interior fields may be appreciable if electromagnetic shielding is much thinner than about 0.025 mm (1 mil). Pickup of such fields by wires and cables interconnecting circuit components could be a source of interference signals of several volts amplitude.

Introduction

The decade-long interest of space scientists in charging as a cause of electrical interference in spacecraft has been advanced in recent years by flight programs such as SCATHA (ref. 1). At the same time, laboratory investigations have been made of discharging phenomena on artificially charged samples of spacecraft material that approach conditions found in space (refs. 2 and 3). Theoretical work on discharge models and coupling schemes has led to elaborate calculations and computer codes (refs. 4 and 5). In part because the detailed character of naturally occurring discharges on spacecraft has not been fully determined, it has not been possible thus far to show conclusively how discharges upset computer-level logic circuitry in spacecraft.

This report presents some order-of-magnitude estimates of interference signals derived from simple arc and blowoff discharge models. With frequency spectra taken from flight data, laboratory discharge current strengths are used in a free-space dipole radiation model to estimate interference signal amplitudes. The attenuation of induction and radiation terms in the dipole fields due to spacecraft walls and shields is discussed, and the interference signals in exposed wires and cables are estimated. At distances of interest, it is shown that, along with electrostatic or capacitive interference field coupling to circuits, inductive and radiative field coupling should be considered significant. The spacecraft design consideration suggested by these results is that electromagnetic shields surrounding interference pickup points and wires must not only have sufficient coverage to reduce electrostatic effects, but also should be several skin depths thick.

Source Characterization

Interference pulses due to naturally occurring electrical discharges have been detected on the P78-2 (SCATHA) satellite (refs. 6 to 8). Typical pulse frequencies in loop and dipole antennas and harness wire detectors were in the range 5 to 30 MHz. Amplitudes of 1 to 30 V and pulse train lengths of 200 ns have been recorded. In laboratory charging studies with simultaneous low- and high-energy electron beams, discharges of dielectric materials have been observed at surface potentials almost as low as those observed in space (ref. 2). In such studies, frequencies of substrate return currents are comparable to interference pulse frequencies seen on SCATHA. Pulse trains are as much as five times longer. The amplitudes of these return currents are 5 to 10 A. In these and other studies, blowoff currents of several amperes lasting for several nanoseconds and having electron velocities as high as 5×10^6 m/s have been observed (ref. 5).

Of the above, only the frequency band and pulse train length data are directly indicative of in-flight source parameters. Detected pulse heights, which measure amplitudes at the pickup points rather than at the sources, indicate only that significant interference is present. The spatial geometry and current strengths of such sources are completely unknown from in-flight data and have been only imperfectly reproduced in the laboratory. Thus, even in the simplest possible radiating source model, a dipole, the necessary arc current length and magnitude must be inferred from laboratory measurements rather than from flight data. With this lack of knowledge, estimates that are based on the simplest source models and coupling schemes that seek to identify significant interference mechanisms should remain useful as guides to spacecraft design.

The Dipole Model

Some discharges on dielectric surfaces in the laboratory appear to be confined to regions quite small as compared with spacecraft dimensions and also with the wavelengths of radiation in the frequency band associated with interference pulses detected in space (ref. 9). For such sources, the current distribution of time-varying dipole is an appropriate model. The various fields that arise depend on the dipole moment of the charge distribution driving the currents and upon its time derivatives. Thus, at a field point $\vec{r} = \hat{n}|\vec{r}|$ in a frame of reference having a dipole $\vec{p}$ at the origin, the fields are

$$
\left.
\begin{aligned}
\vec{E}_{\text{static}} &= \frac{1}{4\pi\epsilon_0 r^3}\ [3\hat{n}(\hat{n}\cdot\vec{p}) - \vec{p}] \equiv \vec{E}_s \\
\vec{E}_{\text{induction}} &= \frac{1}{4\pi\epsilon_0 c r^2}\ [3\hat{n}(\hat{n}\cdot\dot{\vec{p}}) - \dot{\vec{p}}] \equiv \vec{E}_{\text{ind}} \\
\vec{E}_{\text{radiation}} &= \frac{1}{4\pi\epsilon_0 c^2 r}\ \hat{n}\times(\hat{n}\times\ddot{p}) \equiv \vec{E}_{\text{rad}} \\
\vec{B} &= \frac{1}{c}\hat{n}\times(\vec{E}_{\text{ind}} + \vec{E}_{\text{rad}}) \equiv \vec{B}_{\text{ind}} + \vec{B}_{\text{rad}}
\end{aligned}
\right\} \qquad (1)
$$

If the dipole is oriented so as to maximize the various field terms, the resulting magnitudes are

$$
\left.
\begin{aligned}
&E_s \simeq \frac{\eta c p}{r^3} \qquad E_{\text{ind}} \simeq \frac{\eta \dot{p}}{r^2} \qquad E_{\text{rad}} \simeq \frac{\eta \ddot{p}}{c r} \\
&B_{\text{ind}} = \frac{\eta \dot{p}}{c r^2} \qquad B_{\text{rad}} \simeq \frac{\eta \ddot{p}}{c^2 r}
\end{aligned}
\right\} \qquad (2)
$$

where $\eta = 1/4\pi\epsilon_0 c = 30$ in SI units and c is the speed of light in vacuum.

The "static" term in an electric field remains in the limit $\omega \to 0$ (i.e., the electrostatic limit). If a source is placed not in free space but in the presence of conducting bodies, this limit describes the capacitive coupling of the source to its surroundings. In depending on the dipole moment of the charge distribution driving an arc, which may be spread over rather large surfaces such as solar cell covers and booms, the dipole "static" term in equation (1) is not expected to model capacitive coupling well. The dipole model assumes concentration of both current and charge sources. However, discharge currents concentrated in arcs and blowoffs should give rise to fields well modeled by dipole induction and radiation field terms. It will be shown that these terms may be responsible for interference coupling to circuits in addition to the capacitive coupling from "static" fields that is generally regarded as predominant.

A dipole current composed of an oscillating arc superimposed on a constant current of the same magnitude fits the substrate current signatures referred to in the section Source Characterization. For this case, $\dot{p} = \ell I_0(1 + e^{-i\omega t})$ and $\ddot{p} = -i\omega \ell I_0 e^{-i\omega t}$, where ℓ is the length of the combined current segment, I_0 is the current magnitude, and ω is the angular frequency. A blowoff current source I lasting a time Δt and having charge velocity v yields $\dot{p} = I v\ \Delta t$ and $\ddot{p} = I\ \Delta t\ Ee/m$, where E is the electric field magnitude near the blowoff surface and e/m is the charge-to-mass ratio of the released charges, here assumed to be electrons. Tables I and II give representative field magnitudes at various distances and frequencies for these two cases. For the oscillating arc case, a current I_0 of 5 A is chosen. An arc length ℓ of 1 mm is typical of visible arcs in solar cell gaps seen in the laboratory (ref. 9). For the blowoff case, $I = 1$ A, $\Delta t = 10$ ns, and $v = 5 \times 10^6$ m/s (see the section Source Characterization). The electric field $\vec{E}$ near the blowoff surface is, at 3000 V, comparable to surface fields seen in laboratory charging experiments and in-flight episodes. Both blowoff and arc currents have magnitudes like those found in ordinary sparks (ref. 10). The 5- to 50-MHz frequency range expresses, at 5 MHz, the lowest frequencies seen in flight pulse data and, at 50 MHz, the upper response limit of transistor-transistor logic (TTL) circuitry.

Assuming that electric fields of the order of 10 V/m are sufficient to cause interference in circuits, one sees from the tables that electric induction fields are significant out to many centimeters at all frequencies in the 5- to 50-MHz band and that electric radiation fields are significant only at the highest frequencies and the smallest distances. If it is assumed that loops of 1-m^2 area can be linked magnetically, $\dot{B}A$ electromotive forces induced by the magnetic induction term are significant at distances of many centimeters and at middle to high frequencies. Magnetic radiation terms are significant only at the highest frequencies and the shortest distances. These results suggest that free-space dipole fields of sufficient amplitude to warrant consideration as interference hazards are produced by discharges similar to those thought to occur on the surface of spacecraft. The most important terms in the fields considered appear to be the induction terms. Attenuation of signals through spacecraft walls and structures must, however, be estimated.

Field Attenuation

The fields of a time-varying dipole placed near conducting bodies satisfy an exceedingly complex boundary value problem. Even the geometrically simple arrangement of a dipole adjacent to a conducting half-space is tractable only with great effort (ref. 11). Spacecraft structures that intervene between radiative interference sources and sensitive receptor circuits are so complex that little analytical progress seems possible in describing the coupling exactly. Computers must be relied upon for details (ref. 12). However, roughly, one can say that dielectric objects provide no significant barrier to the fields and conductive bodies do, if they are sufficiently thick.

In plane geometry, a very thin conducting sheet can be shown to have a very high electromagnetic reflectivity. This is, however, a special geometry, not particularly applicable to a small spacecraft. According to Stratton (ref. 13), ". . . the reflection losses from surfaces whose

TABLE I. – FIELD STRENGTH ESTIMATES FOR AN OSCILLATING ARC

[$I_0\ell = 5 \times 10^{-3}$ A-m.]

Radius, r, m	Frequency, $f=\omega/2\pi$, MHz	Electric induction field, $\vec{E}_{ind} = 2\eta I_0\ell/r^2$, V/m	Electric radiation field, $\vec{E}_{rad} = \eta\omega I_0\ell/cr$, V/m	Magnetic induction field,[a] $\dot{\vec{B}}_{ind} = \eta\omega I_0\ell/cr^2$, V/m^2	Magnetic radiation field,[a] $\dot{\vec{B}}_{rad} = \eta\omega^2 I_0\ell/c^2r$, V/m^2
10^{-2}	5	3000	1.5	150	0.15
10^{-1}	5	30	.15	1.5	.015
1	5	.3	.015	.015	.0015
10^{-2}	25	3000	7.5	750	3.75
10^{-1}	25	30	.75	7.5	.375
1	25	.3	.075	.075	.0375
10^{-2}	50	3000	37.5	3750	94
10^{-1}	50	30	3.75	37.5	9.4
1	50	.3	.375	.375	.94

[a]$\dot{B}$ is given rather than B so that EMF's can be easily calculated.

TABLE II. – BLOWOFF SOURCE FIELD ESTIMATES

Radius, r, m	Electric induction field, $\vec{E}_{ind} = \eta\dot{p}/r^2$, V/m	Electric radiation field, $\vec{E}_{rad} = \eta\ddot{p}/cr$	Magnetic induction field, $\dot{\vec{B}}_{ind} = \eta\ddot{p}/cr^2$
10^{-1}	15 000	50	5000
10^{-1}	150	5	50
1	1.5	.5	.5

[a]$\dot{B}$ is given rather than B so that EMF's can be easily calculated. The $\dot{B}_{rad}$ term for a blowoff source is missing since it depends on $\dddot{p}$, which is unknown.

radius of curvature is small compared to the wavelength (are) by no means always large and the only significant, general criterion is the value of the attenuation factor β_2 or its reciprocal, the skin depth. . .". Since the shortest wavelengths considered herein are about 1 m and few large, plane surfaces exist on a typical small spacecraft, the situation presented herein would seem to fit Stratton's criterion. For metals such as aluminum and gold the electrical conductivity σ is about 5×10^7 mho/m, which yields skin depths of 1×10^{-5} to 3×10^{-5} m in the 5- to 50-MHz band. With $\mu = \mu_0$, these skin depths are calculated from $\delta = (2/\sigma\omega\mu)^{1/2}$. Attenuation with thickness x of the form $e^{-x/\delta}$ gives a factor of 1 for these values of δ and $x = 1$ nm (10 Å). For $x = 1$ μm the factors range from $e^{-0.03}$ to $e^{-0.1}$. A thickness of 0.025 mm (1 mil) gives factors of 1/3 to 1/10. Thus, unless 0.025 μm (1 mil) or so of conductive material intervenes between sources and circuits, one might expect rather little attenuation of the free-space fields of the model dipole currents. Shielding this thick rarely covers all sensitive points within a spacecraft.

Apertures

Apertures in conductive shielding can admit interference fields to spacecraft interiors. However, if the wavelengths of the fields are long as compared with the linear dimensions of an aperture, penetration is slight. Indeed, for a circular hole in a conducting wall of radius a, the on-axis electric field a distance r beyond the plane of the hole has an attenuation factor of $4\pi f^2 a^3/3c^2 r$, neglecting polarization (ref. 14). For $r = 10$ cm and $a = 10$ cm this factor is 10^{-5} at 5 MHz and 10^{-3} at 50 MHz. Thus, unless a sensitive point lies virtually within an aperture, it is unlikely to pick up interference from nearby sources.

Reception of Interference Signals

The wavelength range of 5- to 50-MHz signals is 6 to 60 m. Exposed wires and cables in small spacecraft, which are likely to be shorter than these wavelengths, constitute "short" antennas for the reception of electric field interference. The voltage induced in a "short" antenna of length ℓ placed in an electric field $\vec{E}$ is $E\ell$, provided that polarization is maximum (ref. 15). The voltage induced in a loop of area A by the magnetic field is $\dot{B}A$. Thus, for the representative values from tables I and II of 10 V/m for E and 10 V/m^2 for $\dot{B}$, which are easily achieved at distances r of 10 cm or more, cables 1 m long and loops 1 m^2 in area would each pick up signals of 10 V. This order of signals was seen in SCATHA and is sufficient to change a TTL or complementary metal-oxide semiconductor (CMOS) logic state, for example. Although these estimates are very rough, it must be remembered that source parameters are not well known and actual inductive and radiative fields could be even larger. In the oscillating arc, for example, an arc length of several or many millimeters, rather than 1 mm, might occur. A proportional increase in the field amplitudes would result. Similarly, in the blowoff source model, current leaving a surface might be much higher than 1 A.

Concluding Remarks

The estimates presented herein suggest that some of the 1- to 30-V interference signals seen in SCATHA might be caused by inductive and radiative field coupling of surface discharges. This kind of coupling may be important in other, less fully documented, cases as well. If so, this suggests that increased attention might be paid to electromagnetic shielding rather than merely electrostatic shielding (i.e., to the thickness as well as the coverage of shielding). Shields should be several skin depths (or 0.025 mm; 1 mil) thick for fields in the range 5 to 50 MHz.

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio, August 11, 1983

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15. Supplementary Notes

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16. Abstract

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