Effects of Extreme Background Conditions on an SPS Microwave Beam

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Abstract

The physical processes that characterize the interaction of high power microwave beams and the neutral and ionized regions of the Earth's aerospace environment are fairly well understood. Consequently it might be thought that predictions concerning both the degradation of solar power satellite (SPS) microwave beams that traverse the ionosphere and atmosphere, as well as the impact of energy losses from SPS beams on the Earth's environment can be readily obtained by model calculations. However, the parameters that characterize the natural background medium can themselves vary considerably and often in an unpredictable way. Furthermore, certain extreme conditions could conceivably lead to catastrophic failure of an SPS system. These conditions can arise through, for example, sudden enhancements in plasma density in the ionosphere due to solar flares and geomagnetic storms or from lightning flashes that raise the temperature of the lower ionosphere to tens of thousands of K. In this paper the potential consequences of such phenomena on the performance of SPS systems are examined.

1. Introduction

Solar Power Satellites (SPS) and related systems are an attractive way of exploiting the huge quantities of energy available in the form of solar radiation and converting this into useful energy at the Earth's surface. Although the technological aspects of this concept are fairly well defined, the effects of trans-ionospheric propagation of the microwave beams which are essential to SPS operation are less well understood. This knowledge gap arises from several factors. Firstly, although the basic mechanisms involved in electromagnetic wave propagation through collisional plasma, like that in the Earth's ionosphere, are well understood, calculations based on mean ionospheric conditions are totally inadequate. The reason is that the ionosphere is highly variable, often in unpredictable ways, on a variety of spatial and temporal scales [1, 2]. Even empirical models, such as the International Reference Ionosphere (IRI), that take account of diurnal and solar cycle variations cannot capture the full picture of the numerous ephemeral effects such as those due to solar flares and magnetospheric storms [3]. A second potential reason for unpredictable behaviour is that at high power densities, such as those encountered in SPS systems, interactions between the electromagnetic waves and the ionospheric plasma can trigger instabilities that involve nonlinear feedback processes. Such nonlinear effects can lead to significant modification of the ionospheric plasma which in turn causes modification of the beam itself. Although the conditions for the onset of nonlinearity can be predicted, the final state of a strongly coupled beam-plasma system may be intrinsically unpredictable.

2. Linear Phenomena: Collisional Absorption

Linear phenomena, which affect radio waves of all amplitudes, constitute an important class of phenomena that can affect the trans-ionospheric propagation of SPS microwave beams. Such linear processes that can affect an SPS system include refraction caused by plasma density dependent phase speeds, phase and amplitude scintillation and collisional absorption. Such (non-deviative) collisional absorption attenuates radio waves as they propagate through the ionosphere. It operates mainly at D-region altitudes (60-90 km) and depends on three parameters: the SPS angular wave frequency, ω, the electron-neutral collision frequency, ν_e, and the electron concentration, N_e [4, 5]. N_e and ν_e are functions of altitude, s, and the total ionospheric absorption, A (in nepers), is given by the integral (1), where e and m are the electronic charge and mass respectively. Also, c is the speed of light, ε_0 is the permittivity of free space and μ, the real part of the refractive index, equals 1 for non-deviative absorption. A specific example of a solar event that can cause enhanced absorption is discussed in section 2.1. Although a frequency of 5.8 GHz has also been proposed for the microwave radiation that constitutes the SPS beam, the discussion presented below assumes a radiation frequency of 2.48 GHz.

$$A = \frac{e^2}{2\varepsilon_0 mc\mu} \int_I \frac{N_e \nu_e}{\omega^2 + \nu_e^2} ds \tag{1}$$

2.1 CME-enhanced Absorption

Coronal mass ejection (CME) events can seriously affect the trans-ionospheric propagation of an SPS microwave beam by increasing the ionospheric plasma content. One such event occurred on 30 October 2003 and data collected using the EISCAT UHF incoherent scatter radar, near Tromsø in northern Norway, indicated unusually high values of N_e (> 10^{11} m^{-3}) measured down to altitudes of 60 km and below. These data were used to extract N_e profiles for both the background and CME-enhanced cases, with N_e being extremely variable due to CME-induced ionization. Also, the MSIS-E-90 model was used to provide a ν_e profile. The left-hand panel of Fig. 1 shows the ν_e profile (solid red) together with N_e profiles for normal conditions (black dashed) and conditions enhanced by a CME (black solid). It is clear that during a CME, N_e is enhanced significantly, particularly at D-region altitudes where most collisional absorption occurs. The amount of absorption affecting a downwards-propagating SPS beam was calculated, with the integral (1), using these N_e and ν_e altitude profiles. The right-hand panel of Fig. 1 shows the power remaining in the SPS beam, as a percentage of the total transmitted power, as the radio waves propagate downwards through the ionosphere. The ν_e and N_e profiles given in the left-hand panel of Fig. 1 were used, with the dashed line giving the power remaining for the normal case, and the solid line showing the power for the case where N_e is enhanced significantly by a CME. It is clear that approximately 18% of the transmitted beam power would be absorbed in the ionosphere. This may be compared to normal background conditions, where the amount of collisional absorption, after trans-ionospheric propagation of the SPS beam, is very low and amounts to about 0.3%.

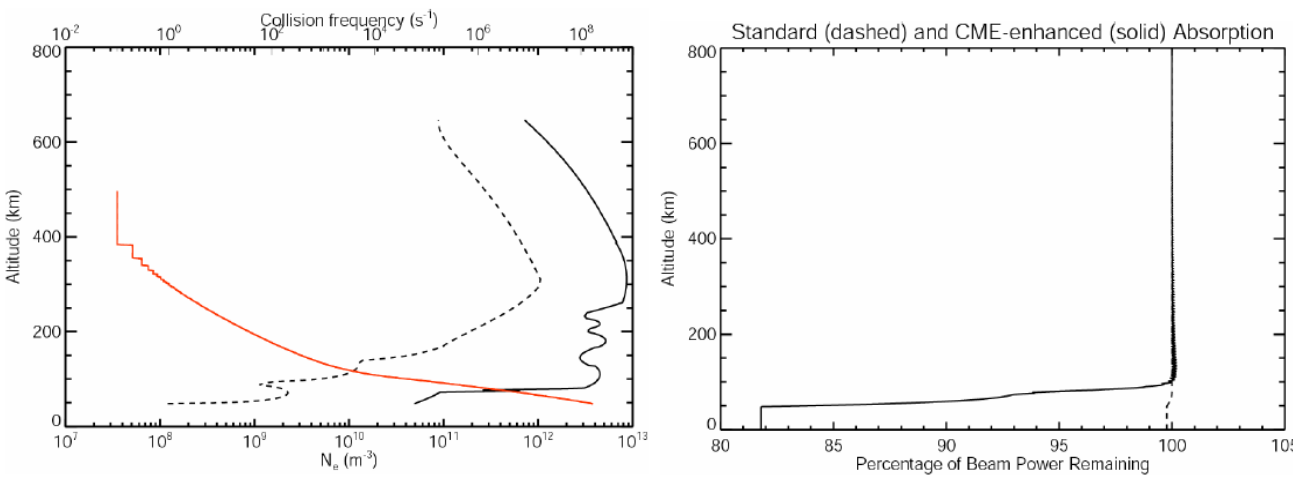

Fig. 1: ν_e and N_e for normal (black dashed) and CME-enhanced (black solid) cases (left-hand panel) and beam absorption for normal (dashed) and CME-enhanced (solid) cases (right-hand panel)

2.2 Other Causes of Collisional Absorption

Other physical mechanisms whose effects may amplify collisional absorption, through increases in N_e and ν_e, include lightning, solar flares and gamma ray flares. Starting with lightning, it has been shown that, through the effects of greatly increased temperature, the D-region ν_e can be increased by a factor of approximately 400 during lightning flashes [6]. Using the same technique as described above for the CME-enhanced case gives lightning-induced collisional absorption of about 3%. Furthermore, characteristic shortwave fadeouts have been attributed to the effects of solar flares [5]. These flares, through the interaction of hard solar X-rays mainly in the D-region, cause increased ionization, leading to enhanced collisional absorption. In addition to lightning and solar flares, it has also been shown that gamma ray flares, such as that detected on 27 December 2004, can cause ionization down to altitudes as low as 30 km [7]. Since ν_e is very large at these very low altitudes, any significant ionization will contribute greatly to collisional absorption.

3. Linear Phenomena: Scintillation

In addition to collisional absorption, another linear process that could affect the operation of an SPS system is phase and amplitude scintillation of the propagating SPS radio waves. Scintillation results from the spatially and temporally varying plasma refractive index of the ionosphere. These variations take the form of geomagnetically field-aligned plasma density irregularities. Such scintillation can result in rapid variations in the amplitude of the waves. An example of the amplitude variations of L-band signals affected by these irregularities has been presented previously [8], where the effects on trans-ionospheric radio waves with frequencies of 136 MHz and 1.7, 4 and 11.5 GHz have been shown. Amplitude fluctuations of up to 10 dB were found to occur over the order of seconds, thereby implying variations ranging from an almost complete loss of power to a doubling of the power, all within a timescale of seconds. These severe scintillation effects were associated with a geomagnetic storm. However, such conditions are not uncommon and are more likely to occur during periods of high sunspot number [9]. It has also been demonstrated that the most severe scintillation effects were likely to occur in the low-latitude regions around dusk and in the polar regions [9]. As scintillation has been shown to affect L-band signals, it may reasonably be assumed that this process would also affect SPS microwaves at 2.48 GHz. In addition to the power variability mentioned previously, the diffractive effects of scintillation could lead to power being diffracted out of the beam and landing on the ground outside the designated collecting area. This has important implications for the location and the size of the SPS ground receiver.

4. Nonlinear Phenomena

The linear processes described above affect radio waves of all amplitudes and therefore have no threshold that the power must exceed order to excite the effect. This is in contrast to nonlinear wave-plasma processes that could also affect the SPS beam. Some of these processes are characterized by the interaction between the high-power SPS electromagnetic wave and electrostatic waves. Such mechanisms have been discussed previously, together with nonlinear phenomena including stimulated Brillouin scattering, where electromagnetic waves can couple to ion-acoustic waves, and stimulated Raman scattering, where electromagnetic waves can couple to Langmuir waves [10]. Both of these processes would apply to the SPS microwave beam. This coupling between electromagnetic and electrostatic waves leads to growth of the electrostatic waves, which remain in the ionosphere and thereby remove energy from the SPS beam. However, in the SPS context, the most important nonlinear phenomenon is probably the self-focusing instability [11, 12], which, through nonlinearity associated with collisional heating, can lead to the generation of plasma density irregularities. These irregularities can cause scintillations of the SPS beam, even when no natural scintillations are present.

5. Conclusion

Linear processes that can affect an SPS system include refraction caused by plasma density dependent phase speeds, collisional absorption and phase and amplitude scintillation of the microwave beam. Greatly enhanced ionospheric collisional absorption can have a serious impact on the amount of beam energy reaching the ground. For example, during a CME, the greatly enhanced ionization, especially in the D-region, increased the level of absorption, which would result in almost 20% of the power being removed from the SPS beam and deposited in the ionosphere. In addition, phase and amplitude scintillation can cause severe fluctuations, of almost 100%, in the power level of the SPS beam over seconds. It can also cause power to be diffracted out of the beam, possibly landing outside the designated collecting area. Other phenomena involve nonlinear effects, such as the self-focusing instability and stimulated Brillouin and Raman scattering. The self-focusing instability can create scintillations even where they are not present naturally, whereas the stimulated scattering processes can remove energy from the beam by transferring it to electrostatic waves. Since both linear and nonlinear processes lead to highly variable beam powers, any successful SPS system must be able to cope with possibly rapid changes in power. It is difficult to predict the occurrence of effects such as scintillation due to the variable nature of the solar-terrestrial plasma environment and considerable international effort is currently focused on improving the ability to forecast these processes. These efforts include global data acquisition, which, when used in conjunction with existing models (e.g. MSIS-E-90 and IRI), can improve the investigation of effects that may influence the successful operation of an SPS system. For example, by using results from the global distribution of riometers, imaging riometers and ionosondes, it is possible to measure the absorption at radio frequencies of approximately 40 MHz, with the results then being scaled for the frequencies at which an SPS system would operate.

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7. References

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