GEOPHYSICAL RESEARCH LETTERS, VOL. 14, NO. 10, PAGES 1015-1018, OCTOBER 1987

ELECTROMAGNETIC FIELDS FROM PULSED ELECTRON BEAM EXPERIMENTS IN SPACE : SPACELAB-2 RESULTS

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Abstract. During the Spacelab-2 mission a small satellite carrying various plasma diagnostic instruments was released from the shuttle to co-orbit at distances up to 300 m. During a magnetic conjunction of the shuttle and the satellite an electron beam modulated at 1.22 kHz was emitted from the shuttle during a 7 min period. The spatial structure of the electromagnetic fields generated by the beam was observed from the satellite out to a distance of 153 m perpendicular to the beam. Electromagnetic radiation at the fundamental and the harmonics of the modulation frequency was observed as well as broadbanded electrostatic noise. The magnetic field amplitude of the strongest harmonics were comparable to the amplitude of simultaneously observed whistlers, while the electric field amplitudes were estimated to 1-10 mV/m. The observations are related to theories for radiation from pulsed electron beams.

1. Introduction

This paper presents new results about the spectrum, intensity, and polarization of electromagnetic wave fields generated by launching a pulsed electron beam into the ionosphere from the space shuttle. Previous experiments with rockets [Cartwright and Kellogg, 1974; Winckler, 1980; Holzworth and Koons, 1981; Winckler et al., 1985] have successfully detected electron beam-produced waves in the VLF and ELF portions of the radio spectrum for brief intervals limited by the rocket trajectory. Earlier measurements by the research groups involved in the present experiments have been made from the shuttle with the OSS-1 mission of STS-3 in March, 1982 [Reeves et al., 1987]. Using plasma diagnostic instruments described later, it was found that electron bursts of various duration and pulsing frequency would generate strong ELF and VLF signals, both at the fundamental pulsing frequency and at various harmonics. Peculiar satellite lines were also found to surround the higher frequency signals up to the limit of observations at 30 kHz. Satellite lines are emissions separated in frequency from the harmonic spectral lines generated by the pulsed electron beam. The separation ranged from 100 Hz to 1 kHz. Most commonly satellite lines appeared as single subsidiary lines, which were higher in frequency than their primaries. However, since the electron source, the Fast Pulse Electron Generator (FPEG), and the instruments of the Plasma Diagnostic Package (PDP) were virtually co-located within the shuttle payload bay, the question of the extent to which these observations represented waves in the ambient plasma medium could not be answered.

The Spacelab-2 mission, flown in the period of July 25 through August 2, 1985, provided a unique opportunity both to repeat the earlier payload bay electron beam experiments and, during two orbital periods, to investigate the behavior of beam associated phenomena with the PDP flying as a co-orbiting, free-flying, satellite. During the course of this fly-around care was taken to permit the PDP and shuttle to have two magnetic conjunctions per orbit. At these times the FPEG in the shuttle payload bay was programmed to fire various sequences with the beam pointed in the direction of the PDP. During the first complete orbit, no FPEG firings were undertaken in order that the PDP could assess the background environment associated with the motion of the Orbiter through the ionospheric plasma. On the second orbit, the first magnetic conjunction was obtained with the PDP above the Orbiter and the FPEG firing a continous (DC) beam. Results from this experiment have been reported by Gurnett et al. [1986], showing the FPEG beam emits copious broad band whistler noise in the VLF, LF and MF bands and that this emission is similar to that found in conjunction with auroral electron beams.

The results presented here were obtained in connection with the fourth magnetic conjunction when the PDP was below the Orbiter at a distance of about 200 m, and the Orbiter payload bay was pointed towards the earth. A sequence emitting an electron beam square-wave modulated at 1.22 kHz began while the PDP was within a few meters of the actual conjunction point and continued for a period of about 7 minutes. During this time the PDP moved 153 meters perpendicular to the magnetic field as seen in the shuttle rest frame. As discussed below, the experiment was highly successful in generating VLF signals of substantial amplitude, both at the fundamental pulsing frequency and at the harmonics.

The PDP was supplied by the University of Iowa. It carried various plasma diagnostic instruments, including an electric dipole antenna and a magnetic search coil, which were connected alternately for 51.2 s to a wave receiver with a 10 kHz bandwidth. When connected, the wave receiver scanned a 30 kHz frequency range by selecting 10 kHz bands as: 0-10 kHz (25.6 s), 10-20 kHz (12.8 s), and 20-30 kHz (12.8 s). In addition, an ELF band at 0.1-1.0 kHz was continuosly monitored by the same antennas. Both receiver outputs were controlled by an Automatic Gain Control (AGC) system, which ensured a 100 dB dynamic range and a roughly constant output level. The output in the ELF and VLF bands was telemetered in analog form, and the 10 kHz VLF band was later digitized at 25 kHz. For a description of the PDP and the instruments, see Shawhan [1984]. The FPEG was part of the Vehicle Charging and Potential (VCAP) experiment supplied by Stanford University and Utah State University. It emitted square-wave modulated electron beams with 100 mA beam current and 1 keV energy. The rise time of the accelerator potential was extremely small, of the order of 10^{-7} s. During the fourth flux-tube connection the beam was pulsed at 1.22 kHz, with the beam on time equal to its off time (50 % duty cycle). For a description of the VCAP instrumentation, see Banks et al. [1987].

Paper number 7L6636.
0094-8276/87/007L-6636$03.00

2. Observations

The shuttle was launched into an almost circular orbit with a nominal altitude of 325 km and an inclination of 49.5°. The trajectory of the PDP relative to the shuttle during the fourth magnetic conjunction is shown in Figure 1. The vertical axis is the distance to the PDP measured along the earth's magnetic field, and the horizontal axis the distance perpendicular to the field. The pulsed beam sequence started at approximately 04:11 UT and lasted for about 7 min. The shuttle attitude was adjusted so that the electron beam was emitted towards the PDP. Thus the beam pitch angle varied from about 3° to 49° during the sequence.

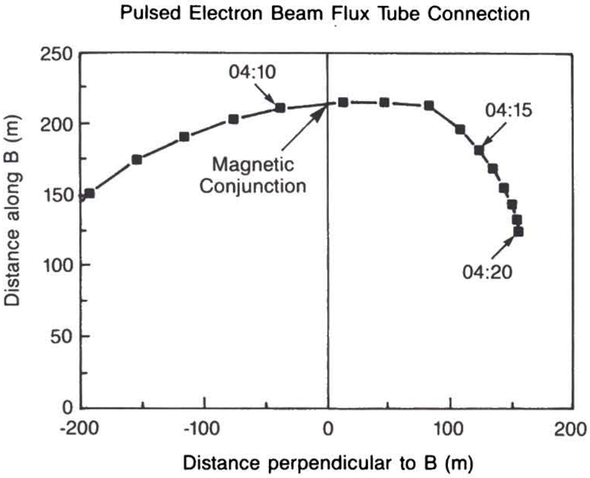

Fig. 1. The trajectory of the PDP relative to the shuttle during the fourth flux-tube connection. The beam was directed towards the PDP.

The conjunction occurred during nighttime. The ambient electron density estimated from the Langmuir probe on the PDP was 3×10^4 cm^{-3} [Hawkins et al., 1987], which corresponds to an electron plasma frequency, f_{pe}, of about 1.1 MHz. The electron gyrofrequency, f_{ce}, varied from 560 kHz to 600 kHz, and the lower hybrid frequency, f_{LH}, from 2.9 kHz to 3.0 kHz, assuming the ion population consisted of O^+.

An example of the magnetic fields observed in the 1-10 kHz range is shown in Figure 2 as function of time. The intensity of the signals is color-coded showing the fundamental and the odd harmonics of the 1.22 kHz pulsing frequency as horizontal lines. During the time interval shown the distance of the PDP perpendicular to the beam increased from about 111 m to 117 m. In addition to the emissions at the odd harmonics, weaker emissions at the even harmonics are also present as well as natural noise in the form of whistler activity. The two most pronounced whistlers are seen at 16-17 s and at the end of the frame. Note that these whistlers reach amplitudes that are comparable to the amplitude of the strongest harmonics.

The PDP was spinning with a spin period of 13 s. Both the magnetic and the electric sensors measured a component of the fields perpendicular to the spin axis. This induces a modulation of the amplitude of the measured fields with a period of 6.5 s. The modulation is very noticable in Figure 2 for the odd harmonics, especially for harmonic numbers 5 and 7. An interesting point is that the spin modulation of the harmonics are not in phase. We expect an analysis of the amplitude modulation to give us important clues as to the polarization of the fields.

Figure 3 shows the electric fields 51.2 s later, when the electric sensor was connected to the receiver and the PDP was at a distance of 124-127 m from the beam. The strongest emissions are at the second and the third harmonics, which are spin modulated 180° out of phase. The amplitude of the harmonics has been estimated using a pre-flight calibration of the receiver and the AGC. The estimate agree with values obtained independently from a filter bank wave experiment. We find that the amplitude of the strongest harmonics vary from about 10 mV/m close to the beam to about 1 mV/m at the maximum distance from the beam.

In addition to radiation at harmonic frequences, the pulsed beam generated broad-banded electrostatic noise seen as the blue background in Figure 3. The noise is present at least up to the electron gyrofrequency with an intensity that decreases with frequency. The level is about 50 dB above the natural noise level in the 0-10 kHz band at closest approach to the beam. Broad-banded electrostatic noise is commonly observed in connection with DC electron beam emissions [Neubert et al., 1986]. The intensity and the frequency characteristics were

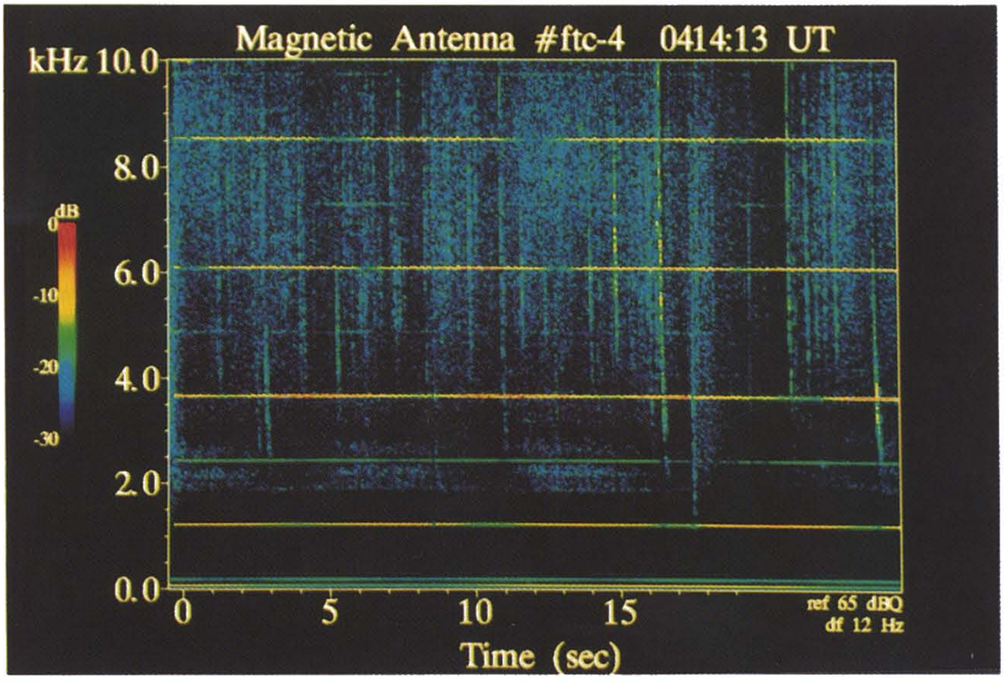

Fig. 2. The magnetic fields in the frequency range 0-10 kHz as a function of time. The perpendicular distance from the beam increased from about 111 m to 117 m.

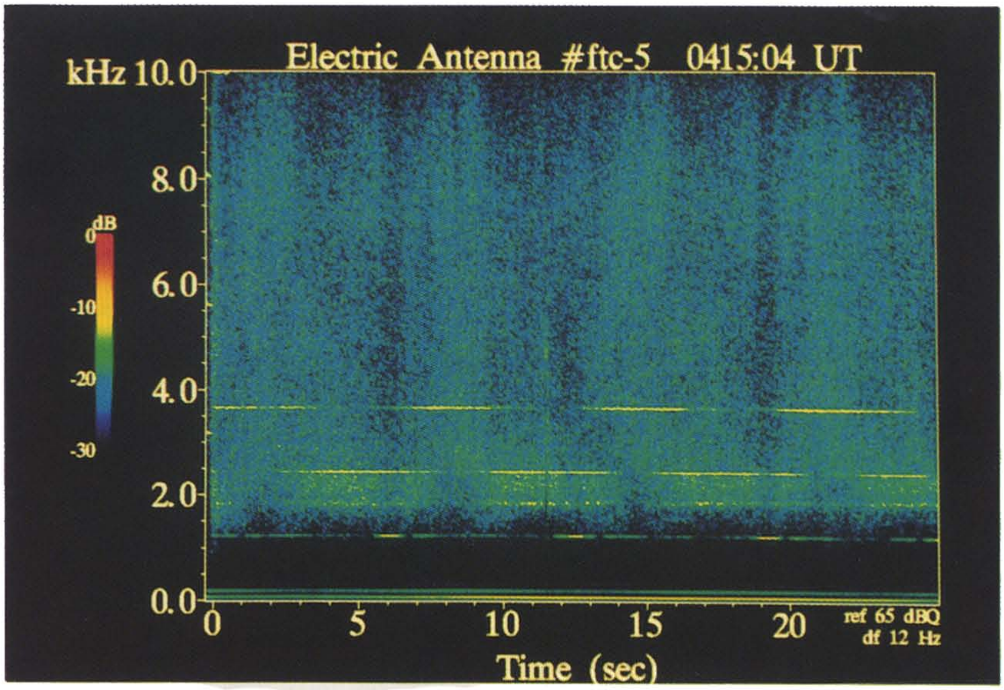

Fig. 3. The electric fields in the frequency range 0-10 kHz as a function of time. The perpendicular distance from the beam increased from about 124 m to 127 m.

comparable to that seen during the earlier DC beam firing at the third flux-tube connection [Gurnett et al., 1987]

Harmonics in the electric signal are detectable mainly below the third harmonic, except when very close to the beam. The apparent lack of emissions at the higher harmonics could be caused by the high level of broad-banded electrostatic noise, which inhibits the detection of lower amplitude harmonics.

As shown in Figure 3, a narrow-band emission is also present at a frequency of about 1.5 times the beam pulsing frequency, and with it, a band of noise extending up to the second harmonic. The noise is spin modulated and has a noticable magnetic component as seen in Figure 2. The lower hybrid frequency induces a cutoff in the natural electromagnetic noise as whistler waves with large wave normal angles are reflected at this frequency. This effect is seen in Figure 2 at about 3 kHz. The spin-modulated noise between 1.5 and 2 times the pulsing frequency is presumably beam-generated and is at frequencies below f_{LH}. This indicates that the noise is propagated in the Afven mode. We note here that electromagnetic noise of a similar nature, were observed earlier during the fly-around when the electron beam was modulated at about 100 Hz. During this period, the position of the PDP was about 200 m from the shuttle along the magnetic field, and 60-90 m perpendicular to the field.

3. Discussion

The theory of Harker and Banks [1987] predicts the coherent contribution of the field intensities generated by a square wave modulated beam emitted at arbitrary pitch angles in a cold magnetized plasma. It is assumed that the beam electrons radiate coherently and that the beam retains an ideal helical structure from the exit of the beam accelerator and to infinity, while processes that destroy the ideal beam coherence are simulated by assuming that the current is exponentially decaying with distance along the magnetic field with the scale length $1/\beta$, also called the coherence scale length. The theory is applicable in both the near- and far-field regions, where an observation point is in the far-field region if the distance from the beam is much larger than a perpendicular wavelength.

We have determined some of the characteristics of the wave-fields predicted by the theory for the experimental conditions of the pulsed flux-tube connection. They are summarized along with a comparison with observations in the following points:

1) From the assumption of an exponentially decaying but perfectly square-wave modulated source current, it follows that the predicted electric and magnetic fields are generated at the odd harmonics of the modulation frequency as found by a Fourier transform of a square wave function with a 50 % duty cycle. While the radiation is electromagnetic in nature, detailed expressions of the amplitudes have so far only been derived for the electric field components. This renders a closer comparison with theory difficult, since the electrostatic noise generated simultaneously is of significant intensity as compared to the coherent radiation at the odd harmonics. However, from the magnetic field data we conclude that electromagnetic fields were predominantly generated at the odd harmonics of the beam modulation frequency as predicted.

2) The fields are generated through a Cherenkov resonance (s = 0) given by the resonance condition:

$$s f_{ce} + k_{\|} v_{\|} - f = 0 \tag{1}$$

where f, k, and v are the wave frequency, the wave normal, and the beam electron velocity, and the subscript $\|$ stands for the component parallel to the earth's magnetic field. The field intensities generated through a cyclotron resonance (s = 1) and anomalous cyclotron resonance (s = -1) are several orders of magnitude lower than the contribution from the Cherenkov resonance.

The perpendicular 'wave-lengths' of the fields generated through Cherenkov resonance at 1-30 kHz are typically larger than a few hundred meters, which brings the observations during the fly-around within the near-field region.

3) With the difficulty mentioned in point 1) in mind, we attempt in the following to compare the variation with radial distance of the electric field amplitudes to the theoretical predictions. Solving the cold plasma dispersion relation for the perpendicular component of the wave normal, $k_{\perp}$, with $k_{\|}$ given by (1) and $s = 0$ gives two physically acceptable solutions for $k_{\perp}$. The one (root 1) is real for frequencies above f_{LH} and corresponds to a propagating whistler mode wave with the wave normal close to the resonance cone. Below f_{LH} this root becomes imaginary and corresponds to an evanescent wave. Root 2 is real in the full 30 kHz frequency range. Below f_{LH} it corresponds to a fast Alfven wave, while above f_{LH} to a whistler wave. The theory finds that the fields corresponding to root

1 are the strongest in the near vicinity. However, the electric component of the evanecent field below f_{LH} is strongly damped with radial distance from the beam, typically about 1 dB/m, leaving the weaker component from root 2 at larger distances.

At increasing distances from the beam, a cutoff at frequencies below about 2 kHz is developed in the broad-banded noise, which is followed by a decrease in the amplitude of the fundamental relative to the higher harmonics. We thus find the same trend in the data as predicted by theory. However, this qualitative agreement exists only when a very large beam coherence length is assumed, and is destroyed when the coherence length is of the order of, or smaller than a parallel wave length. The parallel wavelength was for the experimental conditions about 10 km.

4) With the assumption of an infinite coherence length, the predicted amplitudes of the harmonics are about two orders of magnitude above the observed amplitudes, which reached levels of 1-10 mV/m. The inclusion of a finite coherence length brings the predictions closer to the observations when close to the beam, but create problems at larger distances as mentioned above.

5) The theory predicts the radial component of the electric emissions to be the dominant component at all the observed odd harmonic frequences, and at all distances from the beam covered by the PDP. This has as a consequence that the fields are almost linearly polarized in the radial direction. A spin modulation is thus in general expected, although we yet have to confirm the specific polarization. Note, however, that the observation of a spin modulation at the first harmonic (Figure 3), which is out of phase with the modulation of the third harmonic, is not in accordance with the theory.

In conclusion we find that the theory of Harker and Banks [1987] qualitatively describes the frequency characteristics of the coherent electromagnetic radiation as seen in the magnetic field data. The observations of weaker, but noticable, even harmonics indicate that the current source is not perfectly square-wave modulated, even though the rise time of the accelerating potential of the FPEG gun is of the order of 10^{-7} s. Even harmonics were also present in data obtained with the PDP located in the shuttle cargo bay, in close proximity to the FPEG. We suggest that radiation at even harmonic frequencies is either generated by the return current, or caused by a degradation of the electron beam coherence.

The FPEG beam density is about $7 \times 10^6 cm^{-3}$ at 10 cm from the nozzle [Hawkins et al., 1987], which is at least two orders of magnitude larger than the ambient ionospheric density. Computer simulations for such overdense beams show that electrostatic potentials of the order of the beam energy are created at the so-called stagnation point [Pritchett and Winglee, 1987], which for the conditions of the fly-around would be formed at a distance of some meters from the nozzle. The formation of a stagnation point drastically alters the beam structure by accelerating and reflecting beam electrons. However, as mentioned by Pritchett and Winglee [1987], the conditions for beam experiments performed from the space shuttle differs from the assumptions of the computer simulations. First, the shuttle moves through the ionosphere with a considerable velocity (7.7 km/s) and second, the surface of the return current collection is largely outside of the beam column and the collecting area is large (40 m^2) as compared to the beam cross section. Both these effects are likely to reduce the charge build-up at the stagnation point, and the observations detailed above suggest that the beam escapes the shuttle, largely retaining its square-wave modulated structure (coherence in $v_{\|}$). This does not imply, however, that the helical structure is conserved as assumed in the theory of Harker and Banks [1987]. The observation of field intensities, which are orders of magnitude lower than those predicted for infinite coherence length, and the problem of including a finite coherence length, could point towards the beam losing its helical structure almost immediately (incoherence in $v_{\perp}$).

Finally we point out that the observed electric field amplitudes of 1-10 mV/m are of a magnitude where non-linear wave-particle and wave-wave interactions can become important [Neubert, 1982]. The possibility that the narrow-banded electrostatic emissions at 1.5 and 2 times the modulation frequency may be the result of such processes should be considered.

Acknowledgments. The authors thank W. C. Burgess and J. W. Yarbrough for their help with the spectral analysis and the digitization of the wide-band analog data. The work done at Stanford was sponsored by NASA under contracts NGR-235 and NAG5-476. The Space Physics Analysis Network (SPAN) was used in the preparation of this report.

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(Received July 27, 1987;
accepted August 17, 1987.)