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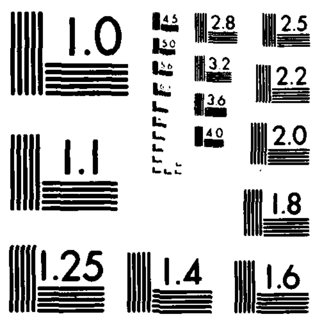

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VLF Emissions from a Modulated Electron Beam in the Auroral Ionosphere

Prepared by R. H. HOLZWORTH and H. C. KOONS
Space Sciences Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, Calif. 90245

15 November 1980

Final Report

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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

J. C. Garcia, Lt, USAF
Project Officer

Joseph J. Cox, Jr., Lt Col.
USAF
Chief, Advanced Technology Division

FOR THE COMMANDER

Burton H. Holaday, Col., USAF
Director, Directorate of Space Systems Planning
Deputy for Technology

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A discrete VLF frequency of 3 kHz was successfully radiated by a modulated electron beam on a rocket launched into an active aurora. Instrumentation on this flight included a programmable electron accelerator on the aft section with various particle and field detectors on the aft section as well as the ejected forward payload. The accelerator programmer included a current modulation period at fixed electron energy for 0.45 seconds duration approximately every 11 seconds throughout the flight. In each of these programs steps 4 kV electrons are current modulated at a 3 kHz rate between I_{min} = 0

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or 10 ma and $I_{max} \cong 80$ ma. The forward payload, which was ejected at about 10 meters per second, included a pair of spherical double probes separated by 2.75 meters and connected to a VLF receiver operating between 30 Hz and 18 kHz. Both this broadband receiver output as well as various narrow band channel outputs were directly telemetered to ground. Post flight spectrum analysis of the broadband VLF data clearly indicates that signals during the 3-kHz accelerator modulation periods were propagated to the forward payload. A detailed analysis of these modulated pulses detected by the VLF receiver is presented. A time-delay analysis between the start of the modulation and detection at the forward payload indicates time delays up to 0.2 seconds. The electron beam is believed to have produced a beam-plasma discharge making a radiation efficiency calculation difficult. However, absolute received signal strength was about 1 mv/m at 1.4 km separation.

PREFACE

The authors wish to acknowledge the support of W. Bernstein, the principal investigator for the flight, S. Monson who provided support for the experiment at the range and W. B. Harbridge and C. W. Jordan in constructing and integrating the payload. The spectral data analysis was assisted by M. Dazey, W. B. Harbridge and R. Maulfair.

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Introduction

In an active experiment to study plasma dynamics in the auroral ionosphere, NASA sounding rocket 27.010 AE was launched on April 9, 1978 from Ft. Churchill, Manitoba, Canada. The rocket carried an electron accelerator and a full complement of plasma diagnostic devices including electric and magnetic receivers, particle detectors and photometers. The accelerator was mounted on the aft payload which remained attached to the rocket motor throughout the flight. The diagnostic devices were arranged on various Throw Away Detectors laterally ejected (TAD's) and a forwardly ejected payload. An important experiment performed in this flight which this paper addresses exclusively involved the 3 kHz modulation of the electron beam current at fixed voltage and the subsequent detection of a 3 kHz signal by electric and magnetic receivers on the forward payload at distances up to several kilometers away.

Following ejection of the forward payload at about 10 m/sec and antenna deployment the electron accelerator on the aft payload was operated in a mode in which the current was modulated between $I_{min} = 0$ to 10 ma and $I_{max} \cong 80$ ma at 3 kHz for 450 msec every 11 sec. Everyone of these accelerator modulation periods (AMP's) were detected by the forward payload in the electric VLF spectrum. In this paper it will be demonstrated that a) the VLF spectrum was sharply peaked at 3 kHz with no significant drifting during AMP's, b) there is a measurable time delay between start of AMP and detection at the forward payload of 1 to 2 tenths of a second, c) that the received AMP's are quite structured in time possibly due to beam plasma discharge phenomena, and d) that the AMP's are also visible in the magnetic spectrum but with time delays which differ from the electric signals.

Instrumentation

The aft payload was equipped with two Machlett EE-65 electron accelerators which injected electron beams at 45° to the spin axis with a half cone angle of about 5°. Partial malfunction of the accelerator programmer caused a variety of spontaneous program variations in flight. However, after a few seconds the accelerator operation settled down and the AMP's appeared relatively reliably throughout the flight. At 4 kV beam energy the maximum current, I_{max}, was about 80 milliamps. Modulation occurred between I_{max} and either 10 ma or 0 ma which could not be distinguished following the accelerator program malfuntions. The DC current step operation of the accelerator along with some of the particle observations have been described by Wilhelm et al., 1980. Accelerators have also been flown on auroral zone rockets by Winckler, 1975 and 1976. The other relevant instruments included magnetic and electric VLF receivers and antennas on the forward payload. These wave receivers are similar to ones flown before (Koons and Pongrantz, 1979) and will be briefly described here.

The electric antenna consists of a pair of spherical probes separated by 2.75 meters on rigid booms mounted ⊥ to the spin axis. The magnetic antenna consists of a ferrite rod with multiple windings mounted inside the forward payload. Following preamps and AGC's both electric and magnetic signals up to 16 kHz were directly telemetered on a wideband channel to ground. The preamps also fed fixed-frequency, narrow-band channel amplifiers with digital telemetry outputs. One of these narrow band filter channels was set at 3 kHz which allowed accurate determination of absolute signal amplitudes for the 3 kHz AMP's. All electronics in these receivers operated perfectly except that onboard EMI away from our range of interest caused the magnetic AGC to operate in its least sensitive mode throughout the flight. Thus the broad band magnetic spectra are considerably more noisy than the electric.

Environmental Flight Conditions

NASA flight 27.010 AE was launched at 04:51:10 UT April 9, 1978 from Ft. Churchill at 152° azimuth and attained an apogee of 246 km at 255 sec after launch. A brief breakup event had occurred about 1/2 hour prior to launch and a bright arc existed just south of the zenith at launch. Ground photometric measurements indicated an intensity of 70 - 100 kR throughout the flight (Bernstein, private communication, 1978). The rocket entered the center of the bright arc from below, penetrated the equatorward boundary near apogee and remained in a quiet environment the remainder of the flight. D. Evans (private communication, 1978) characterized the precipitated electron flux as intense and energetic with a characteristic energy peak between 14 and 20 keV while the rocket was inside the arc. Thus the AMP's were performed under a variety of auroral conditions.

Observations

Figure 1 shows a 25 second sequence of the electric VLF spectrum from 0 to 4 kHz. In this figure three AMP's are shown as indicated along the top. Below each of these modulation periods are expanded electric amplitude - time profiles of a narrowband filter centered at 3 kHz with a 10 Hz bandwidth. The 60 cycle harmonic bands in the lower portion of the spectrogram are artifacts

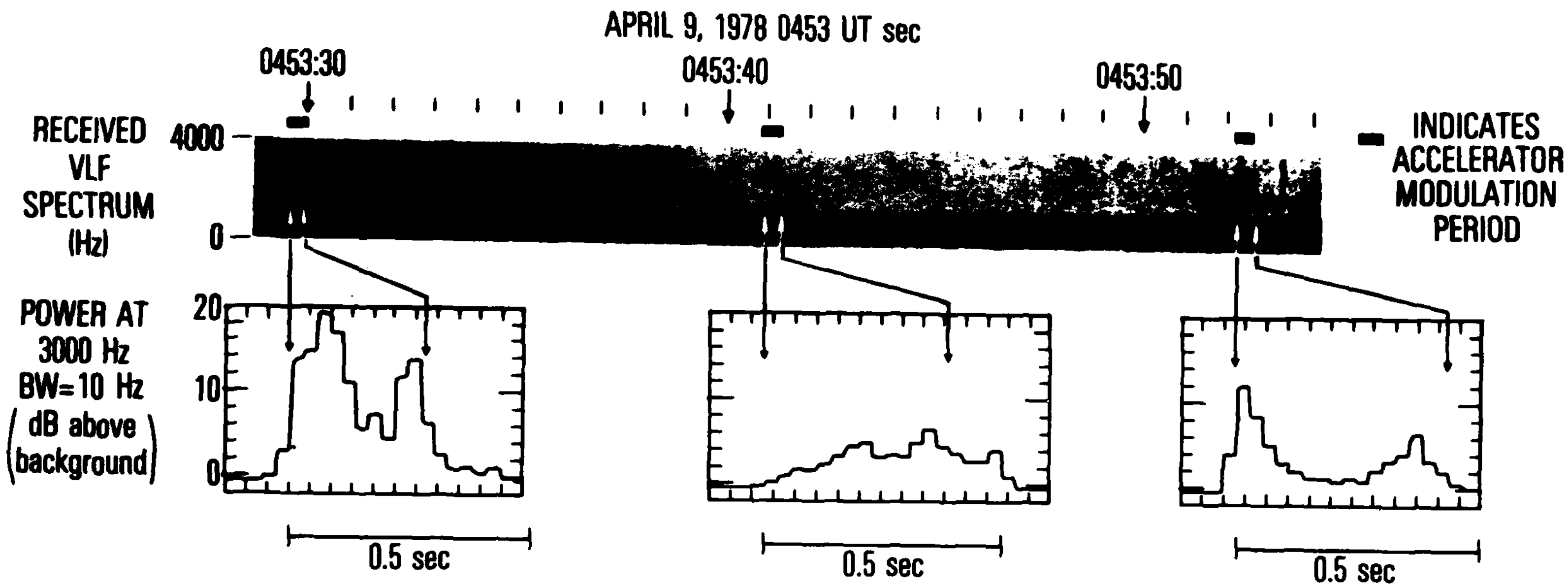

Figure 1. A 25-second VLF spectrum from 0 to 4 kHz along with 3 individual power time profiles during AMP's on the NASA rocket 27.010AE.

of the original telemetry recording. At the time of figure 1 the forward payload is about 1400 m away from the electron accelerator on the aft payload. The three amplitude-time profiles also indicate that the received 3 kHz signals are about the same length and not significantly longer than the 0.45 msec AMP. This, and the absence of rising or falling tones suggests that the local plasma was not unstable to nonlinear growth of this particular VLF frequency. Thus, the received power can be attributed solely to that radiated from the beam/plasma environment generated by the accelerator. The magnetic spectrum during this 25 sec period also shows the 3 kHz AMP's but as mentioned above an EMI problem caused the magnetic signal-to-noise to be lower; individual examples from the magnetic spectra will be shown later.

Figure 2 is an example of an individual VLF electric spectrum during an AMP. This demonstrates the discrete nature of the received signal and that the center frequency is indeed 3 kHz and has not drifted measurably. In this figure the 3 kHz pulse width is less than the 1 Hz bandwidth. Using the calibrated 3 kHz digital filter channel the peak AMP electric field strengths were about 1 mv/m.

Careful time delay analysis was performed in which the digital telemetry channel for the accelerator current from the aft payload was used as a timing mark for the beginning of each AMP. The leading edge of significant power increase in the 3 kHz channel from the digital telemetry was also measured. However in many cases the timing of the leading edge of the received signal was ambiguous because of other natural VLF phenomena such as sferics. Eliminating all such ambiguous cases the time delays between start of AMP and onset

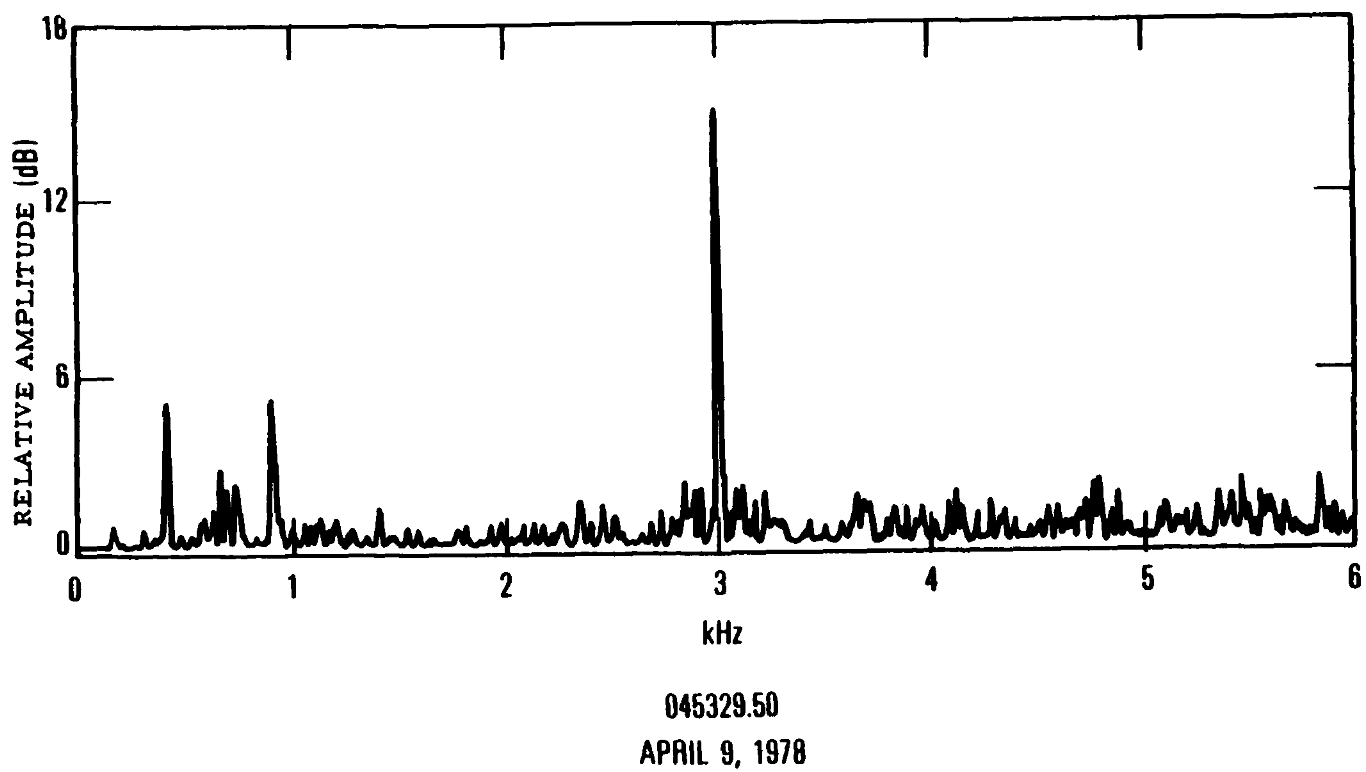

Figure 2. A single spectral sweep during the AMP at 045329.5 UT April 9, 1978. The two low frequency spikes are artifacts of the recording process.

of detection at the forward payload are shown in Figure 3. The gaps in Figure 3 are due to occasional irregularity of occurrance of AMP due to the accelerator programmer troubles as mentioned before or to sferic interference with leading edge or due to extremely low signal to noise. The propagation time for the 3 kHz signal to reach the forward payload is often significantly slower than for an electromagnetic wave which could not be resolved on this time scale. The apparently systematic changes in the time delays shown in this figure suggest that the signals are not simply space charge disturbances eminating from the aft payload. The magnetic spectrum was too noisy to allow this kind of 10 msec timing study in all but a few cases which will be discussed below.

A narrow band filter of 5 Hz was used in Figure 4 on the broadband VLF electric signal at 3 kHz to get a better look at the spiky nature of the received AMP signals. The complicated temporal nature of the received 3 kHz power does not appear to be caused by the slow variation of either the injected pitch angle or the antenna angle to the magnetic field. The electric dipole antenna was oriented nearly to both B and the line from the aft to the forward payloads. Therefore all transverse electromagnetic (e.g., whistler mode, etc.) signals arising from strictly nearby the neighborhood of the accelerator would be seen with maximum efficiency.

The last figure shows a comparison between electric and magnetic VLF spectra at two separate times during the flight. These figures clearly demonstrate that the received electric and magnetic signals are not always coincident in time. In Figure 5a the magnetic signals appears to be slightly delayed from the electric signal but the differing power time profile may be

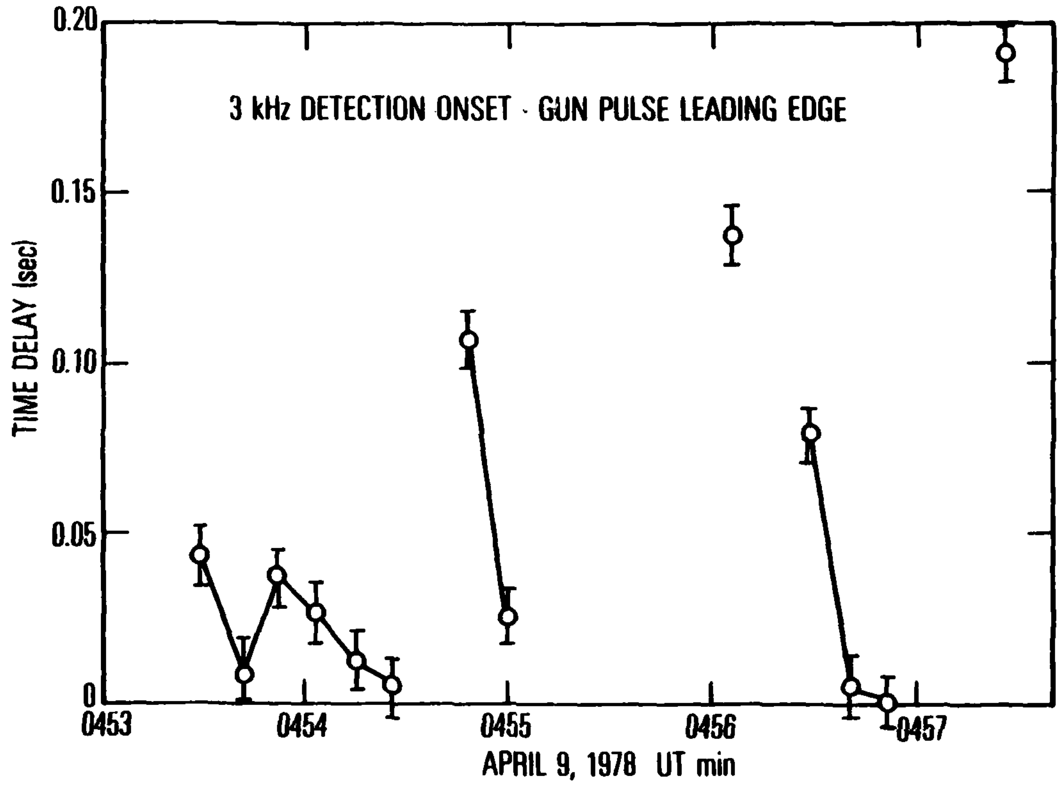

Figure 3. Time delay analysis between turn on of 3 kHz accelerator modulation and leading edge detection at forward payload in the electric spectrum. Data gaps are due to irregularity of occurrence of AMP's and due to leading edge interference by other VLF phenomena.

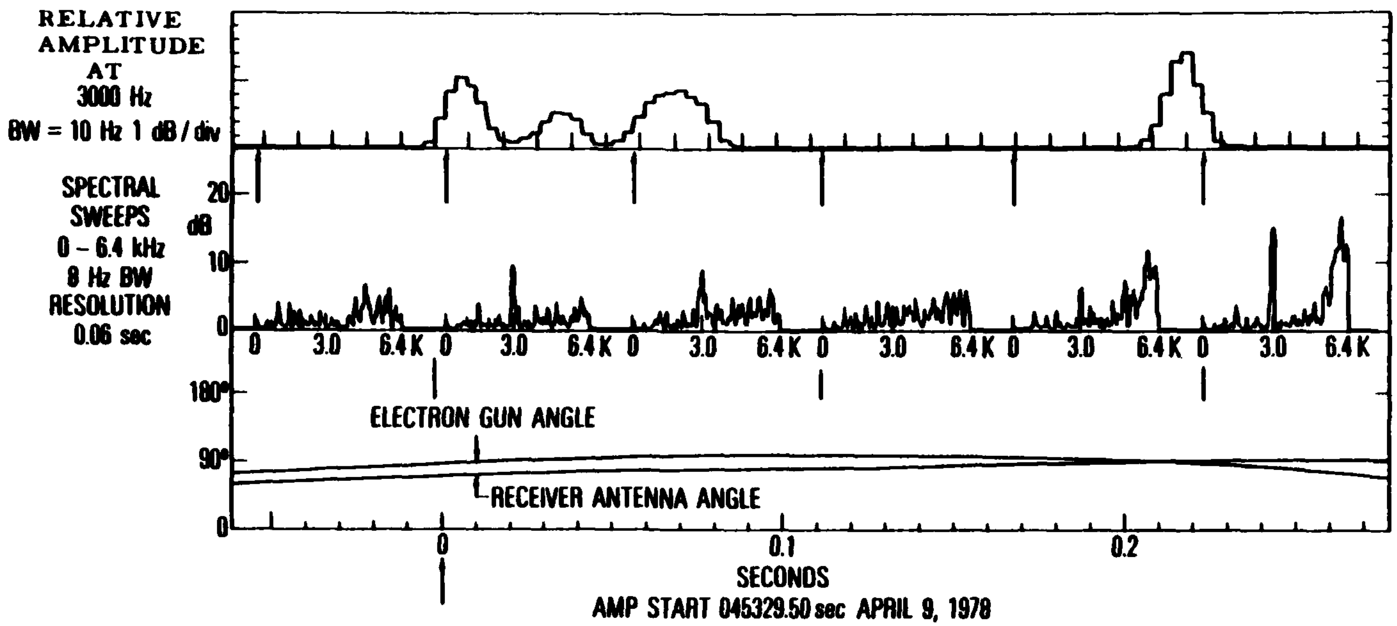

Figure 4. A power-time and spectral study of a single AMP at 045329.5 UT. In this figure the spectral sweeps in the middle panel are averages for 0.06 sec or roughly the length of the plotted spectra starting at the indicated arrows.

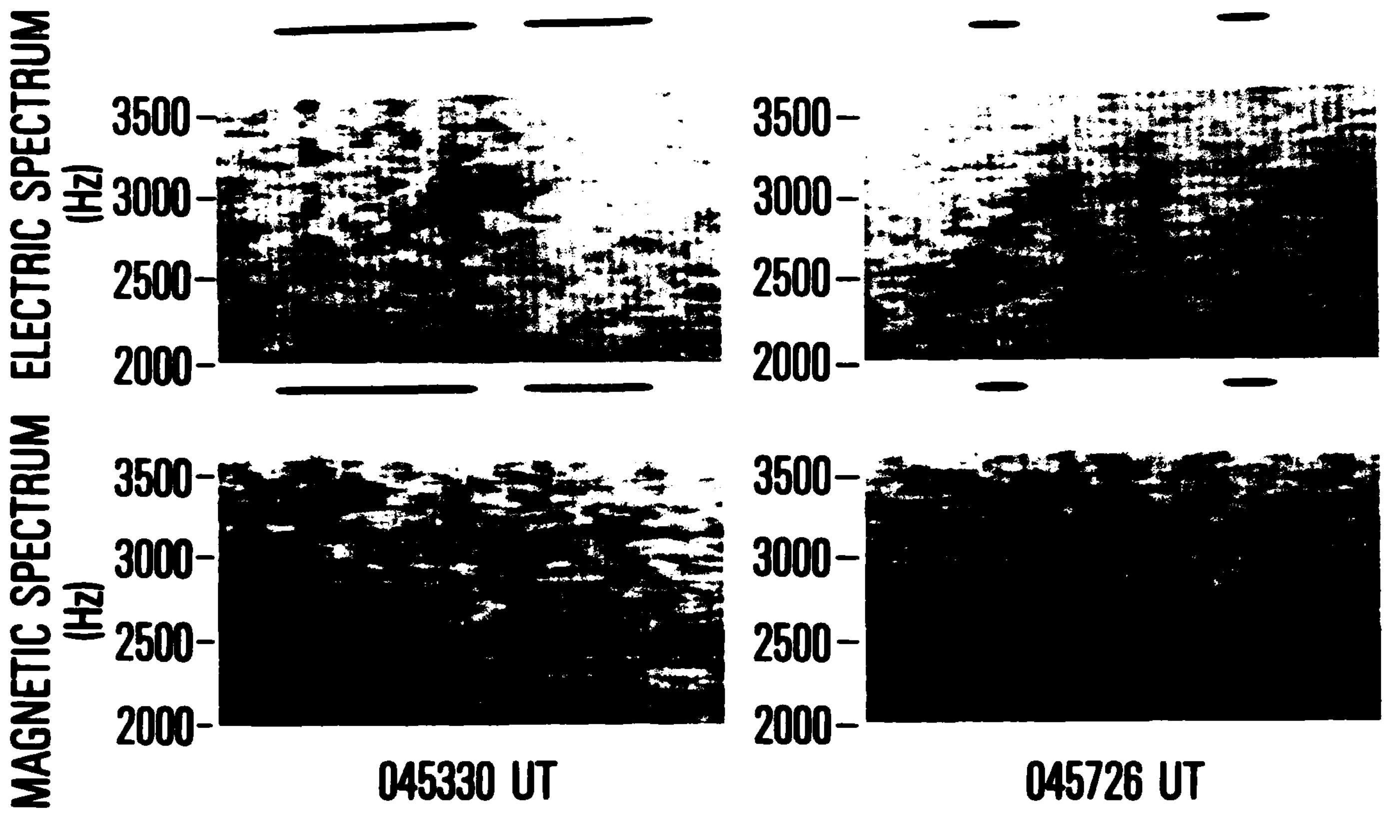

Figure 5. Two cases showing timing variations between received AMP signals in the Electric and Magnetic receivers. Figure 5a shows E field leading B field signals and Figure 5b shows the opposite later in the flight. Pulses above each spectrum indicate time code.

consistent with the two being coincident. However figure 5b shows just the opposite, namely that the magnetic signal leads the electric signal by about 0.2 sec. These two cases are about 4 minutes apart and 5a occurs inside the bright arc while 5b occurs equatorward of the arc. Also, the two payloads are nearly on the same field line on the up leg but definitely on separate field lines on the down leg.

Discussion

In this experiment we successfully radiated a discrete VLF frequency with an electron beam. The radiation efficiency is difficult to calculate because the beam itself was probably generating a beam plasma discharge (BPD). This plasma physics problem is still under investigation by the 27.010 rocket team. BPD has been reported on rocket flights using similar gun currents and voltages (Galeev et al., 1976; Mishin and Ruzhin, 1978) and in the laboratory under simulated ionospheric conditions (Bernstein et al., 1975; 1979). In a BPD some of the beam energy goes into heating the plasma through the two stream or other instability, but it is not clear just how this would affect the current distribution in space which determines the radiation efficiency. At these energies and currents BPD is ignited in the lab within a few tenths of a millisecond consistent with the 3 kHz modulation rate (Bernstein, private communication, 1980).

The electron accelerator delivered a peak DC power of (4kV) (80 ma) = 320 watts with an injection pitch angle which varied with respect to B between 0 and about 135° as the rocket precessed. Thus the field line would act as several stacked dipole radiators of effective length dependent on electron energy and injection angle. Furthermore, in this flight the receiving payload was in the near field region for a whistler mode or ion acoustic wave where the distance to the source was less than or the order of a wavelength. Therefore to determine the antenna radiation pattern requires integration over each dipole or simulated aperture which itself is constantly changing. In order to do this with the beam in BPD would require integration over the electron energy spectrum as well.

While this flight was complicated by accelerator program malfunctions and may involve beam-plasma discharge phenomena it has nevertheless been shown that modulated electron beams in the space plasma environment can be used as discrete frequency VLF antennas.

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