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DIRECT OBSERVATION OF RADIATION BELT ELECTRONS PRECIPITATED BY THE CONTROLLED INJECTION OF VLF SIGNALS FROM A GROUND-BASED TRANSMITTER

W. L. Imhof, J. B. Reagan, H. D. Voss, E. E. Gaines,
D. W. Datlowe, and J. Mobilia
Lockheed Palo Alto Research Laboratory, Palo Alto, CA 94304

R. A. Helliwell, U. S. Inan, and J. Katsufrakis
STAR Laboratory, Stanford University, Stanford, CA 94305

R. G. Joiner
Office of Naval Research, Arlington, VA 22217

Abstract. Radiation belt electrons precipitated by controlled injection of VLF signals from a ground based transmitter have been directly observed for the first time. These observations were part of the SEEP (Stimulated Emission of Energetic Particles) experiment conducted during May - December 1982. Key elements of SEEP were the controlled modulation of VLF transmitters and a sensitive low altitude satellite payload to detect the precipitation. An outstanding example of time-correlated wave and particle data occurred from 8680 to 8740 seconds U.T. on 17 August 1982 when the satellite passed near the VLF transmitter at Cutler, Maine (NAA) as it was being modulated with a repeated ON (3-s)/OFF (2-s) pattern. During each of twelve consecutive pulses from the transmitter the electron counting rate increased significantly after start of the ON period and reached a maximum about 2 seconds later. The measured energy spectra revealed that approximately 15 to 50 percent of the enhanced electron flux was concentrated near the resonant energies for first order cyclotron interactions occurring close to the magnetic equator with the nearly monochromatic waves emitted from the transmitter.

Introduction

Our purpose is to present first observations of direct bounce loss cone precipitation of radiation belt electrons by controlled injection of VLF signals from a ground based transmitter. This result was recently achieved in an active wave-particle experiment called SEEP (Stimulated Emission of Energetic Particles). Past observations have shown that electrons can be precipitated from the radiation belts by ground-based VLF transmitters, but the evidence was predominantly based on observations of electrons in the drift loss cone. Narrow resonant peaks in the energy spectra (Imhof et al., 1974, 1981; Vampola and Kuck, 1978; Koons et al., 1981) and coordinated wave-particle observations (Imhof et al., 1981) have provided evidence for the effects of transmitters. In addition, natural whistlers and emissions have been observed to produce secondary ionospheric effects (x-rays, enhanced D-region ionization and photometric radiation) that have been attributed to VLF wave-induced electron precipitation in the direct bounce loss-cone (Rosenberg et al., 1971; Helliwell et al., 1973; Helliwell et al., 1980; Carpenter and LaBelle, 1982). Theoretical models of the gyroresonant wave-particle interaction in the magnetosphere have been used to predict the levels, energy spectra and temporal variations of particle fluxes that would be precipitated by monochromatic VLF signals at the VLF transmitter frequencies (Inan et al., 1982; Inan, 1981). These models have been useful in carrying out the experiments reported here.

The SEEP experiment was conducted from May until December 1982. Electron counting rate time profiles measured during a coordinated satellite-transmitter operation are presented and compared with the programmed modulation patterns of the VLF transmitter and the observed energy spectra are interpreted in terms of energy selective precipitation mechanisms occurring in the near equatorial regions.

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Description of the Active Experiment and the Satellite Instrumentation

During the course of this experiment the U. S. Navy VLF transmitters at Annapolis, Maryland (NSS), at Cutler, Maine (NAA) and at Jim Creek, Washington (NLK) operating at frequencies of 21.4 kHz, 17.8 kHz, and 24.8 kHz, respectively, and the Stanford University research VLF transmitter at Siple Station, Antarctica operating in the 4 - 6 kHz range were modulated for ten-minute periods during overpasses of the S81-1 spacecraft. At the time of the data presented here, only one transmitter (NAA: 44.65°N, 67.28°W, L = 3.2) was modulated with a SEEP format. The ON-OFF modulations were performed in one of ten selectable formats chosen to provide a variety of periodic, pseudo-periodic and random patterns with ON times ranging from 0.3 seconds to 8 seconds. One commonly used format which also applies to the data presented here consisted of an ON (3-s)/OFF (2-s) pattern repeated for the entire duration of the modulation period, normally 10 minutes.

The SEEP payload on the three-axis stabilized S81-1 spacecraft measured precipitated particles directly with an array of silicon solid state detectors, and indirectly through an imaging x-ray proportional counter to map bremsstrahlung x-rays (> 3 keV) and an airglow photometer to measure optical emissions. The electron spectrometers were oriented at various angles to the

Table 1 Electron Spectrometers

Central Zenith Angle	Central Pitch Angle	Acceptance Half Angle	Geometric Factor (cm^2 ster)
0°	34°	30°	2.47
10°	32°	20°	0.49
50°	46°	20°	0.17
90°	78°	20°	0.17

local vertical and covered an energy range of 2-1000 keV. Several were cooled to -120°C to improve the sensor response characteristics (Voss et al., 1982). Pulse height analyses were performed on the sensor signals to provide the energy spectra. Some key parameters of the electron spectrometers used in the present analysis at 8710 seconds U. T. on August 17, 1982 are summarized in Table 1.

Observations

A good example of electron flux modulations in correlation with the transmitter ON-OFF signals occurred on 17 August 1982 at 8680 to 8740 seconds U.T. when the SEEP payload was passing near the NAA transmitter as it was being modulated with a 3-s ON/2-s OFF pattern. In Figure 1 the electron fluxes measured at various zenith angles are plotted as a function of time. A modulation period of 5 ± 0.1 seconds is clearly seen for 12 consecutive cycles. For reference, the measured ON times of the transmitter at NAA are indicated. From the Stanford recordings at Palmer Station, Antarctica, it was verified that the transmitter modulation began within 6 milliseconds of the exact start of a UT minute.

The measurements were made at a satellite altitude of $\sim$220 km, and at the positions indicated in the abscissa. Due to the South Atlantic Anomaly, the mirror points conjugate to the satellite are below sea level so any electrons measured could not travel from one mirror point to the other (with bounce times of 0.1-0.5s at L=2.3) without interacting with the atmosphere. Ducted waves can travel this distance in less than one second, but unducted waves may take several seconds to reach their reflection points in the opposite hemisphere depending upon their trajectories. From the geometry of the magnetic field line it can be shown that the individual electrons observed by the SEEP payload in the northern hemisphere must have experienced a pitch angle scattering of at least 1° during a single bounce period.

Superposed epoch analyses were clearly not needed to show the strong 5-second modulation, but they were performed to obtain an average shape of the precipitating electron intensities with respect to the transmitter signal. Counts were combined from eight consecutive 5-second intervals and the results are shown in Figure 2 for two counter outputs. A time of 0 seconds refers to the start of the transmitter ON period. The possibility that micropulsations could account for the SEEP spectrometer observations is discounted because micropulsations are generally only psuedo-periodic and are seen mainly at higher latitudes (L≥5) (e.g., Barcus et al., 1966). Also, natural electron microbursts as seen on satellites occur predominantly on higher L shells and at later local times than that of the case in question (e.g., Oliven et al., 1968). Association of the present observation with the NAA transmitter is further supported by the precise 5-second periodicity and the time correlations with the programmed modulation of the transmitter.

Model calculations (Inan et al., 1982) of the time response curve were performed assuming field aligned propagation of the wave and computing the scattering into the loss cone of particles from an assumed trapped distribution by a 3-second long monochromatic signal. The nonlinear equations of motion were integrated in an inhomogeneous medium also accounting for the wave and particle travel times. Using typical transmitter signal intensities applicable to this case it was found that a significant number of individual particles can be scattered in pitch angle by greater than 1° in a single encounter with the wave and this constitutes the fluxes represented by the dashed line in Figure 2. The onset time and the full-width-at-half maximum duration of the prediction are in good agreement with the data, although the calculated response reaches a maximum sooner than that observed. Additional delay in the calculated function and less steepness in the leading and trailing observed ramps may result from the effects of non-field aligned propagation and from wave triggering and amplification. More

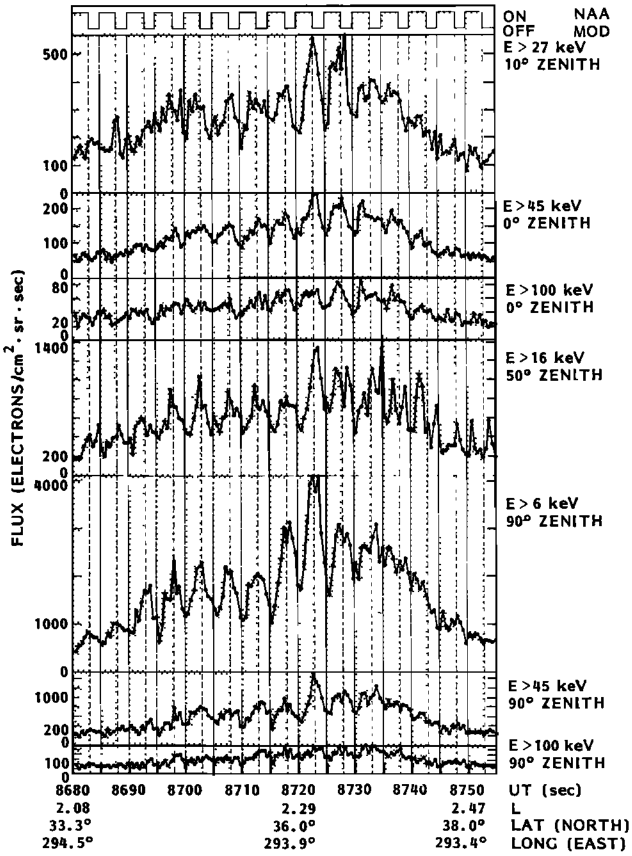

Figure 1. Electron fluxes on August 17, 1982 plotted as a function of time. Also shown are the ON and OFF times of the NAA transmitter.

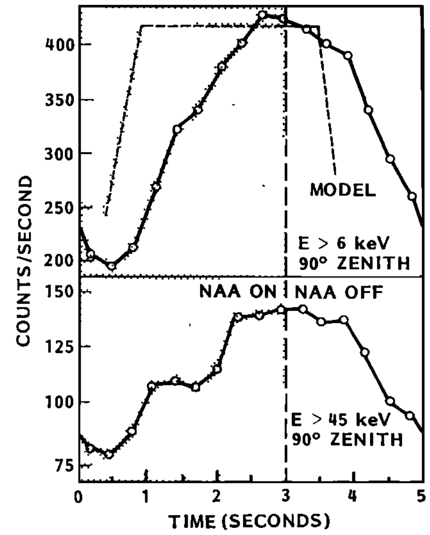

Figure 2. Superposed epoch counts/second versus time profiles from eight consecutive 5.0-second intervals during the period 8690 sec to 8730 sec U.T. on 17 August 1982. Also shown is the normalized time response curve computed using a theoretical model (Inan et al., 1982).

detailed analysis of the precipitation pulse shape and comparisons with theory will be reported later.

Differential energy spectra of the precipitating electrons as measured with the spectrometer oriented at 90^o zenith angle are shown in Figure 3. These are raw counts from the pulse height analyzer, uncorrected for deadtime. Each of the spectra in the upper section is taken from a 1.984 second time interval beginning 1.7 seconds after start of the transmitter ON pulse. In the lower sections the spectra are taken from 1.280 second intervals beginning 4.2 seconds after start of each transmitter ON pulse. The latter spectra correspond approximately to the minima in electron counting rate and are summed from a shorter time period to minimize any contributions from the enhanced flux regions. Prominent peaks appear in the spectra taken during the times of enhanced electron precipitation, but there is little evidence of their presence during times of minimum intensity. The central energies of the peaks in the spectra are labelled and it is clear that the peak energies decrease with increasing L value. From the absolute fluxes it has been estimated that the rate of deposition of energy into the atmosphere was of the order of 10^{-4} ergs/cm^2 sec.

Let us now compare the central energies of the peaks shown in Figure 3 with the energies calculated for first order cyclotron resonance near the equator with 17.8 kHz waves traveling parallel to the earth's magnetic field lines. Figure 4 shows curves representing the calculated resonant energies for assumed cold plasma density models of 3000 $(L/2)^{-4}$ cm^{-3} and half that value along with the measured central energies of the peaks. Plasma density models in this region of space are scarce but those assumed in Figure 4 are consistent with other values quoted and have been used in past investigations of cyclotron resonance interactions in the upper edge of the inner radiation belt (Imhof et al., 1974). The measured peak energies are consistent with those expected for cyclotron resonance with waves traveling parallel to the earth's magnetic field lines. On the other hand, with a 60^o wave normal angle the resonant electron energies for the same plasma density

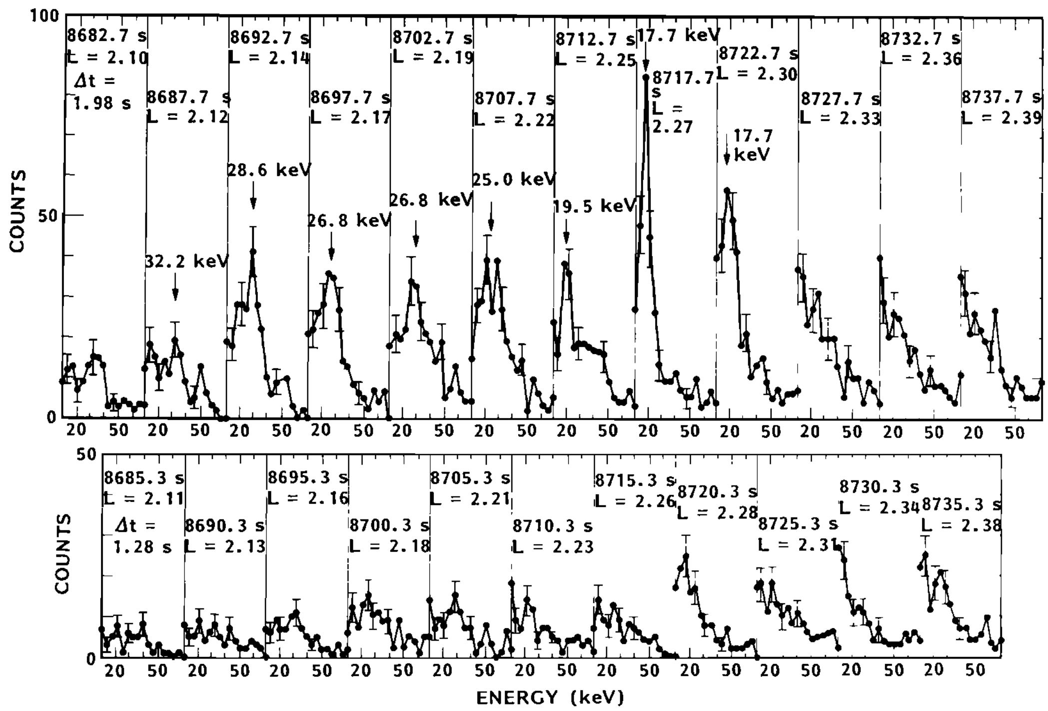

Figure 3. Differential electron energy spectra observed at selected times on August 17, 1982 in the form of raw counts uncorrected for deadtime.

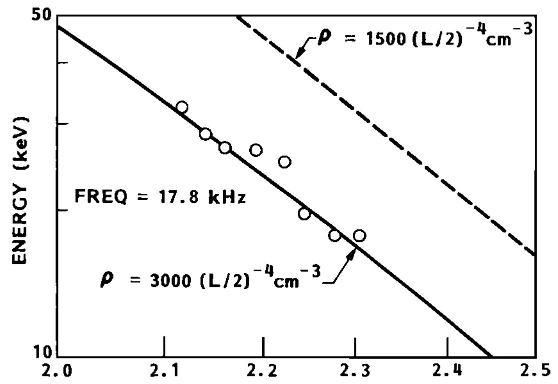

Figure 4. Open circles give measured energies of the peaks; curves represent calculated resonant energies.

would be approximately 1.3-1.5 times larger or equivalently the plasma densities corresponding to the observed resonant energies would be larger by a similar factor. Of particular importance is the finding that approximately 15-50 percent of the enhanced electron flux during the spikes is concentrated close to the resonant energies for near equatorial interactions. The enhanced precipitation at energies off the peaks is probably due to wave-particle interactions occurring off the equator and/or to interactions with waves traveling in various directions with respect to the field line.

Events similar to August 17 were not found to be common, but others with 5-second periods and similar phasings with respect to the transmitters have been found and more details of these events will be published elsewhere. In summary, the first direct observations in the bounce loss cone have been found for the precipitation of radiation belt electrons by controlled signals from a ground-based VLF transmitter. A large data base has been acquired and the surveys are still in preliminary stages.

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