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THE MODULATED PRECIPITATION OF RADIATION BELT ELECTRONS BY CONTROLLED SIGNALS FROM VLF TRANSMITTERS

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Abstract. The first direct observations of the precipitation of radiation belt electrons by the controlled injection of VLF signals from a ground based transmitter were recently reported from data acquired in the SEEP (Stimulated Emission of Energetic Particles) experiment. That outstanding example of time-correlated wave and electron data has now been enhanced by the finding of four additional modulated events out of 65 satellite passes when one of the U. S. Navy VLF transmitters at Cutler, Maine (NAA) or at Annapolis, Maryland (NSS) was being modulated in a 3s ON/2s OFF format. During each of these events the fluxes of precipitating electrons were observed repeatedly to display a characteristic time behavior with respect to the transmitter modulation: a relatively slow rate of increase after start of the ON period leading to a maximum about 2 seconds later. Details of this consistent pattern and the statistics of occurrence of modulation events are presented along with comparisons of the absolute fluxes of precipitating electrons observed during normal transmitter operation with those recorded when one of the transmitters was modulated.

Introduction

Several investigations in the past have addressed the precipitation of radiation belt electrons by VLF signals from a ground based transmitter (Imhof et al., 1974, 1981, 1983; Vampola and Kuck, 1978; Koons et al., 1981; Goldberg et al., 1983). The first direct observations of bounce loss cone precipitation of radiation belt electrons by controlled injection of VLF signals from a ground based transmitter were recently reported by Imhof et al. (1983). In that study, preliminary details were published on an outstanding example of time-correlated wave and electron data on August 17, 1982 when the VLF transmitter at Cutler, Maine (NAA) was being modulated with a repeated 3s ON/2s OFF pattern. To establish the frequency of occurrence of such events and to study the precipitating flux versus time profiles more data have now been surveyed.

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Description of the Experiment

The satellite payload in the SEEP (Stimulated Emission of Energetic Particles) experiment contained an array of cooled silicon solid state detectors to measure electrons and ions directly with high sensitivity and fine energy resolution (Voss et al., 1982). The electron spectrometer of present interest was mounted at 90^o zenith angle and at 90^o to the orbit plane on the three-axis stabilized S81-1 spacecraft which was in a high inclination orbit and for the data presented here at an altitude of ~ 220 km. The spectrometer had a threshold energy of 6 keV, an acceptance angle of $\pm$ 20^o and a geometric factor of 0.17 cm^2 ster.

An important part of the SEEP experiment involved the programmed modulation of U. S. Navy transmitters and the Stanford University research VLF transmitter at Siple Station, Antarctica. Of present interest are the two U. S. Navy transmitters at Cutler, Maine (NAA; 292.72^oE, 44.65^oN) and at Annapolis, Maryland (NSS; 283.55^oE, 38.98^oN) operating at frequencies of 17.8 kHz and 21.4 kHz, and nominal radiated powers of 1000 kw and 265 kw, respectively. Throughout the SEEP experiment, conducted during May-December 1982, the transmitters were modulated for 10 minute periods during overpasses of the SEEP payload in one of 10 formats. Only the 3s ON/2s OFF format is pertinent to the data considered here.

Observations

Surveys of the SEEP electron data have been conducted in the longitude interval 274^oE to 310^oE over the L shell range from 2.0 to 2.75 and only for nighttime passes (near 2230 local time). Higher L shells were precluded in this initial analysis to minimize naturally occurring fluctuations in the electron fluxes. Initially, a tabulation was made of all fluctuations in counting rate of the electron spectrometer at 90^o which met the following criteria: 1) the counting rate increased by a factor of at least 1.5 during the fluctuation, and 2) the time duration of the flux increase fell in the range 1 - 3 seconds. Events were then selected in which four or more such fluctuations occurred with a time spacing of one period. It was required that at least one of the four fluctuations met both of the above criteria but the

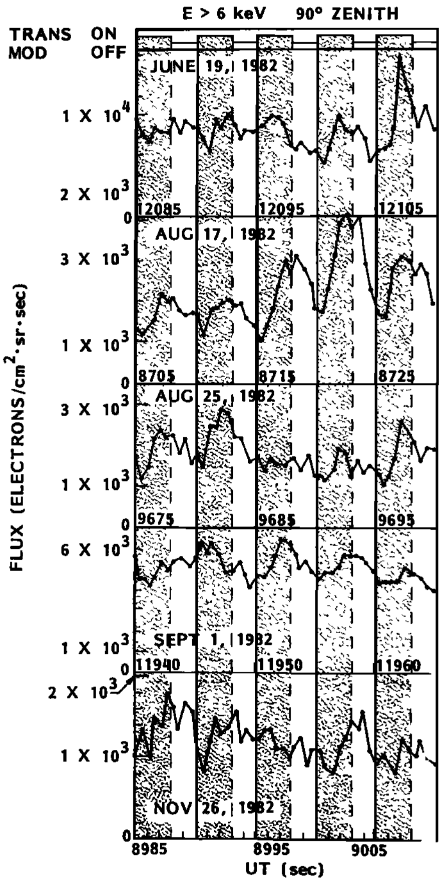

Fig. 1. Electron fluxes measured on five different satellite passes. ON and OFF times of the pertinent transmitter.

counting rate increase could be smaller for the adjoining fluctuations. Using this procedure for finding events, 5 were found from the 65 passes of the satellite when one of the transmitters was being modulated in a 3s ON/2s OFF format. No such events were found in the 175 passes when neither transmitter was being modulated in this format. Within the selected L-shell range, no events meeting these criteria but with periods significantly different from 5 seconds were found.

The electron flux profiles and transmitter ON and OFF times during each of the selected events are shown in Figure 1 for the electron spectrometer at 90° zenith angle. The particles measured by this detector were all near 90° pitch angle and therefore locally mirroring, but in every one of the cases the conjugate point was below sea level so the electrons must have been precipitated into the atmosphere during the bounce period in which they were observed. Corresponding counting rate increases often occurred in other electron spectrometers oriented at different pitch angles, but only data from the 90° detector are considered here.

In order to compare more accurately the time profiles for each of the events, superposed epoch analyses have been performed and these are shown in Figure 2. All of the time profiles display a similar pattern in which the fluxes increase rather slowly after start of the ON period and reach a maximum about 2 seconds later. These temporal features should provide important guidelines for understanding the coherent wave induced precipitation phenomenon in detail and for studying the interactions of VLF waves with trapped electrons (e.g., Helliwell, 1967; Inan et al., 1982). The consistent 5-second period and the phasing with respect to the transmitter ON/OFF times for each of the events strongly support the conclusion that all are related to the transmitter modulation. The absence of any such events when neither transmitter was being modulated in the special format further justifies this conclusion. Within the events large flux differences often exist between successive 5-second periods. Based on these data alone it is not clear whether the differences are associated with spatial or temporal variations in either the wave or particle characteristics.

During a modulation of the NSS transmitter on July 6, 1982 as part of the overall SEEP program, Goldberg et al. (1983) reported a 5-second modulation period in the bremsstrahlung x-rays measured from a rocket. In contrast with the 1 - 2 second delay between transmitter turn-on and electron precipitation reported in the five cases of the present paper Goldberg et al. found no such delay in their one event. The reason for the difference in the two sets of experi-

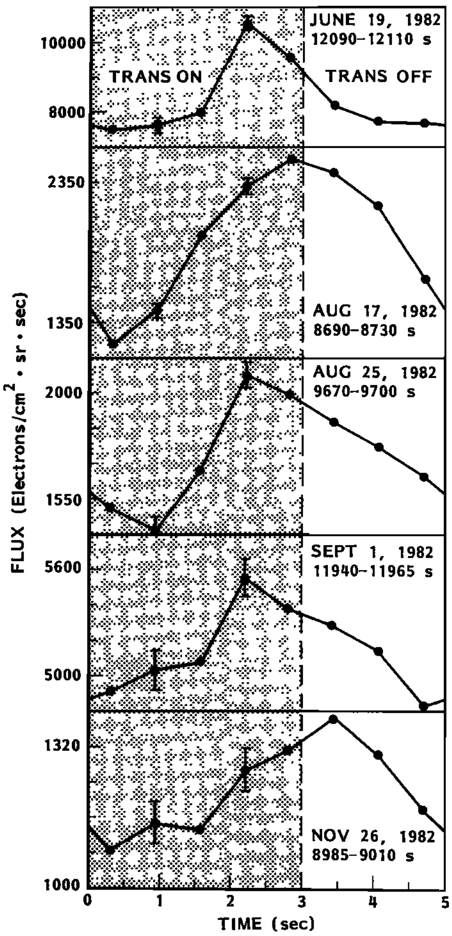

Fig. 2. Superposed epoch flux > 6 keV profiles for consecutive 5.0-second periods.

Table 1 Summary of Events

Date(1982)	Modulating Transmitter	Long. of Observ.	L-Shell Range of Flux Mod.
June 19	NAA	279.1°E	2.63-2.79
Aug. 17	NAA	294.0°E	2.13-2.34
Aug. 25	NAA	289.9°E	2.21-2.38
Sept. 1	NSS	280.0°E	2.46-2.63
Nov. 26	NAA	291.5°E	2.21-2.35

mental results may be due to differences in local time, Goldberg's being near dawn whereas the measurements presented here were all performed about two hours before local midnight, or possibly due to the limited signal to noise ratio of the rocket data.

In past studies of particle precipitation by nearly monochromatic waves generated at ground-based VLF transmitters, narrow L-dependent peaks have been observed in the energy spectra of electrons in the drift loss cone (e.g., Imhof et al., 1981; Koons et al., 1981). Similar peaks were observed in the electrons precipitated by the modulated NAA transmitter during the event of August 17, 1982 (Imhof et al., 1983). We have now found L-dependent peaks during the event of August 25, 1982, but with lower resonant energies suggesting higher cold plasma densities at that time. Pronounced peaks were not observed in the other events. Those on June 19 and Sept. 1, 1982 were at higher L shells where the equatorial cyclotron resonance energies were near the detector threshold. In the Nov. 26, 1982 event the signal to background was relatively weak for spectral analyses.

The longitudes and L-shell intervals of the events are listed in Table 1. Three of the four Cutler events and the one associated with Annapolis occurred at longitudes very near that of the transmitter. The NSS event took place at an L value very close to that of the transmitter, which is located at L = 2.6, whereas all of the NAA events were at significantly lower L values than Cutler (L = 3.2) and three of them were considerably below the upper end of the L-shell range used in the survey. This result may be due partly to the higher energies for near equatorial cyclotron resonance on lower L shells with more favorable observing conditions.

The frequency of occurrence of electron flux modulated events meeting the selection criteria is summarized in Table 2. The limited sample of data indicates that over the L-shell range 2.0 to 2.75 and with the selection criteria used modulations in the electron fluxes occurred in 5 out of 65 cases when one of the transmitters was being operated in the 3s ON/2 s OFF format. For the NAA transmitter alone 4 events were observed out of 26 cases. Consideration of the dependence of the event occurrence upon the choice of transmitter being modulated and upon the longitude of observation as well as other parameters is beyond the scope of this paper.

Even if modulations in the fluxes of precipitating electrons do not appear, the transmitters might still play a significant role in the precipitation. For example, the spread in propagation times could exceed the OFF times and hence inhibit the detection of the modulations (Inan and Helliwell, 1982). To further address the role of transmitters we compare the fluxes measured during normal operations with those observed when the transmitters were operated in the 3s ON/2s OFF format. Normal operation consists of a constant amplitude signal with the frequency shifted as often as once every 25 ms. During the SEEP format a continuous wave with

Table 2 Electron Modulation Events

Status of Transmitter Cutler	Status of Transmitter Annapolis	Number of Cases	Electron Modulation Events
Normal	Normal	175	0
3s ON/2s OFF	Normal	26	4
Normal	3s ON/2s OFF	39	1

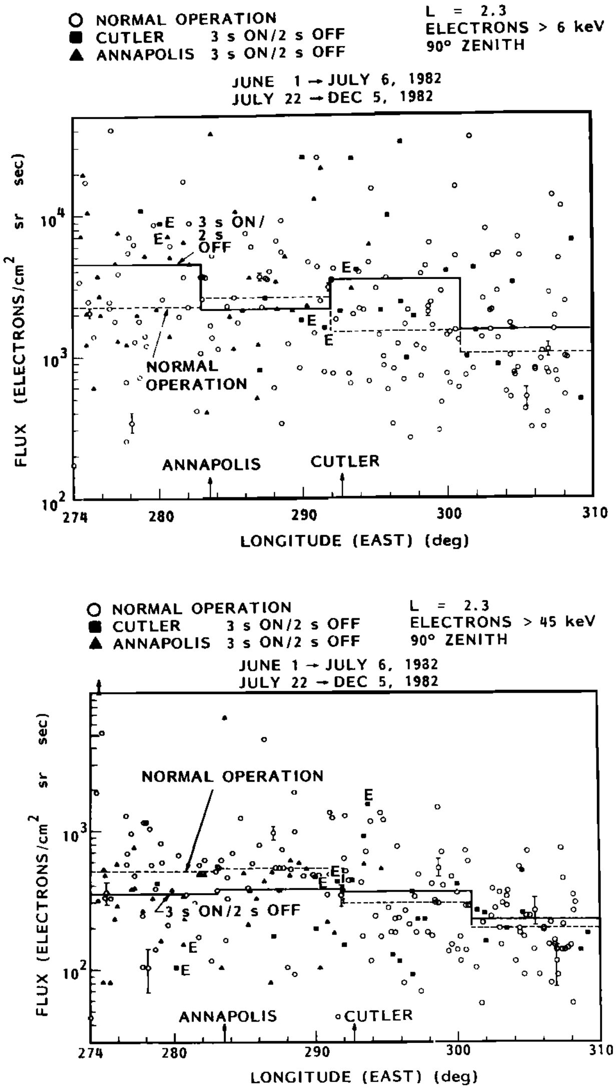

Fig. 3. Electron flux versus longitude. Locations of the transmitters at Annapolis and Cutler are indicated. The letter E indicates fluxes measured on a pass when an event was observed.

fixed frequency and amplitude is turned ON for 3 seconds and OFF for 2 seconds. The frequency spectrum of the transmitted signal is typically wider during normal operation. The reduced coherence of the wider bandwidth signal has been found to inhibit temporal growth and triggering during VLF wave injection experiments from Siple (Raghuram et al., 1977). The results of the present investigation are presented in Figure 3 where the observed electron fluxes >6 keV and > 45 keV are plotted as a function of longitude with separate symbols for the normal operation of both transmitters and for the special modulations of either transmitter. The time period surrounding a major geomagnetic storm on July 14, 1982, when the fluxes of precipitating electrons were significantly higher, has been excluded. Otherwise no selection of events was made on the basis of geomagnetic conditions. Median flux levels over 9^{o} longitude bins are shown. For electrons > 6 keV and all longitudes combined, the median flux values for normal operation and for the special modulation of either transmitter are 1.8×10^3 and 2.7×10^3 electrons/cm^2 ster sec, respectively. For electrons > 45 keV, the fluxes are 3.3×10^2 and 3.2×10^2, respectively. The data do not indicate a significant increase in the average precipitation rate when the transmitters are operated at fixed frequency with a 60% duty cycle as compared to the normal broader frequency operation at 100% duty cycle. Smaller flux changes with mode of transmitter operation may be found when detailed account is taken of the flux variations with longitude and time.

In summary, data have been presented from five events in which modulations were observed in the fluxes of precipitating electrons that were in phase with the controlled modulations of one of the U. S. Navy transmitters at Cutler, Maine or at Annapolis, Maryland. Although only 5 cases were found with the selection criteria used here, others may be discovered after more detailed analyses.

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