Results from the SEEP active space plasma experiment: Effects on the ionosphere

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An active satellite-ground coordinated space plasma experiment was conducted from May to December, 1982, in which electrons were precipitated from the radiation belts into the ionosphere by the controlled injection of VLF signals from ground-based transmitters. The results confirm the hypothesis that electrons can be precipitated from the radiation belts by ground-based VLF transmitters, and they provide information relating to the effects of such precipitation on the ionosphere. The ionization produced in the atmosphere of the northern hemisphere at $L = 2\text{–}3$ by the modulated signals from ground-based VLF transmitters was shown to be as great as one ion pair/cm³ s at 80 km altitude. The ionization at comparable positions produced by naturally occurring electron precipitation varies greatly, and can be as low as 0 1 ion pair/cm³ s, but is also sometimes larger than 100 ion pairs/cm³ s at times of lightning flashes.

INTRODUCTION

An active experiment, stimulated emission of energetic particles (SEEP), was conducted during May–December 1982. In this experiment the U.S. Navy operational VLF transmitters at Cutler, Maine (NAA); Annapolis, Maryland (NSS); and Jim Creek, Washington (NLK) and the Stanford University research VLF transmitter at Siple Station, Antarctica, were operated in special controlled formats at times of overpasses of the low-altitude polar-orbiting satellite S81-1. The spacecraft payload measured both direct electron precipitation >2 keV and bremsstrahlung X rays >4 keV from the atmosphere. The experiment concept is illustrated schematically in Figure 1. The locations of the VLF transmitters are indicated along with a representation of the satellite paths during three successive passes. In addition, the modulated VLF waves and their regions of interaction with the trapped electrons are also shown.

The SEEP experiment payload on the three-axis stabilized polar-orbiting S81-1 spacecraft 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 data presented here were taken with electron spectrometers mounted at 90° zenith angle and at 90° to the orbit plane (TE detector), at 0° zenith angle (ME1) and at 180° zenith angle (ME2). The TE spectrometer had an electron threshold energy of 6 keV, an acceptance angle of ±20° and a geometric factor of 0.17 cm² sr. It is sensitive to both electrons and ions, but on the basis of the responses of other detectors in the payload, all of the precipitation events presented here are taken to be associated with electrons. Each of the ME1 and ME2 spectrometers had an electron threshold energy of 45 keV, an acceptance angle of ±30° and a geometric factor of 2.47 cm² sr. A thick window on ME1 and ME2 prevented ions with energies below 0.5 MeV from impinging on the silicon detector, and therefore in all of the data shown the counts were predominantly due to electrons. The measurements were performed at satellite altitudes of ~220 km.
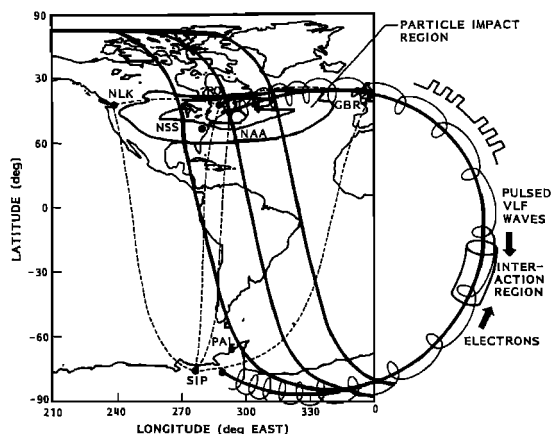
Fig. 1. Schematic illustration of the SEEP experiment concept. The locations of the pertinent VLF transmitters
are indicated along with a representation of the satellite paths during three successive passes. Also shown are the
modulated VLF waves and the region of wave-particle interactions.

With this payload the first observations were made
of direct bounce loss cone precipitation of radiation
belt electrons by the controlled injection of VLF sig-
nals from a ground based transmitter [*Imhof et al.*,
1983*a*]. Although past observations had shown that
electrons can be precipitated from the radiation belts
by ground-based VLF transmitters, the evidence was
based predominantly 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] had
provided evidence for the effects of transmitters. In
spite of the SEEP findings, relatively little is known
about the importance of transmitters in relation to
other loss processes for radiation belt particles. It is
realized, however, that electrons are regularly pre-
cipitated from the radiation belts and that these elec-
trons can cause measurable ionization at midlati-
tudes.

The purpose of this paper is to assess the effects on
the ionosphere of electrons precipitated by the trans-
mitters NAA and NSS during the observed SEEP
events and to compare these with the effects of elec-
tron precipitation induced by natural causes.

OBSERVATIONS OF ELECTRONS PRECIPITATED BY VLF TRANSMITTERS

A good example of electron flux modulations in
correlation with the transmitter on-off signals oc-
curred on August 17, 1982 at 8680-8740 seconds UT
when the SEEP payload was passing near the NAA
transmitter as it was being modulated with a 3-s on
and 2-s off pattern. In Figure 2 the electron fluxes
measured at various zenith angles are plotted as a
function of time. A modulation period of 5 ± 0.1 s is
clearly seen for 12 consecutive cycles. For reference,
the measured on times of the transmitter at NAA are
indicated. The risetime of the electron flux and the
observed delay in decay time of ~ 1.5 s are now un-
derstood [*Inan et al.*, 1985] in terms of the pitch
angle dependence of the particle distribution near the
edge of the loss cone and by the multiple interaction
of the particles with the waves due to significant at-
mospheric backscatter.

Differential energy spectra of the precipitating elec-
trons taken during the times of enhanced electron
precipitation showed prominent peaks but there was
little evidence of their presence during times of mini-
mum intensity. It was shown that the measured peak
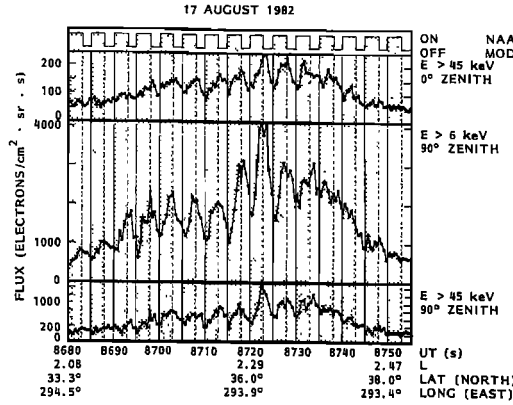energies and their variations with L are consistent

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Fig 2. Electron fluxes on August 17, 1982, plotted as a function of time. Also shown are the on and off times of the NAA transmitter.

with those expected for cyclotron resonance with waves of the transmitter frequency travelling parallel to the earth's magnetic field lines [Imhof et al., 1983a].

From surveys of the SEEP data five electron modulation events were found from the 65 passes of the satellite when one of the transmitters was being modulated in a special 3-s on and 2-s off format. No such events were found in the 175 passes when neither the NAA nor NSS transmitter was being modulated in one of the special SEEP formats. All of the time profiles for the events displayed a similar pattern in which the fluxes increased rather slowly after start of the on period and reached a maximum about 2 s later. The temporal profile and the absolute count rates of the observed fluxes were found to be in good agreement with the predictions of an extended test particle model of the wave-particle interaction in the magnetosphere [Inan et al., 1985].

Although modulated electron precipitation events associated with the controlled injection of VLF signals from a ground-based transmitter were not observed frequently, transmitters may still play a strong role in the precipitation of electrons from the radiation belts. Narrow peaks in the energy spectra of electrons precipitating from the inner radiation belt in the drift loss cone have been shown to result from cyclotron resonance interactions with waves from ground-based transmitters [Imhof et al., 1981]. Even

in the bounce loss cone the transmitters might have contributed significantly to the observed fluxes in the absence of a detectable modulation. To assess the role of transmitters it is important, therefore, to compare the absolute fluxes of electrons measured during normal operations with those observed when the transmitters were either off or operated in a special manner such as in the SEEP 3-s on and 2-s off format. Unfortunately, a significant amount of data were not acquired with both the NAA and NSS transmitters off. Normal operation consisted of a constant amplitude signal with the frequency shifted as often as once every 25 ms. In the SEEP format the frequency was fixed during the on time of 3 s. The wider bandwidth signal during normal operations may possibly have inhibited temporal growth of the waves, as found in earlier Siple experiments [Raghuram et al., 1977].

The possible effects of transmitter operation on the fluxes of precipitating electrons are illustrated in Figure 3 where the median electron fluxes >6 keV observed during a 5.6-s period centered at $L = 2.3$ are plotted as a function of longitude. Separate symbols are used for the normal operation of both transmitters and for the special modulation of either transmitter in the 3-s on and 2-s off format. During the normal mode pass on August 11, 1982, a narrow spike of precipitating electrons with the clear characteristics of those induced by lightning [Voss et al.,
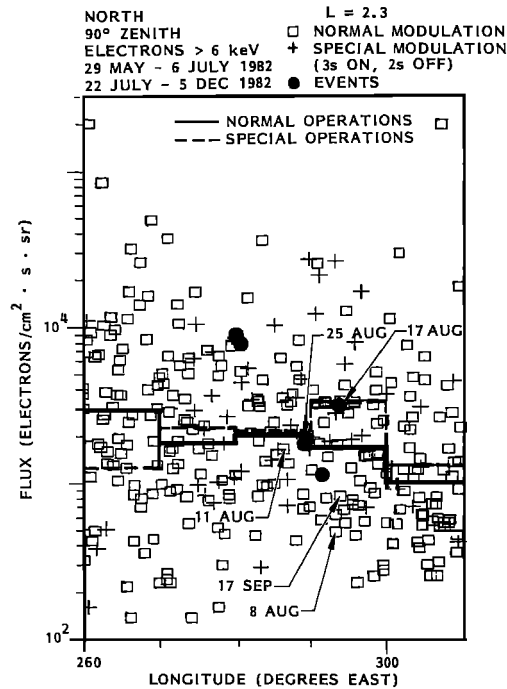
Fig. 3. The median electron flux measured during a 5.6-s period centered at $L = 2.3$ plotted versus longitude. Solid circles indicate fluxes measured on a pass when an event was observed. Median flux levels for normal operation and for modulation in a special format (3-s on/2-s off) are shown in 10° longitude bins.

1984b] was observed at an L value close to 2.3 and that event is treated later in this paper with a shorter summation time interval. To minimize the flux variations associated with magnetic activity the time period July 7–21, 1982, has been excluded from the plot. At the times covered in the figure the electron fluxes in this longitude interval increased by as much as an order of magnitude subsequent to the magnetic storms with a peaking at a time delay of about 4 days [Voss et al., 1984a]. The pronounced transmitter modulation event on August 17, 1982, occurred during one of these enhanced electron periods. The median flux levels shown for 10° longitude bins do not seem to indicate a significant change in the average precipitation rate when the transmitters were operated at fixed frequency with a 60% duty cycle as

compared to the normal broader frequency operation at 100% duty cycle. Although evidence for a strong effect of the transmitters was not found by this technique (see also Imhof et al. [1983b]), it should be emphasized that the ideal experiment was not conducted in which one could compare the fluxes of precipitating electrons observed when both NAA and NSS transmitters were off and when both were on.

EFFECTS OF PRECIPITATED ELECTRONS
ON THE IONOSPHERE

We now consider the ionization in the atmosphere that would be associated with the pronounced transmitter modulation events of August 17 and August 25, 1982, and compare the ionization profiles with other representative cases of electron precipitation.
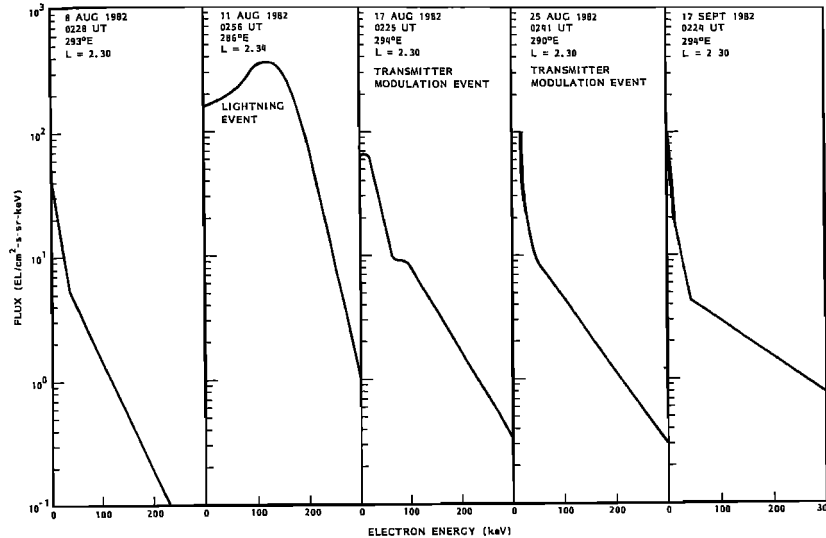
Fig 4   Energy spectra of electrons measured in the northern hemisphere during each of several satellite passes.
The curves are best fits to the measured data points For the August 11, 1982, event the spectrum was summed over
a time period of 0.70 s. For all of the other spectra the summation interval was 8.19 s.

Based on both the energy spectrum and the pitch angle distribution of the precipitating electrons the ionization profile can be calculated by using the AURORA computer program [*Walt et al.*, 1968]. Energy spectra of the electrons in the northern hemisphere were measured with fine energy resolution, and the spectra at $L = 2.3$ and longitudes of 286°E to 294°E during these transmitter modulation events and at other selected times are shown in Figure 4. The applicable time interval is 8.19 s except for the lightning associated spectrum on August 11, 1982, for which the summation time is 0.70 s. These spectra represent electrons observed with the detector at a central pitch angle of 90°–96°. All of the observed electrons have mirror points below sea level in the southern hemisphere; i.e., the electrons were all precipitating within one bounce, except for back-scattering. Only those with pitch angles less than ~78° precipitated in the northern hemisphere, but for purposes of calculating energy deposition profiles we shall assume the spectra of electrons precipitating in the north are the same as shown in Figure 4.

The pitch angle distributions were measured directly at positions above the atmosphere with the array of collimated electron spectrometers in the SEEP payload. However, measurements were made at only a few pitch angles with relatively broad angular resolution. A histogram representation of the fluxes observed in those detectors during the August 17, 1982, measurement is shown in Figure 5. A Gaussian fit (B) to the northern hemisphere measurements is also shown in the figure, normalized to unity at 90°. In addition, a narrower Gaussian pitch angle distribution (C) is plotted based on the measurements in the northern hemisphere for some of the other events. It should be realized that both the absolute fluxes and the shapes of the pitch angle distributions can vary considerably from one satellite pass to another. Although the transmitters were routinely operated at the same power level, the intensities of the waves after passage through the ionosphere are known to vary considerably due to changes in ionospheric conditions [*Heyborne*, 1966].

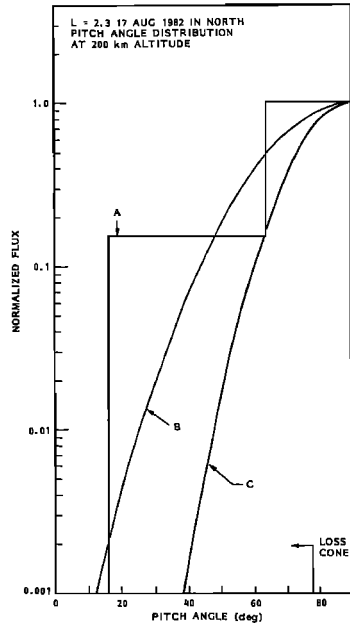We have calculated energy deposition profiles at

Fig. 5. Pitch angle distributions at $L = 2.3$ in the northern hemisphere for electrons >45 keV. Curves A and B are histogram and Gaussian representations, respectively, of the distribution measured during the transmitter modulation event on August 17, 1982 Curve C is a narrower Gaussian distribution based on the TE measurements at a variety of longitudes. The pitch angle distributions are normalized to 1.0 at 90°

suming the narrower pitch angle distribution (C) shown in Figure 5. For this narrower distribution, not actually measured during the event, the energy deposition profile would be reduced by a factor of 2-3. The energy deposition profiles A and B in Figure 6 are equivalent to an energy input of $\sim 10^{-4}$ ergs/cm^2 s and a corresponding riometer absorption of ~ 0.06 dB at 30 MHz [*Reagan et al.*, 1983].

Energy deposition profiles corresponding to the various energy spectra in Figure 4 and for the appropriate histogram pitch angle distributions are presented in Figure 7. The applicable histogram pitch angle distribution is based on the observed responses in detectors TE and ME1 during the satellite pass of interest, and the ratios of these responses are provided in Table 1. In all of these cases the counting rates in detector ME2 were much lower than in ME1. The modulated signals from the NAA transmitter during the August 17, 1982, event produced an ionization rate of ~ 1 ion pair/cm^3 s at 80 km altitude. Both the shapes and the absolute intensities of the ionization
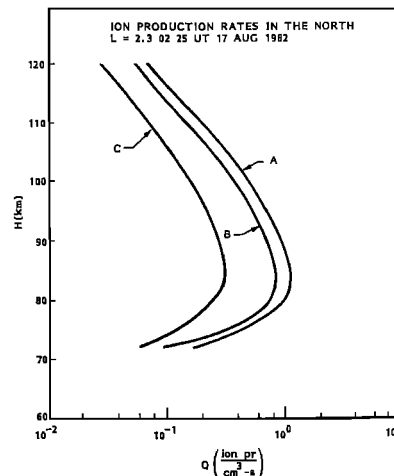

Fig. 6. Energy deposition profiles calculated with the Aurora program for the energy spectrum and pitch angle distributions shown in Figures 4 and 5, respectively. Curve A is for the histogram pitch angle distribution and curve B for the Gaussian pitch angle distribution. For the August 17, 1982, event, curve C corresponds to the narrower Gaussian pitch angle distribution

$L = 2.3$ using the AURORA program for the pitch angle distributions shown in Figure 5 each normalized to the same flux at 90° pitch angle and for the observed spectral shape. The results are shown in Figure 6. As one can see, the differences between the histogram (A) and the corresponding Gaussian pitch angle distribution (B) for the August 17, 1982, event are only of the order of 25% and therefore the details of the pitch angle distribution measured during this event are not critical in regard to the calculated energy deposition profile. The deposition profile for the August 17, 1982, event was also calculated as-
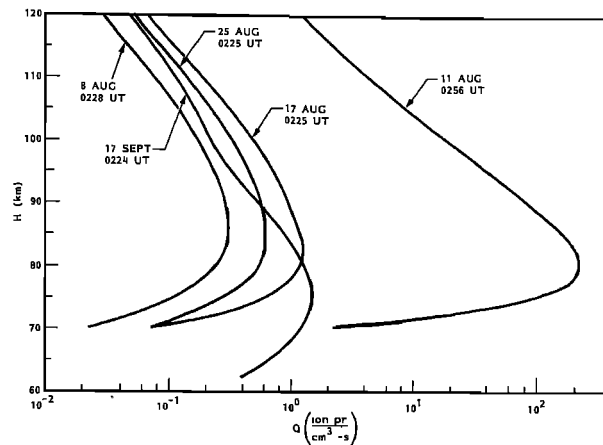
Fig 7. Energy deposition profiles calculated for the energy spectra in Figure 4 and for the appropriate histogram
pitch angle distribution based on the simultaneous counting rates measured in detectors TE and ME1.

profiles at $L = 2.3$ vary over a wide dynamic range,
but may be as low as 0.1 ion pair/cm³ s at (260°–
310°) E in the northern hemisphere. Some of the pre-
cipitation events were fairly steady as observed from
the satellite over broad time and latitude intervals.
At other times, such as during the modulated trans-
mitter events or lightning associated precipitation,
significant variations were observed on a short time
scale. These fluctuations can be particularly large for
the precipitation produced by lightning. The latter
type event on August 11, 1982 was summed over the
peak response period of 0.70 s, but all of the other
profiles were averaged over 8.19 s. For this and other
lightning flashes the ionization rates at ~80 km alti-
tude can be of the order of 100 ion pairs/cm³ s or
greater. Since the average electron precipitation is
comparable to that observed during the August 17

TABLE 1. ME1KTE Flux Ratios

Date	UT	Ratio
Aug. 8, 1982	0228	0.241
Aug. 11, 1982	0256	0 808
Aug. 17, 1982	0225	0.155
Aug 25, 1982	0241	0 149
Sept. 17, 1982	0224	0.243

event, it is not known at present how much of the
ionization normally occurring in the northern hemi-
sphere at $L = 2.3$ in this longitude region is associ-
ated with transmitters and how much results from
other processes.

Analysis of the data acquired on many satellite
passes through the regions of space considered here
shows that a measurable ionization from precipi-
tating electrons is generally produced at altitudes of
70–120 km. Some portion of this ionization in the
northern hemisphere is generally present as a result
of backscatter in the southern hemisphere of elec-
trons in the drift loss cone. One of the two transmit-
ters NAA and NSS was usually operating and so it
has not been possible in this experiment to establish
conclusively what the contribution of these transmit-
ters is to the electron precipitation normally oc-
curring. These ambiguities could be resolved with use
of a much more powerful transmitter operating at a
lower frequency, on a different L shell and/or one
placed above the ionosphere on a satellite such that
the waves from the transmitter are much stronger in
the near equatorial regions and the associated ioniza-
tion effects considerably greater. It may then be pos-
sible to affect the ionosphere significantly through
the controlled precipitation of electrons from the
radiation belts.

SUMMARY

The modulated signals from a ground-based VLF transmitter have been shown to produce ionization rates at altitudes of ~ 80 km in the midlatitude ($L = 2.3$) northern hemisphere as high as 1 ion pair/cm^3 s. The naturally occurring ionization rates in this latitude region show large variations, are longitude dependent, and at (260°–310°) E in the northern hemisphere may be as low as 0.1 ion pair/cm^3 s. At these same locations the ionization at ~ 80 km associated with lightning flashes is sometimes in excess of 100 ion pairs/cm^3 s, but for each flash the time duration of the intense precipitation is of the order of only 1 s.

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