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DE 1 VLF observations during Activny wave injection experiments

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Abstract. We report on coordinated high-altitude satellite observations in support of one of the first space-based VLF wave injection experiments, namely the USSR Aktivny mission. The Activny satellite (A) was designed to carry a VLF transmitter (nominal frequency ~10 kHz, transmitter power ~10 kW) coupled to a 20-m-diameter loop antenna in a nearly polar orbit (83° inclination, apogee ~2500 km, perigee ~ 500 km). We focus our attention on conjunction experiments between the Activny and DE 1 satellites. Because of problems in the deployment of the loop antenna, the radiated power capability of the antenna was significantly reduced. Although this substantially reduced the expectation of receiving detectable signal levels on the satellite, the DE 1/Activny conjunction experiments were nevertheless carried out as a means of possibly placing an upper limit on the radiated power. During the period November 1989 through April 1990, a total of 10 DE 1/Activny wave injection sessions were conducted. During each session the Activny transmitter operated at 10.537 kHz with 1 s On - 1 s Off format, for a period of 6 min centered around the conjunction time. During three conjunction periods (December 12, 26, and 27, 1989) both DE 1 and Activny were in the southern hemisphere, and DE 1 was at relatively low altitudes (ranging from 6211 to 14,810 km), thus providing the best conjunction possibilities according to the ray tracing criteria developed above. On most days, Omega transmitter signals as well as commonly occurring natural wave phenomena such as whistlers (0^+) and hiss were clearly seen well above the background level, but there was no evidence of the Activny 1 s On/ 1 s Off pattern. Though no Activny signals were detected by the LWR on the DE 1 satellite, the experimental constraints allow us to place an upper limit on the total power radiated by the Activny transmitter in the whistler-mode. Using experimental parameters, and the minimum detectable signal level of 0.05 μV/m for LWR, we find the upper limit on the total power radiated by the Activny satellite in the whistler-mode to be ~ 10 mW. Several recommendations for future space-based wave injection experiments are presented.

Introduction

We report on coordinated high altitude satellite observations in support of one of the first space-based VLF wave injection experiments, namely the USSR Activny mission. The nature and the scope of the experiment required international cooperation to facilitate measurements on multiple satellites, and at several ground stations. In the following we provide a brief background on the motivations and objectives of this experiment.

The role and importance of ELF/VLF waves in the physics of the Earth's magnetosphere is well established [*Helliwell*, 1965; *Lyons and Williams*, 1984]. On one hand, the natural electromagnetic wave activity in the magnetosphere is found primarily in this frequency range; on the other hand, these waves interact with the radiation belt particles via cyclotron and Landau resonance processes to determine the equilibrium and the morphology of the radiation belt particles [*Kennel and Petschek*, 1966; *Lyons et al.*, 1972]. While this overall picture is generally accepted, we lack quantitative understanding of the many individual phenomena and their relative geophysical importance. For example, the origins of a variety of VLF signals commonly observed in the magnetosphere, such as hiss, chorus, and wideband impulsive signals are still not explained; the relative importance of atmospheric lightning compared to waves of magnetospheric origin in establishing the overall wave background in the magnetosphere and in precipitating energetic particles is yet to be determined; the question of relative importance and the domain of applicability of linear, quasi-linear, and nonlinear processes in wave-particle interactions remains unclear [*Helliwell*, 1967; *Kennel and Petschek*, 1966]; and new results on the dominant propagation direction of various types of waves continue to emerge [*Lefeuvre et al.*, 1983; *Hayakawa et al.*, 1986; *Sonwalkar and Inan*, 1988]. In the 1960s the initial exploration phase, devoted primarily to discovering the morphologies of the waves and particles in the various regions of the magnetosphere, was accomplished using ground-based and space-based passive probing of the Earth's magnetosphere. It

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became evident that in order to gain detailed quantitative knowledge of the underlying physics of the variety of the ELF/VLF wave phenomena and their interactions with the energetic particles, it was necessary to make measurements under controlled conditions. Consequently, in the 1970s and 1980s, active wave injection experiments were carried out using ground-based ELF/VLF transmitters (these included the Omega navigational transmitters and the Siple Station transmitter in Antarctica) and ground- and space-based receivers. These experiments (particularly those involving wave injection from Siple Station) in which the amplitude, phase, polarization, and frequency of the injected waves were controlled, substantially increased our understanding of the microphysics of wave-particle interactions [*Helliwell*, 1988; *Gurnett and Inan*, 1988]. However, it was realized that ground based wave injection experiments have several inherent limitations: (1) relatively low peak power densities ($B < 10$ pT) due to low antenna efficiencies ($< 2\%$) at VLF frequencies and weak electromagnetic coupling between the lower atmosphere and the ionosphere at VLF frequencies, (2) only a relatively small range of L shells near the transmitter location could be probed effectively, (3) due to the large refractive index in the ionosphere, VLF waves injected from the ground were limited to wave normal directions near vertical. It was recognized that a sufficiently powerful space-based VLF transmitter can overcome all of these limitations and provide a means to carry out a wide variety of active experiments not feasible from ground [*Inan et al.*, 1981].

Apart from the use of a space-borne wave injection facility as a diagnostic tool, there is an important aspect of the experiment related to the determination of the radiation properties of a VLF antenna itself and the effects of near fields excited by it in a magnetoplasma. As pointed out by *Balmain* [1983], little is known about the radiation properties of a VLF antenna in a magnetoplasma. The theories become complex and intractable due to highly nonlinear and anisotropic conditions which prevail at VLF frequencies in the magnetosphere. A detailed theoretical analysis of a loop antenna by *Wang and Bell* [1969] gives a solution only in the linear regime, and at relatively small radiated power. Therefore an in situ experiment is necessary to provide clues to the physics of radiation in a magnetoplasma. Close to the satellite carrying a VLF transmitter, that is, in the near zone, it is expected that strong lower hybrid waves would be excited along a cone of a few degrees centered around the geomagnetic field. For transmitter powers of 1-10 kW the electric field in these cones might reach large values (hundreds of volts per meter) permitting study of interesting nonlinear phenomenon such as electrostriction and various parametric instabilities.

Motivated by the considerations discussed above, a space-borne VLF wave injection experiment was carried out between November 1989 and June 1990. Figure 1 shows the schematic drawing describing the various components of the experiment. The Activny satellite (A) was designed to carry a VLF transmitter (nominal frequency 10 kHz) coupled to a 20-m-diameter loop antenna in a nearly polar orbit (83° inclination, apogee $\sim$2500 km, perigee $\sim$ 500 km). A subsatellite (not shown) was to closely follow the Activny satellite, permitting near field measurements. Two additional satellites, DE 1 and Akebono, were used to attempt to receive signals from Activny. Each of the receiving satellites as well as Activny was equipped to make wave measurements in the VLF range. These satellites also carried instrumentation for other relevant plasma measurements such as energetic particle spectra, ion composition etc. In addition, VLF antenna-receiver systems were set up at various ground locations to monitor Activny signals J. V. Rodriguez et al., manuscript in preparation, 1994). Figure 1 shows a few of the different ways a signal radiated from Activny can reach the various receivers. A VLF signal transmitted from Activny could reach DE 1 either by direct nonducted propagation path, or by a magnetospherically reflected path (MR). The ground reception of the signals can take place by a ducted path, by a subprotonospheric (SP) propagation mode, or by guiding along the plasmapause [*Inan and Bell*, 1977].

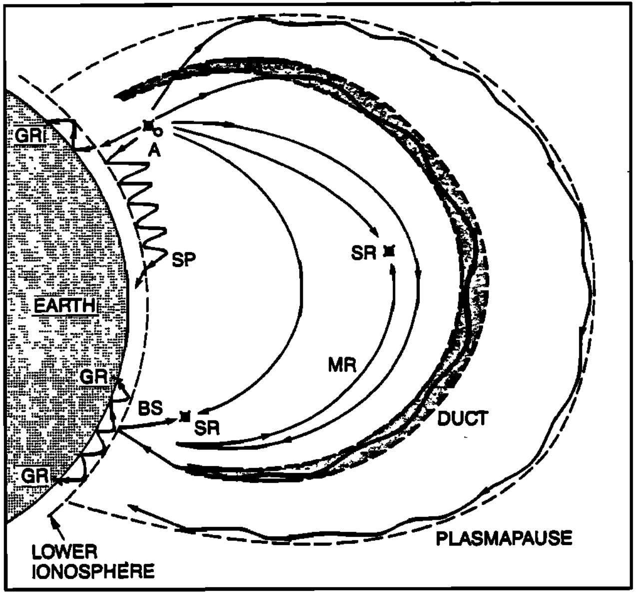

Figure 1. Schematic depicting various propagation paths from the VLF transmitter aboard the Activny satellite (A) to satellite receiver (SR) aboard the DE 1 satellite and to several ground receiver sites (GR). A VLF signal transmitted from Activny can reach DE 1 either by direct nonducted propagation path, or by a magnetospherically reflected path (MR), or by back scattering (BS) of a ducted signal. The ground reception of the signals can take place by a ducted path, by a subprotonospheric (SP) propagation mode, or by guiding along plasmapause.

Specific scientific objectives of the Activny VLF experiments were summarized as follows: (1) measure the radiation characteristics of a 20-m-diameter loop antenna in a plasma under varied parameters, (2) determine the spatial structure of near zone electrostatic fields, (3) investigate nonlinear effects in the near zone, such as electrostriction, parametric instabilities, and cavitons, (4) find the path of propagation of VLF waves including reflection from the ionosphere, (5) search for the precipitation of radiation belt particles caused by large-amplitude VLF waves, (6) measure the properties of VLF emissions triggered by large-amplitude VLF waves.

We focus our attention on conjunction experiments between the Activny and DE 1 satellites, with the 20-m loop antenna on Activny radiating at 10 kHz, and the 200 m electric dipole antenna on the DE 1 attempting to receive the signal. Given the orbit parameters of Activny and DE 1, this configuration is most suitable to achieve objectives (1), (4), (5), and (6) listed above. The other scientific objectives could be achieved in other related experiments, such as Activny-ground conjunction experiments, Activny-subsatellite experiments etc.

The outline of the paper is as follows. We describe the details of the relevant instrumentation on DE 1 and Activny in section 2, followed by the results from three-dimensional ray tracing simulations performed in support of the experiment planning and interpretation (section 3), scheduling the conjunction experiments (section 4), DE 1 observations of VLF waves during the Activny wave injection sessions (section 5), and finally, the summary and recommendations for future experiments are given in section 6.

At the outset we note that due to technical problems which occurred during the deployment of the loop antenna, the radiated power capability of the antenna was significantly reduced (it is now believed that the antenna was deployed into a long narrow ellipse). Test operations suggested a resonant frequency of ~15 kHz instead of ~10 kHz. Since there was no capability to inject signals at 15 kHz and since the tuning circuitry was tune for ~10 kHz, the ability of the antenna to radiate significant power was severely compromised. However, since definitive information concerning antenna configuration was not available, the experiments were carried out as planned. The Activny signal was indeed not detected on the DE 1 satellite in any of the experiments reported here. However, tight experimental constraints have permitted us to place an upper limit on the power radiated by the Activny loop antenna at 10 kHz. The quantitative measurement of the electromagnetic wave background and the prediction of propagation paths provide valuable information necessary for the planning of similar experiments in future.

Orbits and Instrumentation

Orbit Parameters

Table 1 gives the orbit parameters for the DE 1 and Activny satellites. We note that both satellites have nearly polar orbits, allowing for good magnetic conjunction experiments. Also due to the highly elliptic trajectory of DE 1, it was possible to carry out wave injection experiments over a wide range of medium parameters. During the period of experimentation the DE 1 perigee lay in the southern hemisphere, giving the best conjunction possibilities in that hemisphere (see conjunction criteria established in section 3). Typically 5 to 6 conjunctions occurred per day between Activny and DE 1. Unfortunately, only one tracking station, that at Canberra, Australia, was available for DE 1 wideband data acquisition in the southern hemisphere, leading to the realization of only a few Activny-DE 1 conjunction experiments compared to the large number of excellent conjunctions that occurred between the two satellites in the southern hemisphere.

Activny Instrumentation

The principal Activny instruments relevant to the wave injection experiment were a VLF-injector (VLF-G) and a 20-m-diameter loop antenna. The VLF-injector was designed to operate with up to 10 kW of nominal power (corresponding to a current of 150 A in the antenna) over a frequency range of 9.0 to 10.5 kHz with 9.6 kHz the nominal operating frequency. There were eight resonance frequencies within this range (F_1 = 9000 Hz, F_2 = 9191 Hz, F_3 = 9391 Hz, F_4 = 9600 Hz, F_5 = 9818 Hz, F_6 = 10047 Hz, F_7 = 10268 Hz, and F_8 = 10.537 Hz). The stability of the transmitter was better than 0.01% or 1 Hz. The transmitter could be commanded to operate at any one of the eight resonance frequencies and in one of the eight emission modes (formats), each of duration 48 s and 150-A current at nominal power. As shown in Figure 2, for the DE 1 - Activny experiment, a format consisting of 1 s On/ 1 s Off at nominal power was selected. In this emission mode the VLF-injector could operate for 6 minutes (transmitting one 48-s-long format every minute) every 16 hours. The loop antenna was made from a 1-m-thick tube of a soft ductile aluminum alloy. The tube was to be deployed in orbit as a roll and was later unwound into a loop antenna. In addition, the Activny satellite carried various instruments for wave and plasma diagnostics. These included a wideband receiver (0.03-22 kHz) to measure five components of the electromagnetic field (3 electric and 2 magnetic) as well as a 12 channel spectrum analyzer covering a frequency range of 20 Hz to 20 kHz.

Table 1. Orbit Parameters

	Active	DE 1
Apogee, km	2500	23340
Perigee, km	500	485
Inclination, deg	83	89
Orbital period, min	117	411
Latitude of perigee, deg (December 20, 1989)	22.3 N	18.5 S
Rate of change of latitude of perigee, deg/d	1.75	-0.31

DE 1 Instrumentation

The data utilized in this paper were acquired using the linear wave receiver (LWR) on the Dynamics Explorer (DE 1) satellite. The LWR instrument is integrated into the plasma wave instrument (PWI) on the DE 1 satellite [*Shawhan et al.*, 1981] and measures wave amplitude in three frequency bands: 1.5–3 kHz, 3.0–6 kHz and 10.0–16.0 kHz. The gain of the amplifier can be set at 10-dB steps over a 70-dB range and can be varied automatically or commanded to remain fixed at any level. In the automatic mode the gain is reset every 8 s. The response is linear over a 30-dB range in any gain

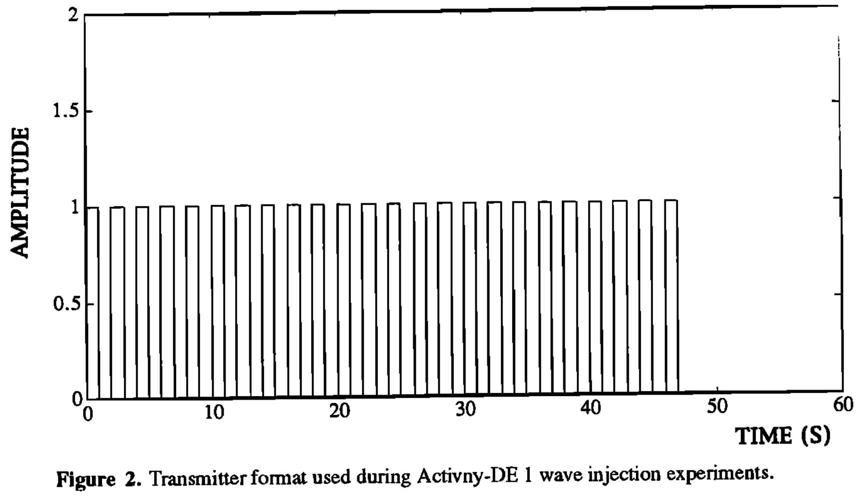

Figure 2. Transmitter format used during Activny-DE 1 wave injection experiments.

position, thus facilitating accurate measurement of signal intensity and temporal growth rate. The LWR can be commanded to cycle between a 200-m-long electric dipole ($L_{\text{eff}} \sim 200$ m) or a 0.8-m by 1.25-m single-turn loop magnetic antenna (threshold sensitivity 6×10^{-10} $\gamma/(\text{Hz})^{1/2}$ at 6 kHz). The input impedance of the LWR preamplifier is $\geq 10^9$ Ω. The LWR allows for detailed quantitative study of phenomena within the passband, providing for measurement of signal growth characteristics as well as spin fading [*Rastani et al.*, 1985; *Sonwalkar and Inan*, 1986]. The antennas on the DE 1 satellite can also be connected to a wideband receiver (WBR) with an automatic gain control (AGC) amplifier. WBR has a dynamic range of 100 dB and covers a wide frequency range. However, because of its rapid AGC action it is difficult to monitor important features of signals which are relatively weak. Another consequence of the AGC is to suppress the spin fading effect, which plays a crucial role in the measurement of wave normal directions [*Sonwalkar and Inan*, 1986]. The results presented here are based on the data received by the LWR operating in 10-16 kHz band and connected to the 200-m-long electric dipole, thus giving the highest possible sensitivity. In the past the DE 1 linear and wideband receivers have successfully measured a large variety of natural and ground transmitter signals, leading to new quantitative results [*Gurnett and Inan*, 1988].

Three-Dimensional Ray Tracing and Conjunction Criteria

For typical magnetospheric plasma parameters, Figure 3 shows the CMA diagrams [*Stix*, 1962] of Activny, DE 1, and Akebono satellite orbits. It is clear that waves should propagate primarily in the whistler mode from Activny to DE 1 and to Akebono. As Figure 1 depicts, waves radiated by the Activny loop antenna can reach a receiver satellite (DE 1 and Akebono) by nonducted as well as ducted propagation. (Ground reception, on the other hand, can take place primarily via ducted propagation [*Helliwell*, 1965]).

Extensive three-dimensional ray tracing simulations were carried out prior to the conjunction experiments to map the path of the plasma waves from the VLF transmitter on Activny to the VLF receiver on the DE 1 satellite. The ray tracing program used for the purpose was originally developed by Stanley Shawhan and was later modified by Jim Green at NSSDC and by Denis Donahue at Stanford. This program is based on the Haselgrove ray tracing equations [*Haselgrove*, 1954], and cold plasma propagation theory for refractive index calculations [*Stix*, 1962]. The International Geomagnetic Reference Field (IGRF 85) was used to model the magnetic field, and the International Reference Ionosphere (IRI) was used to model the ionosphere between 100 and 600 km [*Peddie*, 1983; *Rawar et*

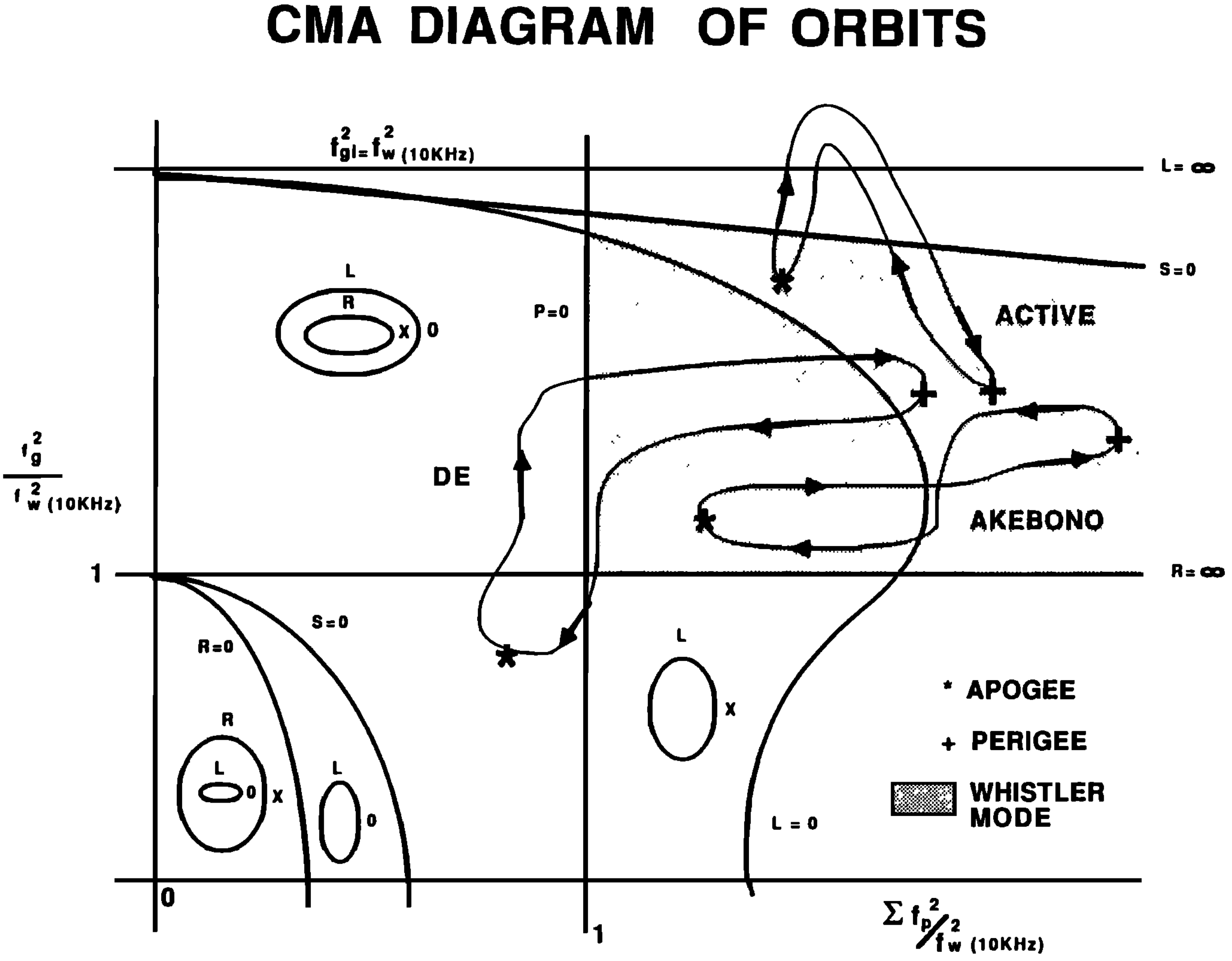

Figure 3. Trajectories of Activny, DE 1, and Akebono satellites on CMA diagram for typical magnetospheric parameters. This diagram indicates that propagation from Activny satellite to DE 1 should take place in whistler mode.

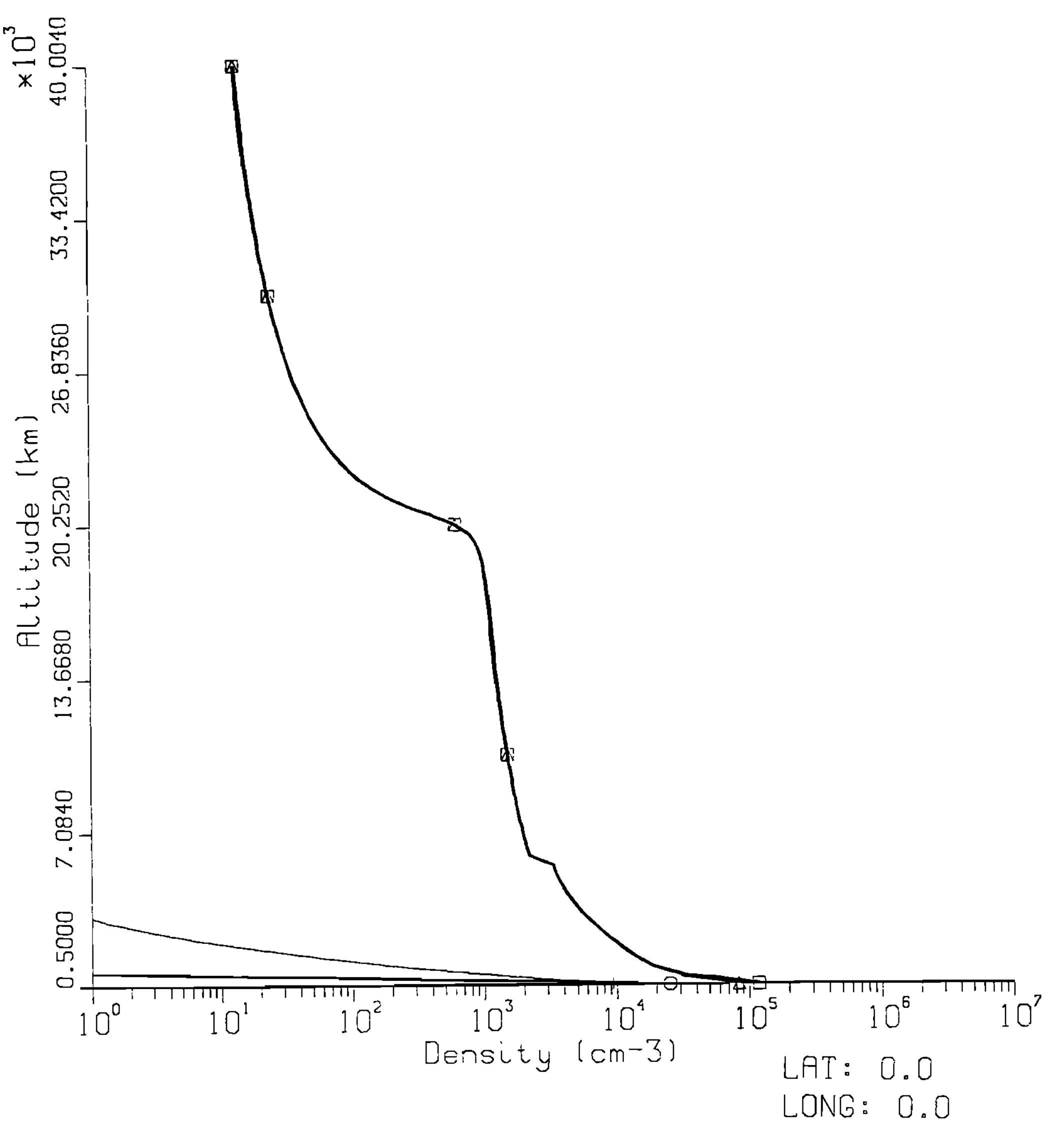

Figure 4. The equatorial electron density used in the ray tracing simulations. The plasmapause was at L = 4.2, a value typical under moderate geomagnetic conditions. The darker curve gives electron and H$^+$ density which are approximately equal for altitudes greater than 500 km. The lighter curves at the bottom give O$^+$ (higher values) and He$^+$ (lower values) densities.

al., 1978]. Above 600 km the model was extended using a diffusive equilibrium model [*Angerami and Thomas*, 1964], and below 100 km, based on numerical factors, a special fit was used to extend the IRI model. Figure 4 shows the equatorial electron density as a function of altitude used for model ray tracing simulations. The plasmapause was assumed to be at L = 4.2 with a width of 0.1 L. These parameters represent a fairly typical magnetosphere under moderate geomagnetic conditions.

Having chosen the magnetospheric model, the next task was to choose appropriate initial conditions for injected rays – wave frequency, wave normal angle, and injection altitude and latitude. On the basis of the Activny orbit parameters (Table 1), it was decided to inject rays at 500 km and 2500 km over a wide range of latitudes. The frequency was chosen to be 10.0 kHz, close to one of the eight transmitter resonance frequencies in 9.0 to 10.5 kHz range. Within this frequency range, ray tracing results as a function of frequency do not change appreciably. The initial wave normal angle was chosen based on the theoretically expected radiation pattern of a 20-m-diameter loop antenna, as shown in Figure 5 which has been

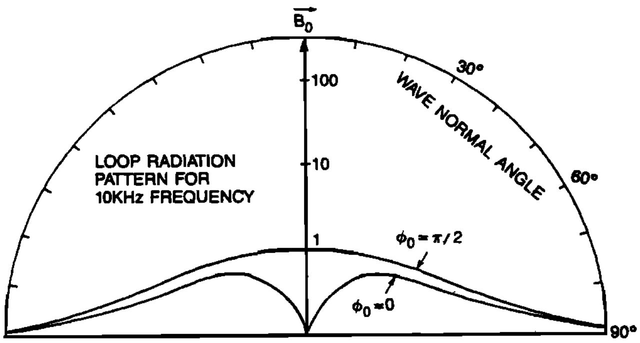

Figure 5. Activny loop radiation patterns plotted as a function of wave normal angle in a magnetoplasma at 10 kHz based on the calculations of *Wang and Bell* [1972a, b]. $\mathbf{B}_0$ is the local geomagnetic field, and ϕ_0 is the angle between the geomagnetic field $\mathbf{B}_0$ and the axis of the loop. The patterns are given for electron density N_e = 2 × 10^{4}electrons/cm^3 and electron gyrofrequency f_H = 1 MHz, and are plotted for ϕ_0 = 0, that is, when the loop axis is parallel to $\mathbf{B}_0$ and for $\phi_0 = \pi/2$, that is, when the loop axis is perpendicular to $\mathbf{B}_0$.

determined by applying the results of *Wang and Bell* [1972a, b] to the parameters of Activny. *Wang and Bell* [1972b] treat a finite size loop antenna in a magnetoplasma, in which the antenna orientation could be arbitrary with respect to the geomagnetic field. Figure 5 shows the radiation pattern in the wavenormal space. The radiation pattern in the configuration space can be derived as in the work by *Wang and Bell* [1972a]. From Figure 5 it is clear that depending on the loop orientation with respect to the local magnetic field, waves can be radiated over a relatively wide range of initial wave normal angle with a pronounced radiation peak at wave normals near the resonance cone. These results are qualitatively in good agreement with recent work of *Stenzel et al.* [1993] that deals with whistler mode radiation from a loop antenna in a laboratory plasma. The upper limit on the wave normal is thus set by the whistler mode resonance cone angle, typically 80°-90° at 10 kHz for Activny altitudes. Therefore the initial wave normal angle was chosen to vary over the −80° to 80° range in two planes: the magnetic meridional plane and the plane perpendicular to magnetic meridional plane.

Since there is no information concerning the actual deployed configuration of the loop antenna, we cannot be certain that Figure 5 actually applies. However, over a very broad range of source configurations we would expect that most of the radiated power is carried by waves whose wave normals are near resonance cone, as long as these sources are small compared to the wavelength at zero wave normal angle [*Wang and Bell*, 1972a].

Figures 6a and 6b, show typical ray tracing results when rays were injected in the magnetic meridional plane and Figures 7a and 7b show results for rays injected in the plane perpendicular to local

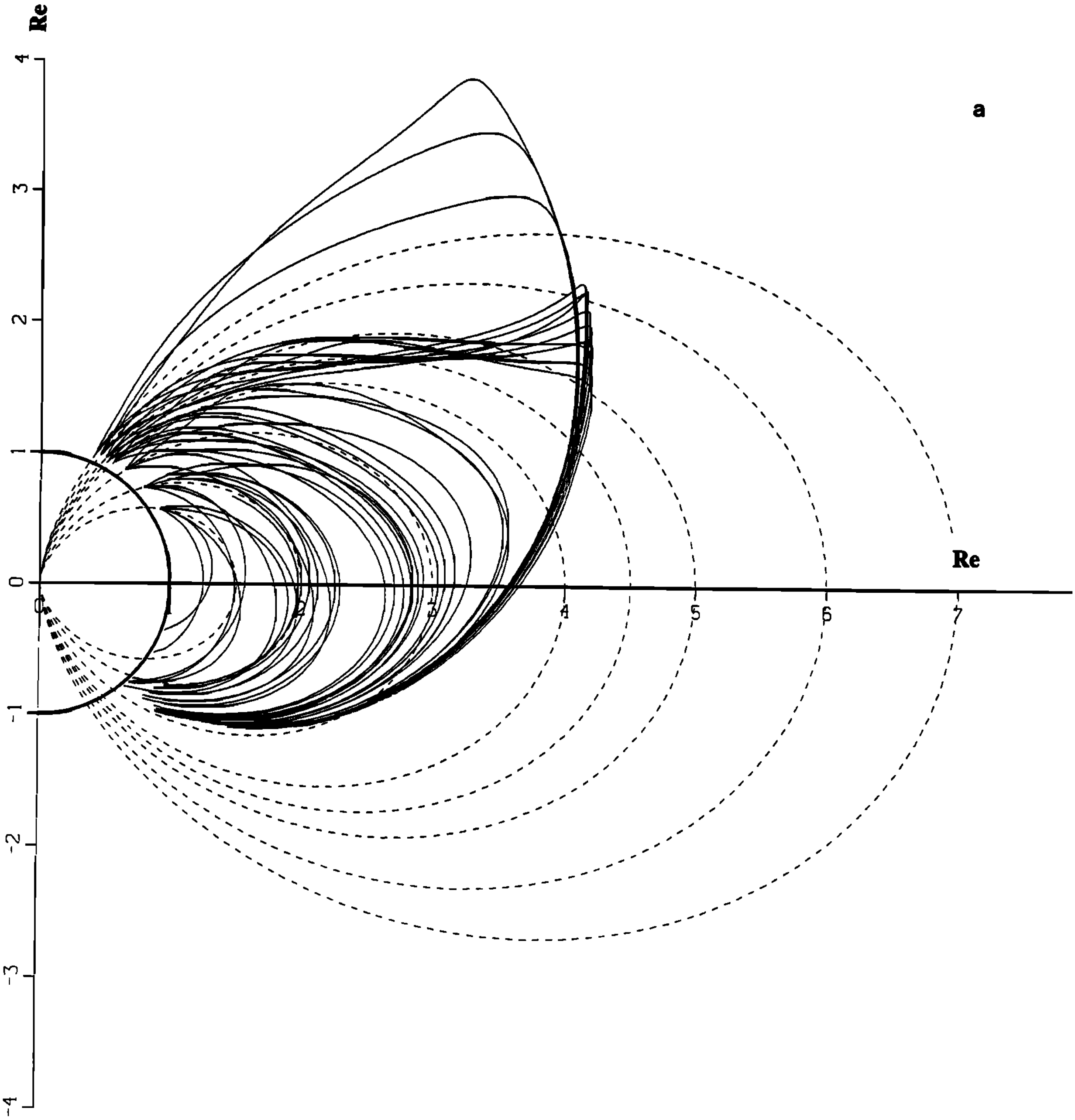

Figure 6. (a) Ray tracing simulation results in the magnetic meridional plane. Rays at 10 kHz were injected in the magnetic meridional plane at 500 km altitude with −80°, 0°, and 80° initial wave normal angles. The L shell of injection point was varied between $L = 1.5$ and $L = 7.0$. (b) projection of the rays in the geomagnetic equatorial plane. ϕ_m is the magnetic longitude.

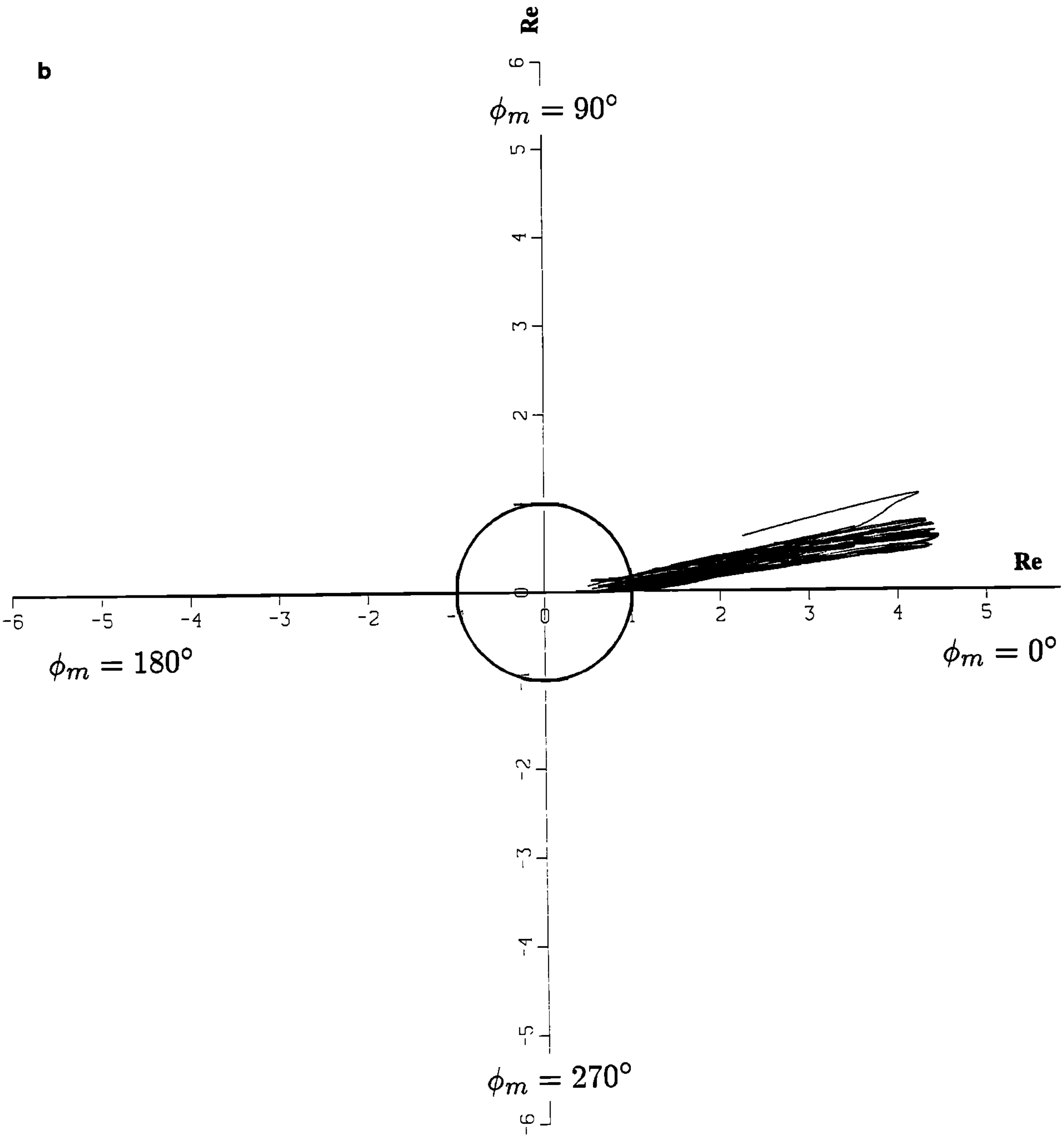

Figure 6. (continued)

magnetic meridian. The results of the ray tracings can be summarized as follows.

1. Depending on the source location wave energy injected at low altitude can populate the entire inner magnetosphere.

2. Rays injected in a magnetic meridional plane spread more in L shell but less in longitude (~ 5° − 10°).

3. Rays injected in a plane perpendicular to magnetic meridional plane spread less in L shell but more in longitude (~ 30°).

4. Rays injected in one hemisphere focus at 30-40° latitudes in the opposite hemisphere between L=2 and L=3.

5. Rays injected near the plasmasphere (inside and outside) in one hemisphere focus in the opposite hemisphere at 30° latitudes near L=3.

6. Rays injected at altitudes from 500 km to 2500 km behave qualitatively in a manner similar to that described above.

On the basis of these ray tracing studies, the following set of conjunction criteria was used to schedule the Activny-DE 1 wave injection sessions.

1. Excellent 1 (EX1): Both satellites in the same hemisphere, DE 1 at low altitudes. Both ducted and nonducted rays can travel from Activny to DE 1, and there is little defocusing of nonducted rays due to close proximity of the two satellites.

2. Excellent 2 (EX2): Satellites in opposite hemispheres. DE 1 between L=2 and L=3 and at 30-40° altitude. Both ducted and nonducted rays can reach DE 1 and nonducted rays are focused.

3. Good (G): Both satellites in the same hemisphere and DE 1 at high altitudes. Both ducted and nonducted can reach the satellite, but nonducted rays are defocused due to spreading in latitude and longitude.

4. Poor (P): Satellites in the opposite hemispheres and DE 1 on high L shells. Neither ducted ($f_H/2$ cutoff) nor nonducted rays can travel from Activny to DE 1 satellite.

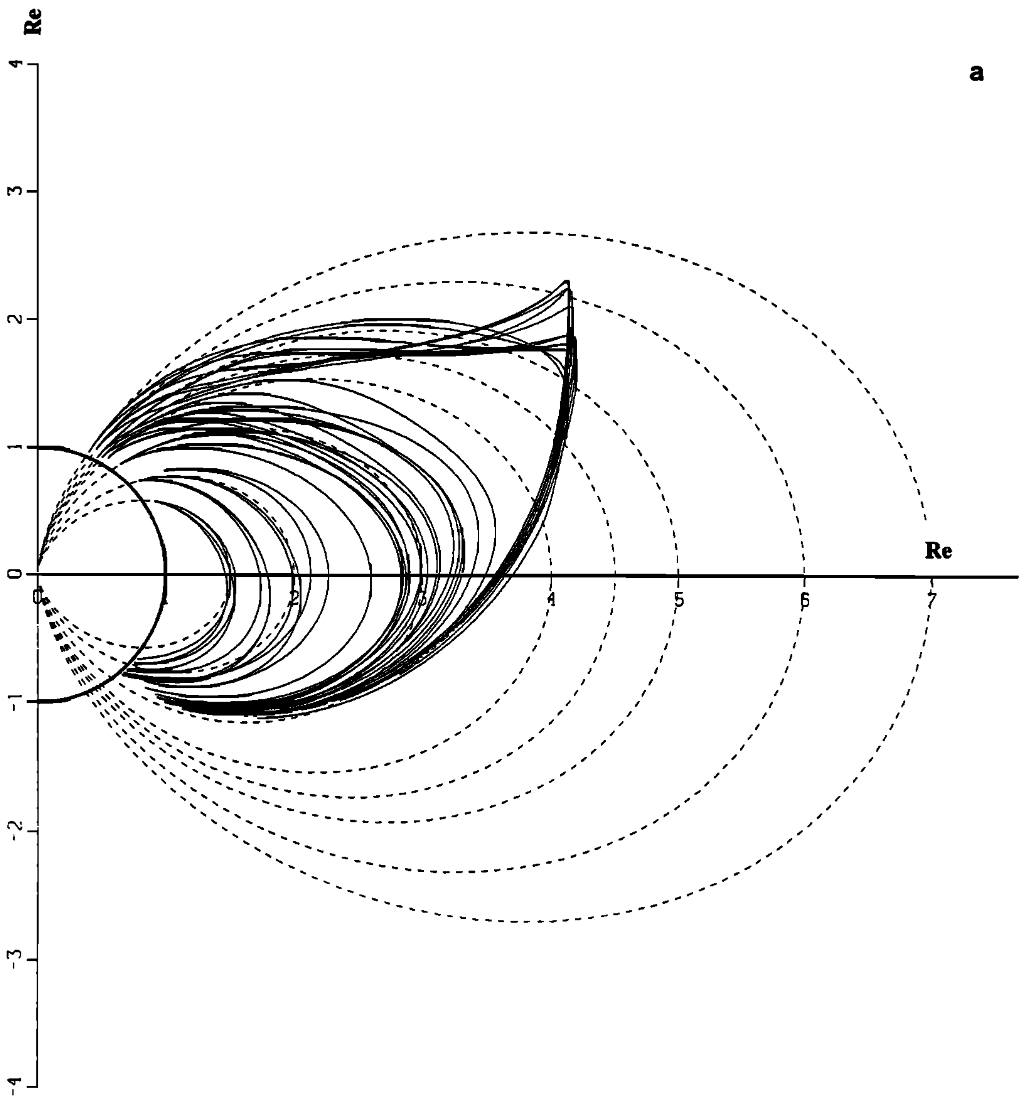

Figure 7. (a) Ray tracing simulation results in the magnetic meridional plane. Rays at 10 kHz were injected in the plane perpendicular to magnetic meridional plane at 500 km altitude with −80°, 0°, and 80° initial wave normal angles. The L shell of injection point was varied between $L = 1.5$ and $L = 7.0$. (b) projection of the rays in the geomagnetic equatorial plane. ϕ_m is the magnetic longitude.

Scheduling of Activny-DE 1 Sessions

Several steps, carried out by various institutions, were involved in planning each of the Activny-DE 1 sessions. First, using the most recently measured satellite orbit elements, NASA (Goddard) calculated orbits and conjunctions for the DE 1 and Activny satellites six weeks in advance for a future 2-week period. NASA also calculated the ground footprint of the Activny satellite for conjunction experiments with the ground receivers. Using the orbit predicts and the conjunction criteria developed with the help of three-dimensional ray tracing simulations discussed above, 30-min periods centered on the predicted magnetic conjunctions were selected for potential Activny-DE 1 satellite sessions. These periods were then transmitted to the DE 1 command center, which would determine whether a suitable ground tracking station were available to receive DE 1 telemetry. Several excellent magnetic conjunctions between the two satellites were not usable, since DE 1 was not visible from the few available NASA tracking stations (e.g., Canberra, Madrid, and Wallops Island).

For those periods when a ground station was available, DE 1 was scheduled to receive wideband data, and these periods were communicated to Stanford, which in turn communicated them to TRW, the US coordinator for the collaborative experiments. TRW would transmit these periods to IKI, the Soviet institution acting as coordinator of the experiments. After reviewing all the possible conjunction experiments (Activny-DE 1, Activny-Akebono, Activny-Ground receivers), and taking into account the limitation that Activny could transmit for only 6 minutes every 16 hours, IKI would choose the best possible experiment, and inform the corresponding experimenters that the particular Activny wave injection session would indeed take place. As a result of this complex process, Activny sessions were scheduled for only a small number of periods when DE 1 was scheduled to receive. For example, out of 20 potential DE 1 receiving periods in December 1989 and January 1990, Activny wave injection sessions were scheduled only for six periods. Because of operational problems with Activny in February 1990 and scheduling restrictions in March, no Activny-DE 1 experiments were conducted during February/March 1990 (DE 1 data

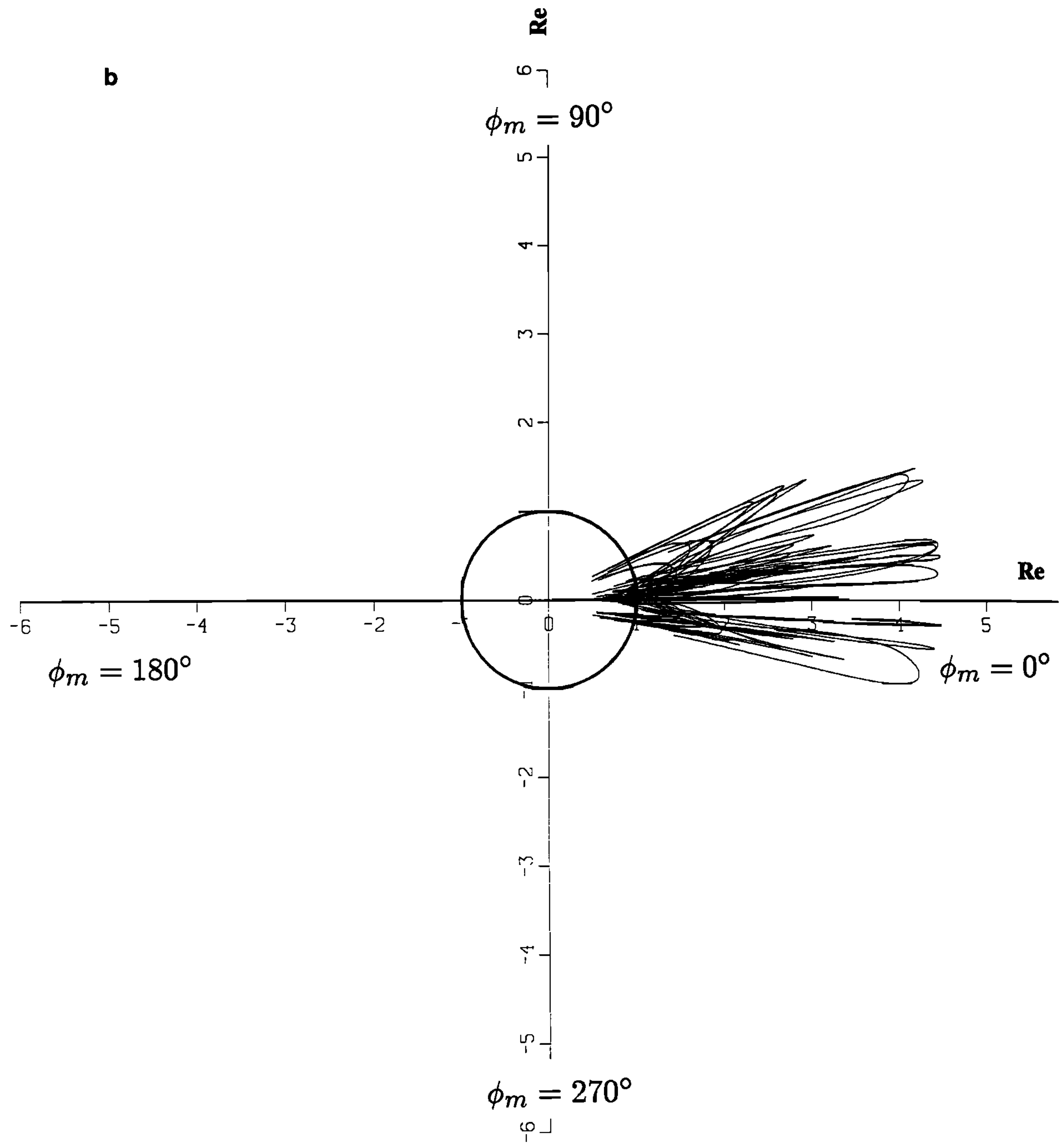

Figure 7. (continued)

were acquired but no sessions were scheduled). In April 1990, four DE 1-Activny sessions were scheduled, and in May and June 1990, none were scheduled.

Observations

During the period November 1989 and April 1990, 10 Activny-DE 1 wave injection sessions were conducted. During each session, the Activny transmitter operated at 10.537 kHz for a period of 6 min centered around the conjunction time. The transmitter format used is shown in Figure 2. DE 1 wideband data (E_x antenna, 10-16 kHz band) were spectrally analyzed for each of the Activny sessions. Two kinds of spectra were made: (1) Compressed spectra of VLF waves received on the DE 1 satellite for the entire 6 minutes of transmission from Activny to DE 1. These spectra were used to attempt to detect the format pattern of radiation from Activny, (2) an expanded (30 cm/min) version to detect individual Activny pulses within the natural background wave spectrum. We present here the details of the DE 1 observations of VLF waves from six representative Activny-DE 1 sessions. Table 2 presents the summary of the DE 1 and Activny satellite orbit locations, conjunction quality, DE 1 receiver sensitivity, and the general features of the VLF wave data observed on the DE 1 satellite for each of these six cases.

During three conjunction periods, December 12, 26, and 27, 1989, both DE 1 and Activny were in the southern hemisphere, and DE 1 was at relatively low altitudes (ranging from 6211 to 14,810 km), thus providing the best conjunction possibilities according to the ray tracing criteria developed above. Figures 8a, 8b, and 8c show the compressed spectra of VLF activity registered by the DE 1 receiver in 10-11 kHz band for these three days. On December 12, 1989,

Table 2. Summary of DE 1 VLF Wave Observations During Active Conjunctions

Date	Time,UT	Satellite	Altitude Km	λ_m, Deg	ϕ_m, Deg	Conjuction Quality	Minimum Signal	Wave Observations
Dec. 12, 1989	0958-1004	AC	1479	-66.6	171.7	EX1	0.5μV/m	Auroral hiss from 9.5-12.0 kHz.
		DE	6211	-75.1	162.5			
Dec. 26, 1989	0814-0820	AC	868	-58.7	180.5	EX1	0.05μV/m	Omega transmitter pulses from 10.2-13.6 kHz; weak hiss between 9-13 kHz; whistlers; chorus.
		DE	14810	-32.0	180.6			
Dec. 27, 1989	0525-0531	AC	1137	-76.1	235.7	EX1	0.05μV/m	Omega transmitter pulses from 10.2-13.6 kHz; strong whistlers up to 16 kHz.
		DE	7389	-59.5	235.1			
Jan. 18, 1990	2046-2052	AC	1573	66.7	323.2	G	0.05μV/m	Strong hiss between 9-11 kHz; occasional whistler; no omega signals.
		DE	22100	50.4	321.2			
Jan. 20, 1990	2104-2110	AC	1680	67.2	312.9	G	0.05μV/m	Weak auroral hiss; occasional impulsive emissions. no omega signals.
		DE	23070	43.1	315.6			
Jan. 22, 1990	2120-2126	AC	1632	58.8	305.0	G	0.05μV/m	Weak auroral hiss; coherent emissions; no omega signals.
		DE	23320	36.9	310.6			

DE 1 (altitude was 6211 km) had the closest conjunction with the Activny satellite. However, DE 1 was in the auroral zone, and the wave activity was dominated by auroral hiss from 9.5 to 12.0 kHz, resulting in a lower sensitivity to the Activny signal (minimum signal was ~ 0.05 μV/m). Neither Activny nor Omega (AUS) signals were detected. The 26 Dec 89 case appeared to be more promising, since DE 1 was at a lower latitude, though at somewhat higher altitude (14810 km) compared to the previous case. Figure 9 shows the satellite orbit in the magnetic meridional and equatorial planes for the case of December 26, 1989. A band of weak hiss (9-13 kHz), whistlers, and chorus were observed. The receiver sensitivity was at its maximum (minimum signal ~ 0.05 μV/m), and Omega (AUS) transmitter pulses from 10.2 to 13.6 kHz were detected throughout the six minute interval. No signals from Activny were detected. The case of December 27, 1989 presented the best possibility for detecting the Activny signals. The DE 1 satellite was at low altitude (7389 km) and subauroral latitudes. Figure 10 shows the satellite orbit in the magnetic meridional and equatorial planes for the case of December 27, 1989. There was no hiss or chorus, though persistent whistler activity was observed up to 16 kHz. The receiver sensitivity was at its maximum (minimum signal was ~ 0.05 μV/m), and Omega (AUS) transmitter pulses from 10.2 to 13.6 kHz were detected throughout the six minute interval. No signals from Activny were detected. Figure 11 shows the expanded version of the spectrum of the wave activity recorded on DE 1 on December 27, 1989 from 0524:55 to 0525:15 UT in the 9.5-14.5 kHz frequency band. The Activny wave injection session started at 0525:00 UT. As the spectrum shows, both whistlers (0^+) and Omega transmitter signals are clearly seen well above the background level, and there is no evidence of the Activny 1 s On/ 1 s Off pattern.

During January 18, 20 and 22, 1990, conjunctions occurred in the northern hemisphere with DE 1 at relatively high altitudes. As shown in Figure 6a, only rays injected at large wave normal angles outside the plasmapause could have reached DE 1, and even then there would be large defocusing of the rays at high altitudes. Consequently, detection of Activny signals was less likely. Figure 8d, 8e, and 8f show the compressed spectra of VLF activity registered by the DE 1 receiver in the 10-11 kHz band for these three days. As predicted by ray tracing simulations, Omega transmitter signals from ground with their small initial wave normal direction, were not detected on any of these days, in spite of the maximum sensitivity of the receiver (minimum signal ~ 0.05 μV/m). No Activny signals were detected on any of these three days. The background wave activity on these days consisted of weak hiss, occasional whistlers, and impulsive emissions.

Discussion

Though no Activny signals were detected by the LWR instrument on the DE 1 satellite, the experimental constraints allow us to place an upper limit on the total power radiated by the Activny transmitter in the whistler mode. To make the power estimates, experimental parameters from the December 27, 1989 sessions were selected. From Table 2 we see that on this day Activny was situated at 1137 km altitude and at -76.1° geomagnetic latitude, placing it outside the plasmasphere. From the ray tracing model, a typical electron density at this location is 2000 electrons-cm^{-3}, and the resonance cone angle at 10 kHz is ~ 88.8°, indicating that the loop antenna could have radiated whistler mode waves at almost all directions. Figure 5 suggests that a loop antenna can be expected to have a radiation pattern that depends only weakly on the loop orientation and which peaks near the resonance cone angle. Ray tracings were performed to estimate the spreading of the rays from injection at Activny to reception at DE 1 (7389 km altitude, and -59.5° latitude). It was found there were two possible initial wave normal directions, ~ 35° and ~ 65°, that corresponded to rays reaching the DE 1 satellite. From Figure 5 we see that the radiation of at wave normals of ~ 35° and ~ 65° is much less than that for wave normals near the resonance cone. Thus we can set an upper limit to radiation at ~ 35° and ~ 65° by assuming that the loop radiates isotropically. For simplicity we adopt the same procedure for the actual loop antenna whose deployed configuration is unknown. Then, taking into account that the typical spreading factor was ~1000, that the local refractive index at the reception point was ~2 and that the minimum detectable signal level was 0.05 μV/m for LWR, we find the upper limit on the total power radiated by the Activny satellite in the whistler mode to be ~10 mW.

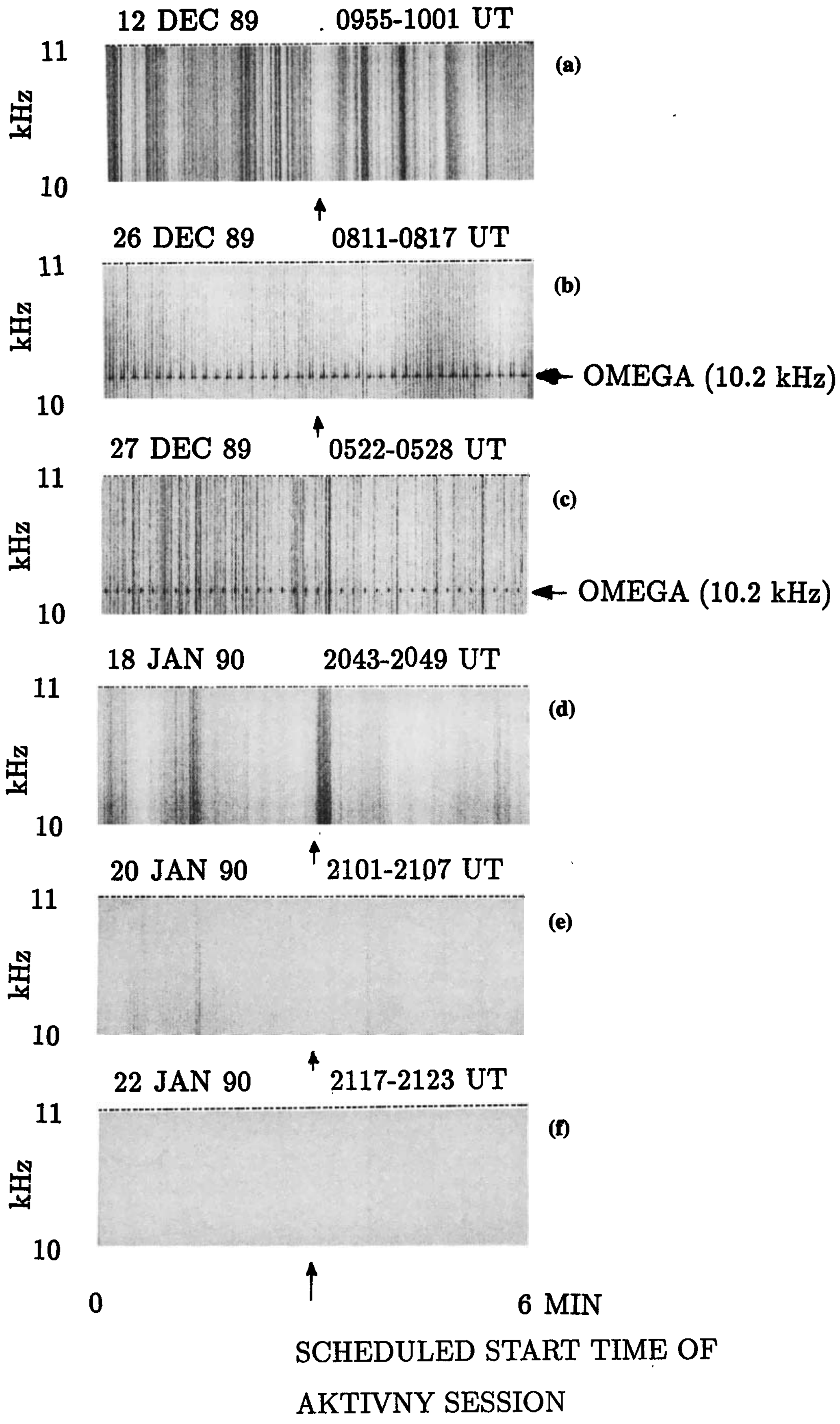

Figure 8. Compressed spectra of 10-16 kHz electric field signals recorded by LWR on DE 1 during the Activny transmission periods for the 6 days listed in Table 2.

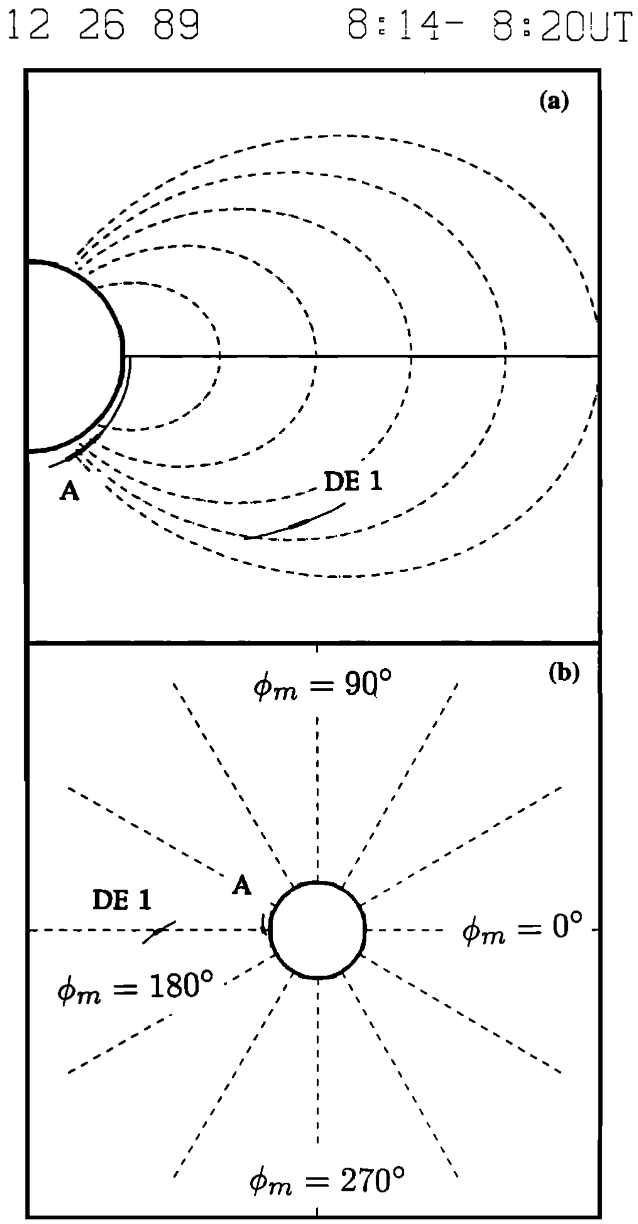

Figure 9. Projections in the (a) magnetic meridional, and (b) magnetic equatorial planes of Activny (A) and DE 1 satellite orbits during the wave-injection experiment on December 26, 1989. The thickened part of the trajectories indicate the satellite locations during the Activny transmission period.

Summary and Recommendations

We conclude that no detectable Activny signal propagated to the DE 1 satellite. The detection of 10.2-kHz Omega signals well above the local noise level on December 26 and 27, 1989 demonstrate clearly that DE 1 antenna and receiver were functioning normally. Moreover, the receiver was operating at the highest possible sensitivity (minimum detectable signal 0.05 μV/m). Thus the absence of any detectable Activny signal can only be attributed to relatively low radiation from the Activny transmitter. However, we must note that only a few sessions were conducted when Activny and DE 1 were situated in the best conjunction locations according to the criteria established above. Assuming isotropic radiation from the Activny satellite, and nonducted propagation to DE 1, we estimate the upper limit on the power radiated by the Activny loop antenna in the whistler mode to be ~ 10 mW. The Activny transmitter was rated at 10 kW of nominal power, and it was expected that several tens-to-hundreds of watts would be radiated in the whistler mode, a value three to four orders of magnitude larger than the radiated power estimated from the experimental observations. There are two main factors thought to be responsible for this discrepancy and both are connected to the incorrect deployment of the loop antenna. First of all, the loop antenna system was designed to be resonant at eight frequencies near 10 kHz assuming that antenna inductance was appropriate to that of a 20-m-diameter loop antenna. Because the antenna was not deployed into a loop configuration, its inductance was smaller than planned and the true resonance frequency was measured to be 15 kHz. Thus the on board transmitter operat-

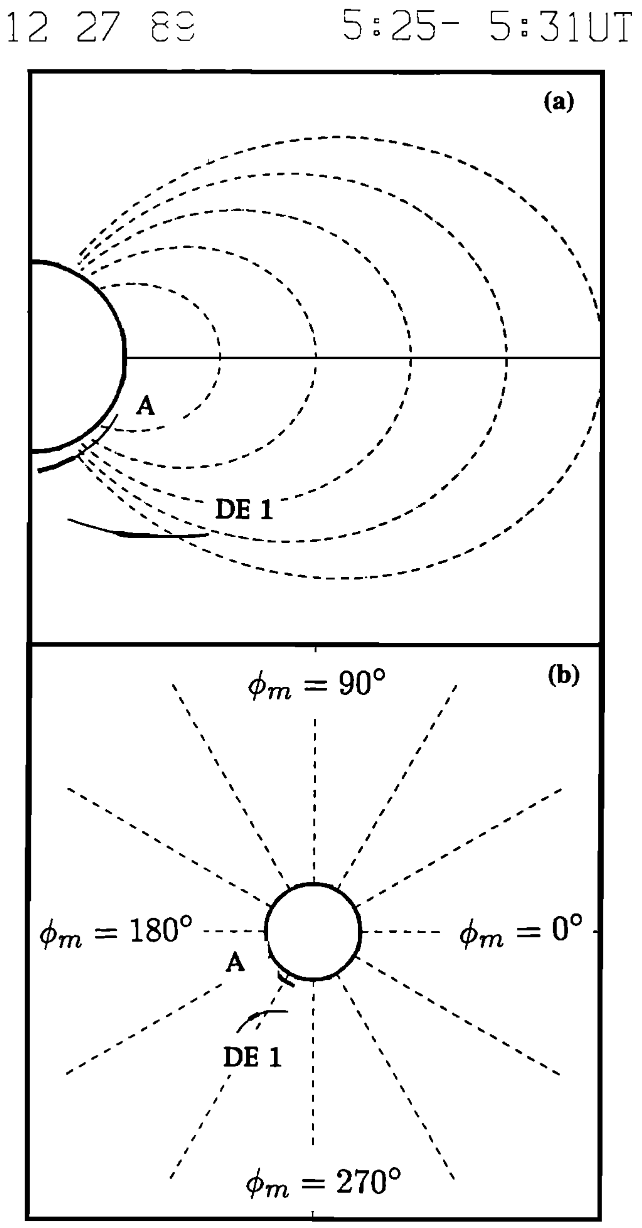

Figure 10. Projections in the (a) magnetic meridional, and (b) magnetic equatorial planes of Activny (A) and DE 1 satellite orbits during the wave injection experiment on December 27, 1989. The thickened part of the trajectories indicate the satellite locations during the Activny transmission period.

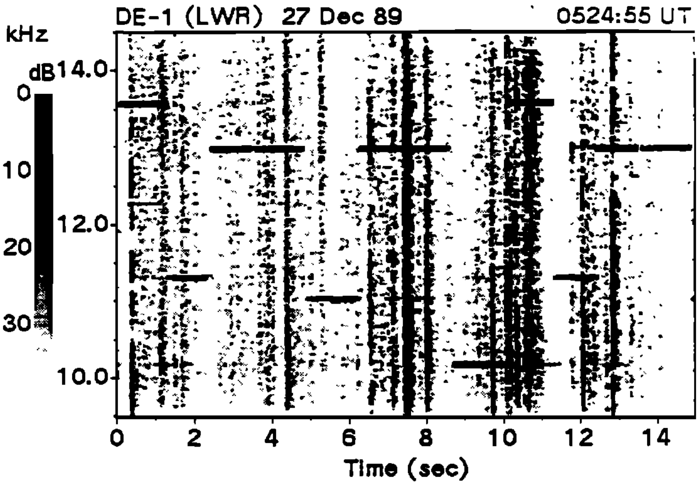

Figure 11. Expanded spectra of 10-16 kHz electric field signals on December 27, 1989. Activny transmission began at 0525:00 UT. Omega (Australia) transmitter pulses are seen between 10.2 and 13.6 kHz, and several 0^+ whistlers are visible between 10 and 14 kHz.

ing at ~10 kHz was delivering power to an untuned antenna with a consequent reduction in radiated power. The second, and most important, factor concerns the magnetic moment of the antenna, which is proportional to the enclosed area. It is thought that the antenna was deployed into a long narrow ellipse with enclosed area A much smaller than that of a 20-m-diameter loop. Since the radiated power is proportional to A^2, the elliptical antenna would radiate much less power than anticipated.

Several recommendations can be made for a future space-based wave injection experiments. As noted earlier, some of the best conjunction experiments could not be carried out due to the unavailability of a ground tracking station for reception of the DE 1 data. Thus more extensive ground support for satellite operations or capability for onboard recording or processing of wideband data is imperative for successful operation of a two-satellite experiment. Second, many sessions could not be scheduled simply due to the logistics involved in organizing the joint sessions between satellites operated by two agencies belonging to different countries. As mentioned earlier, a typical session required a 2 months period to schedule. In general, satellite orbits, particularly those with relatively low altitude perigee, cannot be predicted with accuracy 6 weeks in advance. Thus a better communication (real time) between experimenters and government agencies is desirable. Because of the different inclinations of the two satellites, the actual conjunction between Activny and DE 1 lasted for ~2 min. Since the most probable mode for propagation is the whistler mode, where the rays tend to follow magnetic field lines, the best possible satellite configuration for wave injection-reception experiments in space occurs when both the satellites are in nearly coplanar polar orbits.

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