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The Space Shuttle as a Platform for Observations of Ground-Based Transmitter Signals and Whistlers

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Recent experimental and theoretical studies indicate that coherent VLF waves, such as lightning-generated whistlers and signals from ground-based VLF transmitters, can often produce significant pitch angle scattering in energetic particles in the magnetosphere. However, the relative importance of these waves in controlling the lifetimes of energetic particles is only partially understood due to limited knowledge of the global distribution of the coherent waves throughout the magnetosphere. The present paper presents a preliminary global study of VLF transmitter signals and low-latitude whistlers received at 245 km altitude on the space shuttle. The observations were made in a 5-day period during the STS 3 mission of the space shuttle in March 1982. The threshold sensitivity of the wave receiver when mounted in the shuttle bay was 0.3 pT ± 10 dB (set by the shuttle electromagnetic interference), which was sufficient to detect the whistler mode signals in large regions of the ionosphere. We find that the direct signals from a 10-kW transmitter located at 28°S magnetic latitude were received in a roughly circular region with a diameter of 6000 km centered around the transmitter. The signals propagating through the magnetosphere from a 500-kW magnetically conjugate transmitter at 40°N magnetic latitude were received inside a region extending 5000 km in longitude and 2000 km in latitude. Finally, the direct signals from a 1 MW-transmitter at 31°S magnetic latitude were received in a region extending 22,000 km in longitude, while the latitudinal extent (5000 km) was limited by the shuttle orbit and the day/night terminator. Except for one case, signals were received only during nighttime. Extremely small dispersion whistlers were detected on *L*-shells between 1.04 and 1.11, suggesting that the lack of ducted whistlers on magnetic field lines in this range is not due to transmission loss across the *D* region boundary or to high ionospheric absorption loss, but most likely to a lack of ducts.

1. INTRODUCTION

The dynamics and lifetime of energetic electrons in the magnetosphere depend in large measure on the VLF wave activity both generated spontaneously in the medium and arising from ground-based VLF transmitters and from lightning-generated whistlers. Estimations of whistler wave-electron interactions are usually done with either of two assumptions: (1) that the waves propagate in a ducted mode parallel to the earth's magnetic field; or (2) that the waves are nonducted but their ray paths can be described by two-dimensional ray tracing calculations in which transmeridional propagation is neglected. The ionosphere is often the boundary in these calculations, from which rays are "launched" into the magnetosphere. The actual field amplitudes in the ionosphere are dependent on *D* region absorption, coupling into ducts, and coupling between the two wave polarizations, and thus they are complicated functions of local time, geographic location of the transmitter, geomagnetic activity, and signal frequency. However, both for lightning-induced whistlers and for VLF transmitter signals, in situ measurements of the global distribution of field intensities in the ionosphere (a boundary condition) are rare. With this pilot study, we want to draw attention to the opportunity provided by the space shuttle to resolve this problem.

The STS 3 mission of the space shuttle was carried out in March 1982. The shuttle was launched into an almost circular orbit with an altitude of 240 to 250 km and an inclination of 37°. The nighttime passes were in the southern hemisphere, and the daytime passes in the northern hemisphere, the shuttle crossing the day/night terminator within a few degrees of the geographic equator at local times of roughly 0600 or 1800 LT. The range of *L* shells [*McIlwain*, 1961] covered by the shuttle was from 0.95 to 2.63.

The transmitters we have selected for this study are the USSR Alpha stations in Komsomolskamur and Krasnodar, the Omega stations in Japan, Hawaii, La Réunion, and Argentina, and the NWC transmitter in Australia. The geographic latitude, longitude, radiated power, and frequency range of each of these transmitters are listed in Table 1.

Signals from these VLF stations were most often received during nighttime when the shuttle was in the southern hemisphere. From the distribution in latitude and longitude and the time delays of the Omega and Alpha station signals, we infer that signals from the northern hemisphere stations propagated through the magnetosphere along the earth's magnetic field before reaching the shuttle, while signals propagated directly through the ionosphere up to the shuttle from southern hemisphere transmitters.

The measurements presented here were performed by a wideband analog receiver system, which was part of a plasma

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TABLE 1. List of Transmitters

Transmitters	Latitude, deg	Longitude, deg	Radiated Power, kW	Frequency, kHz
NWC (Australia)	21°49′S	114°10′E	1000	22.3
Alpha				
Komsomolskamur	50°34′N	136°58′E	10–500	11.9–15.6
Krasnodar	45°02′N	38°39′E	10–500	11.9–15.6
Omega				
Japan	34°36′N	129°27′E	10	10.2–13.6
Hawaii	21°24′N	157°49′W	10	10.2–13.6
La Réunion	20°58′S	55°17′E	10	10.2–13.6
Argentina	43°03′S	65°11′W	10	10.2–13.6

Data are from Inan et al. [1984].

diagnostics package (PDP) [*Shawhan et al.*, 1984*a*]. During the mission the PDP was housed in the shuttle payload bay. An electric dipole antenna with two 20-cm-diameter spheres separated by 1.6 m was used to monitor the electric wave field, while the magnetic field was probed by a search coil sensor. A wideband receiver was connected to the electric antenna (51.2 s) alternating with the magnetic antenna (51.2 s). Every eighth 51.2-s format, a Langmuir probe was substituted for a magnetic sensor.

The receiver had a 10-kHz bandwidth, selecting nominally 0–10 kHz (25.6 s), 10–20 kHz (12.8 s), and 20–30 kHz (12.8 s). The frequency format was synchronized with the antenna format. The 10- to 20- and 20- to 30-kHz range were heterodyned down to 0–10 kHz. In the process, the 10- to 20-kHz band was inverted, so that an assumed 20-kHz signal appears as a 0-kHz signal.

Signals from ground-based stations were most commonly seen in the magnetic field data, and thus the data presented here are primarily based on measurements from the search coil. The wideband receiver was designed to give high frequency and time resolution in the VLF frequency range, but not to give accurate field intensities. However, the search coil sensor was also connected to a 30-Hz to 178-kHz receiver with 16 logarithmically spaced channels. This receiver has been calibrated. It has been found that the magnetic fields in the range 10.0–17.8 kHz and 17.8–31.0 kHz have amplitudes of 7 pT ± 10 dB in each of the two bands and that the noise primarily consists of a number of narrow-band emissions from power converters, etc. [*Shawhan and Murphy*, 1984*b*]. This noise level is independent of the orbiter attitude and only slightly time dependent as systems in the payload bay are turned on or off. To estimate an approximate threshold field amplitude for detection of the transmitters in gray scale spectrograms, scans of amplitude versus frequency at selected times have been inspected. Comparing the amplitudes on these scans, of a transmitter signal and the most dominant interference lines, we estimate that the threshold amplitude is about 0.3 pT ± 10 dB.

The wideband data base consists of about 24 hours of observations which were acquired over a total of roughly 16 orbits. In the following sections the data are presented and discussed. We also provide brief comments on the advantages of the space shuttle and its orbit for future wave experiments.

2. OBSERVATIONS

Typical examples of VLF transmitter signals and whistlers detected by the wideband receiver are shown in Figure 1*a* and 1*b*. Figures 1*a* shows 51.2 s of data from the magnetic antenna followed by 51.2 s of data from the electric antenna. Each 51.2-s section is divided into three parts, marked I, II, and III. Part I represents data in the 0 to 10-kHz range; part II represents data in the 10 to 20-kHz range which has been heterodyned down to the 0 to 10-kHz range and inverted so that the base corresponds to 20 kHz, while the top part of the spectrogram corresponds to 10 kHz. Part III represents data in the 20 to 30-kHz range which has been heterodyned down to 0–10 kHz. In this part the base corresponds to 20 kHz, while the top part of the spectrogram corresponds to 30 kHz.

Figure 1*a* contains signals from two VLF transmitters, Komsomolskamur and NWC. The transmission format of the Alpha station Komsomolskamur consists of a sequence of 400-ms CW pulses, each at one of the three frequencies 11.905, 12.649, and 14.881 kHz, while the NWC Australia transmissions consist of a continuous stream of 5-ms pulses at either of the two closely spaced frequencies 22.3 kHz ± 50 Hz. From Figure 1*a*, we note that the signals appear to be relatively stronger on the magnetic antenna. This is at least partly due to the strong broadband electrostatic noise level presumably generated by the shuttle interacting with the ambient plasma [*Shawhan et al.*, 1984*b*], which imposes a higher threshold for detection of the electric component of the signals.

Figure 1*b* shows an echoing whistler train observed at $L \sim 2.3$. This type of whistler train has been observed on other spacecraft in the past (for example, see *Bell et al.* [1983]). The echoing components are believed to consist of whistler mode waves which have leaked from ducts and have subsequently scattered to the spacecraft position. Although numerous whistlers were observed during the STS 3 mission, their occurrence rate was generally low compared with the rates of 1 to 10 per minute commonly measured at mid-latitude on other low-altitude spacecraft [*Carpenter et*

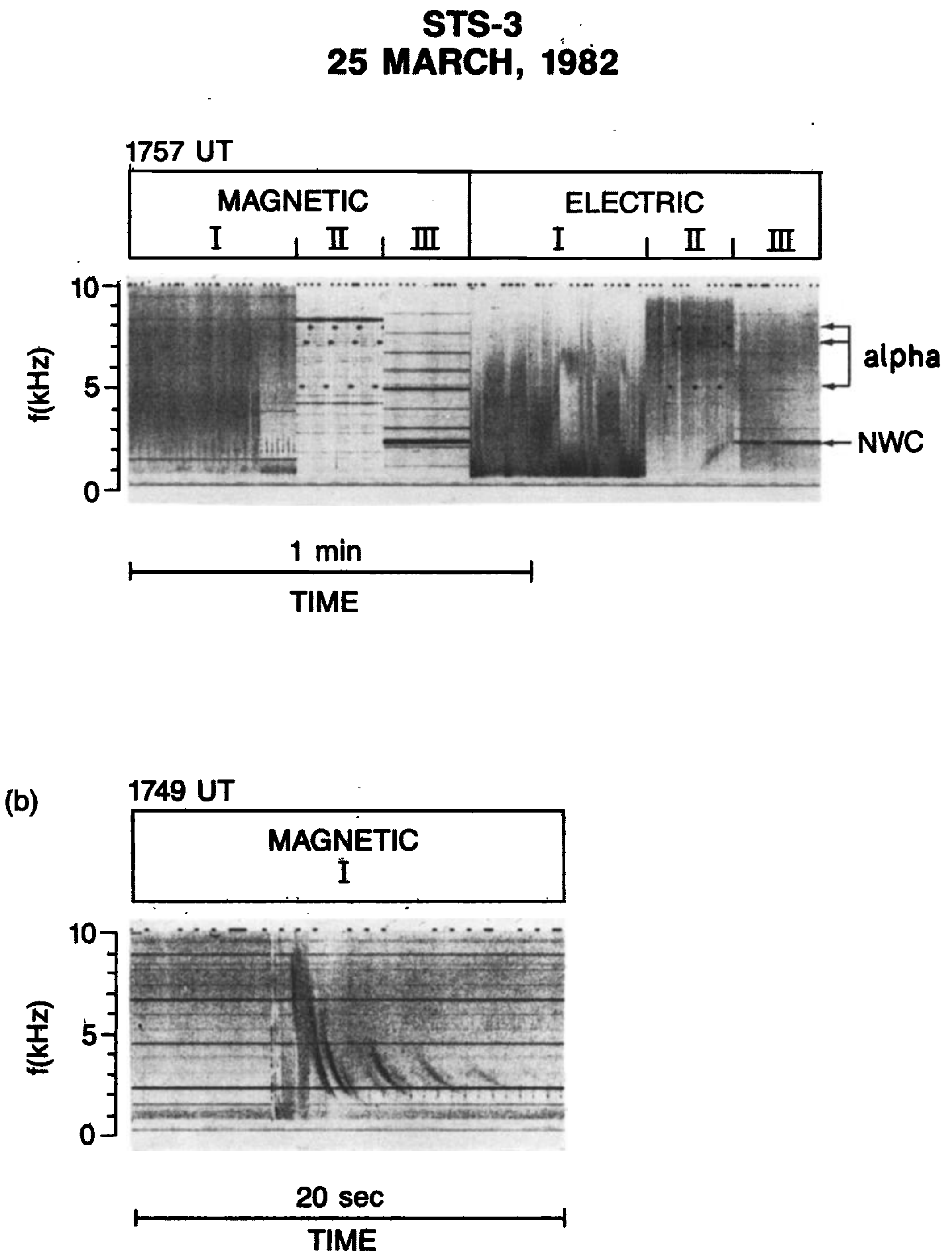

Fig. 1. Gray scale spectrograms showing (*a*) the reception of signals from the Alpha station Komsomolskamur (KO) seen as a dot pattern and the NWC Australia station seen as a constant frequency line, and (*b*) the reception of whistlers. Also indicated is the antenna format and the frequency format; I: 0–10 kHz, II: 20–10 kHz, and III: 20–30 kHz.

al., 1968; *Smith and Angerami*, 1968; *Walter and Angerami*, 1969]. This low rate cannot be attributed to a lack of sources since the shuttle often passed over Indonesia, a well-known area of thunderstorm activity [*Lewis*, 1982]. Instead we believe that the low rate can be attributed to the relatively high level of electromagnetic interference (EMI) which existed in the payload bay.

The time resolution of the measurements is limited by the antenna and frequency format. Any of the bands at 10–20 kHz and 20–30 kHz are monitored by a particular antenna for 12.8 s every 102.4 s. In the 89.6-s time interval that a frequency band is not monitored by for instance the magnetic antenna the shuttle moves about 700 km with a velocity of 7.8 km/s.

Assuming that the signals from the ground-based VLF transmitters largely propagate along the earth's magnetic

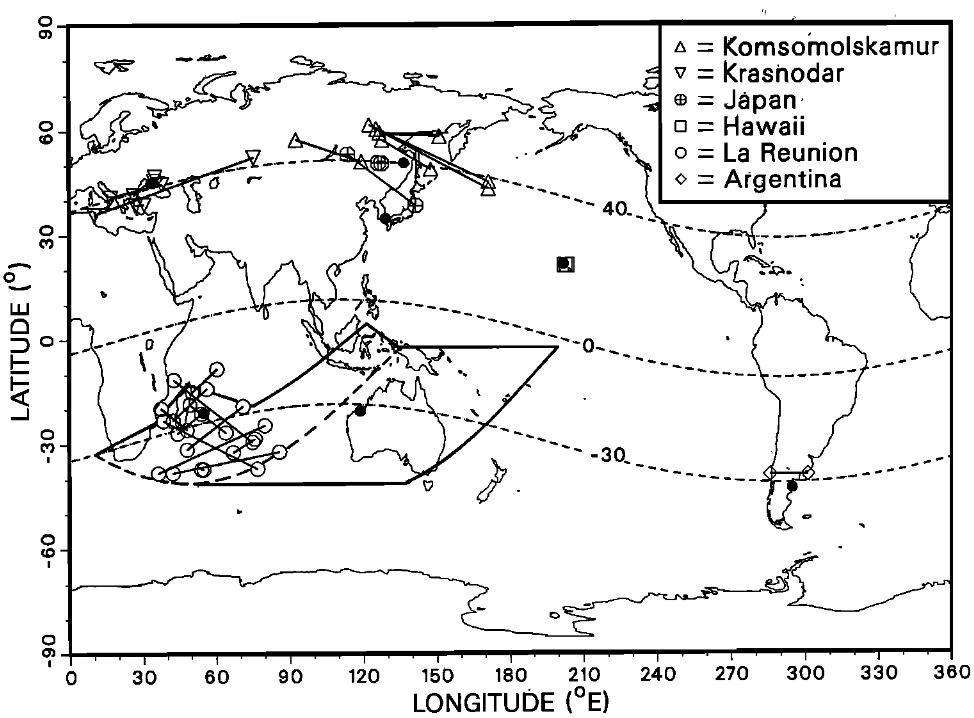

Fig. 2. The global reception of VLF transmitter signals. The magnetic footprint of the shuttle is shown when signals from the Alpha and Omega transmitters were first received and when they later disappeared. The orbit during reception is approximated by straight lines. The contour limiting the reception of the NWC Australia transmitter is also shown. The location of the transmitters is indicated by solid circles and the 40°, 0°, and -30° magnetic latitude contours by dashed lines. One orbit during reception of the NWC station is also shown.

field lines, for instance in a ducted mode when propagating from a transmitter located in the opposite hemisphere of the shuttle, the global reception of ground-based VLF transmitter signals during the shuttle mission can be summarized as in Figure 2. This figure shows the location of the shuttle when projected along the earth's magnetic field to the surface of the earth during times when ground-based transmitters were received. The projection has been done by approximating the earth's magnetic field with a dipole field centered at the earth's center and the magnetic pole at 11.435° colatitude and -69.761° east longitude. The shuttle location is projected toward the hemisphere where the transmitters are located. Since the transmitters are received almost exclusively at nighttime, the shuttle itself was in the southern hemisphere. For the Alpha and Omega stations are shown the magnetic footprint of the shuttle when the signals are first received and when they disappear, and the orbit during reception is approximated with straight lines. For the NWC Australia station, the contour limiting the region of reception and one projected orbit are shown. Also indicated are the location of the transmitters (solid circles) and the 40°, 0° and -30° magnetic latitude lines (dashed lines). Note that the Omega station in Australia was not in operation at the time of the STS 3 flight.

Signals from the NWC transmitter were observed during six orbits, and receptions were confined solely to the nighttime sector. In fact, from 120° to 200° longitude the northern boundary of reception was aligned with the geographic equator, the approximate latitude at which the spacecraft crossed the day/night terminator. Signals disappeared here within 20 min of 0600 LT, the time of terminator crossing. The eastern boundary is determined by limitations in the wideband data set, and the southern boundary by the shuttle orbit. The western boundary, however, is a true boundary of reception.

Figure 3 gives an oveview of the data base containing the Alpha and Omega stations ordered in local time. It is based on visual inspection of gray scale spectrograms and includes only these stations because they have an easily recognizable frequency format distinct from the shuttle interference lines. The abscissa is the local time divided into 1-hour bins. The top panel shows the number of times the orbiter passed through a LT bin while receiving one of the stations. The bottom panel shows the number of times when the magnetic footprint of the shuttle (both direct and conjugate projection) was within 10° latitude and longitude of a transmitter without receiving the signal from this station. Figure 3 shows that the stations almost exclusively were received during nighttime, althought opportunities were also present during the daytime as defined by the 10° latitude and longitude criterion. While the limited data base and the uncalibrated wideband receiving system do not allow us to perform any deeper statistical analysis, the results shown in Figure 3 suggest that the reception of the signals has a strong dependence on LT, in that the signals were rarely observed during the daytime. This is not surprising as the higher D region plasma density is expected to increase the absorption by about 20 dB at 10 kHz and 30 dB at 30 kHz [*Helliwell*, 1965].

During nighttime when the shuttle was either magnetically conjugate to a transmitter or in the same hemisphere within 1000 km, the signals from this transmitter were usu-

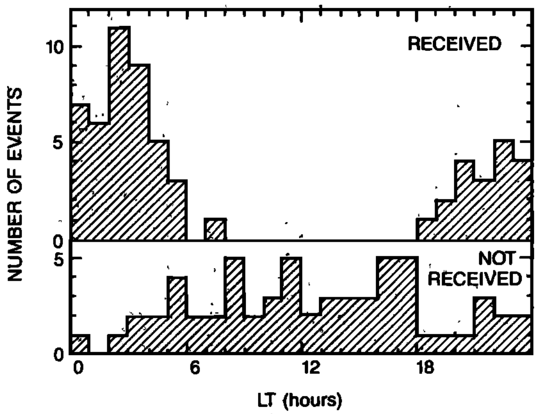

Fig. 3. Local time (LT) is divided into 1-hour bins. Top panel shows the number of times the shuttle passed through a LT bin and received signals from one of the stations. Bottom panel shows the number of times signals were not received when the footprint of the orbiter passed a transmitter within 10° in latitude and longitude.

ally received on the magnetic antenna. The only exception is the Argentina transmitter whose signals occasionally were not received during the nighttime. This transmitter is also comparatively rarely observed on satellites (*T. F. Bell*, personal communication, 1987). The coverage of this transmitter is unfortunately poor in the present data set, with data from only four orbits passing within 10° in latitude and longitude of the transmitter. Out of the four opportunities, the signals were missing in three. The lack of reception could be influenced by the increased ionospheric electron density expected near the South Atlantic anomaly [*Vampola and Gorney*, 1983], which would increase the absorption losses.

3. DISCUSSION

The detailed analysis of magnetospheric interactions between energetic electrons and coherent signals from ground-based transmitters requires knowledge of both the input and output signals as well as information concerning the energetic particle distribution function. In past experiments, measurements of these parameters have been made on both rockets and high- and low-altitude satellites, and important advances in knowledge have resulted from the analysis of these data [*Inan et al.*, 1978; *Bell et al.*, 1981, 1983; *Neubert et al.*, 1983; *Kintner et al.*, 1983; *Imhof et al.*, 1974, 1976, 1983*a*,*b*]. However, most past work has involved case studies in limited regions of the magnetosphere and little has been published concerning the global distribution of wave energy from ground-based VLF transmitters. This is a quantity that must be known in order to understand the details of wave injection experiments, as well as to assess the importance of VLF transmitters, vis a vis the ambient wave background in determining the lifetimes of energetic electrons in the magnetosphere [*Imhof et al.*, 1974, 1976, 1983*a*,*b*].

In principle, the radiation fields in the ionosphere from ground-based transmitters could be calculated from a full-wave solution of Maxwell's equations extending from the earth-ionosphere waveguide through the ionosphere. However, important properties of the ionosphere, such as collision frequencies and plasma density distributions, are not well known near the locations of most ground-based transmitters. Consequently measurements of input wave properties in the ionosphere will be necessary to calibrate future theoretical models. From this point of view, wave measurements made at shuttle altitudes can play an important part in understanding wave-particle interactions in the ionosphere and magnetosphere.

An example of ionospheric wave magnetic field data as observed on STS 3 is shown in Figure 4. The signals were transmitted from the NWC transmitter at 22.3 kHz and received during the pass shown as a dashed line in Figure 2. The figure shows the wave magnetic field amplitude as a function of the distance between the transmitter and the foot of the magnetic field line on which the shuttle was located (we define the "foot" of the magnetic field line as the point of intersection of the field line with the earth's surface in the hemisphere of the transmitter). The amplitude is given in relative units and is compared to a very simple model proposed by *Inan et al.* [1984], which predicts the relative amplitude variation with distance from a transmitter. It can be seen that the fit between theory and observations is reasonably good, insofar as the relative amplitude variation is concerned. The absolute value of the wave amplitude cannot be predicted from the simple theory. Note however, that with the current assumption of 0.3 pT ± 10 dB for the threshold field sensitivity, the maximum field strength received during this pass reaches 15 pT ± 10 dB, which is consistent with previously reported magnetic field amplitudes of waves from ground based VLF stations measured from satellites [*Heyborne*, 1966; *Inan et al.*, 1984].

Recent theories predict enhanced energetic electron precipitation above LF and MF transmitters through a cyclotron resonance interaction between the electrons and the wave field in the topside ionosphere above the transmitters [*Neubert et al.*, 1987]. However, in situ measurements of wave fields in this frequency range are rather scarce. The shuttle could provide, with a wave experiment flown on consecutive launches, a global map of LF and MF field intensities in the ionosphere.

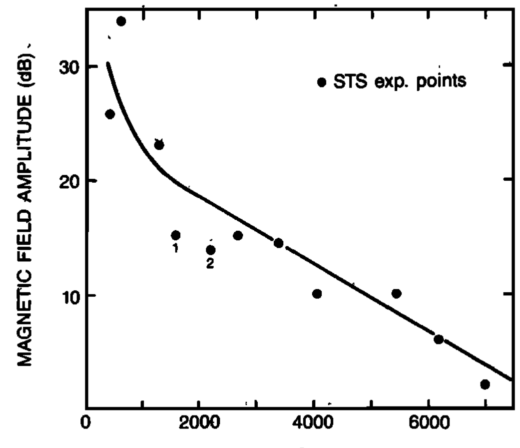

Fig. 4. Amplitude of the NWC transmitter signals as a function of distance from the transmitter of the Shuttle magnetic footprint for the orbit indicated on Figure 2. The 0-dB level corresponds to 0.3 pT ± 10 dB. Also shown is the relative amplitude variation predicted from a simple model [*Inan et al., 1984*]. The experimental points marked 1 and 2 are from the pass north of the transmitter when the distance was increasing.

VLF wave amplitude measurements in the topside ionosphere would be important for understanding the propagation characteristics of low-latitude whistlers by complementing ground based measurements [*Tsuruda and Hayashi*, 1975; *Okada et al.*, 1977, 1981; *Hayakawa et al.*, 1981]. It has been proposed to use low-latitude whistlers as a diagnostic tool to determine the distribution of cold plasma within the inner radiation belts ($L < 2$). However, a number of unsolved problems remain concerning the mode of propagation of whistler mode waves on low-latitude paths and the efficiency of whistler duct excitation at low latitude [*Hayakawa and Tanaka*, 1978; *Ohta et al.*, 1984; *Hayakawa et al.*, 1985]. Wave magnetic and electric field measurements of whistlers and signals from ground-based transmitters at shuttle altitudes (245–400 km) would be very useful in attempting to answer these questions.

In the present study, extremely small dispersion whistlers were detected on days 84, 85, and 86 as the spacecraft crossed magnetic shells in the range $1.04 \leq L \leq 1.11$. Examples were obtained at local times of both ~ 0600 and ~ 1700 LT. The dispersions of the whistlers lay in the range D =1.5–2.5 $s^{1/2}$, which is within the expected range for short-fractional hop whistlers (direct propagation from the ground through the ionosphere).

These observations give direct evidence that VLF waves can be transmitted across the D region boundary at these low latitudes and can propagate through the ionosphere to altitudes near the F region plasma density peak. Past work on low-latitude whistlers has indicated that ducted whistlers are generally not observed at geomagnetic latitudes less than 15° ($L < 1.13$), and the smallest measured values of dispersion are roughly $D \sim 10\ s^{1/2}$ [*Hayakawa and Tanaka*, 1978]. The present observations suggest that the lack of ducted whistlers at $L < 1.13$ is more likely due to a lack of whistler mode ducts on these L shells, rather than to high ionospheric absorption or high transmission loss across the D region boundary. Since the dispersion is closely proportional to the integral of the electron plasma frequency along the ray path, it can in principle be used as a diagnostic tool to determine plasma density variations below the spacecraft.

The STS 3 VLF wave data show that even though the shuttle EMI imposes limits on the threshold sensitivity of the wave receivers, valuable measurements of VLF wave activity can be performed even when the antennas are housed in the shuttle bay. Thus, with calibrated receivers, global studies of VLF magnetic field intensities may be performed accurately at shuttle altitudes close to the F peak region of the ionosphere. It is clear, however, that the electric field measurements are significantly disturbed by shuttle-generated noise. For such measurements the wave experiment must be free flying at some distance from the shuttle, say 100–300 m, as was done during the Spacelab 2 mission [*Gurnett et al.*, 1986].

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