JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. A12, PAGES 27,149–27,156, DECEMBER 1, 1996

Simultaneous ground-satellite observations of structured Pc 1 pulsations

R. E. Erlandson

Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland

K. Mursula and T. Bösinger

Department of Physical Sciences, University of Oulu, Oulu, Finland

Abstract. Structured Pc 1 pulsations are investigated using simultaneous multipoint ground-satellite observations recorded on September 10, 1986, during Viking orbit 1103. The multipoint Pc 1 observations were acquired using the Viking magnetic field experiment at 13,550 km altitude from $L = 5.1$ to 5.5 and three Finnish ground stations at Rovaniemi, Ivalo, and Kilpisjärvi. These stations are all located within 30 min magnetic local time and 1° in latitude of the ionospheric field line footprint of the Pc 1 source field line. Structured Pc 1 pulsations between 0.5 and 1.0 Hz were observed both on the ground and in space at similar frequencies, with similar frequency dispersion, and with a similar repetition period. The wave source region, based on Viking Langmuir probe observations, was just inside the plasmapause. The wave transit time between Viking and the ground was 12 ± 2 s, where Viking leads the ground. This implies that the waves propagate downward from Viking to the ground, consistent with previous downward Poynting flux estimates.

Introduction

Energetic ions in the equatorial magnetosphere from the plasmasphere to the outer magnetosphere are often unstable to the electromagnetic ion cyclotron instability [*Mauk and McPherron*, 1980; *Young et al.*, 1981]. These waves are generated in the Pc 1 frequency range (0.2 to 5 Hz) and have peak occurrence in the early afternoon sector [*Bossen et al.*, 1976; *Roux et al.*, 1982; *Fraser and McPherron*, 1982] and outer magnetosphere ($L > 7$) [*Anderson et al.*, 1992a, b]. In most cases, these waves propagate away from the equatorial source region, toward the ionosphere [*Mauk and McPherron*, 1980; *Erlandson et al.*, 1990; *LaBelle and Treumann*, 1992; *Fraser et al.*, 1996], and to the ground, where they are commonly observed.

The earliest ground-based Pc 1 observations were reported by *Sucksdorff* [1936] and *Harang* [1936]. *Sucksdorff* [1936] commented that the time series of these micropulsations resembled a pearl necklace, from which the term "pearl pulsation" arose as a major type of Pc 1 pulsation at midlatitude and low latitude [*Troitskaya*, 1961; *Saito*, 1969]. Pearl pulsations appear as repetitive bursts of Pc 1 waves. The repetition period of Pc 1 waves is thought to be due to Pc 1 wave packets, which propagate along magnetic field lines between conjugate points [*Jacobs and Watanabe*, 1964; *Obayashi*, 1965]. Not all Pc 1 waves contain repetitive bursts, a fact which leads to the general Pc 1 wave classification of unstructured and structured (pearl) pulsations. Further characterization of Pc 1 wave morphology as observed on the ground is given by *Fukunishi et al.* [1981].

Paper number 96JA02645.
0148-0227/96/96JA-02645$09.00

Downward propagating Pc 1 waves are thought to be partially reflected at ionospheric altitudes back toward the equator where they are amplified, giving rise to the repetition structure of structured Pc 1 pulsations. However, the reflected wave's **k** vector is perpendicular to magnetic field **B**, while it must be parallel to **B** in order for wave growth to occur upon return to the equatorial magnetosphere. Therefore structured Pc 1 pulsations are thought to occur near the plasmapause density gradient as ray-tracing studies indicate that the wave **k** vector can remain field aligned in the presence of a density gradient [*Thorne and Horne*, 1992]. Similarly, *Mazur and Potapov* [1983] find that conditions for generation of pearl pulsations are only possible for sufficiently large plasma density gradients and when the equatorial amplification exceeds the damping decrement of waves reflected at ionospheric altitudes.

The source region of structured Pc 1 pulsations has also been investigated using satellite-borne observations. *Perraut* [1982] observed Pc 1 waves using GEOS 2 magnetic field data with a repetition period which was half that observed near the conjugate point on the ground. In general, very few structured Pc 1 waves were observed in the GEOS data, which suggests conditions suitable for their generation are not generally met near geostationary orbit [*Gendrin et al.*, 1978]. *Fraser et al.* [1989] performed a detailed analysis of a structured Pc 1 wave event observed on the ground during an overflight of the ISEE 1 satellite, finding that the source region occurred just inside the plasmapause. Similarly, *Erlandson et al.* [1992] found that the source region of a structured Pc 1 pulsation observed in Viking magnetic field data also occurred inside the plasmapause.

In this paper, we present observations of a structured Pc 1 pulsation event observed simultaneously in the magnetosphere and at multiple sites on the ground. The observations are used to determine the relationship of the wave source region to the plasmapause and the transit time of waves propagating between Viking and the ground.

Table 1. Location of the Finnish Search Coil Magnetometers

Station	Geographic Latitude, deg.	Geographic Longitude, deg.	Geomagnetic Latitude, deg.	Geomagnetic Longitude, deg.	L Value, at 300 km	MLT, hours
Rovaniemi	66.8	25.9	63.2	107.4	5.1	UT + 2.50
Ivalo	68.7	27.3	65.0	109.9	5.8	UT + 2.68
Kilpisjärvi	69.0	20.9	65.7	105.3	6.1	UT + 2.37

Instrumentation

Pc 1 wave data discussed in this paper were acquired using instruments on the Viking satellite and from search coil magnetometers located in Finland. Viking was launched on February 27, 1986, into a 98.8° inclination orbit with an apogee altitude of 13,550 km and perigee of 817 km [*Hultqvist*, 1987]. Pc 1 waves at Viking were recorded using a three-axis fluxgate magnetometer sampled at 53 Hz with a ± 1 nT resolution [*Potemra et al.*, 1987]. Ground-based Pc 1 data were recorded using search coil magnetometers sampled at 10 Hz with a ± 1 pT/s resolution at 1 Hz. Data from the search coil magnetometers were converted to units of nanotesla for this study. The ground stations used in this study are located at Rovaniemi (ROV), Ivalo (IVA), and Kilpisjärvi (KIL) (Table 1). Recall that the field line guidance of Pc 1 waves stops in the ionosphere [*Lewis et al.*, 1977]. This fact implies that the effective ground station L value for Pc 1 waves is determined by the L value at ≈ 300 km altitude. The L values at the geographic location of ROV, IVA, and KIL at an altitude of 300 km are listed in Table 1.

Observations

Twenty-one Pc 1 wave events have been observed in the Viking satellite magnetic field data [*Erlandson et al.*, 1990]. Seven of these events were observed within ± 3 hours magnetic local time (MLT) and $\pm 4°$ invariant latitude (INV) of at least one of the Finnish ground stations (Table 1). Pc 1 wave activity was observed on the ground during all seven of these events, although in some cases the wave frequency observed on the ground differed from that observed at Viking. Further analyses of these events are in progress. In this study, we focus on one Pc 1 event observed on magnetic field lines which map extremely close to ROV and IVA within 0.5 hours MLT and 1° in geomagnetic latitude (Figure 1). This event was recorded on September 10, 1986, during Viking orbit 1103 during a magnetically quiet interval ($Kp = 2$).

Plate 1 shows a spectrogram of magnetic field fluctuations recorded at ROV, IVA, KIL, and Viking during orbit 1103. Structured Pc 1 waves were observed on the ground at all three stations throughout the entire 30-min interval associated with the Viking Pc 1 wave event. At Viking, Pc 1 waves were observed during only a 5-min interval from 0850 to 0855 UT, extending from $L = 5.1$ to 5.5. A sketch of Viking's location during orbit 1103 projected onto the noon-midnight plane and the $L = 5.1$ and 5.5 magnetic field lines are shown in Figure 2. The Pc 1 waves were recorded at an altitude of 13,550 km and a magnetic elevation angle (magnetic latitude) of $\approx 50°$. The short duration of this event in space, the continuous observation of the event on the ground, and the polar orbit of Viking lead to the conclusion that the short-event duration at Viking is due to a limited spatial extent of the Pc 1 source field line.

The Pc 1 wave source field lines are just inside the plasmapause, based on the Viking Langmuir probe observations (Figure 3). The significance of this source region just inside the plasmapause will be discussed below. The electron density, $n_e \propto I/\sqrt{T_e}$, can be estimated by assuming an electron temperature, $T_e = 1$ eV, where I is the Langmuir probe current. The actual electron temperature is unknown since the Langmuir probe was operated in a fix bias mode in the electron saturation regime during this orbit [*Holmgren and Kintner*, 1990]. Using this assumption, the electron density at Viking during the Pc 1 wave interval is between 300 and 400 cm^{-3}.

The repetition period of the structured Pc 1 waves observed on the ground is ≈ 2 to 3 min (Plate 1). The Pc 1 bursts at

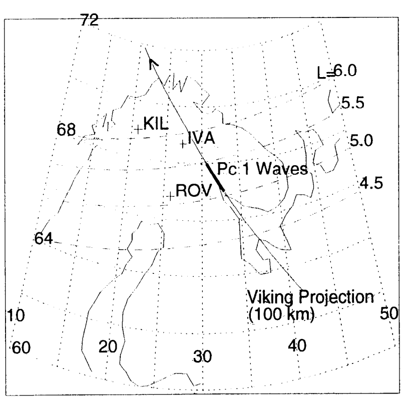

Figure 1. Detailed map of the Finnish ground search coil magnetometer chain and magnetic field line footprints of Viking during orbit 1103 (September 10, 1986). The L-value contours represent the geographic location of L at 300 km altitude. The thick portion of the line denotes the projected location of Viking Pc 1 wave activity.

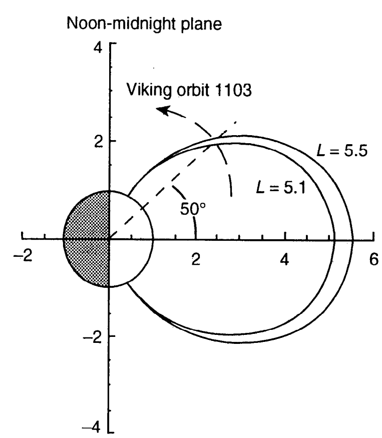

Figure 2. Location of the Viking satellite during orbit 1103 (September 10, 1986) projected onto the noon-midnight plane. The magnetic field lines at $L = 5.1$ and 5.5 represent the L-value extent of the Pc 1 wave activity.

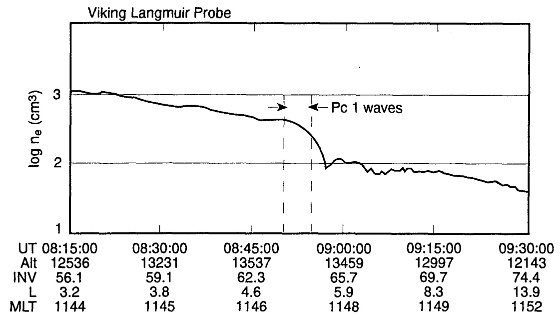

Figure 3. Electron density recorded by the Viking Langmuir probe instrument [*Erlandson et al.*, 1990, Figure 2]. An assumed electron temperature of 1 eV was used to calculate the electron density.

ROV and IVA occur at nearly the same time. These Pc 1 bursts are coincident with weak Pc 1 bursts at KIL, for example, near 0846 and 0851 UT from 0.8 to 1.1 Hz (Plate 1). However, the waves at ROV and IVA are not coincident with the strongest Pc 1 bursts at KIL. This will be shown in more detail below. The wave frequency of the ROV and IVA bursts increase with time at 0851 UT, for example, indicating the Pc 1 waves are dispersive. The ROV and IVA frequency dispersion at 0851 UT is 0.020 ± 0.005 Hz/s, which is comparable to previous ground [*Gendrin et al.*, 1971] and Freja satellite [*Mursula et al.*, 1994] observations. The weak bursts at KIL (0846 and 0851 UT) show a similar frequency dispersion. However, there was no observable dispersion associated with the strongest bursts at KIL.

At least two Pc 1 bursts were observed in the Viking satellite magnetic field data (Plate 1). The bursts at Viking occur at nearly the same time as the bursts at IVA and ROV; this detailed timing will be discussed below. In addition, the Viking Pc 1 bursts appear to be dispersive. The dispersion associated with the first burst is 0.025 ± 0.005 Hz/s. This observation combined with the ground-based observation implies that the source of the wave dispersion is formed on magnetic field lines equatorward of Viking, consistent with known dispersive propagation properties of Pc 1 waves [*Gendrin et al.*, 1971] and

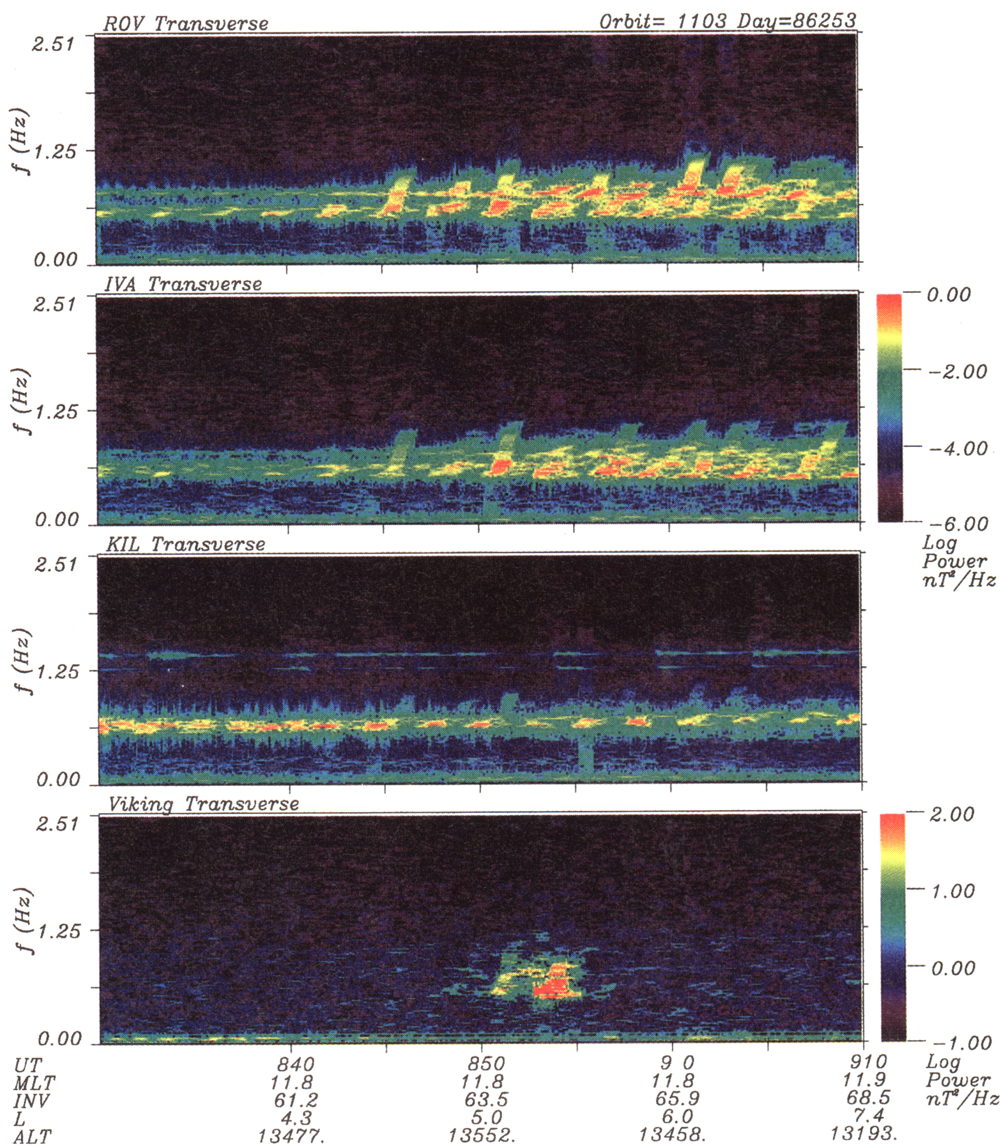

Plate 1. Frequency-time spectrogram of the transverse magnetic field at Rovaniemi (ROV), Ivalo (IVA), Kilpisjarvi (KIL), and Viking on September 10, 1986 (orbit 1103).

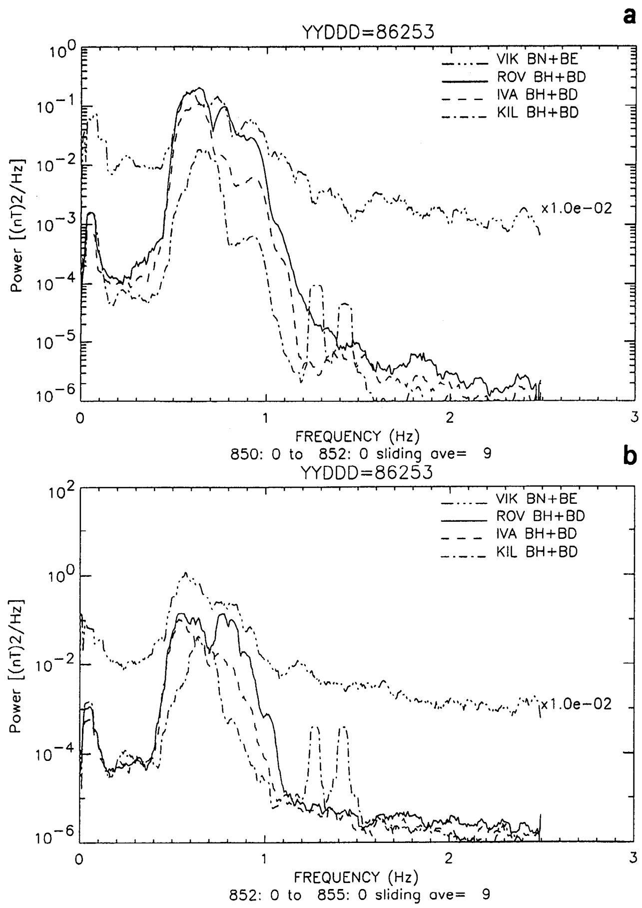

Figure 4. Frequency spectra of Pc 1 waves recorded on the ground and at Viking from (a) 0850 to 0852 UT and (b) 0852 to 0855 UT during orbit 1103 (September 10, 1986). Viking spectral density has been divided by 100.

with recent Freja observations of dispersive Pc 1 waves [*Mursula et al.*, 1994].

The frequency spectra of Pc 1 waves recorded on the ground and at Viking are shown in Figure 4. This figure contains spectra during two intervals corresponding to the Viking Pc 1 bursts, one from 0850 to 0852 UT (Figure 4a) and another from 0852 to 0855 UT (Figure 4b). The two narrow spectral peaks in the KIL spectra at 1.25 and 1.40 Hz are due to instrumental interference. The Viking spectral density has been divided by 100 to aid in the comparison with the ground-based spectra. The Pc 1 spectra in Figure 4 contain a superposition of individual Pc 1 bursts (see Plate 1). For example, three peaks were observed at 0.6, 0.75, and 0.9 Hz during the first interval (Figure 4a) and two peaks were observed at 0.55 and 0.8 Hz during the second interval (Figure 4b) at ROV, IVA, and Viking. Changes in the spectral structure from one burst to the next are evident in the wave spectrogram (Plate 1), indicating the dynamic nature of the wave spectral structure. At KIL, the wave spectral structure is less dynamic (Plate 1). A peak at 0.65 Hz was observed during both intervals, although a higher-frequency peak at 0.9 Hz was observed during the first interval but not the second (Figure 4a and 4b). Comparing these spectra, it is found that the low-frequency peak (0.65 Hz) does not match the wave frequencies at the other stations and do not occur at the same time as the bursts at the other stations, as will be shown below. Finally, although the frequencies of the spectral peaks at ROV, IVA, and Viking are similar, the relative power between these peaks differ from one location to the next. Differences between the Viking ground observations can be understood by recalling that Viking obtains a single point measurement, while ground-based sensors measure waves from both local and distant sources.

The similarity and differences in the Pc 1 waves recorded at the different observing sites are further illustrated by showing the band-pass power (0.6 to 0.7 Hz) calculated using a 256-point fast Fourier transform and a 28-point (5.6 s) sliding window (Figure 5). The modulation in the band-pass power is due to the repetitive occurrence of Pc 1 bursts observed at the various observing sites. The peak band-pass power at Viking is observed over a very short time interval, consistent with a spatially limited source region (as discussed above). The Pc 1 bursts occur at nearly the same time at ROV, IVA, and Viking (in phase). However, the Pc 1 bursts at KIL do not occur at the same time as the bursts recorded at the other stations or Viking. It is concluded that the dominant waves at KIL are not the same as those recorded at ROV, IVA, and Viking. The wave spectra observed at KIL are also slightly different from the spectra at the other sites (Figure 4), which supports this conclusion. This fact raises the question concerning the source

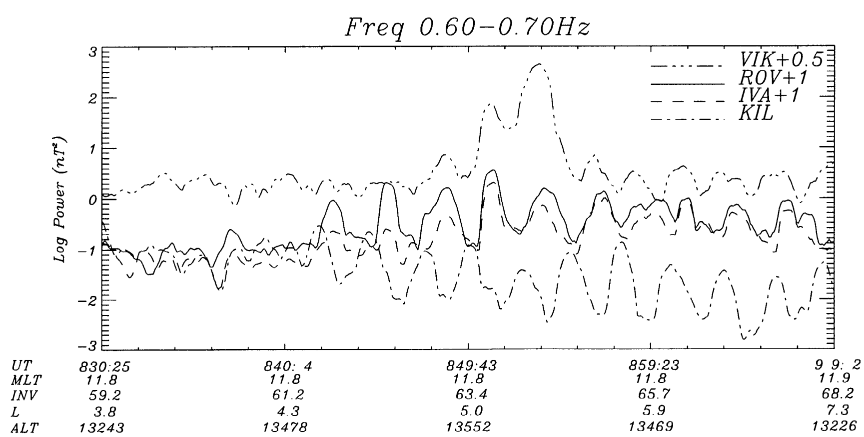

Figure 5. Band-pass power from 0.6 to 0.7 Hz of the transverse component of Pc 1 waves recorded at ROV, IVA, KIL, and Viking on September 10, 1986. The log power has been offset by the values indicated in the key.

of waves at KIL, as Viking did not observe waves near the KIL field line ($L = 6$). This question will be addressed below.

A significant difference was observed in the wave power at Viking and on the ground. The power at Viking was a factor of 100 and 1000 times greater than observed on the ground during the first and second intervals, respectively (Figure 4a and 4b). In terms of amplitude, the waves at Viking were a factor of 10 and 30 times greater than observed on the ground. The larger ratio during the second interval was due to a larger wave amplitude at Viking, as the satellite crossed the wave source field line at this time (Figure 5). *Iyemori and Hayashi* [1989] observed that the Pc 1 amplitude was more than 2 orders of magnitude greater at ionospheric altitudes than on the ground, although the stations were located 1000 to 2000 km from the Magsat orbit, resulting in significant attenuation of the waves in the ionosphere. In this study, the ground stations are located much closer to Viking, and thus the Viking-to-ground amplitude ratio is much smaller.

Discussion

Latitude Width of Source

The combined ground-satellite observations were used to remove the ambiguity between the latitudinal and temporal interpretation in the satellite observations. The latitudinal extent of the Pc 1 source field lines at Viking's altitude is from 63.7° to 64.7° INV ($L = 5.1$ to 5.5). At ionospheric altitudes, the latitudinal width of this source region is ≈120 km. *Iyemori and Hayashi* [1989] noted that the short-duration (5 to 10 s) Pc 1 waves recorded at ionospheric altitudes suggest a latitudinally narrow source < 100 km. *Mursula et al.* [1994], using data acquired by the Freja satellite during very quiet geomagnetic conditions at 600 km altitude, found a spatial extent of ≈ 0.5° in magnetic latitude (≈ 60 km). Recently, a median duration in the noon sector of 10 s was found in a statistical study of 390 Pc 1 waves recorded using DE 2 electric field data at ionospheric altitudes [*Erlandson and Anderson*, 1996], which corresponds to 80 km if interpreted as a spatial structure. The spread of Pc 1 wave duration found in the DE 2 statistical study is sufficient to account for the slightly larger spatial size found for the Viking orbit 1103 event.

Connection to Plasmapause

The locations of the Pc 1 source field lines are just inside the plasmapause (Figure 3). This finding is consistent with previous satellite Pc 1 and electron density observations [*Erlandson et al.*, 1992], ground Pc 1 and satellite electron density observations [*Fraser et al.*, 1989], and ground-based Pc 1 observations [*Roth and Orr*, 1975; *Lewis et al.*, 1977; *Webster and Fraser*, 1985]. There are at least two ways the electron density gradient can affect the location and spatial extent of the Pc 1 source region. First, the ion cyclotron wave growth rate could maximize for plasma densities associated with the plasmapause, which is related to the idea of a critical density associated with ion cyclotron wave growth [*Gendrin*, 1971]. Second, electron density gradients at the plasmapause allow the wave propagation vector to remain field aligned and thus experience larger wave growth [*Mazur and Potapov*, 1983; *Thorne and Horne*; 1992]. Unstructured Pc 1 waves are commonly observed in the plasma trough and in the outer magnetosphere, but we are unaware of any direct observations of structured Pc 1 waves that were not associated with the plasmapause density gradient.

Pc 1 Wave Transit Time

The simultaneous observations of structured Pc 1 pulsations were used to measure the Pc 1 repetition period. The repetition period, or time between consecutive Pc 1 wave bursts, is interpreted as the time it takes Pc 1 waves to travel to the conjugate hemisphere and back. The Pc 1 repetition period at ROV, IVA, KIL, and Viking were determined by calculating the autocorrelation coefficient of the 0.6 to 0.7 Hz band-pass power shown earlier in Figure 5. The Viking band-pass power was detrended before performing the autocorrelation. The average repetition period from 0847 to 0857 UT was 152 ± 4 s, 158 ± 4 s, 156 ± 4 s, and 154 ± 4 s at Viking, ROV, IVA, and KIL, respectively (Figure 6).

The Pc 1 transit time between Viking and the ground may be estimated from cross-correlation analysis of the band-pass power. The time delay between Viking-ROV and Viking-IVA is 12 ± 2 s, where Viking leads the ground stations (Figure 7). This time delay is consistent with downward propagating Pc 1 between Viking at 13,500 km altitude and the ground. There was no appreciable time delay between IVA and ROV. This outcome was expected, as the distance between these stations and the Pc 1 source field line are similar, and the propagation velocity of Pc 1 waves in the ionosphere is large. The negative time delay between Viking and KIL is due to the fact that KIL is out of phase with Viking and the other ground stations.

The Pc 1 wave repetition period and transit time may be determined theoretically using the ion cyclotron wave group velocity from the linearized dispersion relation [see *Gomberoff and Neira*, 1983]. Unfortunately, the group velocity and transit time depend on a number of unknown quantities such as the plasma density profile and He^+ concentration along the magnetic field line. Nonetheless, we calculated the repetition period using a diffusive equilibrium model for the plasma density such that the electron density matched the measured electron density

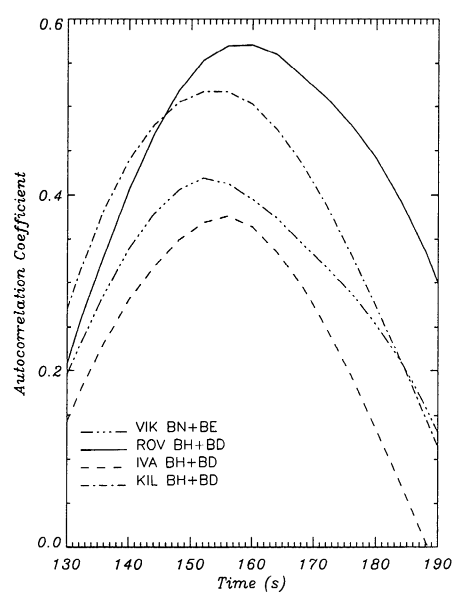

Figure 6. The autocorrelation coefficient of the 0.6 to 0.7 Hz band-pass power at ROV, IVA, KIL, and Viking from 0847 to 0857 UT on September 10, 1986.

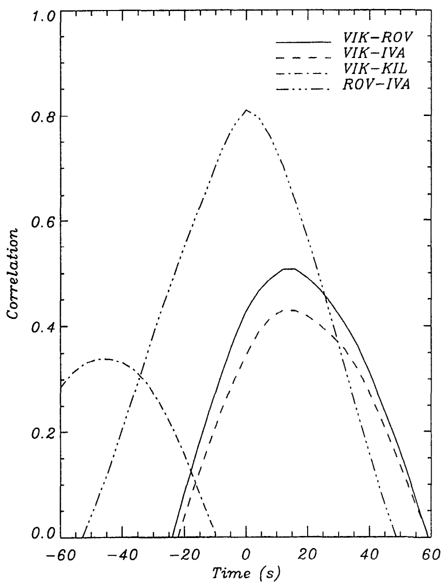

Figure 7. The cross correlation of the 0.6 to 0.7 Hz band-pass power from 0845 to 0900 UT between Viking and ROV, Viking and IVA, ROV and IVA, and VIK and KIL.

at Viking: a dipole magnetic field model, a wave frequency of 0.6 Hz, a He^+ concentration of 5% limited to within $\pm 5°$ of the equator, and an energetic ion density of 1 cm^{-3}. The calculated repetition period and transit time at $L = 5.3$ were 164 and 12 s, respectively. However, slight variations in the He+ concentration and plasma density profile resulted in changes of more than a factor of 2 in the repetition period. The transit time is dependent mainly on the electron density profile between Viking and the ionosphere.

The observed repetition period is similar to previous observations of structured Pc 1 waves. For example, *Fraser et al.* [1989] observed repetition periods between 135 and 160 s for a 0.57 to 0.69 Hz structured Pc 1 wave with a source region near $L = 4.7$. The most significant aspect, however, of the observed Viking-ground transit time is that Viking leads the ground station. This fact confirms the net downward propagation of Pc 1 waves determined from the earlier Poynting flux calculation of *Erlandson et al.* [1990].

Comparison of Waves on the Ground

There were both similarities and differences between the Pc 1 waves on the ground at ROV, IVA, and KIL. The similarities are particularly evident at frequencies above the frequency of peak power (0.5 to 0.8 Hz). This is illustrated in Figure 8, which contains the band-pass power at the three ground stations between 0.8 to 0.9 Hz. The band-pass power is correlated at all three stations, indicating that waves in this frequency range originate from the same source. The 0.8 to 0.9 Hz wave power was strongest at ROV, weaker at IVA, and weakest at KIL, suggesting that the wave source is closer to ROV than IVA. The wave power on the ground is expected to decrease as a function of distance from the source field line due to ionospheric attenuation. A study is in progress to quantitatively address ionospheric attenuation using a number of Viking ground-satellite Pc 1 events.

There were a number of differences in the properties of the strongest Pc 1 waves recorded at KIL and the other ground sites. For example, the strongest waves at ROV and IVA were observed at the same time and frequency, whereas the strongest waves at KIL did not occur at the same time as the waves recorded at ROV and IVA (see Figures 2 and 5). In addition, as discussed above, the spectral characteristics of the waves at KIL differed from those observed at ROV and IVA (see Figure 4). It is concluded that the most intense waves at KIL did not originate from the same source as the strongest waves observed at ROV and IVA (and Viking). There are at least two possible explanations. First, the source of waves recorded at KIL may not have extended to the later local times of the ROV and IVA stations. This hypothesis, however, is not consistent with the long duration of the Pc 1 wave event recorded on the ground from 0730 to 1045 UT (0900 to 1315 MLT). A second possibility is that the latitudinal width of the Pc 1 source at $L = 6$ was narrow, and the phase of the repetitive Pc 1 burst was such that Viking did not observe it. As an example, the waves at KIL had a repetition period of about 160 s and a duration of 80 s. If the source region width is less than 240 km at Viking's altitude (< 40 km at ionospheric altitudes), then the wave could be missed by Viking if the satellite crosses the source at the wrong time. A narrow latitudinal width is consistent with the DE 2 Pc 1 wave statistical study, which indicates that in the noon sector the distribution of events peak at a du-

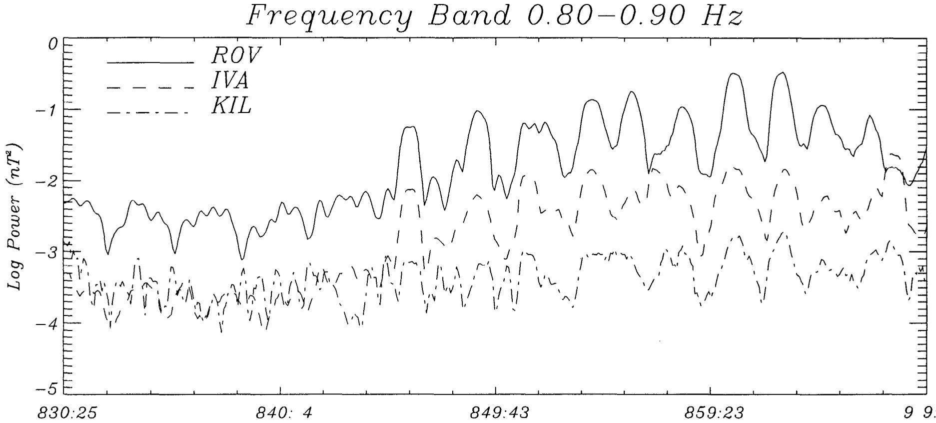

Figure 8. Band-pass power from 0.8 to 0.9 Hz of the transverse components at ROV, IVA, and KIL on September 10, 1986.

ration of 5 s (≈ 40 km) [*Erlandson and Anderson*, 1996, Figure 5]. Periodic variations were observed in the Viking band-pass power from 0855 to 0910 UT ($L \approx 6$); however, these waves were weak and probably would not be observed on the ground (Figure 5). In summary, the most probable explanation of the source at KIL is that the source region was narrow and Viking crossed the source region at a time that was out of phase with the repetitive Pc 1 burst.

Conclusions

Structured Pc 1 waves were recorded simultaneously at three sites on the ground and at the Viking satellite. The source field line of Pc 1 waves recorded at Viking maps to within 30 min MLT and at magnetic latitudes between ROV and IVA. The source of the structured Pc 1 pulsations was identified just inside the plasmapause based on simultaneous Langmuir probe observations. This finding supports previous theoretical calculations that suggest that density gradients allow the wave propagation vector to remain field aligned, which results in a higher amplification of ion cyclotron waves responsible for the Pc 1 pulsations [*Mazur and Potapov*, 1983; *Thorne and Horne*, 1992].

The transit time of Pc 1 waves propagating from Viking at 13,500 km to the ground was also estimated. Both the Viking-ROV and Viking-IVA transit times were 12 ± 2 s, where waves at Viking lead the waves on the ground. This observation implies downward propagation of these waves and is consistent with the previous observation of a downward directed Poynting flux [*Erlandson et al.*, 1990].

The Pc 1 wave fine structure of the strongest Pc 1 waves at KIL was out of phase with the waves at Viking and the other ground sites. It is concluded that the waves recorded at IVA and ROV were from a source region extending from $L = 5.1$ to 5.5, based on Viking observations. The waves recorded at KIL appeared to be from a local source near $L = 6.0$, although at Viking the wave power was very low. It is possible that the most intense waves observed at KIL were from a latitudinally narrow source region (< 40 km at ionospheric altitudes) which Viking crossed at a time that was out of phase with the repetitive Pc 1 wave.

Acknowledgments. This work was supported by the National Science Foundation Office of Polar Programs OPP-9224511. We wish to thank B. Anderson (JHU/APL) for his valuable comments regarding the interpretation of these data. We also thank Doug Holland (JHU/APL) for the Viking data processing, and R. Kuula (University of Oulu) for the ground-based station data processing. We also thank G. Holmgren (Swedish Institute of Space Physics, Uppsala Division) for providing Viking Langmuir probe data.

The Editor thanks J. LaBelle and J. L. Rauch for their assistance in evaluating this paper.

References

Anderson, B. J., R. E. Erlandson, and L. J. Zanetti, A statistical study of Pc 1-2 magnetic pulsations in the equatorial magnetosphere, 1, Equatorial occurrence distributions, *J. Geophys. Res., 97*, 3075, 1992a.

Anderson, B. J., R. E. Erlandson, and L. J. Zanetti, A statistical study of Pc 1-2 magnetic pulsations in the equatorial magnetosphere, 2, Wave properties, *J. Geophys. Res., 97*, 3089, 1992b.

Bossen, M., R. L. McPherron, and C. T. Russell, A statistical study of Pc 1 magnetic pulsations at synchronous orbit, *J. Geophys. Res., 81*, 6083, 1976.

Erlandson, R. E., and B. J. Anderson, Pc 1 waves in the ionosphere: A statistical study, *J. Geophys. Res., 101*, 7843, 1996.

Erlandson, R. E., L. J. Zanetti, T. A. Potemra, L. P. Block, and G. Holmgren, Viking magnetic and electric field observations of Pc 1 waves at high latitudes, *J. Geophys. Res., 95*, 5941, 1990.

Erlandson, R. E., B. J. Anderson, and L. J. Zanetti, Viking magnetic and electric field observations of periodic Pc 1 waves: Pearl pulsations, *J. Geophys. Res., 97*, 14,823, 1992.

Fraser, B. J., and R. L. McPherron, Pc 1-2 magnetic pulsation spectra and heavy ion effects at synchronous orbit: ATS-6 results, *J. Geophys. Res., 87*, 4560, 1982.

Fraser, B. J., W. J. Kemp, and D. J. Webster, Ground-satellite study of a Pc 1 ion cyclotron wave event, *J. Geophys Res., 94*, 11,855, 1989.

Fraser, B. J., H. J. Singer, W. J. Hughes, J. R. Wygant, R. R. Anderson, and Y. D. Hu, CRRES Poynting-vector observations of electromagnetic ion cyclotron waves near the plasmapause, *J. Geophys. Res., 101*, 15,331, 1996.

Fukunishi, H., T. Toya, K. Koike, M. Kuwashima, and M. Kawamura, Classification of hydromagnetic emissions based on frequency-time spectra, *J. Geophys. Res., 86*, 9029, 1981.

Gendrin, R., S. Lacourly, A. Roux, J. Solomon, F. Z. Feigin, M. V. Gokhberg, V. A. Troitskaya, and V. L. Yakimenko, Wave packet propagation in an amplifying medium and its application to the dispersion characteristics and to the generation mechanism of Pc 1 events, *Planet. Space Sci., 19*, 165, 1971.

Gendrin, R., S. Perraut, H. Fargetton, F. Glangeaud, and J. Lacoume, ULF waves: Conjugated ground-satellite relationships, *Space Sci. Rev., 22*, 433, 1978.

Gomberoff, L., and R. Neira, Convective growth rate of ion cyclotron waves in a H+ - He+ and H+ -He+ -O+ plasma, *J. Geophys Res., 88*, 2170, 1983.

Harang, L., Oscillations and vibrations in magnetic records at high-latitude stations, *J. Geophys. Res., 41*, 329, 1936.

Holmgren, G., and P. M. Kintner, Experimental evidence of widespread regions of small-scale irregularities in the magnetosphere, *J. Geophys. Res., 95*, 6015, 1990.

Hultqvist, B., The Viking project, *Geophys. Res. Lett., 14*, 379, 1987.

Iyemori, T., and K. Hayashi, Pc 1 micropulsations observed by MAGSAT in the ionospheric F region, *J. Geophys. Res., 94*, 93, 1989.

Jacobs, J. A., and T. Watanabe, Micropulsation whistlers, *J. Atmos. Terr. Phys., 26*, 825, 1964.

LaBelle, J., and R. A. Treumann, Poynting vector measurements of electromagnetic ion cyclotron waves in the plasmasphere, *J. Geophys. Res., 97*, 13,789, 1992.

Lewis, P. B., Jr., R. L. Arnoldy, and L. J. Cahill Jr., The relation of Pc 1 micropulsations measured at Siple, Antarctica to the plasmapause, *J. Geophys. Res., 82*, 3261, 1977.

Mauk, B. H., and R. L. McPherron, An experimental test of the electromagnetic ion cyclotron instability within the Earth's magnetosphere, *Phys. Fluids, 23*, 2111, 1980.

Mazur, V. A., and A. S. Potapov, The evolution of pearls in the Earth's magnetosphere, *Planet. Space Sci., 31*, 859, 1983.

Mursula, K, L. G. Blomberg, P. A. Lindqvist, G. T. Marklund, T. Braysy, R. Rasinkangas, and P. Tanskanen, Dispersive Pc 1 bursts observed by Freja, *Geophys. Res. Lett., 21*, 1851, 1994.

Obayashi, T., Hydromagnetic whistlers, *J. Geophys. Res., 70*, 1069, 1965.

Perraut, S., Wave-particle interactions in the ULF range: GEOS-1 and -2 results, *Planet. Space Sci., 30*, 1219, 1982.

Potemra, T. A., L. J. Zanetti, R. E. Erlandson, P. F. Bythrow, G. Gustafsson, M. H. Acuna, and R. Lundin, Observations of large-scale Birkeland currents and Viking, *Geophys. Res. Lett, 14*, 419, 1987.

Roth, B., and D. Orr, Locating the Pc 1 generation region by a statistical analysis of ground-based observations, *Planet. Space Sci., 23*, 993, 1975.

Roux, A., S. Perraut, J. L. Rauch, C. de Villedary, G. Kremser, A. Korth, and D. T. Young, Wave-particle interactions near Ω_{He+} observed on board GEOS 1 and 2, 2, Generation of ion cyclotron waves and heating of He^+ ions, *J. Geophys. Res., 87,* 8174, 1982.

Saito, T., Geomagnetic pulsations, *Space Sci. Rev., 10*, 319, 1969.

Sucksdorff, E., Occurrence of rapid micropulsations at Sodankyla during 1932 to 1935, *J. Geophys. Res., 41*, 337, 1936.

Thorne, R. M., and R. B. Horne, The contribution of ion-cyclotron waves to electron heating and SAR-arc excitation near the storm-time plasmapause, *Geophys. Res. Lett., 19*, 417, 1992.

Troitskaya, V. A., Pulsations of the Earth's electromagnetic field and their connection with phenomena in the high atmosphere, *J. Geophys. Res., 66*, 5, 1961.

Webster, D. J., and B. J. Fraser, Source regions of low-latitude Pc 1 pulsations and their relationship to the plasmapause, *Planet. Space Sci., 33*, 777, 1985.

Young, D. T., S. Perraut, A. Roux, C. de Villedary, R. Gendrin, A. Korth, G. Kremser, and D. Jones, Wave-particle interactions near Ω_{He+} observed on GEOS 1 and 2, 1. Propagation of ion cyclotron waves in He^+ - rich plasma, *J. Geophys. Res., 86*, 6755, 1981.

T. Bösinger and K. Mursula, Department of Physical Sciences, University of Oulu, Oulu, Finland 90571.

R. E. Erlandson, Applied Physics Laboratory, Johns Hopkins University, Johns Hopkins Road, Laurel, MD 20723-6099. (e-mail: erlandson@jhuapl.edu)

(Received May 13, 1996; revised August 29, 1996; accepted August 29, 1996.)