Transequatorial propagation of the Pc1 emission on 23 October 1997

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[1] A Pc1 emission event with uncommon propagation characteristics was revealed in the study of the search-coil magnetometer data from two Russian midlatitude observatories separated by 4000 km. Dynamic spectra of the emission showed pronounced structure with a repetition period of about 130 s. By comparing the wave form plots for the two locations we found an unusually large phase difference as much as nearly 180 between the plotted envelopes. We discuss a most probable model assuming that the signal received at one of the two observatories must propagate from the source region in the opposite hemisphere. *INDEX TERMS:* 2487 Ionosphere: Wave propagation (6934); 2772 Magnetospheric Physics: Plasma waves and instabilities; 2439 Ionosphere: Ionospheric irregularities; *KEYWORDS:* ionosphere, waveguide, Pc1 emissions, total electron content

1. Introduction

[2] Electromagnetic Pc1 emissions in the frequency range from 0.2 to 5 Hz are probably one of the most interesting wave phenomena in the Earth's magnetosphere [*Guglielmi and Pokhotelov*, 1996]. Their specific appearance with a chain of pearl-type envelopes in wave form plots was interpreted as a sequence of packets of ion cyclotron waves generated near the equatorial plane in the magnetosphere on the magnetic shells with $L = 3-8$, where L is the MacIlwain parameter [*Gendrin and Troitskaya*, 1965; *Obayashi*, 1965]. Clear evidence that Pc1 emissions originate in the magnetosphere was provided by a conjugate experiment on simultaneous observation of Pc1 waves carried out at the Sogra and Kergelen observatories, each in the opposite hemisphere [*Gendrin and Troitskaya*, 1965]. The wave packets came to these sites alternately, which was assumed to be connected with their propagation along a magnetic field line with amplification in the vicinity of the equatorial plane [*Tepley*, 1964]. It is believed that the Pc1 signal from the magnetosphere is coupled with the magnetosonic mode in the ionosphere and propagates horizontally along the ionospheric waveguide. The theory of ionospheric waveguide was developed [*Tepley and Lanshoff*, 1966; *Manchester*, 1968; *Fujita*, 1988; *Fujita and Tamao*, 1988], and a number of campaigns for synchronous observations of Pc1 in large areas were undertaken to test theoretical models. The horizontal propagation velocity of Pc1 was shown to be equal to the Alfvén velocity lying in the range of several hundred kilometers per second [see, e.g., *Manchester*, 1968, 1970]. Pc1 wave packets decay as they propagate along the waveguide. The apparent attenuation was measured and was shown to fall in the wide range between 0 and 13 dB/1000 km [*Althouse and Davis*, 1978]. In this paper we present a case study of the Pc1 event with an extremely low apparent propagation velocity. The observations were made at two midlatitude observatories separated by four thousand kilometers. The repetition period of structure patterns at both stations was about 130 s, which represents the time of double propagation along a magnetic field line between two reflection points in the ionosphere. The cross correlation of the signal envelopes at the two observatories showed an about 180 phase shift which is an unusually large value compared to ordinary Pc1 events observed simultaneously at both locations. In the next sections we will try to understand the nature of the peculiarities of the Pc1 event and suggest a situation modeling the observed results.

2. Instrumentation and Data Sampling

[3] We use the data acquired by three-component digital search-coil magnetometers at two midlatitude observatories: Borok (58.0°N, 38.3°E, L = 2.9), and Mondy (51.6°N, 100.8°E, L = 2.1). Local time is LT = UT + 2.6 for Borok and LT = UT + 6.7 for Mondy. The distance between these sites is 3913 km. The amplitude versus frequency response of the magnetometers has a slope of 6 dB per octave in the frequency range of 0 to 2.5 Hz with a sensitivity of about 5 pT at 1 Hz. The output analog signal is sampled at a rate of 10 vectors/s by the 12-bit analog-to-digital converter. The time base of the sampling is managed accurate to 20 ms by inferring the data from the GPS system.

[4] All recorded data were subjected to a special processing on a regular basis which includes selecting intervals of simultaneous Pc1 observation at both observatories, calculating FFT spectra for the selected intervals, and applying an

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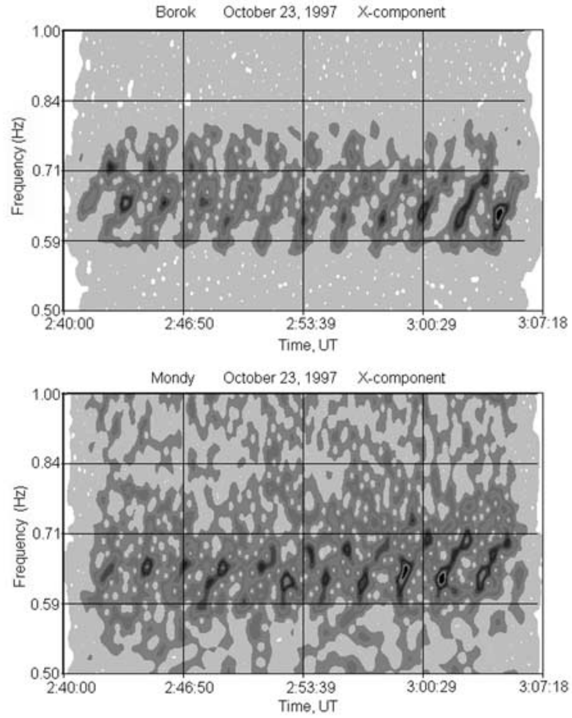

Figure 1. Dynamic spectra of the oscillations at the two observatories.

inverse FFT transform upon multiplying the original spectra by the exponential core. This procedure provided three filtered samplings of three field components for each event from both stations. Details of the processing can be found in [*Potapov et al.*, 2000; *Potapov et al.*, 2001].

3. Results

[5] The event under consideration was observed on 23 October 1997 at 0220–0316 UT. It was a magnetically very quiet period, $Kp = 0_0$. Moreover, the previous magnetic storm with $Dst = -130$ occurred on 10–11 October 1997, almost two weeks before the case we are studying here. It may be interesting to note that five hours after Pc1 event, at 0804 UT, a weak storm began ($Dst = -60$). Figure 1 shows the dynamic spectra of the oscillations produced from the *H*-component data recorded at Borok and Mondy for the above interval. One can see here a typical series of structured Pc1 with slanted patterns within the frequency band between 0.6 and 0.8 Hz. The main spectral peak of emission derived by the FFT method corresponds to the frequency of 0.63 Hz at both locations. The oscillation amplitude at Borok is about four times that at Mondy, which corresponds to a 12 dB decay along the great circle propagation path. These characteristics are all quite usual for Pc1 observed at midlatitudes. In order to measure the repetition period τ of structure patterns we calculated the autocorrelation function of the envelopes of the signal horizontal component. It was found that $\tau = 133$ s both at Mondy and at Borok.

[6] The peculiar properties of the event become evident if we compare the signal arrival times at the two stations. A common way to find the time lag between two oscillation processes is to calculate the cross-correlation function of the oscillation envelopes. Figure 2 plots the cross-correlation

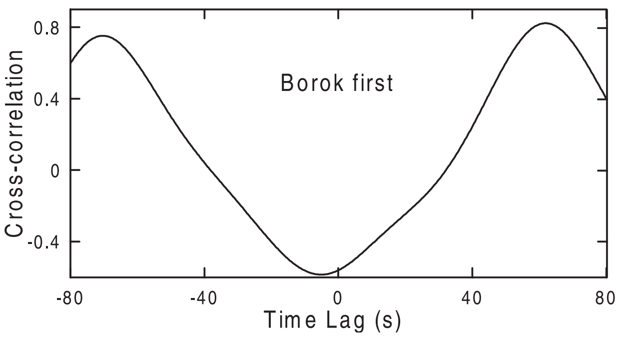

Figure 2. Cross-correlation function of the horizontal component envelopes at the two stations.

function of the horizontal component envelopes at the two stations. One can see here two peaks of a nearly equal height. The left peak corresponds to the case where the signal first arrives at Borok and then at Mondy with a delay of $\Delta t_1 = 70.4$ s, and the right peak corresponds to the opposite case when the signal first comes to Mondy and then to Borok with a delay of $\Delta t_2 = 61.4$ s. In the first case the apparent velocity of signal propagation is $V_1 = 55.6$ km/s, and in the second case we have $V_2 = 63.7$ km/s. Both values are too small. The smallest value of the propagation velocity reported in the literature is 320 km/s [*Duong and Fraser*, 1977]. A minimum velocity found earlier for the Borok-Mondy pair of stations is 421 km/s [*Potapov et al.*, 2001]. Such small velocities, 55.6 or 63.7 km/s, as obtained for this Pc1 event cannot be expected within the framework of ordinary conditions of the Earth's ionosphere. Thus we are forced to pursue other plausible ways to understand the unusual Pc1 event.

[7] Figure 3 shows the hodograms produced from the filtered signal of the horizontal components during two

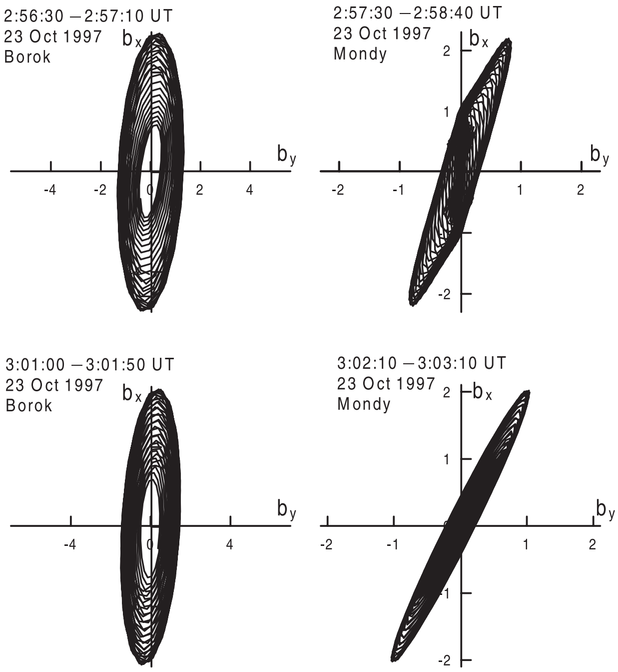

Figure 3. Hodograms of the filtered signal horizontal components.

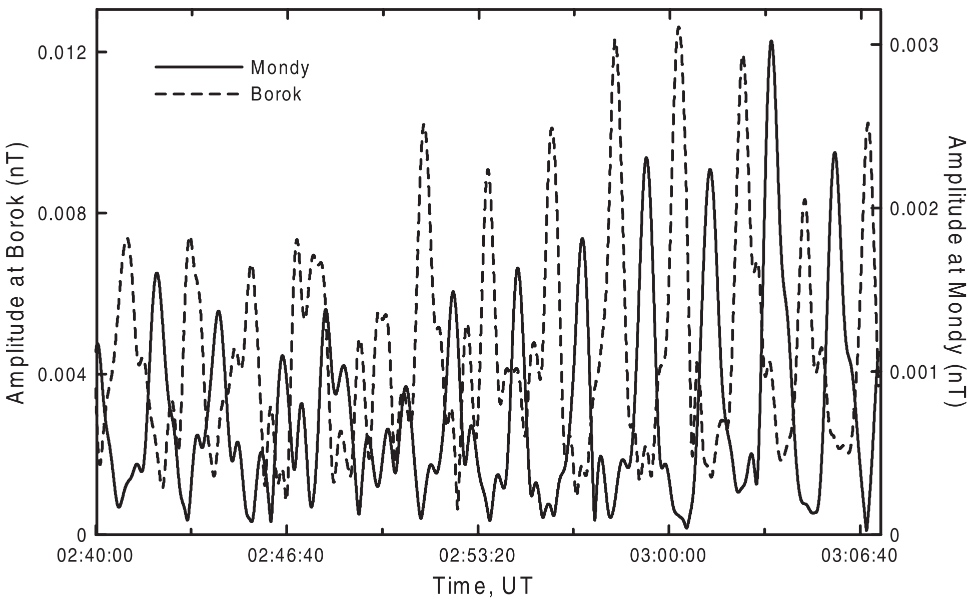

Figure 4. Horizontal component envelopes for the two observatories.

periods of time, each of which includes one packet of oscillations at each station. Timing of packets does not coincide between the two locations due to a large lag time. One can see that the major axis of the polarization ellipse at Borok is aligned virtually along the north-south direction. Examination of polarization for all packets in the Pc1 event shows that the orientation of the major axis of each polarization ellipse at Borok does not deviate very much from the magnetic meridian, 4 deg on average, scattering within a range of −1 and +8 deg. Here the deviation angle between the meridian and the major axis of the polarization ellipse is taken to be positive if the axis is directed from the southwest to northeast direction. At Mondy this deviation lies in the range of +14 – +26 deg, the mean value being 20 deg.

4. Possible Interpretation

[8] Let us take a look at Figure 4. It plots the envelopes of the horizontal components observed at Borok and Mondy. The behavior of the curves is reminiscent of that of the Pc1 envelopes recorded at Sogra and Kergelen [*Gendrin and Troitskaya*, 1965], when the structure patterns of Pc1 ("pearls") were shown to appear alternately at magnetically conjugate points. (The first single observation of this kind was reported by [*Lokken et al.*, 1963; *Yanagihara*, 1963].) This fact gave impetus to the development of the theory of Pc1 generation by the ion cyclotron instability of wave packets oscillating between the conjugate ionospheres and being amplified in the near-equatorial region [*Jacobs and Watanabe*, 1964; *Cornwall*, 1965; *Tverskoy*, 1967]. The alternating appearance of wave packets at Borok and Mondy suggests that the signal comes to these observatories from different hemispheres. Figure 5 shows a sketch of the possible relative location of the ionospheric Pc1 source and our observatories. An amplitude comparison and polarization analysis reveals that the magnetospheric source is located near the Borok meridian. Bouncing along a field line, the wave packet is reflected from both ionospheric altitudes, one to the north of Borok in the Northern Hemisphere, and the other in the Southern Hemisphere at the magnetically conjugate point. The signal coming from the northern ionospheric source is received with a small delay at Borok. But this signal is not detected at Mondy due to some reasons to be discussed later; instead, the signal coming from the other source in the Southern Hemisphere is received at Mondy with a larger delay time. It should be noted that the sketch given in Figure 5 is true only for a horizontally uniform and isotropic ionosphere which is usually not the case even for magnetically quiet conditions

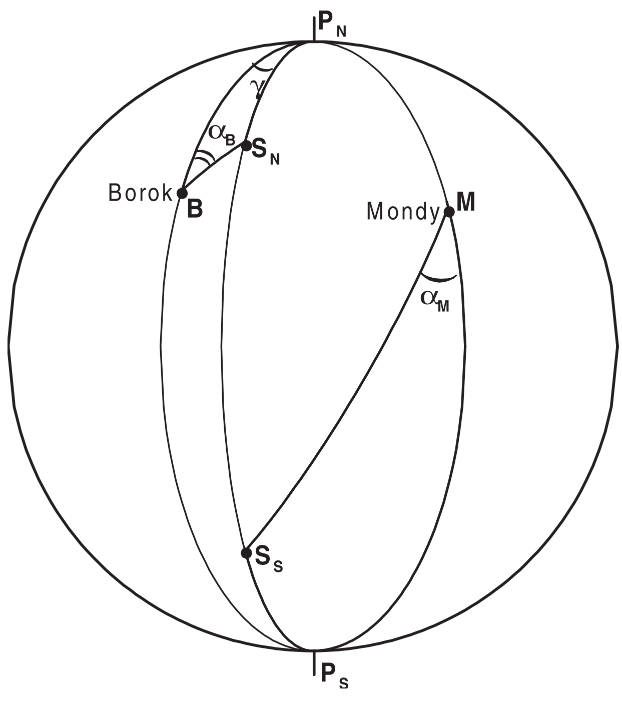

Figure 5. Diagram of the possible relative location of the ionospheric Pc1 sources.

with $Kp = 0_0$ [*Summers and Fraser*, 1972; *Althouse and Davis*, 1978]. Nevertheless, we believe that such a simplification would help us to understand the mechanism of wave propagation for this unusual Pc1 event.

[9] Let the initial point in time be the time when the wave packet is reflected from the northern ionosphere once it arrives from the magnetosphere. Then the signal comes to Borok at the time t_B which is the time of propagation in the ionospheric waveguide. On the other hand, the packet of ion cyclotron waves reflected from the northern ionosphere arrives at the southern ionosphere at (the time) $\tau/2$, where τ is the repetition period of structure patterns, i.e., the time taken by the wave packet to bounce along a field line there and back. The signal reaches Mondy at $\tau/2 + t_M$, where t_M is the time of propagation in the ionospheric waveguide from the source at the southern conjugate point to Mondy. Then the difference $t_M - t_B$ is

$$t_M - t_B = \Delta t_1 - \tau/2 = 3.9 \text{ s.}$$

Let now the initial point in time be the time when the wave packet is reflected from the southern ionosphere. Then the signal arrives at Mondy at t_M, and reaches Borok at $\tau/2 + t_B$. In this case the difference between the times of signal propagation in the ionospheric waveguide to the two stations from the two respective sources is

$$t_B - t_M = \Delta t_2 - \tau/2 = -5.1 \text{ s.}$$

The negative sign shows that in this case also $t_M > t_B$, as we might expect. A minor discrepancy (1.2 s) between the two estimates may be due both to errors in measurements and to the possibility that the packet propagates in the magnetosphere along different paths there and back. (In the latter case the value of $\tau/2$ should be different in the two versions of calculations.)

[10] Hence it becomes clear why the polarization ellipses are aligned in the same manner as described in the previous section. It is widely believed that the polarization ellipse becomes prolate and that its major axis points to the source when the observation site is remote from the ionospheric source [*Baranskiy*, 1970; *Fraser and Summers*, 1972], though some authors accept the just mentioned regularity as a tendency only [*Althouse and Davis*, 1978]. We infer that each major axis of the polarization ellipse observed at Borok and Mondy points to an ionospheric foot print in the northern and southern hemispheres, respectively, at the ends of the magnetospheric bouncing path. We can estimate the locations of the conjugate foot prints using the mean values of the angle, alpha, between the magnetic meridian and the major polarization axis at each observation site. One way to do this is to solve a set of equations describing two spherical triangles $BP_N S_N$ and $MP_S S_S$ in Figure 5

$$\begin{aligned}\sin\gamma \cot\alpha_B &= \sin \breve{BP}_N \cot \breve{P_N S_N} - \cos \breve{BP}_N \cos\alpha_B \sin(\Theta - \gamma) \cdot \cot\alpha_M \\ &= \sin \breve{MP}_S \cot \breve{P_S S_S} - \cos \breve{MP}_S \cos\alpha_M,\end{aligned}$$

where γ is the angle between the Borok meridian and the meridian of the mean location of the source, Θ is the angle between the Borok and Mondy geomagnetic meridians, $\Theta = 59.3°$, $\breve{BP}_N$, $\breve{MP}_S$, and $\breve{P_N S_N} = \breve{P_S S_S}$ are the arcs of the great circle shown in Figure 5. Solving the above set of equations and discarding meaningless solutions, we get $\gamma = 2.3°$, $\breve{P_N S_N} = 23°$, when $\alpha_B = 4°$ and $\alpha_M = 20°$. Thus we show the mean position of the ionospheric projections of the source to have the corrected geomagnetic coordinates $\Phi \approx \pm 67°$ and $\Lambda \approx 117°$. If we take into account the observed scatter of α_B and α_M values (see the previous section) we get some probable location of conjugate regions of the ionospheric sources: $\Phi = \pm(58° - 76°)$ and $\Lambda = 113° - 124°$. The distances between the observatories and the corresponding mean source locations along the Earth's surface are BS_N = 1500 km and MS_S = 13,500 km. The difference of 12,000 km between BS_N and MS_S requires a propagation velocity along the great circle as large as 2400 km/s if we take the above estimated value of $\sim$5 s for $t_M - t_B$. This is a relatively high value for the propagation of the magnetosonic mode in the ionosphere but not very uncommon for the night time during a solar minimum epoch. The attenuation, on the other hand, has a very low value, about 1 dB/1000 km. Possible errors of the estimated velocity and attenuation values can be attributed to the uncertainties in the determination of the polarization azimuth directions and the unreliability of the polarization technique we mentioned above.

5. Discussion

[11] We admit that the above model attempting to explain the unusual Pc1 event must answer several more questions below.

1. Can the propagation velocity be as high as that?
2. Can the attenuation be as low as that?
3. Can there be such a situation where in the Northern Hemisphere we could not see the signal from the northern source, but do see it from the southern one?
4. Can some other examples of the Pc1 transequatorial propagation be found in the literature?

[12] As a matter of fact, each of these questions can be answered in the affirmative if we refer to the previous literature.

1. The velocities of 3050 and 2300 km/s were obtained by *Bomke et al.* [1960] and *Campbell and Thornberry* [1972], respectively. *Bomke et al.* [1960] and *Bostick et al.* [1964] predicted the presence of a second higher-velocity duct above the lower ionospheric duct usually considered. The possibility must not be ruled out that the ionospheric Alfvén resonator [*Demekhov et al.*, 2000] can form an effective channel for Pc1 propagation along the ionosphere.
2. *Manchester* [1970] using the data from two Australian stations, Newcastle and Hobart, observed for some events an attenuation as low as 1.6 and even 1.14 dB/1000 km.
3. *Campbell and Thornberry* [1972], analyzing two Pc1 events observed at four North American stations, found that pulsations were not seen in the daytime hemisphere, i.e. they could not see them at the eastern station, though the source, as they triangulated it, was situated to the east of all stations. On the other hand, *Tepley* [1964] observed the Pc1 signal coming from the Southern Hemisphere at station Palo Alto at 43 deg of the northern geomagnetic latitude, a latitude only by 4 deg less than that of obs. Mondy.
4. *Tepley* [1964, p. 2284] stated: "hm emissions not only can propagate across the equator but can sometimes be

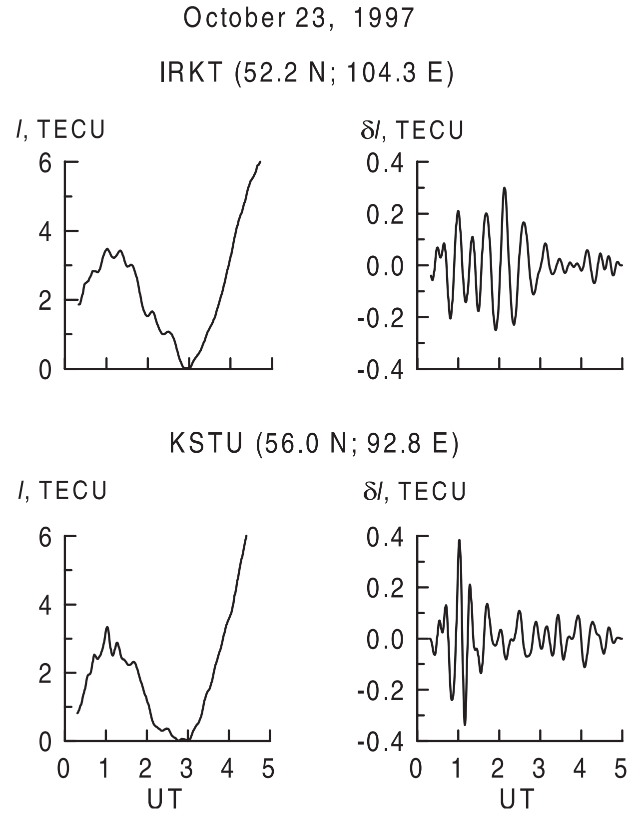

Figure 6. Total electron content $I(t)$ (left) along the ground-satellite (PRN 26) trajectory converted to a vertical column and its variations $\delta I(t)$ (right) obtained by filtering $I(t)$ in the 10–50 min period band at two GPS stations during the first 5 hours of 23 October 1997 (1 TECU = 10^{16} el/m^2).

observed at relatively high latitudes in the hemisphere opposite that in which they are first received."

[13] However, we have one more question, the only one which cannot be answered on the basis of the previous Pc1 studies: Why does the magnetometer at Mondy see the signal coming along the ionospheric waveguide from the opposite Southern Hemisphere but does not see the signal coming from the same Northern Hemisphere? It seems that the attenuation along the path S_NM was at least an order of higher compared to one along the path S_SM. It is enticing to explain this observational fact by conclusions from the theory of Pc1 waveguide propagation [*Galejs*, 1973; *Greifinger and Greifinger*, 1973] which predicts the preference for the meridian propagation in the waveguide. However, the results of our previous work [*Potapov et al.*, 2001] show that Pc1 events are not rare (more than 20 events during 2 years) when Pc1 pulsations of the ordinary type coming from the Northern Hemisphere are clearly observed in comparable amplitudes at both locations. Several possible reasons for the lack of a direct signal at Mondy from the northern ionospheric source can be suggested. It can be a too large attenuation in the illuminated ionosphere for waves propagating in an approximately west-east direction, or it can be a too high wall to penetrate from the ionosphere to the ground, or it can be "horizontal variations in the ionospheric parameters... which may cause sufficient mode conversion and reflection to reduce drastically the amplitude of ducted signal" [*Greifinger and Greifinger*, 1973, p. 4617].

[14] In order to find just a hint to choose which one of the possibilities mentioned above is the reason for absence of the direct signal, we checked the ionospheric conditions along the path S_NM. Unfortunately, ionosonde data are unavailable to date. However, the relevant total electron content (TEC) data of GPS observations demonstrate a very interesting behavior. Figure 6 shows the time variation of TEC along the vertical ground-satellite trajectory for two GPS stations: KSTU (Krasnoyarsk) and IRKT (Irkutsk), between 0 and 5 UT. TEC values were converted to a vertical column. The first station is about 250 km east of Mondy, and the second one is 700 km northwest of it, that is, approximately along the S_NM path (compare the diagram in Figure 5 with the map in Figure 7). At Irkutsk we see quasi-sinusoidal oscillations of TEC. The method of detecting these oscillations was described by *Afraimovich et al.* [1998]. The amplitude of the variations is about 3–4% of the vertical TEC, and the period changes from about 20 to 30 min. The oscillations recorded at Krasnoyarsk have the shape of a pulsed signal with a similar amplitude and period. The closest available GPS station to the south of Mondy SHAO (31°N, 121°E), China, shows no such variations, nor does the Zwenigorod GPS station near Borok. TEC variations of a regular form, such as these ones, are not frequent. For example, an analysis of the Irkutsk GPS station data for 30 arbitrary days brought to light just two similar events; however, they have a much smaller amplitude and a less regular shape. Having no ionosonde data we hardly can speculate about the source

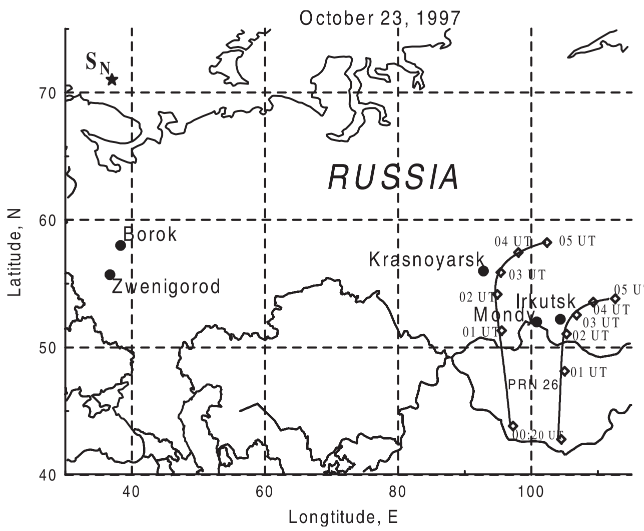

Figure 7. Locations of GPS stations Zwenigorod, Krasnoyarsk and Irkutsk, and of the magnetic observatories Borok and Mondy in geographic coordinates. Solid curves represent the trajectories of the subionospheric points for the PRN 26 satellite at the height of 300 km. Light diamonds along the trajectories correspond to the coordinates of the subionospheric points at the indicated instants of universal time. The asterisk marks the location of the northern ionospheric Pc1 source S_N.

of the oscillations, but it is clear that some intense periodic structure, a stationary or wavelike one, existed in the ionosphere that day. A more detailed study of the revealed new type of TEC oscillations which includes a spectral analysis and search for other similar events related to other Pc1 observations is in progress now. At this point, however, it is quite safe to assume that this structure produces strong horizontal irregularities in the ionosphere, declining or reflecting waves propagating in the ionospheric waveguide. This explains the lack of the Pc1 signal from the northern source, in accordance with the above Greifingers' statement.

6. Conclusions

[15] An unusual event of Pc1 emission observed on 23 October 1997 at two midlatitude observatories in the Northern Hemisphere has been analyzed searching for the reason of the unbelievably small value of the apparent velocity of Pc1 ionospheric propagation. Arguments were found in favor of the idea that the signal comes to the two stations from the opposite hemispheres. Data on total electron content were invoked in an attempt to explain the lack of the direct signal at one of the observatories. This gives a more or less satisfactory explanation of the phenomenon observed. Here we have checked only one possible explanation of the observed Pc1 characteristics. The other possibilities can be connected with the curvature of the propagation trajectories or with some exotic paths of propagation, such as the transpolar propagation.

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