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Field line resonance studies in North America and Central Europe

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It is believed that geomagnetic pulsations in the Pc3–Pc4 range can have both magnetospheric and solar wind origins. Some researchers have found relationships between the frequencies of some Pc3–Pc4 pulsations and parameters of the solar wind. Others have found Pc3–Pc4 pulsations that did not agree with those relationships. We believe that there are at least two types of Pc3–Pc4 pulsations, one which is derived from solar wind upstream waves, and another which represents resonant oscillations of local field lines. Unfortunately, their frequency spectra are similar. This means, that if one mistakes a field line resonance for an upstream wave derived pulsation, attempts to use the pulsation frequency to derive solar wind parameters will fail, because the field line resonance frequency depends only on field line parameters. We show that the high spatial gradients of amplitude and phase which characteristises field line resonances may be used to identify them. Other pulsations exhibiting extremly low or zero spatial gradients in amplitude and phase may be those derived from upstream waves. Phase and amplitude gradients were measured over 150 km baselines, along magnetic meridians, in North America and 100 km in Central Europe. Cross power spectral density analysis of data from station pairs clearly and reliably identified field line resonances during local daylight hours in Central Europe and North America. Pulsations having zero spatial gradients were also identified and may be derived from solar wind upstream waves.

Keywords: Earth, magnetic field, plasmasphere, magnetosphere, solar wind

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1. Discussion

TROITSKAYA et al. [1971] as well as GUL'ELMI and BOLSHAKOVA [1973] showed that some pulsations in the Pc2–Pc4 band, recorded at Borok in the former USSR, seemed to demonstrate a dependence of oscillation period on the amplitude of the Interplanetary Magnetic Field (IMF). Satellite measurements of the IMF were used to verify the relationship. This relationship became known as the Borok B–Index. Pulsations whose characteristics (such as oscillation period) seem to be diagners were unable to verify the Borok B–Index, suggesting the presence, sometimes, of other pulsations not obeying the Borok B–Index relationship [RUSSELL, FLEMING 1976]. We think that upstream waves, propagating in the solar wind can enter the dayside magnetosphere, giving rise to pulsations in the Pc3–Pc4 band, having a relatively broad frequency spectrum and exhibiting coherence over a large extent of longitude (ten's of degrees) and latitude (at least a few degrees). Evidence for these assertions is presented later in this paper. We further think that these broad spectrum, solar wind controlled upstream waves are ubiquitous in the dayside magnetosphere and are capable of exciting local field lines at their individual resonance frequencies. It is shown that the field line resonance spectra are very narrow and that field line resonances are characterized by high spatial gradients of amplitude, phase, and frequency along magnetic meridians. Upstream waves, on the other hand, are characterized by very low spatial gradients in meridional and longitudinal directions. *Table I*, below, summarizes what we believe are salient characteristics of these two classes, of dayside pulsations.

A. Upstream Waves/Solar Wind Controlled Pulsations

1. Originate in solar wind; some penetrate into Earth's magnetosphere.
2. Frequency spectrum probably determined by solar wind parameters.
3. Broad frequency spectrum.
4. Low or zero spatial gradients of amplitude, phase, and frequency.
5. May excite local field line resonances.
6. Occur mainly on dayside.

B. Field Line Resonances

1. Originate as standing wave, Alfven resonances on local field lines.
2. Frequency spectrum determined only by local field line parameters.
3. Narrow frequency spectrum.
4. High spatial gradients of amplitude, phase, and frequency.
5. Resonant oscillations may be excited by upstream wave energy.
6. Occur only on dayside.

Table I. Salient characteristics of dayside pulsations
I. táblázat. A nappali pulzációk legfontosabb tulajdonságai

A plot of the power spectral density of one component of the geomagnetic field (say, the North Horizontal component) at a single point would yield a broad spectral 'bump'. This 'bump' would represent the superposition of power from local and neighboring field line resonances, upstream waves, and other phenomena. Determining the centroid of this broad spectral bump would likely tell us nothing about either the frequency of the local field line resonance or the frequency spectrum of the upstream waves. Since, in practice, these spectral bumps may span a decade or more of frequency, one can readily understand why using power analysis alone will usually not give us accurate enough information about upstream wave frequency to determine IMF to within an order of magnitude.

Recent work has shown that spatial gradients of amplitude and phase may be used to uniquely identify field line resonances [BARANSKY et al. 1990 and GREEN et al. 1993]. The work described in the present paper verifies those results and further suggests that phase gradients may be used to identify upstream waves, as well.

2. The Global Field Line Resonance Network

Scientists from the U.S. Geological Survey (USGS) Geomagnetism Group, Golden, Colorado, USA, and from the Eötvös Loránd Geophysical Institute of Hungary, at Budapest and Tihany, proposed a global network of gradient stations to identify field line resonances. Stations will eventually be located at the six sites shown on the map of *Figure 1*. These sites span a range of L shells from 1.4 to 5. 5 and a range of over 170 degrees of longitude as shown below in *Table II*.

Fairbanks-Healy, AK, USA	L=5.5	Longitude = 147 W
St. Petersburg-Red Lake, Russia	L=3.5	Longitude = 30 E
Nurmijärvi-Hankasalmi, Finland	L=3.4	Longitude = 25 E
Boulder-South Park, CO, US	L=2.4	Longitude =105 W
Lviv-Kovel, Ukraine	L=2.1	Longitude = 23 E
Tihany-Hurbanovo, Hungary/Slovakia	L=1.9	Longitude = 18 E

Table II. Gravity stations
II. táblázat. Gravitációs állomások

Fig. 1. Location of existing and planned gradient pair sites. At each site there are 2 stations separated by about 100 km along the local magnetic meridian
1. ábra. A tervezett és már meglévő regisztráló állomáspárok elhelyezkedése. Két mérőhely minden esetben a mágneses meridián mentén egymástól 100 km körüli távolságra van

Two additional Hungarian sites are planned in order to refine our observations in Hungary and also to investigate East–West phase gradients.

At each site there are located a pair of stations separated by about 150 km along the local magnetic meridian. For example, the Tihany site consists of a station at the Tihany Geomagnetic Observatory and another station at Hurbanovo, Slovakia, which is about 100 km to the North of Tihany along the magnetic meridian. At each station there is a three component magnetometer, a Global Positioning System (GPS) receiver, and a digital data acquisition system. Sampling rate is 1.0 Hz; data are band pass filtered from 3 millihertz to 200 millihertz; GPS time accuracy is at least 1.0 millisecond, and overall system noise less than 0.02 nanotesla. Data are recorded on magneto optical discs. Cross power spectral density is computed continuously for each station pair for a 24 hour Universal Time (UT) interval. Cross power spectral density is the Fourier transform of the cross correlation function between the two time series. Unlike auto power spectral density, cross power spectral density is a complex function having both real and imaginary parts. It may be represented by amplitude and phase functions. By continuously computing cross power spectral density between the two points over time, one can identify a frequency at which a distinct phase difference exists; this is the resonance of the field line half way between the two points. The phase shift may be of the order of 40 degrees for pairs separated by 150 km [BARANSKY et al. 1995] and may persist during the daylight hours (10 hours or more) as the field line resonance slowly changes frequency during the course of a day [GREEN et al. 1993]. With support from the U.S.–Hungarian Science and Technology Joint Fund, ELGI, and the U.S. Geological Survey, we have established a pair of stations in North America (Boulder and South Park, Colorado) and in Central Europe (Hurbanovo, Slovakia, and Tihany, Hungary). This paper describes preliminary results from analysis of data from these two pairs of stations.

Figures 2 and *3* show simultaneous pulsations for a 15 minute period at Hurbanovo, Slovakia, and Tihany, Hungary.

Figure 4 shows cross power amplitude and cross power phase for a 24 hour period. The field line resonance is readily identified on the phase plot as the red/brown line (about 20 to 40 degrees of phase shift) at a frequency of 55 millihertz between about 0800 and 1500 UT. The resonance is not at

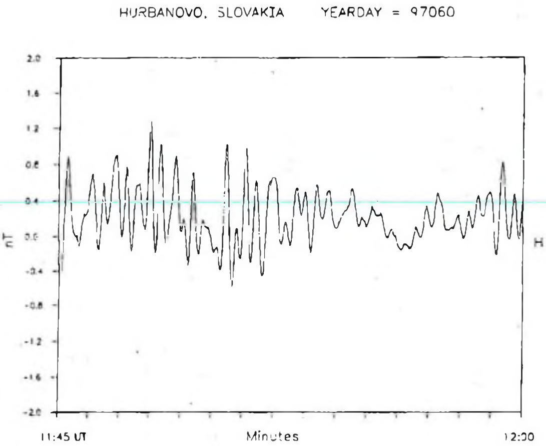


Fig. 2. Field line resonance pulsations at Hurbanovo, Slovakia between 11:45 UT and 12:00 UT on 1 March 1997. They have been recorded in a frequency band from 3 mHz to 200 mHz and exhibit a typical resonance frequency of 50 mHz (period of 20 seconds)

2. ábra. Erővonalrezonancia okozta pulzációk Hurbanovoban, 1997 március 1-én 11:45 UT és 12:00 között. A felvételek a 3 mHz és 200 mHz közötti tatományban készültek és 50 mHz-es jellemző rezonanciafrekvenciát mutatnak (20 másodperces periódus)

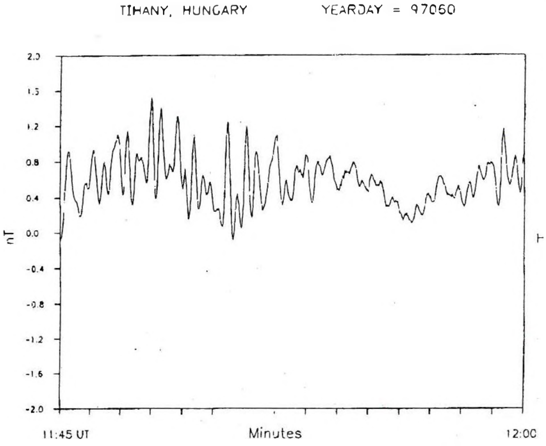


Fig. 3. Field line resonance pulsation at Tihany, Hungary between 11:45 UT and 12:00 UT on 1 March 1997. They have been recorded in a frequency band from 3 mHz to 200 mHz and exhibit a typical resonance frequency of 50 mHz (period of 20 seconds)

3. ábra. Erővonalrezonancia okozta pulzációk Tihanyban, 1997 március 1-én 11:45 UT és 12:00 UT között. A felvételek a 3 mHz és 200 mHz közötti tatományban készültek és 50 mHz-es jellemző rezonanciafrekvenciát mutatnak (20 másodperces periódus)

HURBANOVO, SLOVAKIA TIHANY, HUNGARY

YEARDAY = 97060 MAR 1, 1997

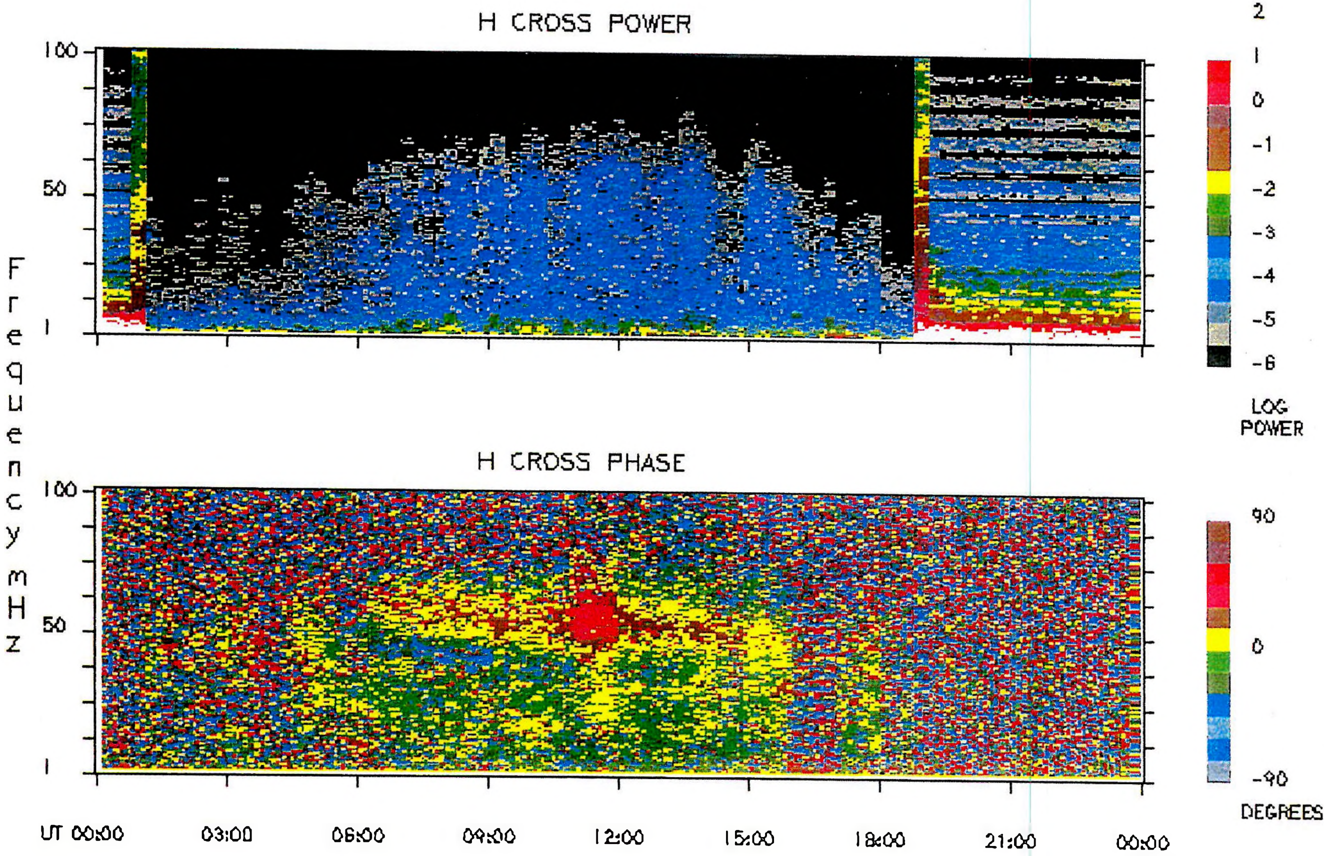


Fig. 4. Cross Phase versus time and frequency between Hurbanovo and Tihany on 1 March 1997. The resonance frequency is clearly outlined in the phase function

4. ábra. Keresztkorrelációs amplitudó és fázis 1997. március 1-re Hurbanovo és Tihany állomásokra. A rezonancia frekvencia világosan látszik a fázisfüggvényben all apparent from the power plot: since the power plots contribute nothing to the identification of the resonance, they are omitted in the subsequent plots.

The resonance has a phase gradient of about 0.45° per km over the 100 km separaton of the stations. It may be shown from GREEN et al. [1993] that the calculated frequency gradient is 0.028 Hz/km (increasing southward) and the amplitude gradient is 0.025 nT/km. It is also shown that the cross power density spectrum is a more reliable means of identifying the resonance frequency than are amplitude and frequency grades. So we use the phase gradient exclusively.

Figures 5 and *6* show simultaneous pulsations for a 15 minute period at Boulder, Colorado, and South Park, Colorado, in the USA. The phase plot of *Figure 7* shows a resonance at about 30 millihertz from about 1400 to 2300 UT. The red color shows that the phase shift is between 45 and 60 degrees.

In all cases for both Central Europe and North America, the field line resonances are a dayside phenomena. This fact is illustrated by the five-day series of repeated strong resonances shown in *Figure 8*.

We have also observed that, on the phase plots, a region of yellow-green color extends from a frequency below the field line resonance frequency to one above the resonance frequency. Since yellow-green represents a phase difference between the stations of near zero degrees, we think that the yellow-green region signifies the presence of pulsations having a broad frequency spectrum and having spatial coherence over the distance between the stations. We think that these represent upstream waves, and that when the upstream wave power extends through the local field line resonance frequency, the local resonance is triggered.

The examples cited above suggest that the waves corresponding to the broad spectrum power having zero phase between stations are coherent over distances of at least 100 km. Indeed, these upstream waves may be spatially coherent over distances considerably in excess of 150 km. In an effort to test coherence over long distances, we computed cross power spectral density on simultaneous records at Boulder, Colorado, USA, and Tihany, Hungary. These sites are separated by about 120 degrees of longitude. At the time we had only a few simultaneous recordings from North

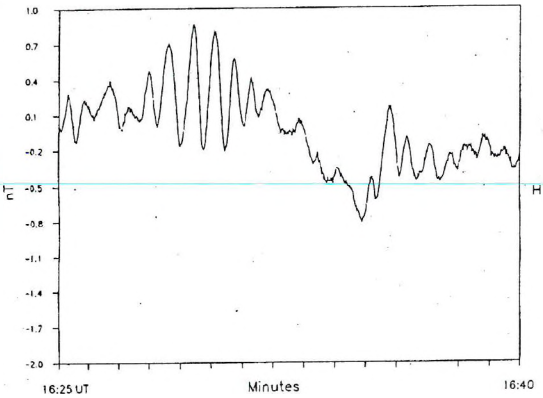


Fig. 5. Field line resonance pulsations at Boulder, Colorado, USA between 16:25 UT and 16:40 UT on 23 March 1997. Because of the longer field line (higher *L* shell) the frequency is lower, about 30 mHz (or 33 second period)

5. ábra. Erővonalrezonancia okozta pulzációk Boulderben, 1997 március 23-án 16:25 UT és 16:40 UT között. A hosszabb erővonalak miatt (nagyobb *L* érték) a frekvencia itt alacsonyabb, körülbelül 30 mHz (vagy 33 másodperces periódus)

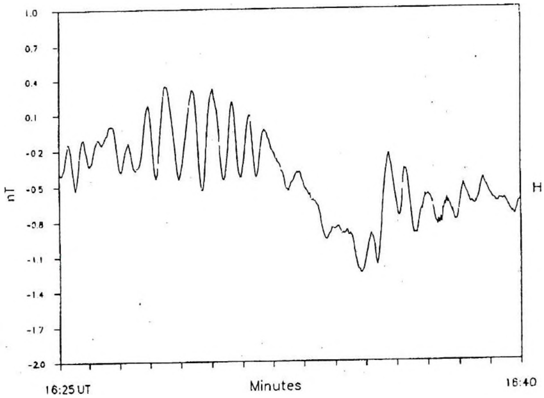
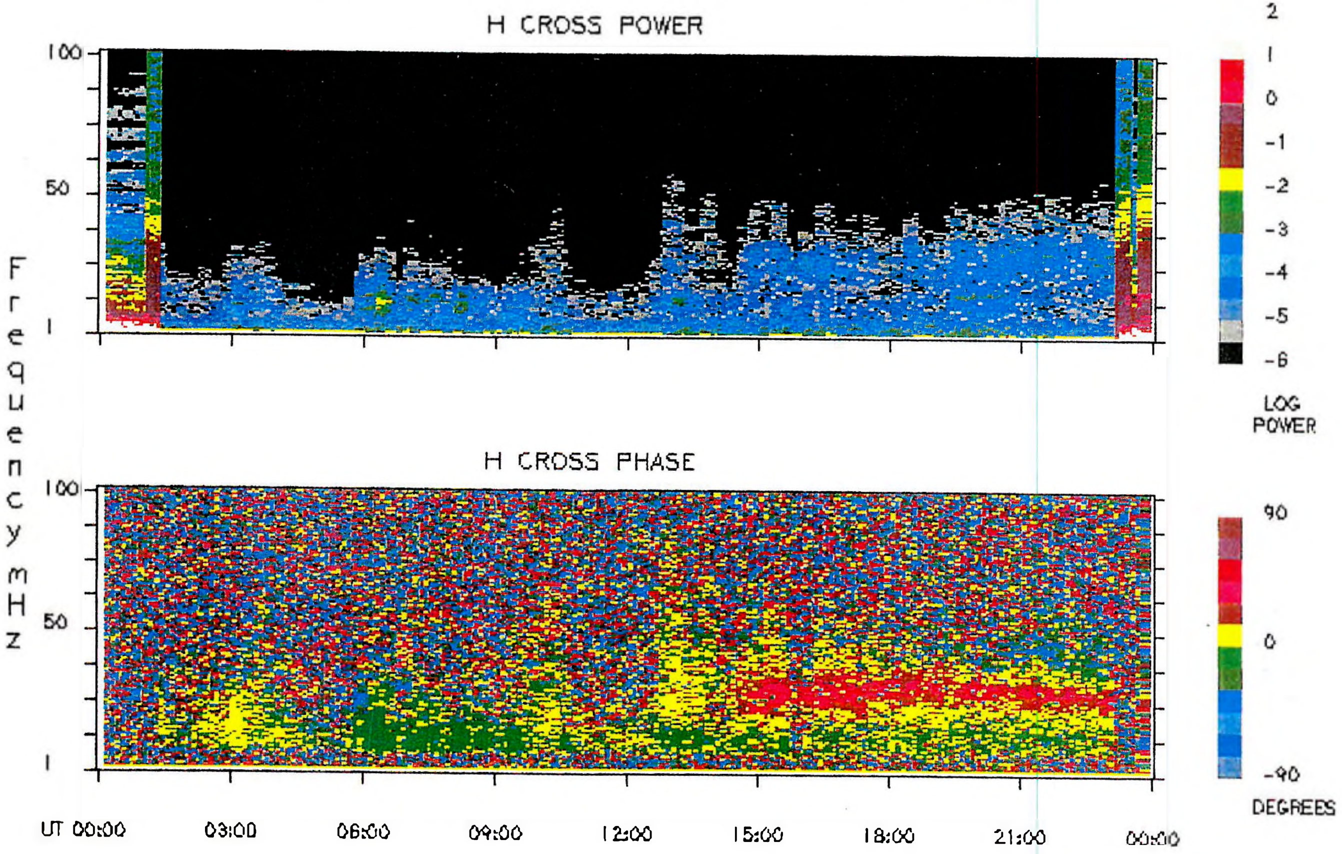


Fig. 6. Field line resonance pulsations at South Park, Colorado, USA between 16:25 UT and 16:40 UT on 23 March 1997. Because of the longer field line (higher *L* shell) the frequency is lower, about 30 mHz (or 33 second period)

6. ábra. Erővonalrezonancia okozta pulzációk South Parkban, 1997 március 23-án 16:25 UT és 16:40 UT között. A hosszabb erővonalak miatt (nagyobb *L* érték) a frekvencia itt alacsonyabb, körülbelül 30 mHz (vagy 33 másodperces periódus)

BOULDER, CO, USA SOUTH PARK, CO, USA

YEARDAY = 97082 MAR 23, 1997



H CROSS POWER

H CROSS PHASE

Fig. 7. Cross phase versus time and frequency between Boulder and South Park on 23 March 1997. The circled region suggests upstream waves with central frequency of 25 mHz having zero phase difference

7. ábra. Boulderi és South Park-i adatok teljesítmény- és keresztkorrelációs függvénye 1997. március 23-ára. A bekeretezett tartomány 25 mHz központú upstream pulzációkat sejtet nullához közeli fázisdiferenciával

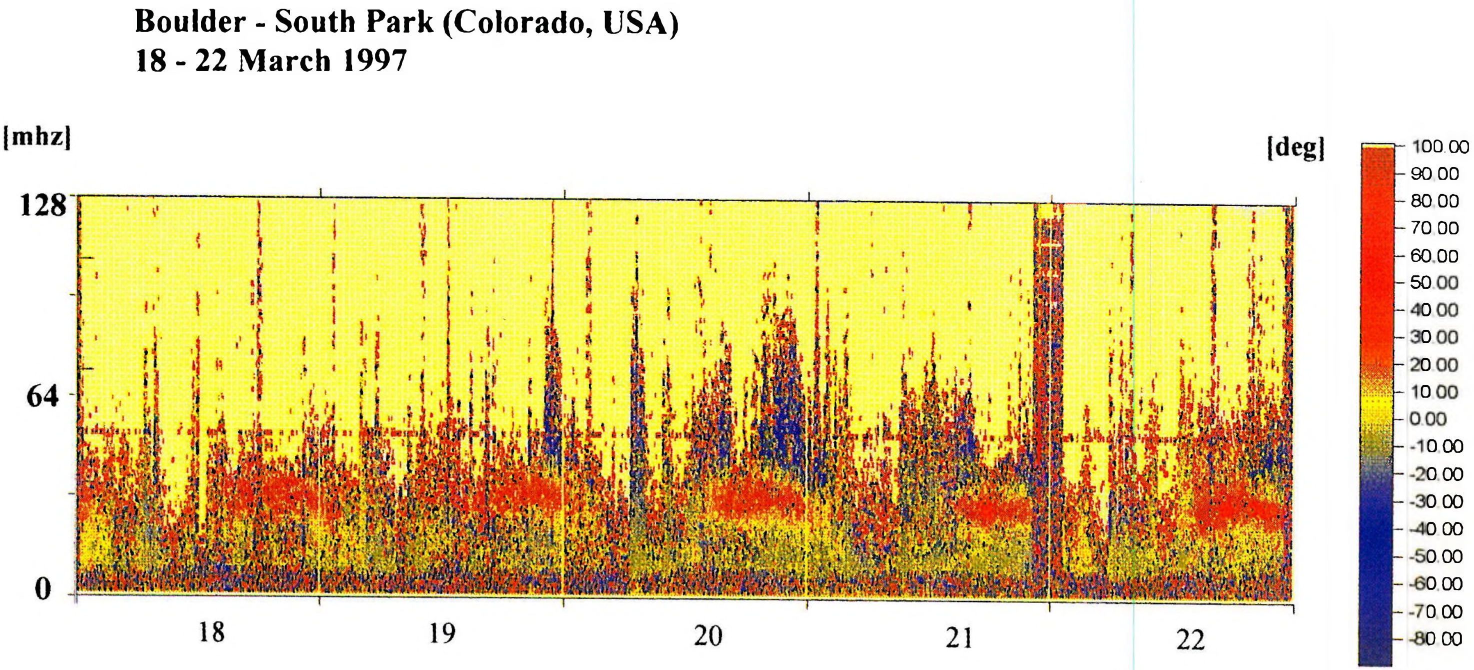


Fig. 8. Repeat daytime resonances for 5 days at Boulder on 18-22 March 1997, indicate that field line resonances are daytime events

8. ábra. 5 egymást követő napon jelentkező, ismétlődő rezonanciák Boulderben, 1997. március 18-22. között. Az ábra csak nappal előforduló jelenségre utal

BOULDER, CO, USA TIHANY, HUNGARY

YEARDAY = 97087 MAR 28, 1997

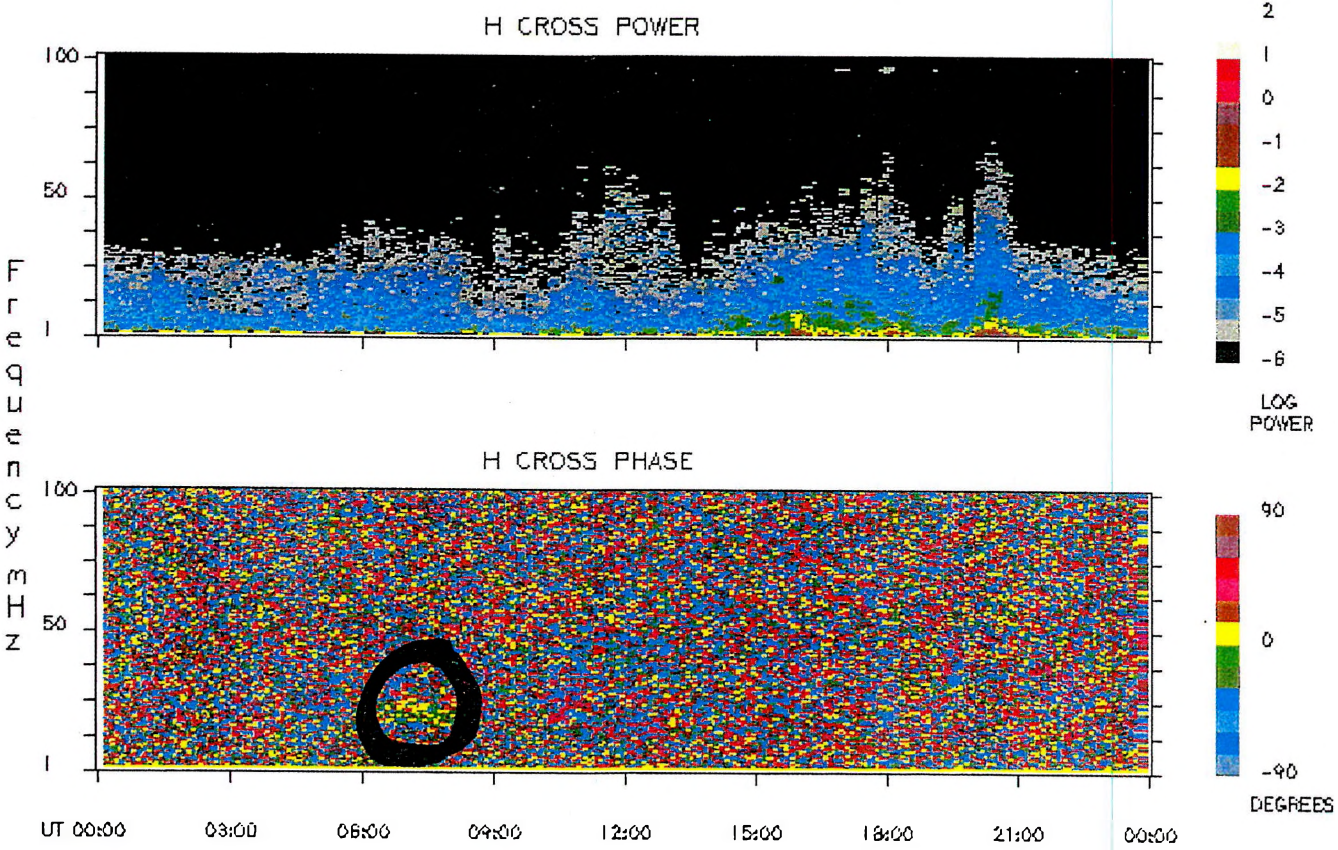


Fig. 9. Region of zero phase between Boulder and Tihany, 28 March 1997

9. ábra. Nulla fáziskülönbségű tartomány boulderi és tihanyi adatok összehasonlításából 1997. március 28-ra

America and Central Europe. One set of records, however, showed an example of apparent coherence of waves over this great distance. In *Figure 9*, we see a yellow-green region of zero phase from 0700 to 0800 UT on 28 May 1997 in a frequency band from about 13 to 30 mHz. We belive that the lack of phase difference between Colorado and Hungary means that these waves are upstream waves whose characteristics are unrelated to local *L* values and are determined only by conditions of the solar wind. In *Figure 10*, we have superimposed records of pulsations for Boulder and Tihany during this interval of small zero phase. The coherence is quite good, suggesting the presence at those widely separated sites of upstream waves with essentially zero phase difference. At this point, the paucity of data means that these results are to be considered tentative.

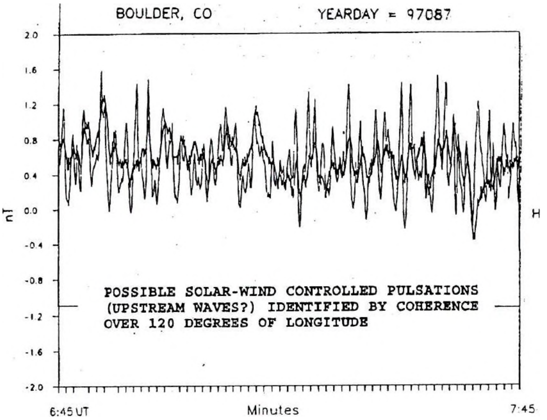


Fig. 10. Superimposition of pulsations from Boulder and Tihany at the time of the zero phase event suggests coherence over this great distance, suggesting that these are upstream waves

10. ábra. A nulla fáziskülönbségű időszak egymásrahelyezett boulderi és tihanyi regisztrátuma nagy távolságokra fennálló koherenciára és így upstream típusú hullámokra enged következtetni

3. Conclusions

— Cross power spectral density (CPSD) analysis may be used to separate waves having high spatial gradients of amplitude, phase, and frequency from those having low spatial gradients of amplitude, phase, and frequency.

— CPSD gradient analysis (particularly, phase) may be used to very accurately determine field-line resonance (FLR) frequencies and their time dependence. FLR's are characterized by very high spatial phase gradients.

— CPSD phase analysis has identified waves whose broad frequency spectra span the field line resonance frequency line. Those 'spanning' waves have been present during all field line resonance events that we analyzed. Those 'spanning' waves maybe upstream waves and may trigger FLR's. These upstream wave candidates are characterized by very low spatial wave gradients.

Acknowledgements

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REFERENCES

BARANSKY L. N., BELOKRYS S. P., BOROVKOV Yu.E., GREEN C. A. 1990: Two simple methods for the determination of the resonance frequencies of magnetic field lines. Planet. Space Sci. **38**, pp. 1573–1576

BARANSKY L. N., GREEN A. W. , FEDOROV E. N. , KURNEVA N. A., PILIPENKO V. A., WORTHINGTON E. W. 1995: Gradient and polarization methods of ground-based monitoring of magnetospheric plasma. J. Geomag. Geoelectr. **47**, pp. 1293–1309

GREEN A. W., WORTHINGTON E. W. , BARANSKY L. N., FEDOROV E. N., KURNEVA N. A., PILIPENKO V. A., SHVETZOV D. N., BEKTEMIROV A. A., PILIPOV G. V. 1993: Alfven field line resonances at low-latitudes (L=1.5). J. Geophys. Res. **98**, pp. 15693–15699

GUL'ELMI A. V., BOLSHAKOVA O. V. 1973: Diagnostics of the interplanetary magnetic field from ground-based data on Pc2–4 micropulsations. Geomagn. Aeron., **13**, pp. 513–521, .

RUSSELL C. T., FLEMING B. K. 1976: Magnetic pulsations as a probe of interplanetary magnetic field. A test of Borok B-index. J. Geophys. Res. **81**, pp. 5882–5887

TROITSKAYA V. A., PLYASOVA–BAKOUNINA T. A., GUL'ELMI A. V. 1971: Relationship between Pc2–4 pulsations and the interplanetary magnetic field. Dokladi Akademii Nauk SSSR, English Transl. **197**, pp. 1312–1322

Erővonal rezonanciák tanulmányozása Észak-Amerikában és Közép-Európában

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Az általános nézet az hogy a Pc3–Pc4 tartományba eső pulzációk magnetoszférikus vagy napszél eredetűek is lehetnek. Néhányan összefüggést találtak a Pc3– Pc4 pulzációk frekvenciája és a napszélparaméterek között, mások viszont találtak olyan Pc3–Pc4 pulzációkat, melyek nem felelnek meg ennek az összefüggésnek. Mi azt állítjuk, hogy a Pc3–Pc4 pulzációknak legalább két különböző típusa van, az egyik a napszél upstream hullámaitól ered, a másik pedig a helyi erővonalak rezonanciájával kapcsolatos. Sajnos a két típus frekvenciaspektruma hasonló. Ebből az következhet, hogy ha valaki összetéveszti őket és megpróbálja a pulzációk frekvenciáját a napszél paramétereinek meghatározására használni, akkor könnnyen téves eredményre juthat, mert az erővonal rezonancia frekvenciája csak az erővonal paramétereitől függ. Bemutatjuk, hogy az erővonalrezonanciákra jellemző nagy, térbeli amplitúdó és fázisgradiens használható az ilyen pulzációk azonosítására. A többi pulzáció ugyanakkor nagyon kis térbeli amplitúdó és fázisgradienst mutat. Az erővonalak mentén 150 illetve 100 km-es távolságokban elhelyezkedő állomáspárok segítségével Észak-Amerikában és Közép-Európában fázis- és amplitúdógradienseket mértünk és az állomáspárok adatainak keresztkorrelációja egyértelműen mutatott erővonalrezonanciákat a helyi nappali időszakokban. Ezek mellett sikerült azonosítani nagyon alacsony térbeli gradienssel jellemezhető pulzációkat, melyek a napszél upstream hullámai okozhatnak.

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Arthur W. GREEN photograph and biography not available at the time of publication.

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Tanya A. PLYASOVA-BAKOUNINA, photograph and biography not available at the time of publication.

Alpár KÖRMENDI, for a photogprah and biography, see this issue, p. 27.

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Walter GOEDECKE photograph and biography not available at the time of publication.

Zoltán Vörös was born in Komarno, Slovakia, in 1959. He received his degree in nuclear physics from Comenius University, Bratislava, Slovakia, in 1983, and his Ph. D. degree in geophysics from the Slovak Academy of Sciences in 1992. In 1983 he joined the Geophysical Institute SAS, Bratislava where he became head of the Hurbanovo geomagnetic observatory in 1990. His research interest is focused on nonlinear magnetosphere physics.