

Upstream Wave Related Pc3 Pulsations Observed by the MM100 Meridional Magnetometer Array

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A b s t r a c t

The upstream waves (UWs) are typically 20-30 s magnetosonic waves generated in the Earth's foreshock region. Under appropriate interplanetary conditions the UWs are able to enter the magnetosphere, propagate across field lines down to the ionosphere and reach the ground as Pc3 geomagnetic pulsations. In the past years, a semi-automated method was developed to monitor UW-related geomagnetic pulsation activity. The method was based on cross spectral density estimation of signals recorded at meridionally distributed stations or by satellites at LEO (CHAMP). The MM100 meridional array, including Finnish, Polish, Slovak and Hungarian observatories, was established in 2001. In the present pa-

per we review the first results of the analysis of UW-related ground pulsations observed by the MM100 network. We demonstrate the relation of these pulsations to upstream phenomena and consequently, to the state of the interplanetary medium.

1. Introduction

Modern history of pulsation study in Tihany Geophysical Observatory started in 1996, when on the initiation of A.W. Green (USGS Geomagnetism Group) two identical magnetometers were installed in Tihany (Hungary) and in Srobarovo (Slovak Republic) with the support of the US-Hungarian Joint Fund. The Srobarovo-Tihany magnetometer pair was planned to be a part of a global network of gradient stations to identify field line resonances and upstream waves (Green *et al.* 1999). Although this network was never completed, two further stations were later installed in Hungary, one in Nagycenk and another in Farkasfa in 1999 and 2000, respectively.

The need for a mid-latitude high resolution magnetometer array emerged again in 1999 on preparing a measuring campaign organised for the observation of the possible geomagnetic effects of the total solar eclipse of August 11, 1999. In addition to one minute mean, normal observatory records, our aim was to observe one second data, as well, in as many stations in Europe as possible, for Pc3 (22-100 mHz) pulsation studies. At that time, our initiation was supported by the Sodankylä, Nurmijärvi, Belsk and Hurbanovo observatories. The results of this eclipse campaign were published recently (Heilig *et al.* 2001, Bencze *et al.* 2007).

The analysis of most pulsation phenomena requires magnetic networks rather than single stations. The reliable identification of field line resonances can be realized with meridional pairs of closely (100-250 km) spaced stations according to the gradient method (Green *et al.* 1993). On the other hand, monitoring the upstream wave related pulsations claims several stations from different latitude zones (Heilig *et al.* 2007). Meridional array consisting of gradient pairs, or a properly dense meridional magnetometer chain can fulfil both criteria.

There are only a few meridians in the Earth with sufficient land coverage suitable for establishing a meridional array connecting both polar regions. Beside the circum-Pacific region and the American continent, Europe and Africa form a natural basis for global meridional arrays. The Circum pan-Pacific Magnetometer Network (70°N – 65°S mag. lat.) have been operating since 1995, its predecessor, the MM210 was started in 1990 (Yumoto *et al.* 2001). A meridional network, McMAC is currently being formed in the American continent, but a similar array is still missing in Europe. Existing European regional networks (IMAGE and SAMNET in Scandinavia and North-Western-Europe, and low-latitude SEGMA in Southern-Europe) are not connected with each other. MM100 is the first initiative to fill the gap between high and low latitude European networks.

2. The MM100 Meridional Magnetometer Array

MM100 is the acronym for a quasi-meridional magnetometer array established for pulsation study, in September 2001. The array consists of Finnish, Estonian, Polish, Slovak and Hungarian stations from high to mid latitudes ($L = 6.09$ to 1.84). The

Finnish and Estonian sites belong to the IMAGE (Lühr *et al.* 1998) array. The Polish and Slovak observatories are maintained by the national Academies of Sciences. Tihany, Farkasfa and Nagycenk stations in Hungary were installed in 1996, 1999 and 2000, respectively, as a result of a joint project of the USGS Geomagnetism Group and ELGI (Hungary). Nagycenk station is operated by the Geodetic and Geophysical Institute (GGRI) of the Hungarian Academy of Sciences.

Below we list the AACGM coordinates and L-shell values of MM100 stations in the order: **Station name**, **IGA code**, operating institute, AACGM-2001 latitude (North) and longitude (East), L-shell-value; **Kilpisjärvi**, **KIL**, *op*: FMI, *aacgm*: 66.10°, 104.00°, *L*: 6.09; **Sodankylä**, **SOD**, *op*: Oulu University SGO, *aacgm*: 64.16°, 107.46°, *L*: 5.26; **Hankasalmi**, **HAN**, *op*: FMI, *aacgm*: 59.01°, 104.78°, *L*: 3.77; **Nurmijärvi**, **NUR**, *op*: FMI, *aacgm*: 57.23°, 102.34°, *L*: 3.41; **Tartu**, **TAR**, *op*: FMI, *aacgm*: 54.48°, 103.04°, *L*: 3.01; **Belsk**, **BEL**, *op*: PAS, *aacgm*: 48.01°, 96.15°, *L*: 2.23; **Hurbanovo**, **HRB**, *op*: SAS, *aacgm*: 43.56°, 92.86°, *L*: 1.90; **Nagycenk**, **NCK**, *op*: ELGI-GGRI-USGS, *aacgm*: 43.27°, 91.53°, *L*: 1.89; **Farkasfa**, **FKF**, *op*: ELGI-USGS, *aacgm*: 42.43°, 91.00°, *L*: 1.84; **Tihany**, **THY**, *op*: ELGI-USGS, *aacgm*: 42.44°, 92.39°, *L*: 1.84.

The instrumentation at these stations is not identical. However, high resolution, low noise fluxgate or torsion photoelectric magnetometers are used in each station with GPS synchronized timing and sampled at least at 1 Hz. The most important technical parameters of current MM100 stations are given in Table 1. All MM100 data are transformed into the magnetic field oriented HDZ system and archived in uniform format, in ELGI.

3. Upstream Waves

Upstream waves (UWs) are typically 20-30 s magnetosonic waves generated in the Earth's foreshock. These waves are driven by a wave-particle interaction, i.e. the ion-cyclotron instability. The resulting waves are swept back to the magnetosphere by the super-Alfvénic solar wind. The frequency of the generated UW is directly proportional to the interplanetary magnetic field (IMF) strength. Their amplitude is controlled by the solar wind speed and the so-called cone angle, i.e. the angle between the Sun-Earth line and the direction of the IMF. Under appropriate conditions the UWs are able to enter the magnetosphere, travel down to the ionosphere and finally reach the ground as Pc3 (22-100 mHz) geomagnetic pulsations (e.g. Yumoto *et al.* 1984).

4. Data Processing

In the past years we developed a semi-automated method to monitor UW-related geomagnetic pulsation activity based on the comparison of spectral energy densities of signals recorded at meridionally distributed locations or in low-Earth-orbit satellites (CHAMP). In a single station magnetic record, the UW pulsations are usually masked by local field line resonances (FLR). For this reason the UW frequency can be determined only from the records of a set of meridionally distributed magnetometers. Supposing that the UW related pulsations are coherent over large areas extending up to

Table 1
Instrumentation at MM100 stations

IAGA code	Magnetometer		f_{sampling}	Band-width DC –	Resolution	rms noise (0.01-0.1 Hz)	Timing
	model	type					
KIL	LEMI 004	fluxgate	1 Hz	1 Hz	10 pT	20 pT	GPS
SOD	PSM	torsion photo-electric	2 Hz	0.3 Hz	3 pT	20 pT	GPS
HAN	FGE	fluxgate	1 Hz	1 Hz	10 pT	50 pT	GPS
NUR	FGE	fluxgate	1 Hz	1 Hz	10 pT	50 pT	GPS
TAR	FGE	suspended fluxgate	1 Hz	1 Hz	10 pT	50 pT	GPS
BEL	PSM 8511-01P	torsion photo-electric	1 Hz	0.3 Hz	3 pT	10 pT	GPS
HRB	Magson	fluxgate	1 Hz	n/a	100 pT	50 pT	GPS
NCK	Narod S-100	fluxgate	1 Hz (16 Hz*)	5 Hz*	1 pT*	20 pT	GPS
FKF	Narod S-100	fluxgate	1 Hz (16 Hz*)	5 Hz*	1 pT*	20 pT	GPS
THY	Narod S-100	fluxgate	1 Hz (16 Hz*)	5 Hz*	1 pT*	20 pT	GPS

* In January of 2004, band-pass (3-200 mHz) filter cards and DAQ system were replaced, sampling rate was increased to 16 Hz. In this study we use 1 Hz means.

thousands of kilometres on the ground, this UW-related activity can be emphasised by calculating the cross spectral densities of the signals recorded at MM100 stations on different geomagnetic latitudes. The averaging at the same time suppresses the latitude dependent FLRs. The method is described in details in Heilig *et al.* (2007). In the current paper, the peak frequencies estimated from time series recorded in January of 2003 are analysed.

Hourly pulsation activity indices are routinely calculated for all MM100 stations. The local activity index is the rms amplitude of the Pc3-band-pass filtered H-component signal expressed in pT. The value of this index depends on both UW and FLR activity. In this paper we used the 2003 activity indices for all stations (except for SOD, where only the first six months data were considered).

5. Results

5.1 Distribution of Pc3 power

The MM100 activity indices yield a possibility to map the distribution of Pc3 power in a zone bounded by the 42° and 66° magnetic latitudes (Fig. 1). At lower than 60° latitude this distribution can be characterised by a gradual increase after sunrise

followed by a decrease after the local noon till sunset. This behaviour is typical for mid-latitude Pc3s and thought to be related to the upstream origin of this activity. Along the MM100 array, two activity maxima can be established. The first one is located near the latitude of 48° (BEL). The average UW frequency estimated from the IMF magnitude was in the range of 30-40 mHz in the considered period. Since the local FLR frequency at BEL is usually within this range, the coupling of the incoming fast mode and Alfvén mode waves is the strongest near the latitude of the BEL (Heilig *et al.* 2007), the resulting FLRs may be responsible for the observed peak. The enhanced power poleward from the 60° magnetic latitude is considered to be caused by processes taking place at the magnetopause.

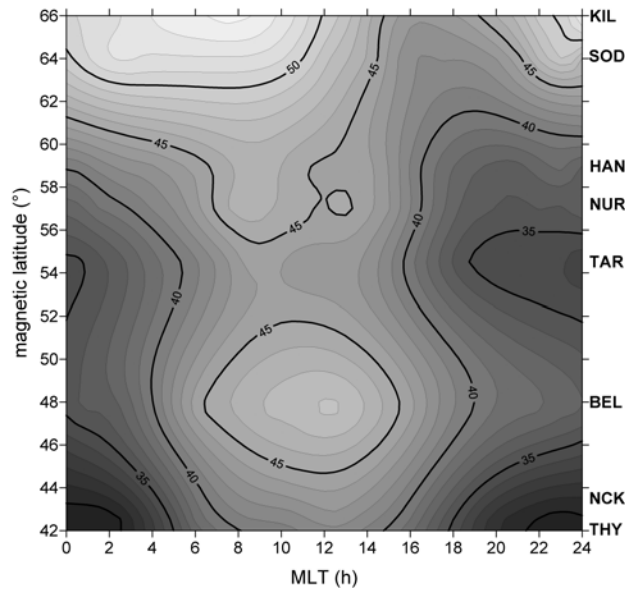


Fig. 1. Average distribution of Pc3 power as $20 \cdot \log_{10}(\text{Pc3ind})$ vs. magnetic local time and magnetic latitude (KIL, SOD, HAN, NUR, TAR, BEL, NCK, THY, January 1 to December 31, 2003).

The relation between the daily (solar zenith angle $< 60^\circ$) activity levels at different latitudes can be well approximated by linear formulae, as

$$\text{Pc3ind}_{\text{STA}} = a \cdot \text{Pc3ind}_{\text{STA_ref}} + b,$$

where STA and STA_ref stands for the code of the investigated and an arbitrary reference stations, respectively. Taking THY as a reference station and limiting the THY activity within the 20-300 pT range, the linear regression yields the following parameters for 2003: for NCK $a = 1.191$, $b = 15$ pT; for BEL $a = 1.762$, $b = 48$ pT; for TAR $a = 1.225$, $b = 23$ pT; for NUR $a = 1.575$, $b = 26$ pT; for HAN $a = 1.358$, $b = 38$ pT; for SOD $a = 1.993$, $b = 70$ pT; and for KIL $a = 2.497$ and $b = 71$ pT. The high correlations with THY at stations located at magnetic latitudes lower than 60° (0.99, 0.85, 0.69, 0.71, 0.72, 0.50 and 0.48 for the case of NCK, BEL, TAR, NUR, HAN, SOD,

KIL, respectively) suggest the common source of Pc3s in this latitude range, at least partially.

5.2 The relation of Pc3 pulsations to interplanetary conditions

The Pc3 activity at all stations correlates with radial solar wind speed and anti-correlates with interplanetary cone angle (Fig. 2). The former property of Pc3 pulsations can be explained by different source mechanisms including the upstream wave theory. The dependence on the cone angle, however, unambiguously indicates the role of upstream waves in the generation of ground Pc3s. Nevertheless, the most widely accepted test for the verification of upstream origin of selected pulsation events is the comparison of the dominant Pc3 frequency with the magnitude of the IMF. Based on the ion-cyclotron origin, there exist several theoretical, as well as empirical evidences (e.g. Yumoto *et al.* 1984) that confirm the following relation between the frequency of UWs and the IMF strength: f_{UW} (mHz) = $(6 \pm 1.5) \cdot B_{IMF}$ (nT). The UW candidate events selected by our algorithm behave exactly the expected way (Fig. 3). We argue then, that this result unambiguously validates the efficiency of our automated event selecting algorithm.

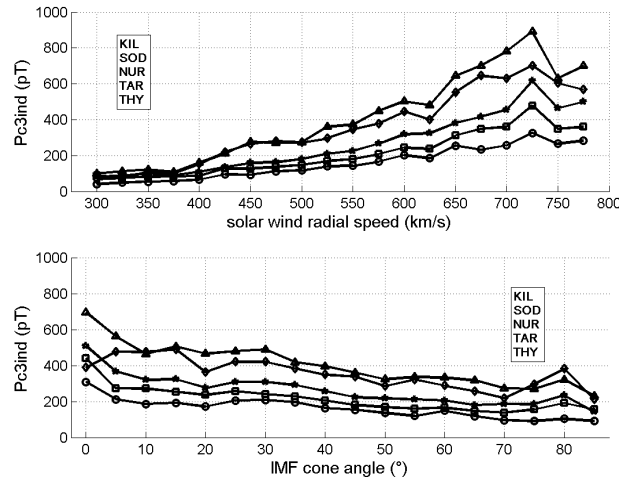


Fig. 2(a) The relation of Pc3 activity index to ACE solar wind speed at KIL (triangles), SOD (diamonds), NUR (stars), TAR (squares) and THY (circles) MM100 stations in 2003, (b) relation of Pc3 activity index to ACE IMF cone angle, format is the same as in the case of (a).

The most important advantage of the automated algorithm is that it makes possible a comprehensive statistical analysis of UW related pulsations. Most of the questions still open in this area could have not been answered so far because of the lack of large enough reliable datasets. Using the automatically selected UW events, our first important result was the confirmation of the existence of the Doppler-shift of UWs in the solar wind (Heilig *et al.* 2007). The dependence of pulsation activity on the subsolar distance of the magnetopause and on upstream Alfvén Mach number was also demonstrated for the first time (Heilig 2007).

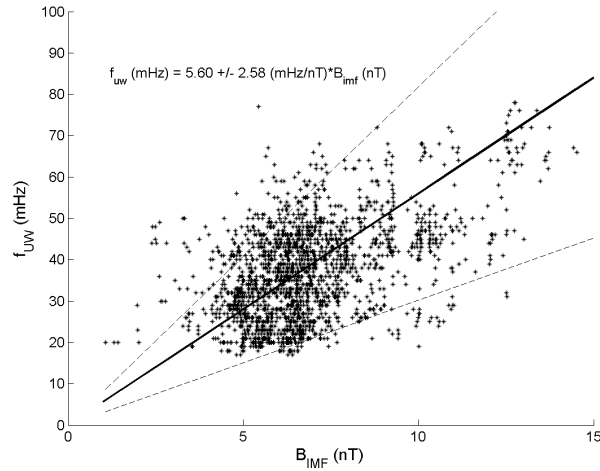


Fig. 3. Relationship between peak frequency and IMF strength, January 2003. The solid line and the equation in the left upper corner represent the result of the linear regression; the dashed lines limit the range containing 90% of all 2171 cases.

5.3 Interstation and space-ground coherence

In Bencze *et al.* (2007) it was demonstrated that interstation coherence calculated between stations located far away from each other can also be used to estimate the UW frequency. The coherence spectra have a peak at the dominant frequency of UWs. However, if the UW frequency is close to the local field line resonance at one of the considered stations, the coherence drops to a lower level near the resonant frequency.

The first results of our space-ground coherence analysis (Heilig *et al.* 2007) verified both the direct propagation of UW related waves from the subsolar magnetopause (CHAMP-THY case) and the existence of a field guided propagation of Alfvén mode waves coupled to the incident fast mode waves (CHAMP-NUR case).

6. Summary

The MM100 magnetometer array established in 2001 is maintained by institutes of 5 EU countries. As it was shown, the MM100 network can give an important contribution to the study of magnetospheric ULF pulsations. In this paper, some preliminary results of our multistation approach have been presented. Our results indicate that UW related pulsations can be traced using the MM100 array. Based on the large amount of events selected by our method, it is planned to carry out a comprehensive statistical analysis on UW related pulsation events in the near future.

The MM100 project is a registered Coordinated Investigation Program of IHY2007 under the nr. CIP 39 (ULF waves in the magnetosphere). Monitoring of plasmaspheric mass density is also targeted by this project, this topic was not discussed here.

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