GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 1, PAGES 103-106, JANUARY 1, 2001

Modification of Daytime Compressional Waves by the Ionosphere: First Results from OERSTED

Geeta Jadhav, Mita Rajaram, and R. Rajaram

Indian Institute of Geomagnetism, Mumbai 400 005, India.

Abstract. Ionospheric modulation of compressible hydromagnetic waves has been examined using the scalar magnetic field data obtained from the Oersted satellite and ground magnetic data from the Japanese sector. It is shown that the day side ionosphere introduces significant phase delays for frequencies in excess of about 20 mHz. The phase delay increases with frequency and with increase in the conductivity of the ionosphere. There is also an increase in the amplitude of the wave above equatorial day side ionosphere. The uniformly excellent coherence between the satellite and ground oscillations and systematically good correlation between the filtered time series at the two levels suggests that the compressible hydromagnetic waves are phase coherent over a wide range of latitudes.

1. Introduction

Geomagnetic pulsations, in the period range of 1 to 1000 mHz are manifestations of hydromagnetic waves generated through a combination of mechanical and electromagnetic forces. They originate mainly in the magnetosphere but are observed both on the surface of the earth and at satellite altitudes at various radial distances. Recently, there has been an increased interest in the study of compressional waves in the 10 to 100 mHz frequency range making up the Pc3-4 and Pi2 pulsation [Kim and Takahashi, 1999; Kim et al., 1998]. They tried to identify cavity waves from the amplitude and phase relations between the satellite and surface measurements. An estimate of the modifications introduced by the ionosphere is essential in any such exercise. In the present study, the amplitude and phase changes introduced by the ionosphere on compressional hydromagnetic waves passing through it are examined. Ground based geomagnetic data from the low latitude Japanese sector and Oersted satellite data have been utilized in the analysis.

The Oersted satellite was launched on 23rd February, 1999 with a near polar orbit. The orbital plane has a small drift with respect to the local time. The altitude varies between 650 km and 900 km. The satellite instrumentation includes an Overhauser proton magnetometer for scalar measurements. The accuracy of the scalar magnetometer is 0.5 nT but the resolution, which is more relevant in the present context, is better than 0.1 nT on board the satellite. Since Oersted is a polar orbiting satellite, it allows us to study the latitudinal variation associated with the hydromagnetic wave. An orbital period of approximately 100 minutes implies that temporal variations with periods well in excess of one minute or so cannot be unambiguously identified because the spatial variations associated with quiet day ionospheric currents, including the equatorial electrojet, can masquerade as temporal variations in the satellite data. The study has, therefore, been restricted to frequencies in excess of 10 mHz. Ground based support is provided by the data from the Japanese stations of Kanoya (KAN: Geographic $31^o25'N$,$130^o52'E$; Geomag 21.4^oN,200.3^oE), Kakioka (KAK: Geographic $36^o13'N$, $140^o11'E$; Geomag 26.9^oN,208.3^oE) and Memambetsu (MEM: Geographic $43^o54'N$,$144^o11'E$; Geomag 34.9^oN,210.8^oE). The component data from these stations have sampling rates of 1 sec. and a resolution of 0.01 nT. The present study examines specific periods that are characterized by the presence of oscillations (within the frequencies of interest) both in satellite and in ground data.

2. Data Selection And Treatment

The analysis is restricted to satellite passes in the geographic longitude zone between 125^oE and 155^oE to minimize any complexities that may arise in the data interpretation because of large differences between satellite and ground station longitudes. The special reference field model, IGRF(10c/99), based on the Oersted data [*Olson et al.*,

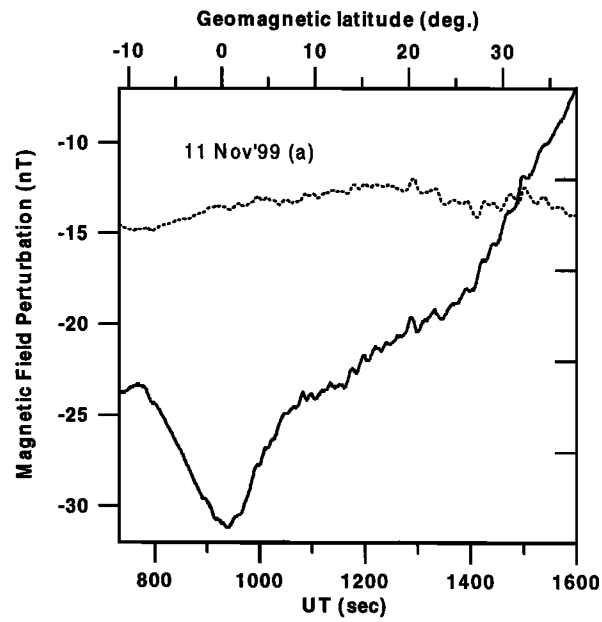

Figure 1. Plot of the unfiltered satellite scalar field (ΔF) variations (——) for a single pass. The corresponding field variations at Kanoya (baseline arbitrary) multiplied by a factor of 1.5 are also shown (...).

Paper number 2000GL011940.
0094-8276/01/2000GL011940$05.00

Table 1. LT and Geomagnetic Latitude ranges of passes

Date	LT (hr:min)	Geomag. lat(°N)
14 Mar'99	26:25 - 25:53	+24.47 to -39.18
5 Apr'99(a)	26:05 - 25:34	+23.18 to -39.60
3 Apr'99	14:03 - 13:33	-31.96 to +26.14
5 Apr'99(b)	14:01 - 13:31	-32.49 to +26.03
1 May'99	13:41 - 13:10	-37.35 to +23.04
2 Nov'99	10:52 - 10:22	-35.27 to +22.54
11 Nov'99(a)	10:32 - 09:52	-10.97 to +46.86
11 Nov'99(b)	10:50 - 10:20	-46.14 to +12.23

2000] is used to subtract out the background field at each satellite position. The model includes internal main field coefficients to the order 13, secular changes to the order 8 and corrections for external fields derived from Dst values. The rms error of the departures from the observed quiet time fields at satellite orbits is around 3 nT for latitudes within ±50° of the geomagnetic equator. The total field is computed from the model using hourly Dst values for external field corrections and subtracted from the satellite scalar magnetic field (F) to get the residual scalar magnetic field (ΔF) data that forms the basic time series in our analysis.

Plots of the residual satellite field and the corresponding ground station values were generated. The plots showed clear signature of oscillations in both the satellite and ground data for all the events considered. A typical plot of the unfiltered satellite residual field and Kanoya magnetic field variations for the pass on November 11, 1999 pass (a) are presented in Figure 1 with the current geomagnetic latitude of the satellite shown on the top axis. The plots show clear oscillations in both the fields that are closely related. This establishes the suitability of the data for the present analysis. A total of around 60 days of satellite data were similarly examined out of which around 25% of passes exhibited oscillations in the selected longitude zone. The present study includes two nighttime passes and six daytime passes. Date and ranges of local time (LT) and geomagnetic latitude for the passes selected are given in Table 1. To remove long period trends and high frequency noise, the time series of the satellite and the three ground stations was passed through a band pass filter that allowed only 10 to 100 mHz oscillations. The filtered time series for the satellite and three ground stations consisting of 1024 points for each pass are used for further analysis.

3. Coherence and Cross Phase

The data is subjected to an analysis similar to Kim and Takahashi [1999]. This requires cross-spectral analysis [*Robinson*, 1983] of the satellite and ground data to obtain the coherence and the phase relations between the satellite and each of the ground station time series. Identical analysis was performed for each of the passes listed in Table 1 using time series of 1024 points for each of the series. Barring a few exceptions coherence is greater than 0.9 for all the peaks.

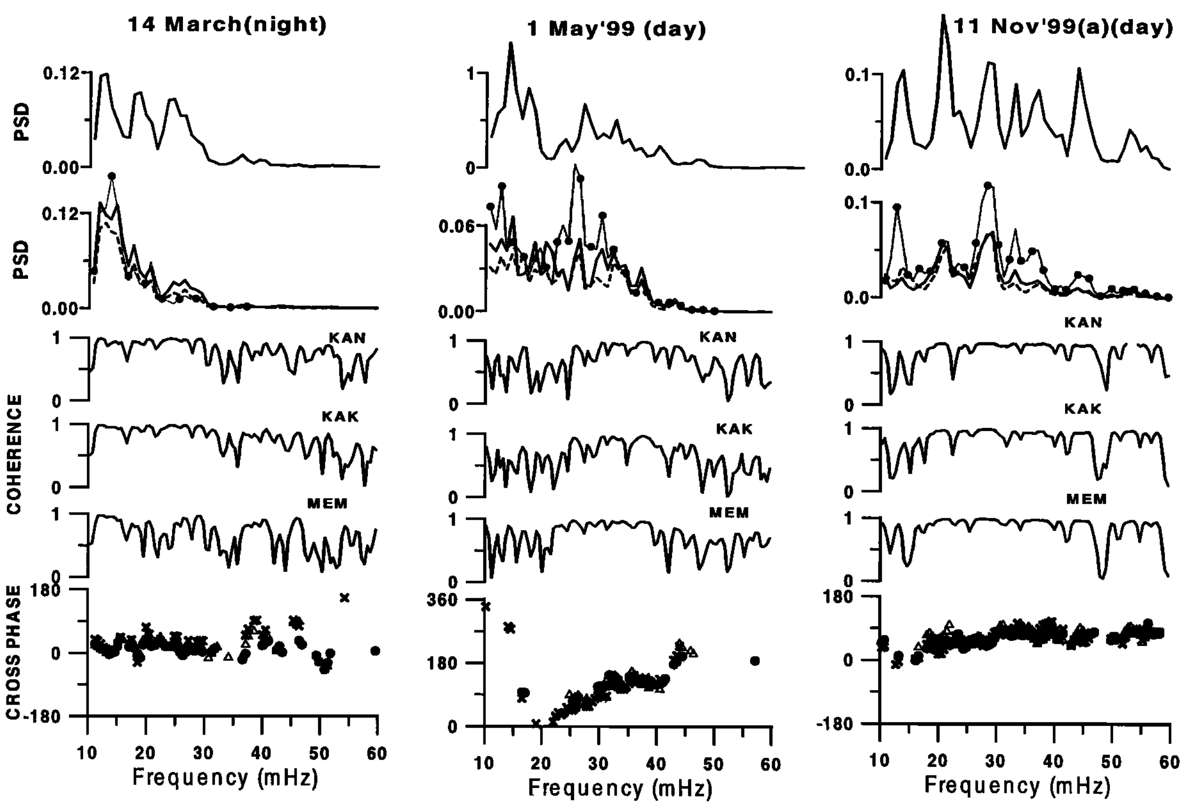

Figure 2. Power spectral density (PSD) for satellite, Kanoya (——), Kakioka (- - -), Memambetsu (-•-) and coherence with satellite oscillations for each of the ground stations. Cross phase for Kanoya (•), Kakioka (Δ) and Memambetsu (×) are depicted when coherence with satellite oscillations is greater than 0.85.

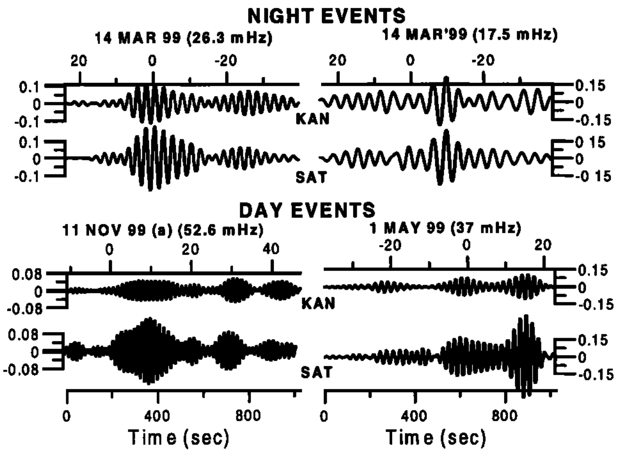

Figure 3. Amplitude (nT) of filtered time series for specific passes. Geomagnetic latitudes are shown on the top for each event.

We display in figure 2 results for one nighttime event and two daytime events representing different local time conditions. The left panel corresponds to nighttime, the middle panel to the afternoon (LT 13-14 hrs.) and the right panel to forenoon (LT 10-11 hrs.) conditions. The ionospheric conductivity, which depends on the solar zenith angle, is greatest in the afternoon sector. The upper panel of Figure 2 depicts the power spectral density (PSD) at the satellite height and the corresponding PSD at the three ground stations. Comparison of the spectra reveals that a number of peaks are common. The relationship between the spectra is brought out by the coherence between the signals at the satellite and the ground stations depicted in the middle panel. The coherence at the well defined common peaks is better than 0.9. The lower panel shows the cross-phase or the phase difference between the satellite and ground signals at the three stations. The phases are represented by discrete symbols characteristic for each station when coherence exceeds 0.85 for that particular frequency. The cross-phase information is very revealing. It clearly shows that the satellite and ground oscillations are in phase during the night conditions. The phase lag is close to zero even in the daytime at lower frequencies but the phase lag increases with frequency. The rise is much steeper in the afternoon than in the forenoon hours. The phase lag thus increases with frequency as well as with the conductivity of the ionospheric medium it is passing through. This feature is consistently brought out by the cross-phases at all the three ground stations.

4. Time and Latitudinal Structure

To get the time and latitudinal structure associated with each of the peaks, we use the 1024 point time series generated for each of the passes and subject it to narrow band pass filtering centered at each of the peaks. Figure 3 gives the resultant time variations at satellite and at Kanoya for two nighttime and two daytime events. The figure shows that hydromagnetic oscillations occur in bursts that are almost simultaneous at ground and satellite heights. In the nighttime events the pulses at the satellite and ground have about the same amplitude but during the day the amplitude of the pulses at the satellite heights are significantly larger especially at the lower latitudes. We find that this is universally true for daytime events. The satellite amplitude is enhanced within ±20° of the dip equator while outside this region the satellite and ground amplitudes are nearly same. The ground station is fixed and the observed amplitude cannot in any way depend on the position of the satellite. This enhancement could be a result of partial screening of the wave due to the enhanced conductivity associated with the equatorial electrojet region. Screening generates a weak image current that reduces the field below the ionosphere but in the process enhances the field above. Unfortunately no suitable ground station was available in the electrojet region to verify this.

While it is obvious from the figure that the same source of oscillations are seen at the two heights, it is possible to get a quantitative confirmation by taking the correlation between the satellite and ground time series at various time lags. There are standard test for testing the significance for the level of peak correlation obtained in each event [*Fisher*, 1970]. This is better than 99.9% in all the cases. In the majority of cases the peak correlation is in the region of 0.8 to 0.9. The time lag required for the maximum cross correlation gives another estimate of the phase delay because it indicates how much the filtered ground data has to be shifted backward in time to get the best correlation with the corresponding satellite data. The values obtained by the two methods are always very close in all the cases examined. This increases our confidence in our result. We show, in figure 4, the phase delays at Kanoya as a function of frequency, for all passes analyzed. The plot reaffirms the conclusions obtained from just one nighttime and two daytime passes depicted in Figure 2. The nighttime (Δ) ionosphere does not introduce any phase delay while during the day (•, □), a phase delay is produced by the ionosphere. This phase delay increases with frequency and also with the conductivity of the ionosphere.

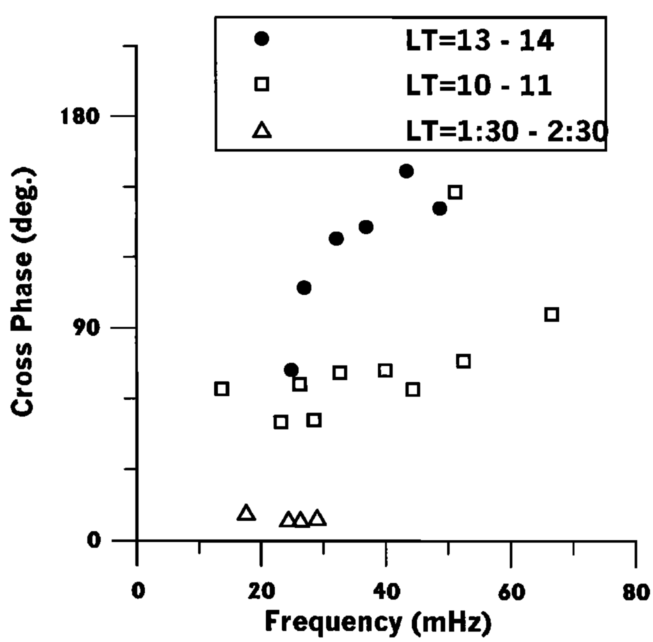

Figure 4. Phase lags as a function of frequency.

5. Results and Discussion

We find a high degree of coherence between the satellite and fixed ground oscillation despite the fact that the satellite covered a significant latitudinal distance. Even the time structures show a high degree of correlation over the large orbital distance. This suggests that the incident hydromagnetic waves are phase coherent over a large range of latitudes. The ionosphere introduces a phase delay which increases with increase in frequency of the oscillation as well as the electrical conductivity of the ionosphere. The frequency dependence is consistent with the results of Kim et.al [1998]. Theoretical models for computing shielding and phase delays introduced by the high latitude ionosphere [*Nishida*, 1978; *Hughes et al.*, 1976] are not valid in the latitude range of interest here. Kim and Takahashi [1999] computed the phase delay based on the model of Nishida [1978] and found that the phase shifts predicted are too small. Our values are in fair agreement with the observed phase delays of Kim and Takahashi [1999] which are around 50^o to 60^o at the period of 20 mHz. These are much larger than the 7^o to 25^o suggested by the model calculations. A full fledged non-local model which takes into account the varying inclination and conductivity with latitude may be required to provide the right answers.

Acknowledgments. We are grateful for support of the Oersted Project Office and the Oersted Science Centre at the Danish Meteorological Institute. The Oersted Project is funded by the Danish Ministry of Transport, Ministry of Research and Information Technology and Ministry of Trade and Industry. Additional support was provided by National Aeronautics and Space Administration (NASA), European Space agency (ESA), Centre Nationale d'Etudes Spatiales (CNES) and Deutsche Agentur fur Raumfahrtangelegenheiten (DARA). We are very thankful to WDC-C2, Kyoto, for making available the ground data of the Japanese stations and the Dst indices on the Internet.

The Editor would like to thank the reviewer of this manuscript.

References

Fisher, R. I. *Statistical methods for research workers,* 189 pp., Macmillan Publishing Co.,New York, 1970.

Hughes, W. J., and D. J. Southwood, The screening of micropulsation signals by atmosphere or ionosphere, *J. Geophys. Res., 81,* 3234-3240, 1976.

Kim, K.H., K. Takahashi and B. J. Anderson, Ground-satellite coherence analysis of Pc3 pulsations, *J. Geophys. Res., 103,* 11755-11769, 1998.

Kim, K.H. and K. Takahashi, Statistical analysis of compressional Pc3-4 pulsations observed by AMPTE CCE at L=2-3 in the dayside magnetosphere, *J. Geophys. Res., 104,* 4539-4558, 1999.

Nishida, A. *Geomagnetic Diagnosis of the Magnetosphere,* Springer-Verlag, New York, 1978.

Olson, N., Sabaka T. J. and L. Toffner-Clausen, Determination of the IGRF2000 model, *Earth Planet and Space,* 2000 (in press).

Robinson, E. A. *Multichannel time series analysis with digital computer programs,* 179 pp., Goose Pond press, Houston,Texas, 1983.

G. Jadhav, M. Rajaram, and R. Rajaram, Indian Institute of Geomagnetism, Dr. Nanabhoy Moos Marg, Colaba, Mumbai 400 005, India. (e-mail: geeta@iig.iigm.res.in; mita@iig.iigm.res.in; rrajaram@iig.iigm.res.in)

(Received June 23, 2000; revised September 4, 2000; accepted September 26, 2000.)