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Whistler Mode Waves Observed by DEMETER and Kannuslehto: Spatial Extent and Propagation to the Ground

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Abstract

Conjugate observations of magnetospheric whistler mode waves were conducted by the DEMETER spacecraft (altitude ≈ 660 km) and the Kannuslehto station, operated by the Sodankylä Geophysical Observatory in Finland. The aim of this paper is to investigate how these waves propagate to the ground and what their characteristic spatial scales are. The study calculates correlations between the measured power spectral density (PSD) and Kp indices for DEMETER and Kannuslehto, respectively, as a function of the wave frequency. The direct correlations between PSDs measured by the spacecraft and the ground-based station are further evaluated with respect to their geomagnetic longitude/L-shell separation. This allows us to estimate typical spatial scales of the observed waves. Altogether, the analysis covers more than 500 DEMETER half-orbits from November 2006 to March 2008. This period marks the overlap between the DEMETER and Kannuslehto data sets, with frequencies analyzed up to 16 kHz.

1. Introduction

Right-handed circularly polarized electromagnetic waves below the plasma frequency and the electron cyclotron frequency are known as whistler-mode waves [1]. They are generated by various mechanisms. The waves that propagate through the terrestrial magnetosphere can originate directly in the magnetospheric plasma due to various plasma instabilities or/and through wave-particle interactions [2]. Additionally, they can be generated by lightning activity in the Earth's atmosphere [3]. Such waves, after travelling a certain distance in the Earth-ionosphere waveguide, are able to penetrate through the ionosphere into the space environment. During propagation through the ionosphere, their attenuation can be significant, especially during daylight hours. Another possible mechanism of a whistler mode wave generation is an anthropogenic activity, either intentional (very low frequency transmitters) or unintentional (power line harmonic radiation) [4].

We use simultaneous observations by the Kannuslehto station and the low-altitude DEMETER spacecraft to investigate the correlations of the measured wave intensities with respect to the L-shell and geomagnetic longitude separations of the observation points. The primary goal is to identify the distinctive spatial scales of the observed wave phenomena and better understand the wave propagation to the ground.

2. Dataset

The current investigation uses electromagnetic wave observations from the low-altitude DEMETER satellite and the ground-based Kannuslehto station operated by the Sodankylä Geophysical Observatory (SGO) in Finland. The Kannuslehto station is located at 67.74° N 26.27° E. The corresponding geomagnetic longitude is about 120° and L-shell about 5.38. It operates in several months-long campaigns. The wave measurements are mediated by two orthogonal vertical magnetic loop antennas oriented in the east-west and north-south directions. The signal is sampled at 78.125 kHz, and full waveforms are available [5]. This work uses corresponding frequency-time spectrograms of total power spectral density with frequency resolution of 4.8 Hz and time resolution of 6 s at frequencies up to 16 kHz.

DEMETER was a French microsatellite that operated between the years 2004 and 2010 at the altitude of about 660 km. Its orbits were nearly Sun-synchronous with the corresponding local times of about 10:30 (“daytime”) and 22:30 (“nighttime”) hours, respectively. The performed measurements were continuous at geomagnetic latitudes lower than 65°. The instrumentation on board consists of an electric field instrument, ion analyzer, search coil magnetometer, energetic particle detector, and a Langmuir probe. Only the electric field data are used in this study due to the large number of interferences in the magnetic field data. These provide us with onboard calculated frequency-time spectrograms of a single electric field component with a time resolution of about 2 s and a frequency resolution of about 20 Hz [6].

3. Results

Average wave intensities measured by the DEMETER spacecraft and the Kannuslehto station are shown in Figure 1. DEMETER spacecraft measurements are limited to two narrow local time intervals. Hence, the wave intensities are plotted for each of them with respect to the frequency and L-shell. On the other hand, the ground-based station measurements cover all local times, while their L-shell is fixed. The wave intensities are thus plotted as a function of frequency and local time.

It is evident that, during nighttime orbits, DEMETER measured a higher wave intensity than during a daytime orbit for higher frequencies. Analogously, during night hours at Kannuslehto, the measured power spectral densities are higher than during daylight hours.

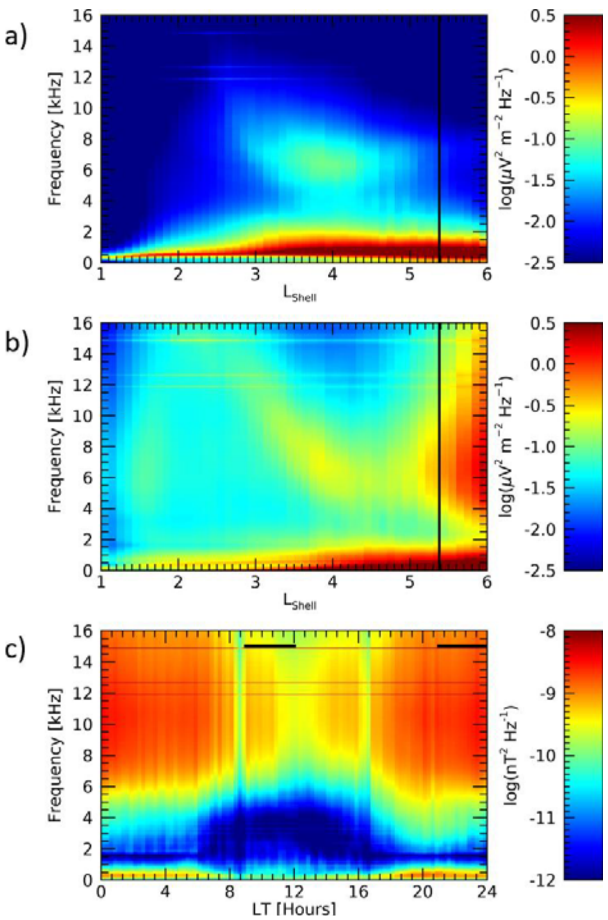

Figure 1. Average wave intensities as a function of frequency and L-shell/local time (LT). a)-b) Data measured by DEMETER during daytime and nighttime half-orbits, respectively. Vertical black lines denote the L-shell of Kannuslehto. c) Data measured by Kannuslehto. Horizontal black lines denote the daytime and nighttime at Kannuslehto.

Whether or not the ground-based station and the spacecraft observe at a given time the same wave event is given primarily by their spatial separation. For this reason, we investigate the correlations of measured wave intensities as a function of the L-shell separation ($\Delta L = L_{DEMETER} - L_{Kannuslehto}$) and geomagnetic longitude separation (Δ mlon = $mlon_{DEMETER} - mlon_{Kannuslehto}$) of the two instruments. Moreover, the situations during the daytime and nighttime DEMETER half-orbits are considered separately, as the daytime/nighttime ionospheric conditions are very different. The analysis was further performed separately for the times when DEMETER was in the northern and southern hemispheres, respectively. However, the results obtained did not show any significant differences, and only the results obtained for the DEMETER in the northern hemisphere are thus presented here.

A correlation analysis is performed at 750 Hz wide and 3-minute long frequency-time intervals (note that, during one half-orbit, the spacecraft collects data for approximately 30-40 minutes). The calculated correlations are then averaged over the respective spatial separation intervals. Figure 2 shows the calculated average correlations of measured wave intensities in the frequency bands 750 – 1500 Hz and 2000 – 2750 Hz. These bands are just below/above the first Earth-ionosphere waveguide cut-off frequency. During daytime, the correlations are visibly higher than during nighttime. The correlations are also higher for the lower investigated frequency band and when the spacecraft and the ground-based station are near each other.

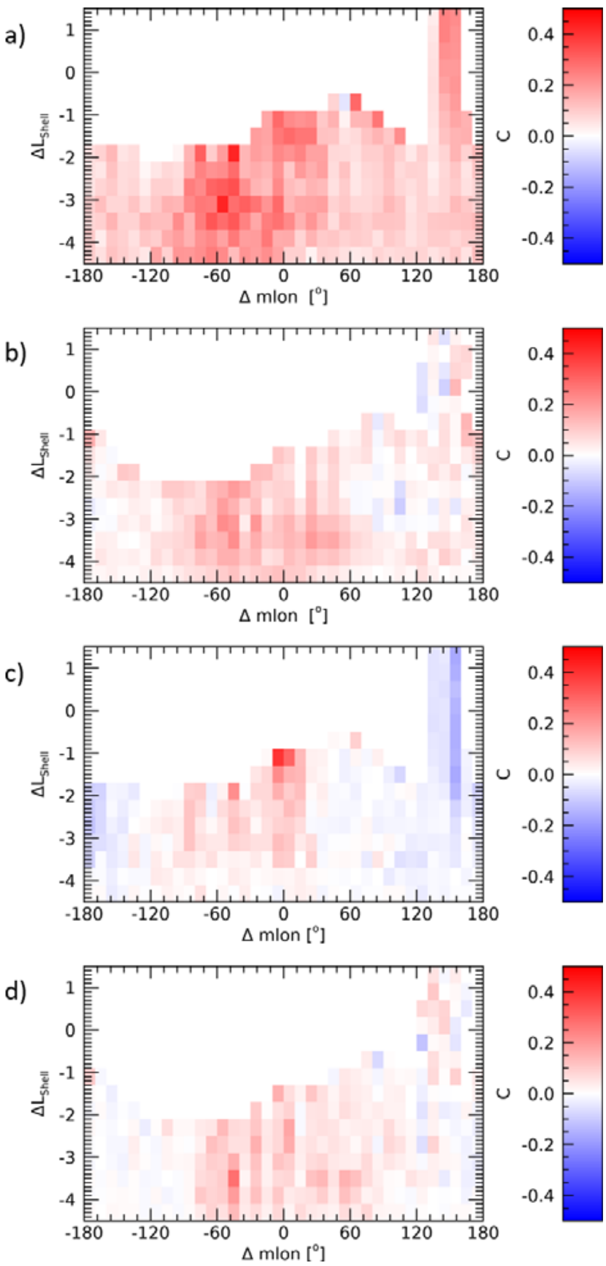

Figure 2. Calculated correlations of wave intensities as a function of the geomagnetic longitude and L-shell separation for a) 750 – 1500 Hz (daytime orbits), b) 750 – 1500 Hz (nightime orbits), c) 2000 – 2750 Hz (daytime orbits), d) 2000 – 2750 Hz (nighttime orbits).

Correlations of wave intensities measured by the DEMETER spacecraft and Kp indices are shown in Figure 3. The data are plotted as a function of a wave frequency and L-shell for daytime and nighttime orbits separately. The wave intensity is well-correlated with geomagnetic activity for higher L-shells and all frequencies during the nighttime orbit. For the daytime orbit, the data exhibit high correlation for the frequencies below 7 kHz. Waves with lower frequencies are well correlated during both day and night.

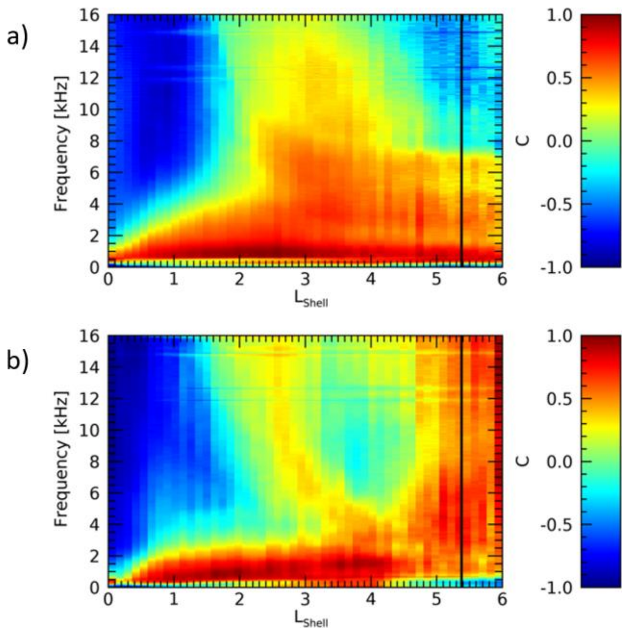

Figure 3. Correlations of wave intensities and Kp indices for DEMETER during a) daytime orbits, b) nighttime orbits. Vertical black lines denote the L-shell of Kannuslehto.

Correlations of wave intensities measured by the ground-based station and Kp indices are shown in Figure 4. Kannuslehto data are plotted only as a function of wave frequency, because the position of the ground-based station is fixed at L-shell ≈ 5.38. The highest correlations are obtained during the day for lower frequencies. During the night, the correlation is negative essentially all over the analyzed frequency range. The three dotted horizontal lines show the frequencies of the Alpha transmitter signals. The power of these signals is significantly anticorrelated with the geomagnetic activity at night.

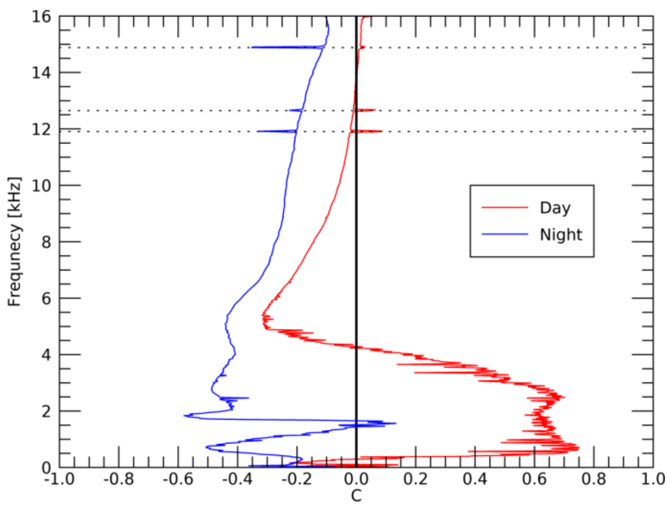

Figure 4. Correlations of wave intensities and Kp indices for Kannuslehto. Horizontal dotted black lines denote the frequencies of the Alpha transmitters.

5. Discussion

The intensity of the waves generated on the ground detected by the DEMETER spacecraft is lower during the daytime due to the more significant wave attenuation when penetrating through the ionosphere. At the same time, the Kannuslehto ground-based station also detects higher intensity during the night hours.

During the daytime, the frequency band 750 – 1500 Hz shows the highest correlation between the DEMETER and Kannuslehto measured wave intensities, peaking when the ground-based station and the spacecraft are close to each other. The lack of correlation dependence on ΔL is possibly due to a combination of ionospheric reflections [7] and wave propagation in the Earth-ionosphere waveguide, effectively spreading the wave power over a significant area.

The daytime correlation of power spectral density measured by Kannuslehto and the geomagnetic activity is positive as anticipated. During the night, the Kannuslehto-measured wave intensity and geomagnetic activity are anticorrelated, indicating the presence of a phenomeon that prevents the waves from reaching the ground at the time of higher geomagnetic activity. It might be due to the geometry of the magnetic field lines, which become more prolonged and deviate considerably from a dipole at these higher L-shells [8], or due to some changes in the ionospheric configuration. On the other, the wave intensities measured by DEMETER agree with the expectation of higher wave intensities during increased geomagnetic activity.

5. Conclusions

We analyzed simultaneous wave measurements by the low-altitude DEMETER spacecraft and the Kannuslehto ground-based station. The observed wave intensities are well correlated during the day when the instruments are not too far in geomagnetic longitude (L-shell separation does not play a significant role). The wave intensities measured by the ground-based station are anticorrelated with the geomagnetic activity during the nighttime, which contrasts with DEMETER observations. This may indicate that the waves detected by DEMETER do not propagate to the ground (at least not at the large L-shells of Kannuslehto).

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