STUDIES OF GEOMAGNETIC PULSATIONS USING MAGNETOMETER DATA FROM THE CHAMP LOW-EARTH-ORBIT SATELLITE AND GROUND-BASED STATIONS: A REVIEW

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ABSTRACT

We review research on geomagnetic pulsations carried out using magnetic field measurements from the CHAMP low-Earth-orbit (LEO) satellite and ground-based stations in South Africa and Hungary. The high quality magnetic field measurements from CHAMP made it possible to extract and clearly resolve Pi2 and Pc3 pulsations in LEO satellite data. Our analyses for nighttime Pi2 pulsations are indicative of a cavity mode resonance. However, observations of daytime Pi2 pulsation events identified in ground station data show no convincing evidence of their occurrence in CHAMP data. We also studied low-latitude Pc3 pulsations and found that different types of field line resonant structure occur, namely discrete frequencies driven by a narrow band source and L-dependent frequencies driven by a broad band source.

Keywords: Geomagnetic pulsations, LEO satellite, Magnetometer data, Pi2 pulsation, Pc3 pulsation, Field line resonance

1 INTRODUCTION

In this review we show how research on geomagnetic pulsations can be carried out using magnetic field data from the CHAMP low-Earth-orbit (LEO) satellite and ground-based stations. The review deals specifically with research led by the Hermanus Magnetic Observatory (HMO). However, a number of other research groups have also carried out research on geomagnetic pulsations utilizing CHAMP data. For example, Vellante et al. (2004) used CHAMP vector magnetometer data to study Pc3 field line resonances; Heilig et al. (2007) used CHAMP total magnetic field data to study upstream waves; while Pilipenko et al. (2008) used LEO satellite data to model the structure and propagation mechanisms of Pc3 pulsations. Since the emphasis of the workshop is on the recording and processing of geomagnetic field data, we also illustrate the value and importance of high quality magnetometer data, i.e., good resolution and accurate timing, for pulsation studies.

Geomagnetic pulsations are the magnetic signatures of ultra low frequency (ULF) waves in the Earth's magnetosphere. These oscillations have short periods, usually of the order of seconds to minutes, and small amplitudes, usually less than one part in 10^4 of the Earth's main field. Like longer period disturbances, such as magnetic storms and substorms, they are mostly of solar origin, in contrast to the Earth's main field and secular variation, which are of internal origin (see McPherron, 2005, for a review of geomagnetic pulsations). Observations indicate that geomagnetic pulsations may be divided into two broad classes. Those of a regular and mainly continuous character are known as Pc, covering the period range from 0.2 to 600 sec and are divided into five sub-groups depending on their period. Pulsations with an irregular and impulsive nature are known as Pi and divided into two sub-groups based on period (Jacobs et al., 1964). Geomagnetic pulsations serve as extremely useful and powerful diagnostics of the Earth's magnetosphere. For example, Pi2 pulsations recorded at low latitudes are regarded to be one of the clearest indicators of magnetospheric substorm onsets and intensifications (Saito et al., 1976); consequently, they can play an important role in space weather forecasting. Pc3 pulsations can be used as a diagnostic for determining plasma density along geomagnetic field lines and have recently been demonstrated to be a means of tracking the temporal variations of the plasmapause (Menk et al., 2004).

The CHAMP satellite was launched on 15 July 2000 into a near polar circular orbit at an initial altitude of 454 km (Reigber et al., 2002). The orbit, which lies roughly a similar distance above the E-region ionosphere as ground stations are below, provides a unique opportunity to study geomagnetic pulsations and the effects of the ionosphere on their propagation. The magnetic field observations from CHAMP have a particular advantage over ground-based data for pulsation studies. It is difficult to discriminate between shear Alfvén and fast mode waves using ground-based data since both manifest themselves in the H (magnetic north) component, due to the effects of the ionosphere. An advantage of using LEO satellite data is that the two wave modes manifest themselves in different components above the ionosphere, so that it is easier to discriminate between them.

The ground-based data used in this study were the induction magnetometer data recorded at two low latitude stations in South Africa, namely Hermanus (HER; 34.42°S, 19.23°E) and Sutherland (SUT; 32.40°S, 20.67°E), and fluxgate magnetometer data recorded at Tihany, Hungary (THY; 46.90°N, 17.89°E) and Kakioka, Japan (KAK; 36.23°N, 140.18°E).The induction magnetometer data were converted to nanotesla units by correcting for the frequency-dependent amplitude and phase response of the magnetometer system. All data sets were sampled at 1 s intervals. The stations HER and THY are roughly conjugate while HER and KAK are separated by about 8 h in local time.

2 OBSERVATIONS OF Pi2 PULSATIONS AT LOW LATITUDES

The pulsations most commonly observed during local nighttime are Pi2 pulsations, which are impulsive, damped oscillations of the geomagnetic field in the frequency range 5-30 mHz and with amplitudes in the range 0.25-2.5 nT. The braking of high-speed ion flows in the near-Earth central plasma sheet, at the boundary between regions of dipolar and tail-like field, produce the substorm current wedge and compressional pulses, which lead to Pi2 pulsations at high and low latitudes respectively (Shiokawa et al., 1998). At high latitudes, Pi2 pulsations are shear Alfvèn waves associated with the “switch on” of the substorm current wedge (Baumjohann & Glaßmeier, 1984) and are observed only close to local midnight. At low latitudes Pi2 pulsations are due to cavity mode resonances (Takahashi et al., 1995). At low latitude ground stations, they are observed at all local times at night and also often observed during local daytime (Sutcliffe & Yumoto, 1989, 1991).

The CHAMP data used for Pi2 studies were the pre-processed data from the fluxgate vector magnetometer transformed into the North-East-Centre (NEC) coordinate system (product identifier CH-ME-2-FGM-NEC) with 1 s sampling. Data selection commenced by determining times when CHAMP was located within 60° of longitude of Hermanus or Kakioka and at latitudes less than 50°N and 50°S; the latter condition was specifically applied to exclude times when the satellite was crossing current systems associated with the auroral electrojets. The nightside ground station data (Hermanus or Kakioka) for these times were then scanned for suitable Pi2 pulsation events. The satellite data for the times spanning the ground station Pi2 events were then further processed to determine whether Pi2 pulsations were present and observable (Sutcliffe & Lühr, 2010). The supplemental processing of the satellite data was similar to that described in detail by Sutcliffe and Lühr (2003, 2004) and involved four stages. The first step was to initially subtract a main field model from the observed data and to inspect the residual field in order to ensure that the interval did not contain disturbances (of amplitude tens of nanoteslas) that when filtered may have leaked into the Pi2 band and could be erroneously interpreted as Pi2 pulsations. The second step in processing of the data was to subtract a lithospheric magnetic field anomaly model. Consideration of the scale size of lithospheric magnetic anomalies and the rate at which these are traversed by CHAMP indicates that they will result in variations falling within the Pi2 band of frequencies (Sutcliffe & Lühr, 2004). The data were then rotated into a field-aligned coordinate system, for which the background magnetic field was determined from the lowpass filtered NEC data. In this coordinate system, the compressional component (B_{com}) is aligned with the ambient magnetic field direction B (positive northward), the toroidal component (B_{tor}) is transverse to B in the azimuthal direction (positive eastward), and the poloidal component (B_{pol}) is transverse to B in the magnetic meridian plane (positive inward). Finally, the data were bandpass filtered in the Pi2 frequency band (0.0067−0.025 Hz). The ground station data were filtered with the same frequency bandpass.

Using data from CHAMP, Sutcliffe and Lühr (2003) were for the first time able to extract and clearly resolve Pi2 pulsations in vector magnetometer data at low Earth orbit. Previously, the difficulty had been to extract the relatively small pulsation perturbation from the relatively large background field due to the limited digitization step size of the satellite magnetometer and to the environmental noise. The magnetic field measurements from CHAMP are of unprecedented accuracy and resolution, which have enabled clearly resolved observations of Pi2 and Pc3 pulsations in the ionosphere at low latitudes using vector magnetic field data (Sutcliffe & Lühr, 2003; Vellante et al., 2004; Ndiitwani & Sutcliffe, 2009) and upstream waves using total magnetic field data (Heilig et al., 2007).

Figure 1 shows two examples of night-time Pi2 pulsations observed on CHAMP and the near-conjugate ground stations HER and THY. The time series plotted in each panel show the compressional (top), toroidal (middle), and poloidal (bottom) components at CHAMP (solid line) and the H, D, and H components, respectively, at HER (dashed line) and THY (dotted line). Panel (a) shows an event that occurred on 2 July 2004 with onset shortly after 2331 UT; respective local times are shown in the figure. During the 10 min interval of the event, CHAMP was in the Southern Hemisphere and travelled from approximately 41°S to 3°S. The similarity and in-phase relationship between the compressional and poloidal components at CHAMP with the H component oscillations at HER and THY are striking; the in-phase relationship with H implies that the compressional and poloidal components are in phase with each other. There does not appear to be a clear relationship between the toroidal component at CHAMP and the D components on the ground.
Panel (b) shows an event that occurred on 11 April 2004 with onset shortly after 1844 UT. In contrast to the first event, CHAMP was located in the Northern Hemisphere during most of this event and travelling southward. This example again illustrates the excellent in-phase relationship between the compressional and H components. During the major

part of the Pi2 pulsation following onset, the CHAMP poloidal component oscillates in antiphase with the H components; however, in the latter part of the pulsation, after CHAMP crosses into the Southern Hemisphere, this changes to an in-phase relationship.

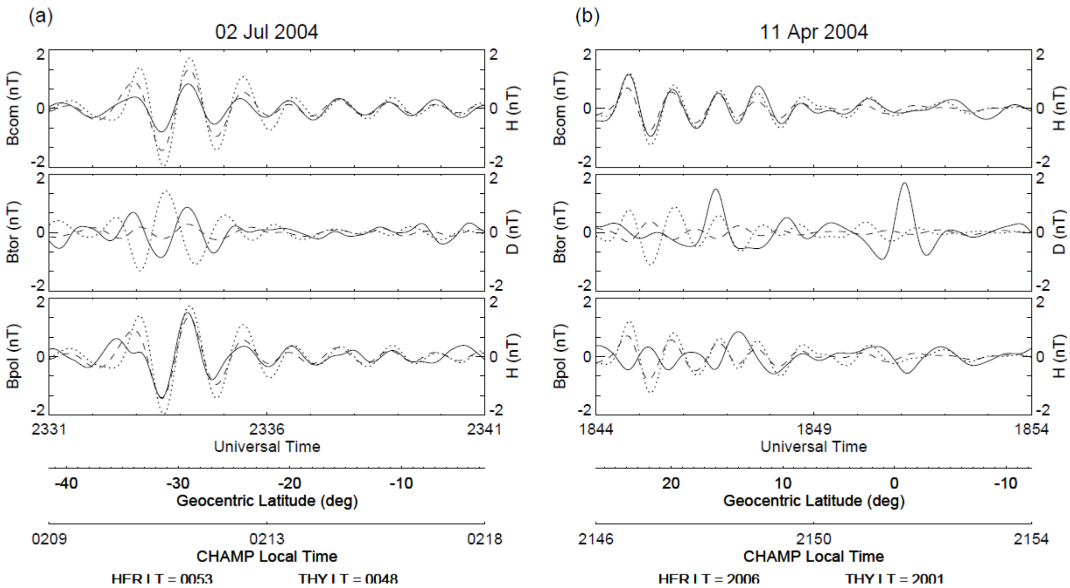

Figure 1. Observations of night-time Pi2 pulsations on the CHAMP satellite (solid line) and the near-conjugate ground stations HER (dashed line) and THY (dotted line) when (a) CHAMP was in the southern hemisphere and (b) CHAMP was in the northern hemisphere.

The examples shown in Figure 1 are in good agreement with numerous other examples of night-time Pi2 pulsations that have been observed simultaneously on CHAMP and on the ground at HER and THY (Sutcliffe & Lühr, 2003, 2010). The good correlation found between the compressional and poloidal modes above the ionosphere with the H component on the ground for these night-time Pi2s is indicative of a fast mode oscillation (Kivelson & Southwood, 1988). Furthermore, the phase relationships between the compressional and poloidal components at CHAMP and the H component on the ground are indicative of a cavity mode resonance. In particular, the fact that the phase relationship between the compressional and poloidal (i.e., the fast mode) components on CHAMP and the H component on the ground remain fixed as CHAMP moves across L shells indicates that CHAMP is observing a standing wave. In addition, the differences in phase relationships for CHAMP in the northern and southern hemispheres indicate that the compressional mode has an anti-node at the equator while the poloidal mode has a node at the equator. The ground-to-satellite phase relationships observed with the satellite above the ionosphere agree with those observed by Takahashi et al. (1995) when the satellite was deeper within the cavity or near its outer boundary. The phase relationships of these nighttime observations therefore agree with those of the simple cavity mode resonance model proposed by Takahashi et al. (1995).

Pi2 pulsations are often observed during local daytime at low-latitude ground stations (Sutcliffe & Yumoto, 1989, 1991); however, it is not clear whether or not daytime Pi2 pulsations are observed in space. Consequently, Sutcliffe and Lühr (2010) used CHAMP magnetometer data to search for the occurrence of daytime Pi2 pulsations in the F-region ionosphere. Events were selected for times when CHAMP and HER were located in the dayside hemisphere and KAK observed Pi2s located on the nightside or visa-versa for HER and KAK. They regularly observed Pi2 pulsations during local daytime at HER and KAK; however, they have not been able to clearly identify Pi2 pulsations above the ionosphere using CHAMP magnetometer data.

We illustrate this result in Figure 2 by considering an event that occurred on 4 December 2004 with onset shortly after 1300 UT; the mean local times at CHAMP, HER, and KAK were 1203, 1422, and 2226 respectively. The time series are plotted in Figure 2(a), where the panels from top to bottom respectively show the compressional, toroidal, and poloidal components at CHAMP (solid line) and the H, D, and H components at HER (dashed line) and KAK (dotted line). The figure shows an in-phase relationship between the HER and KAK H components and an anti-phase relationship between the D components. Although there are oscillations at CHAMP, they do not appear to match the oscillations at HER or KAK. Figures 2(b) and (c) show the spectral characteristics of the compressional and poloidal components respectively relative to the H component oscillations. The top panels show the amplitude spectra for CHAMP (solid), HER (dashed), and KAK (dotted). The H component spectra at HER and KAK are very similar. The power in the spectrum for the CHAMP compressional component tends to lie at lower frequencies; however, the poloidal component spectrum exhibits a number of peaks in the Pi2 band. The center and bottom panels show the coherence and phase difference respectively for HER/CHAMP (solid) and HER/KAK (dotted) and demonstrate that the H component oscillations at HER and KAK are coherent and in-phase in the Pi2 band. There is no evidence of coherent oscillations in the CHAMP compressional component. Although there is some evidence of coherent oscillations where there are small peaks in the poloidal component spectrum, this only occurs at isolated frequencies (18 and 27 mHz) rather than throughout the Pi2 band.

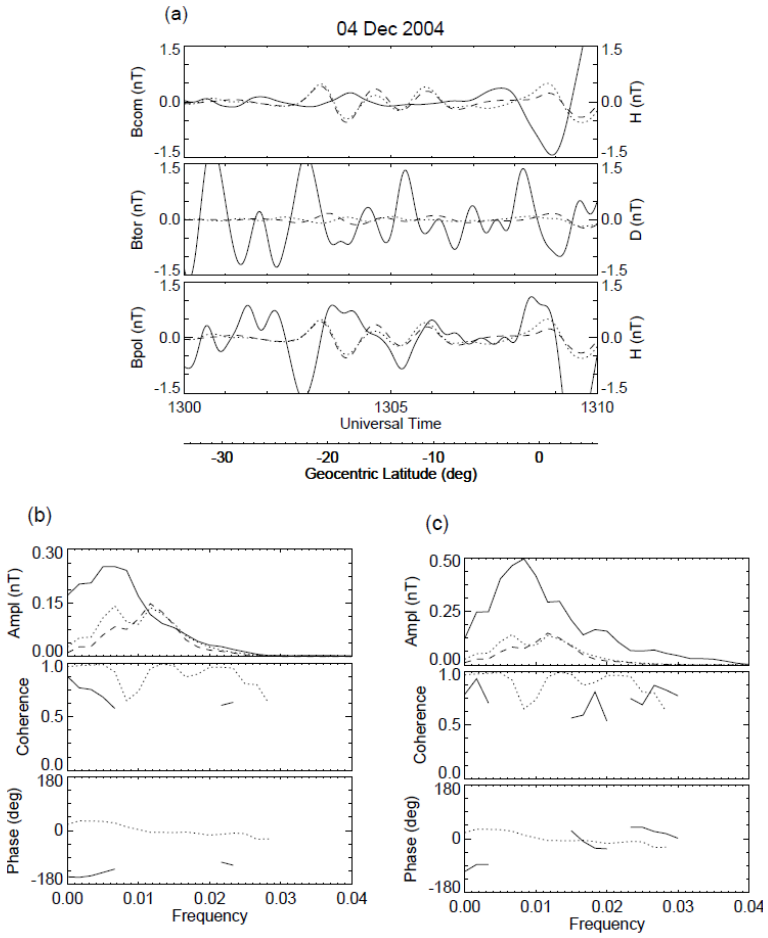

Figure 2. Observations of oscillations on 4 Dec 2004 when CHAMP (1203 LT) and HER (1422 LT) were located in the dayside hemisphere and KAK (2226 LT) was located on the nightside. (a) Clear Pi2 pulsations are observed at HER (dashed lines) and KAK (dotted lines). The oscillations at CHAMP (solid lines) do not appear to match the oscillations at HER or KAK. (b) & (c) This is confirmed by plots of the spectral characteristics.

In summary, Sutcliffe and Lühr (2010) found that although daytime Pi2 pulsations are regularly observed on the ground, they could find no convincing evidence of their occurrence in CHAMP data. Consequently, they concluded that Pi2 pulsations on the dayside differ from their night-time counterparts. In contrast, Han et al. (2004) reported two events in Ørsted satellite data on the dayside, which they interpreted as being Pi2 pulsations oscillating in anti-phase to ground Pi2s; however, their results are not entirely convincing for a number of reasons as explained by Sutcliffe and Lühr (2010).

3 OBSERVATIONS OF Pc3 PULSATION FIELD LINE RESONANCES

The geomagnetic pulsations most commonly observed at low to middle latitude stations, such as Hermanus, during local daytime are Pc3 and Pc4 quasi-sinusoidal continuous pulsations. The frequency of oscillation is generally in the range 25-100 mHz, and amplitudes typically range from 0.1-1.0 nT. The dominant characteristics of these pulsations are consistent with those expected of field line resonances (FLRs), which are transverse standing Alfvén waves along geomagnetic field lines, that is, equivalent to the concept of a vibrating field line fixed between the ionospheres in opposite hemispheres.

Baransky et al. (1985) initially proposed a method for the direct measurement of the eigenfrequency of magnetic field lines using ground-based magnetometer data. They demonstrated that either the difference or ratio of Pc3-4 pulsation amplitude spectra observed at two closely spaced meridianal ground stations can be used to determine the eigenfrequency associated with the field lines between the two stations. Waters et al. (1991) proposed a more reliable technique of determining the presence of a field line resonance (FLR) by the use of the cross-phase spectrum. With this method, the peak in the phase difference of the H-components from two closely spaced stations identifies the resonant frequency. Figure 3 illustrates the use of these methods for FLR frequency determination. Figure 3(a) shows a 10 min interval of Pc3 band-pass filtered data recorded at SUT and HER. The three panels in Figure 3(b) show the FFT amplitude spectra, the amplitude difference, and the phase difference respectively for the data in Figure 3(a). Figure 3(c) shows dynamic amplitude and phase difference spectra for the interval 05-17 UT; the dynamic spectra were computed using a 10 min data window, which was progressively shifted by 5 min. The figure clearly indicates the occurrence of a FLR centered on a frequency close to 50 mHz. Dynamic spectra such as those in Figure 3(c) were generated for the dates of all Pc3 pulsation events studied on CHAMP in order to serve as confirmation of the presence of FLRs.

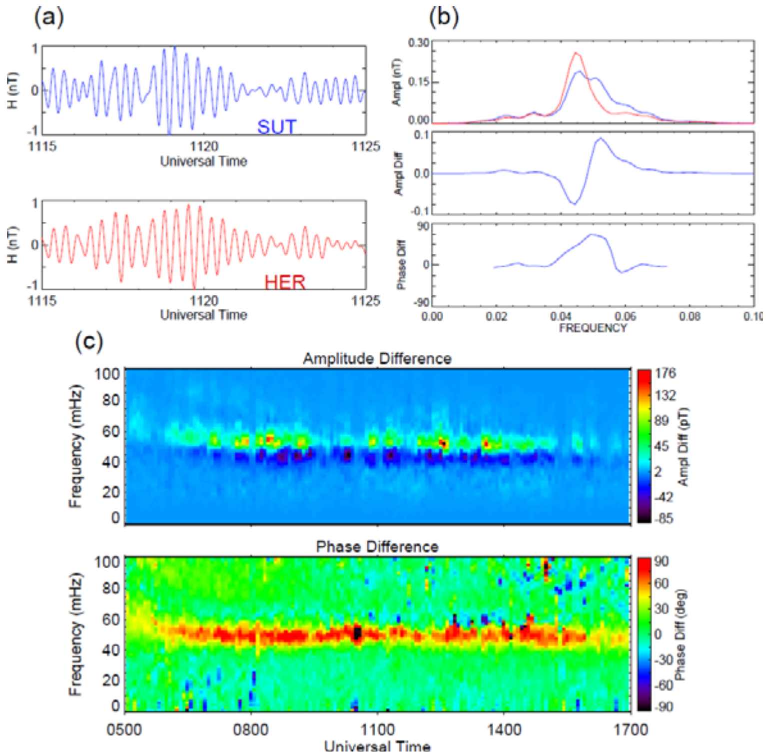

Figure 3. Example of Pc3 FLR frequency determination from SUT and HER induction magnetometer data using the amplitude difference and phase difference methods.

Since the stress of this workshop is on the recording and processing of geomagnetic field data, we deviate very briefly at this point to illustrate the importance of accurate timing in magnetometer data for pulsation studies. In order to ensure that the results of scientific research are exact, it is generally essential that the data utilised be accurate and correct; consequently, it is sometimes stated that “no data is better than incorrect data”. In Figure 4 we illustrate the effect of a timing error in the data at one of the pair of stations used to determine the FLR frequency. Although the results given by the amplitude difference method appear to be acceptable when there is a time error, the FLR frequency is incorrect. The results given by the phase difference method are clearly incorrect due to the rapid roll-over of phase, which is probably an advantage over the amplitude difference method. Another advantage of the phase difference method is that it can be used to correct the timing error by time shifting the incorrect data set until the dynamic phase plot appears to be correct.

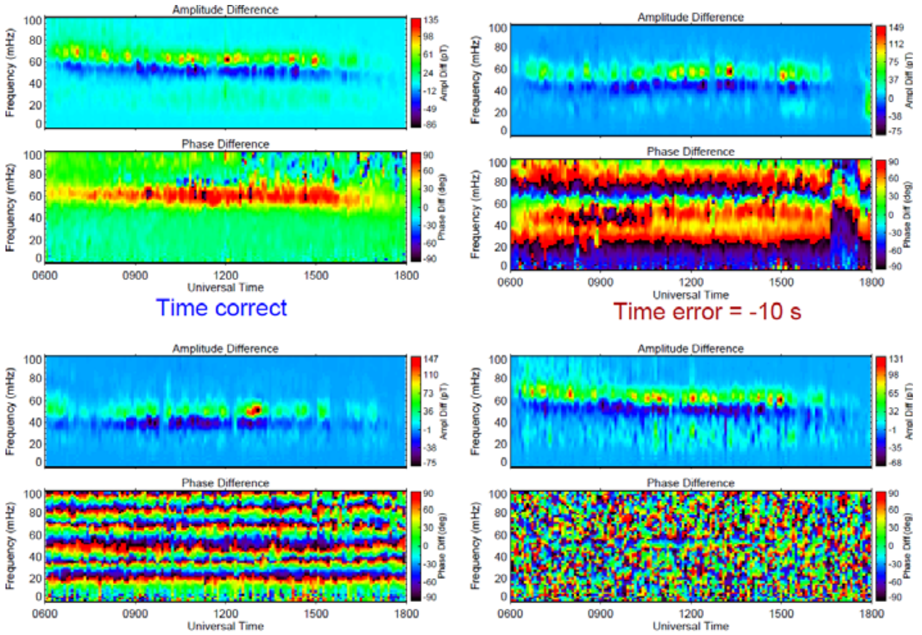

Figure 4. Examples where there is a timing error in the data from one of the stations (SUT) used to determine the FLR frequency.

The CHAMP data used for Pc3 studies were the pre-processed data from the fluxgate vector magnetometer in the sensor reference frame (product identifier CH-ME-2-FGM-FGM). Data in this reference frame were preferred because the data transformed into the North-East-Centre (NEC) coordinate system are contaminated by attitude noise and not entirely suitable for Pc3 studies. However, the satellite data were rotated into a field-aligned coordinate system determined from the low pass filtered data prior to further analysis. Data selection for the Pc3 FLR study was made for times when CHAMP traversed the southern African region within 20^0 of longitude of HER; the ground and satellite data were then scanned for Pc3 pulsations. Due to CHAMP's orbit, it traverses the latitudinal structure of geomagnetic field lines very rapidly and covers a latitudinal range of 1^0-2^0 in one Pc3 wave period; consequently, traditional methods of spectral analysis such as the FFT are not suitable (Vellante et al., 2004, Ndiitwani & Sutcliffe, 2009). Maximum entropy spectral analysis (MESA) was used since it provides greater resolution than linear methods and has the ability to analyze short data records (Haykin & Kesler, 1979). We used the Ulrych and Clayton (1976) method for computing the prediction error filter (PEF) coefficients (see Ndiitwani & Sutcliffe, 2009 for details). In order to study the latitudinal FLR structure, we generated dynamic MESA spectra computed for 90s data lengths, which were progressively shifted by 10s.

Figure 5 shows the MESA dynamic spectra at HER and CHAMP for a Pc3 pulsation that occurred on 15 Feb 2003 when CHAMP traversed southern Africa (Ndiitwani & Sutcliffe, 2009). The HER H-component spectrum plotted in the upper panel of Figure 5(b) clearly shows a field line resonance around 45 mHz. The dynamic spectra for CHAMP, plotted in Figure 5(c), show multiple frequency structures that change over the 10 minute interval in all components. During the first three minutes, clear oscillations at 45 and 65 mHz are observed in the compressional and poloidal components. There is a short interval of intense oscillations in the toroidal component B_{tor} at 60 mHz centred at 11h17.5 UT when CHAMP was at geocentric latitude of 27^0 S. This is followed by a short interval of intense oscillations at 40 mHz centred at 11h19 UT when CHAMP was at geocentric latitude of 34^0 S and crossing close to HER. These are FLRs driven by the fast mode oscillations at 65 mHz and 45 mHz respectively. However, the B_{tor} oscillations observed on CHAMP suffer an apparent Doppler shift in frequency and are shifted to slightly lower frequencies relative to the fast mode oscillations and the FLR observed on the ground at HER. This is a consequence of the rapid poleward motion of the satellite across the resonance region where the phase varies rapidly (Vellante et al. (2004).

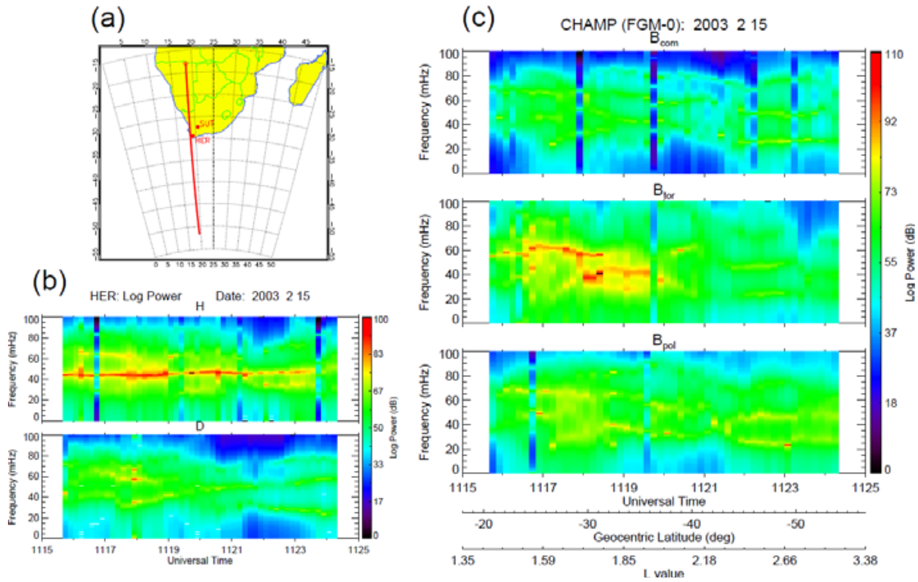

Figure 5. (a) Map of the southern African region showing the CHAMP ground-track as it traversed the region during a Pc3 pulsation on 15 Feb 2003. (b) & (c) MESA dynamic spectra of the magnetic field components observed at Hermanus and CHAMP respectively. Axes for geocentric latitude and L-value along the satellite track are included.

The occurrence of a FLR when CHAMP was crossing over HER provided the opportunity to test the theoretical prediction that transverse Alfvén waves will be rotated by 90^0 on transmission through the ionosphere. Figure 6 shows hodograms in the B_{pol}-B_{tor} plane for the satellite and in the H-D plane for the ground measurements for three consecutive 20 second time intervals during CHAMP's path over HER. The 90^0 rotation of the magnetic field components due to ionospheric Hall current is clearly observable.

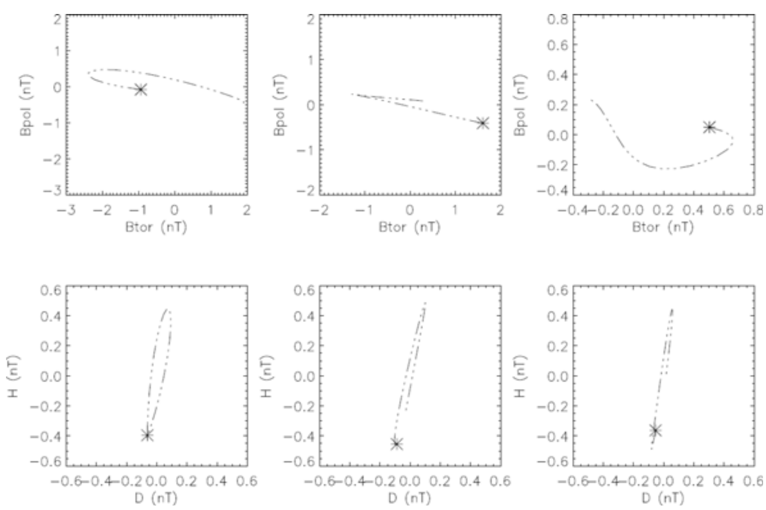

Figure 6. CHAMP (top panel) and ground (bottom panel) wave hodograms for three consecutive 20 second intervals at the time when the satellite was passing over the Hermanus ground station.

Figure 7 shows MESA dynamic spectra at HER and CHAMP during Pc3 pulsation activity on 13 Feb 2002 (Ndiitwani & Sutcliffe, 2010). A field line resonance is clearly visible in the HER H-component in Figure 7(a) with frequency centred around 34 mHz between 0727 and 0735 UT. The dynamic spectra for CHAMP are shown in Figure 7(b) and exhibit multiple frequency structures that change over the 10-min interval. An important feature in B_{com} is the broadband frequency structure of enhanced intensity between 30 and 60 mHz, increasing to 70 mHz, between 0726 and 0733 UT. The most outstanding feature in the toroidal component (Btor) is an intense oscillation at a frequency of 30 mHz commencing at about 0727 UT that increases to a maximum of 50 mHz at about 0730 UT when the satellite reaches a shell value of L~1.6. In contrast to the event shown in Figure 5, the multiple fast mode frequency structures observed in this event do not appear to drive discrete FLRs.

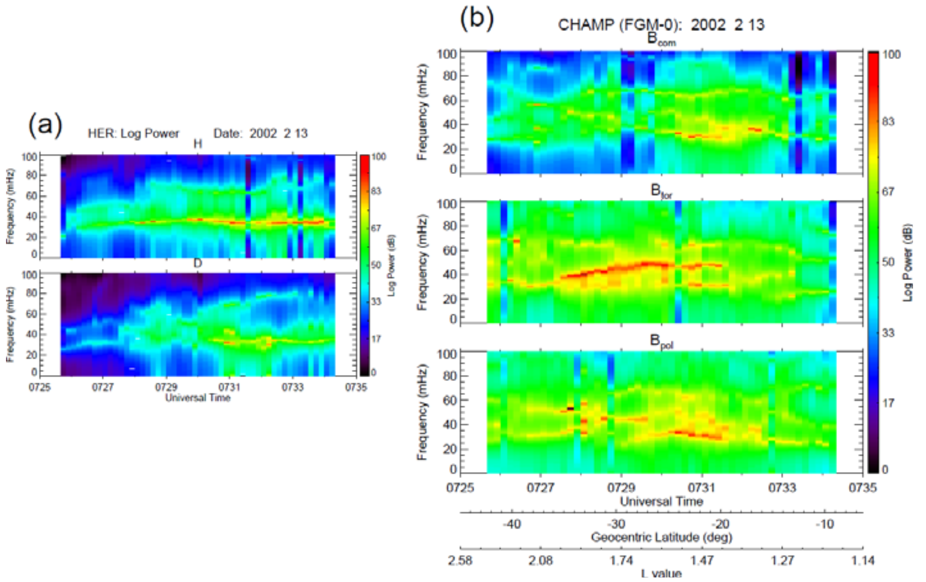

Figure 7. (a) & (b) MESA dynamic spectra of the magnetic field components observed at Hermanus and CHAMP respectively on 13 Feb 2002. Axes for geocentric latitude and L-value along the satellite track are included.

The analysis of Pc3 pulsations observed on the ground and on CHAMP can be summarised as follows (Vellante et al., 2004, Ndiitwani & Sutcliffe, 2009, 2010). When a number of discrete frequency components are observed in the fast mode wave, they drive field line resonances at latitudes where they match the field line resonant frequency. However, when a broadband compressional source spectrum is observed in the fast mode wave, toroidal mode resonant oscillations with continuous L-dependent frequency are observed on CHAMP. The toroidal mode observed on CHAMP experiences a Doppler frequency shift due to the rapid motion across the resonance region. Polarization hodograms in the resonance region clearly show the expected 90º rotation of the field line resonant magnetic field components.

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