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Ionospheric localisation and expansion of long-period Pi1 pulsations at substorm onset

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[1] We examine the initial ionospheric localisation and expansion of Pi1 pulsations associated with a substorm onset observed on 1st November 2006 with the combined CARISMA and THEMIS GMAG network of ground-based magnetometers. We demonstrate how the first ionospheric pulsation disturbance lies in the long-period Pi1 band. The long-period Pi1 pulsations at substorm onset are initially localised in longitude, and expands away from an epicentre in the ionosphere, with ~16 s timing between stations. We further establish a link between the location of the downward field-aligned current (FAC) element which subsequently develops within the substorm current wedge (SCW), and the initial location of the onset of long-period Pi1 pulsations. The arrival of the initial long-period Pi1 wavepacket demonstrates the importance of global networks of ground-based magnetometers for probing substorm onset. The Pi1 expansion proceeds westward at a rate of approximately 1 MLT hour per ~20 seconds, representing a very rapid expansion of the Pi1 signal at the ground. The resolution of the Pi1 localisation and the rate of expansion suggest Pi1 waves can play an important role in studies of the causal sequence of energy release in substorms. **Citation:** Milling, D. K., I. J. Rae, I. R. Mann, K. R. Murphy, A. Kale, C. T. Russell, V. Angelopoulos, and S. Mende (2008), Ionospheric localisation and expansion of long-period Pi1 pulsations at substorm onset, *Geophys. Res. Lett.*, *35*, L17S20, doi:10.1029/2008GL033672.

1. Introduction

[2] Substorm expansion-phase onsets are traditionally identified in ground magnetometer data in Pi2 (40–150 s period) wave signatures occurring in conjunction with magnetic bays which develop when the night-time magnetosphere dipolarizes, leading to the formation of the substorm current wedge (SCW). Studies of the polarisation of the Pi2 [e.g., *Lester et al.*, 1983] have shown this to be an excellent indication of the location of the substorm current wedge, both for locating the upward and downward field-aligned current (FAC) elements, and estimating the latitude of the centre of the electrojet. However, timing substorm onsets with Pi2s has the inherent limitation that the period of the wave (40–150 s) limits the accuracy with which the onset can be timed. This time resolution is the same order as the "2-minute problem" of uncertainty generally associated with determining the location in space of substorm expansion phase onset (e.g., see *Ohtani* [2004] and the review by *Petrukovich and Yahnin* [2006]). With the detection of a higher frequency class of ULF waves associated with substorm onset, namely Pi1 (periods of 1–40 s), substorm onset timing resolution can at least in theory be improved by using the shorter wave periods in the Pi1 band. The ground-based observatory network [*Mende et al.*, 2008] of the THEMIS mission is equipped with magnetometers with 2Hz time resolution for precisely this reason. The THEMIS/GBO network complements the capabilitites of pre-existing networks which results in a dense array of stations with sufficient spatial and temporal resolution to capture such waves and determine substorm onsets to within the mission requirement of 30 second resolution or better [e.g., *Sibeck and Angelopoulos*, 2008].

[3] Studies of onset-related Pi1 pulsations have in general concentrated on a short-period class of broadband and bursty signals in the ~0.1–1 Hz frequency range and denoted as Pi1B [e.g., *Bösinger*, 1989; *Lessard et al.*, 2006]. Pi1B pulsations have been associated with a variety of geophysical phenomena; ionospheric currents, including upward field-aligned currents [*Bösinger et al.*, 1981]; enhanced E-region conductance and electrojet currents [*Heacock and Hunsucker*, 1981]; auroral luminosity fluctuations [*Troitskaya*, 1961; *Arnoldy et al.*, 1987]; and cosmic noise absorption [*Heacock and Hunsucker*, 1977]. These Pi1B pulsations have also recently been identified as localised phenomena associated with substorm onset [e.g., *Bösinger and Yahnin*, 1987; *Arnoldy et al.*, 1987; *Bösinger*, 1989]. *Bösinger and Yahnin* [1987] first explored the possibility of using the Pi1B as a reliable and high-fidelity substorm onset indicator. In their paper, *Bösinger and Yahnin* [1987, p. 237] note that the "use of Pi1B's for reliable timing requires a large dense network. "*Arnoldy et al.* [1998] presented several case studies of ground- and in-situ observations of Pi1B pulsations, and noted that Pi1B waves were usually broadly associated with substorm onset, and that power appears at the lower boundaries of higher latitudes, and closer to midnight; and thus concluded that this class of ULF waves are likely a result of fluctuating ionospheric currents (likely due to fluctuating ionospheric conductivities) rather than fluctuating electric fields.

[4] *Lessard et al.* [2006] revisited the Pi1B and its relationship to substorm onset and presented case studies of short-period 0.1–1 Hz Pi1B and showed that a mode conversion may take place between predominantly compressional Pi1B pulsations observed at geosynchronous

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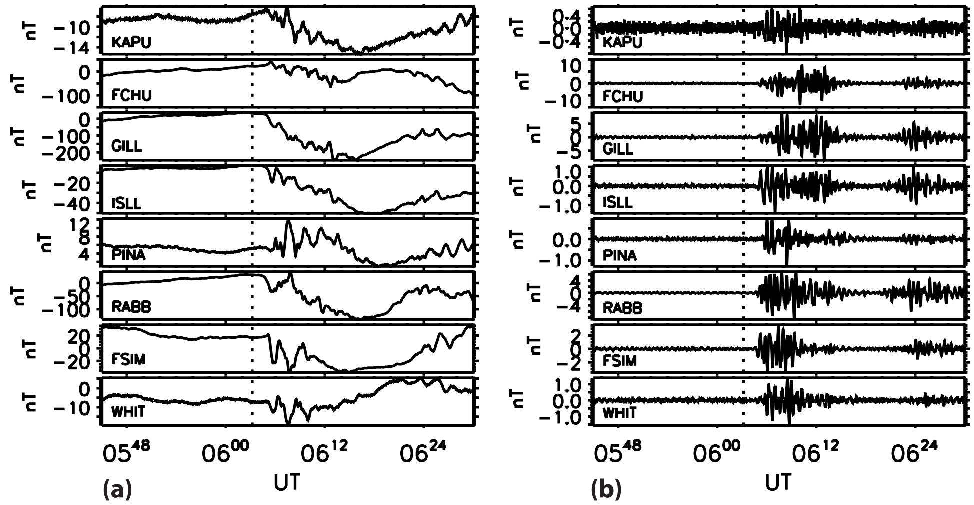

Figure 1. (a) Selected CARISMA and THEMIS GMAG H-component magnetograms from 0545–0630 UT on the 1st November 2006 from east to west, and in decreasing latitude. (b) The Pi1 (1–40 s duration) filtered H-component magnetograms from the same sites and during the same time interval. The vertical dashed line denote 06:03:12 UT.

orbit, and the predominantly Alfvénic Pi1B observed at low-altitudes. *Posch et al.* [2007] examined the relationship between Pi1B and Pi2 pulsations and substorm onsets identified in IMAGE FUV data, and found that the Pi1B pulsations occurred within the 2-minute temporal cadence of the imager. In their study, *Posch et al.* [2007] presented a statistical study of the spatial localisation of the 0.1–10 Hz Pi1B signal in ground magnetometer data, and found that there was a severe drop-off of Pi1B amplitude away from the substorm onset location as identified by IMAGE FUV.

[5] In this paper, we identify the initial location of substorm expansion phase onset on the ground, and determine the propagation characteristics of the initial long-period Pi1 disturbance in the ionosphere. Using a discrete wavelet transform (DWT) employing a Meyer wavelet basis, we examine the first wave signature in the Pi1 band at substorm onset. We find that the initial Pi1 disturbance occurs at the long-period end of the Pi1 band, and is spatially localised in the region of the SCW. The onset of the Pi1 pulsations then propagates isotropically away from this location. With these arrays an inter-station timing resolution ∼16 s is resolvable for this event.

2. Observations: 1st November 2006

[6] The magnetometer data in this study were taken from the expanded and upgraded CARISMA (I. R. Mann et al., The expanded and upgraded CARISMA magnetometer array, submitted to *Space Science Reviews*, 2008), THEMIS GMAG [*Russell et al.*, 2008] and CANMOS magnetometer arrays. Figure 1a shows selected CARISMA and THEMIS GMAG H-component ground magnetic fields observed between 0545–0630 UT on the 1st November 2006: KAPU is eastern-most, FCHU-PINA are the "Churchill Line" and RABB-WHIT are arranged east-west. A small substorm, identified by a small (<280 nT) negative H-bay starting at ∼0605 UT at GILL occurred in the Canadian sector. Also visible in Figure 1a are the associated Pi2 waveforms clearly apparent in the ∼10 minutes following expansion phase onset (for brevity, the Pi2 filtered signals are not shown here). Figure 1b shows the Pi1 filtered (1–40 second) H-component during the same interval 0545–0630 UT and for the same stations. There is a clear latitudinal and longitudinal dependence of the onset of Pi1 signatures across the CARISMA and THEMIS arrays, such that the Pi1 signal is first seen at RABB, and seen last at PINA and DAWS (not shown). However, a more quantitative estimate can be made from analysis of the amplitude of the signals in the combined and contiguous Pi1 and Pi2 bands via the discrete wavelet transform (DWT). With this technique, the entire spectrum of ULF waves associated with substorm onset can be accurately timed to approximately half of the wave period within any given frequency band. The DWT decomposes the time-series into basis functions (wavelets) that are localised in both frequency (J) and time, and are thus ideal for studying even broadband ULF wave signals. In this study, we utilise the Meyer wavelet outlined and applied to the Pi2 waveform by *Nosé et al.* [1998]. The Meyer wavelet is band-limited in frequency, and therefore minimises overlap in adjacent frequency wavelength bins. Large (small) J wavelet coefficients have a high (low) temporal resolution but a low (high) frequency resolution. The Pi1 band occurs in the J = 5–9 bands, while the Pi2 lies in the J = 4–5 band (note the overlap in frequency bands). In this event, the onset of the Pi1 pulsations lie in the Meyer wavelet basis 6 with period content of 12–48 seconds, whose central period lies at 16 s. This central frequency lies in the longer-period Pi1 band, but overlaps the short-period Pi2 band.

[7] Figure 2 shows plots of the wavelet power as a function of J (frequency) and time. There is a clear and definitive onset of J = 6 (long-period Pi1) power at RABB at 06:03:12 UT (±8 s). Consequently, we define the event start time, which may also correspond to the substorm expansion phase onset time, at RABB as 06:03:12 UT (±8 s). Interestingly, using the earliest of the J = 4–5 bands as the onset of Pi2 pulsations renders an estimate of substorm onset time as 06:05:28 UT (±32 s), some ∼140 s

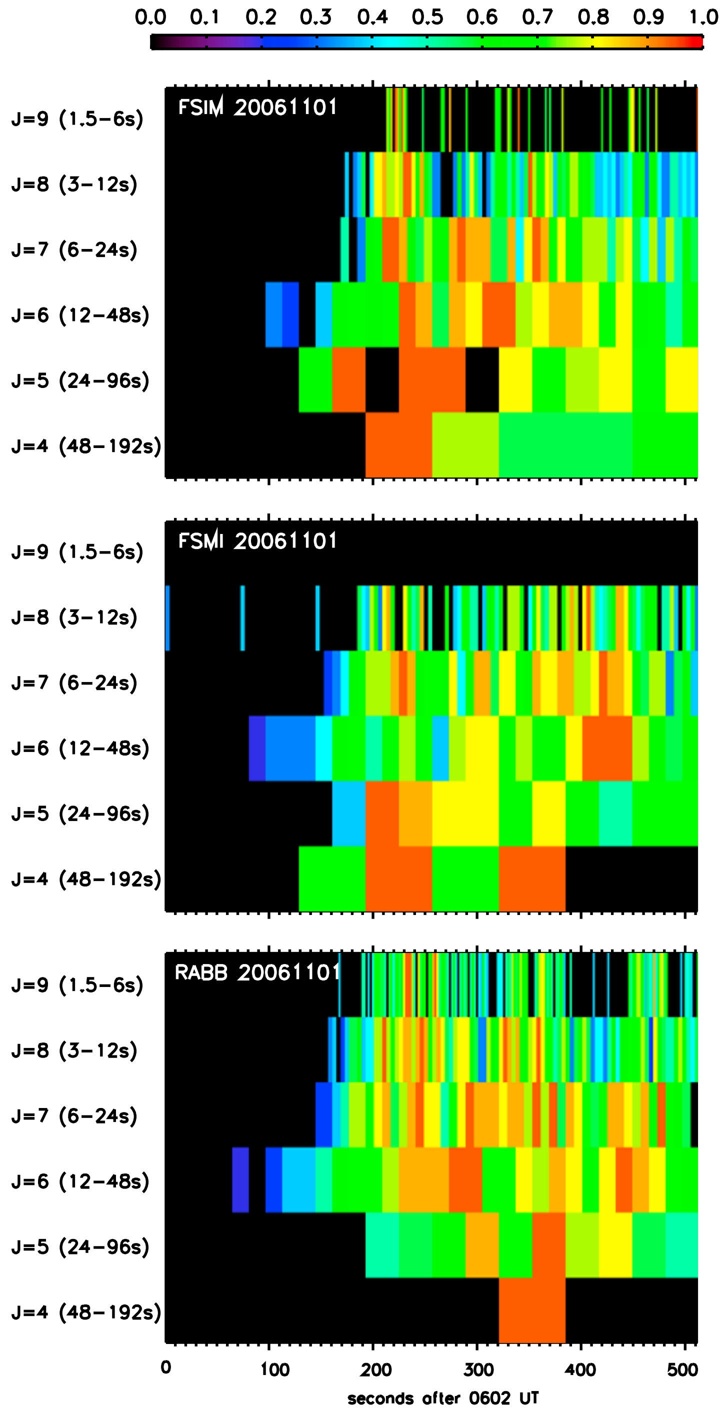

Figure 2. The Meyer Discrete Wavelet Transform (DWT) of the FSIM, FSMI and RABB magnetometer data in descending order west to east along L∼6.6. The x-axis denotes time in seconds starting from 0602 UT, and the y-axis denotes wavelet period, T, and coefficient, J. Each frequency band is normalized independently to the highest power in each frequency band.

after the first Pi1 signature at RABB. Figure 3 shows a two-dimensional spherical harmonic fit to the onset time of the J = 6 wavelet band for the 14 magnetometers used in this study. The grey contours are 40 s apart, epoch time zero is 06:03:12 UT. There is a clear and coherent propagation pattern to the initial onset of J = 6 long-period Pi1 pulsations in the ground magnetometer data. The onset of the Pi1 ULF waves occurs first at RABB (06:03:12 UT), 16 s later at GILL and FSMI, and spreads out to the surrounding stations in a coherent manner from this location, such that the Pi1 pulsations at DAWS and KAPU are observed 128 s following the onset at RABB. The features of definitive onset location and coherent propagation of the Pi1 signal across the array suggest that the DWT Pi1 pulse arrival time is physical. The initial spatial localisation in the ionosphere also suggests that the Pi1 waves at onset are associated with a localised physical process. How the ionospheric Pi1 signature corresponds to the physical processes and magnetosphere-ionosphere cou-

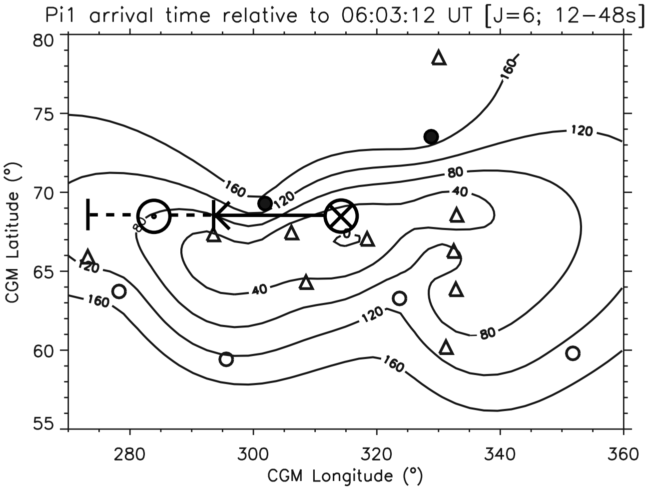

Figure 3. Contour plot of the J = 6 Pi1 onset times according to the Meyer DWT analysis on the 14 magnetometer stations used in this study. CARISMA stations are denoted by the solid squares, THEMIS GMAG stations by the solid circles, and CANMOS stations by the solid triangles, and contours (grey) are 40 s apart. The approximate location of the upward and downward field-aligned current elements and the electrojet latitude are denoted by the symbols and arrow.

pling occurring during substorm onset will be an active area of future study.

[8] We compare the ground magnetic bay perturbations in the H-, D-, and Z-components with the results from a simple SCW model [e.g., *Cramoysan et al.*, 1995]. Fitting to this model, we can estimate the location of the upward and downward FAC elements and central electrojet latitude in relation to the locations of the ground stations. Thus, we infer that the downward FAC element must be situated close to RABB, and the central electrojet latitude must be located just poleward of the DAWS-FSIM-FSMI-RABB-GILL longitudinal chain. These locations are shown in Figure 3.

[9] These initial estimates can also be compared to locations determined from the Pi2 polarisation technique [cf. *Lester et al.*, 1983]. Utilising the average Pi2 polarisation in the 0610–0620 UT interval, the inferred central meridian of the SCW lies between FSIM and FSMI. Furthermore, the location of the upward field-aligned current region must be situated between DAWS and FSIM, although we cannot confirm exactly where in this region due to lack of longitudinal station coverage. Finally, the location of the downward field-aligned current element must lie between FSMI and RABB, thus confirming the estimate using the SCW model. These results both indicate that the long-period Pi1 pulsations are observed first in the region of the downward FAC at RABB, demonstrating the importance of that region for substorm onset physics.

3. Discussion and Conclusions

[10] In this paper, we outline a new capability to determine the time and location of the initiation of long-period Pi1 pulsations in the ionosphere during substorm expansion phase onset using a discrete wavelet transform. Use of this technique for the Pi1 frequency band has only recently been possible due to the upgrade to high cadence (~1 s) magnetometer data in a longitudinally and latitudinally extended magnetometer array. The ground magnetics enable timing and ionospheric Pi1 propagation to be determined across the array to an accuracy of ~tens of seconds. This compares very favourably to the two-minutes or more timing resolution which is typically available using standard Pi2 techniques. Indeed, with the application of the Meyer DWT to ground-based magnetometer data, it is possible to monitor ULF wave activity during substorm onset across a broad range of frequencies and to analyse both the long-period Pi1 and Pi2 bands simultaneously with a high degree of timing accuracy. Certainly, our results suggest that in terms of the start of the burst of pulsation power, the onset signals extend from the short-period Pi2 band into the long-period Pi1 band. Both frequency ranges should therefore be considered at onset.

[11] With this Meyer DWT technique, we analysed a small isolated substorm on the 1st November 2006, and showed that there is a distinct and definitive pattern to the evolution of the onset time of the first long-period Pi1 signatures in the ionosphere. In this case study, the Pi1 pulsations occur first at a location in the centre of the Canadian continent (RABB), and the onset time propagates nearly isotropically, with a rate of 1 MLT hour per 20 s in the east- and west-ward directions. The expansion rate of the Pi1 pulsations is consistent with the Pi2 expansion rate observed by *Samson and Harrold* [1985] and is much faster than the expansion of the Westward Travelling Surge (WTS) based on optical signatures [cf. *Roux et al.*, 1991; *Angelopoulos et al.*, 2008]. Our results support the conclusions of *Samson and Harrold* [1985] that the initial Pi1/2 pulsations at onset are the result of a different process than that responsible for the generation of the WTS.

[12] Furthermore, using two separate techniques we identify the locations of the upward and downward field-aligned current elements, and the latitude of the westward electrojet. Remarkably, we found that the location of the onset of the initial long-period Pi1 signatures was co-located with the region where the downward field-aligned current element subsequently developed during this interval. If this result is typical during expansion phase onset, this provides crucial information on the physics and magnetosphere-ionopshere coupling accompanying substorm onset. One possible explanation for the co-location of the downward FAC and initial onset of Pi1 activity is that the ionospheric feedback instability [e.g., *Atkinson*, 1970; *Sato*, 1978; *Lysak*, 1986, 1991] grows preferentially in regions with low conductivity [*Lysak and Song*, 2002; *Pokhotelov et al.*, 2002] which are also likely to characterise the region where the downward FAC element develops (W. Lotko, personal communication, 2007). Alternatively, an Alfvén wave source in the equatorial onset region of the magnetotail may launch an Alfvén wave towards the ionosphere which is subsequently reflected. The Alfvén wave propagation and reflection is required to set up the upward and downward FAC elements of the SCW. The Alfvén wave reflection and propagation along the entire field line naturally creates both the decaying Alfvén wavetrain and the substorm bays which correspond to the magnetotail-ionosphere FAC which are set up in the SCW. Whether both the long-period Pi1 and

Pi2 are signatures of the Alfvén waves carrying the FAC remains to be determined. One possible scenario is that the long-period Pi1 may be related to energetic electrons which are accelerated ahead of Alfvénic perturbations associated with the Pi2s, perhaps via the resonant mechanism described by *Watt et al.* [2005]. Certainly, the J = 6 (12–48 s) long-period Pi1 waves occur ~1 minute before the J = 5 (24–96 s) Pi2. More studies are required.

[13] A considerable controversy continues to surround the question of whether plasma instabilities in the near-Earth plasmasheet are responsible for initiating substorm onset, or whether the near-Earth disturbances follow prior bursts of magnetic reconnection in the mid-tail. These can be distinguished in terms of the region where the first expansion phase onset activation occurs – either at a near-Earth neutral line around 20–25 R_E [e.g., *Nagai et al.*, 1998] or from a variety of potential plasma instabilities closer to the Earth at ~10–15 R_E [e.g., *Roux et al.*, 1991; *Lui et al.*, 1991; *Rostoker*, 1996; *Angelopoulos*, 2008]. Central to answering this question is the ability to accurately monitor the timing and location of substorm expansion phase onset. The wavelet-based Pi1 technique described here offers the potential to both accurately time (~10–20 seconds) and also locate initially localised regions of Pi1 activations in the ionosphere. How these long-period Pi1 pulsations in the ionosphere relate to activations in the tail, and also to magnetosphere-ionosphere coupling, during substorm onset remain to be fully determined. The Pi1 timing can be completed independent of cloud cover and may represent an extremely important technique augmenting the information available from the THEMIS network of ground-based all-sky cameras. The Pi1 timing technique described here, together with the conjugate data available in the tail from the THEMIS satellites, hence has the promise to enable significant progress to be made in solving the problem of understanding the initiation of substorm expansion phase onset.

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