GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L20103, doi:10.1029/2007GL030492, 2007

Observations of Pi2 pulsations by the Wallops HF radar in association with substorm expansion

J. W. Gjerloev,[1] R. A. Greenwald,[1] C. L. Waters,[2] K. Takahashi,[1] D. Sibeck,[3] K. Oksavik,[1]
R. Barnes,[1] J. Baker,[1] and J. M. Ruohoniemi[1]

Received 24 April 2007; revised 5 June 2007; accepted 9 July 2007; published 23 October 2007.

[1] We report the first sub-auroral Pi2 pulsations observations by a SuperDARN type HF radar. The Wallops radar LOS measurements obtained at ionospheric altitudes, ~56° magnetic latitude, 23 hour magnetic local time, are shown to be highly correlated with ground magnetic field perturbations obtained at Ottawa. The period of the Pi2 pulsations is 118 s and the m-number is ~2.3. The availability of both ionospheric LOS measurements and ground based magnetic field perturbations enable us to constrain the properties of the wave. A predominantly shear Alfven mode wave is able to explain both the amplitude and phase relations of our observations. Although the solar wind dynamic pressure is fairly stable the IMF Bz is highly variable thereby preventing an unambiguous identification of a solar wind trigger. Rather, magnetotail observations of a clear dipolarization and an intensification of the auroral westward electrojet producing a modest ground magnetic bay indicate that the wave is associated with the onset of a weak substorm. **Citation:** Gjerloev, J. W., R. A. Greenwald, C. L. Waters, K. Takahashi, D. Sibeck, K. Oksavik, R. Barnes, J. Baker, and J. M. Ruohoniemi (2007), Observations of Pi2 pulsations by the Wallops HF radar in association with substorm expansion, *Geophys. Res. Lett.*, *34*, L20103, doi:10.1029/2007GL030492.

1. Introduction

[2] ULF waves of irregular nature, Pi2 pulsations, are well known for their association with magnetospheric substorms. Numerous papers have utilized these waves to determine the time of the substorm onset [e.g., *Rostoker et al.*, 1980]. Historically, the magnetic field component of the Pi2 pulsations has received more attention than the electric field component. This is primarily due to observational constrains but with the emergence of mid-latitude SuperDARN type HF radars it is now possible to compare the ground magnetic field perturbations with the ionospheric plasma drift. At auroral latitudes PC-type pulsations have been observed with HF radars [e.g. *Walker et al.*, 1979; *Ziesolleck et al.*, 1998; *Ponomarenko et al.*, 2001]. The short lifetime and small amplitude Pi2 pulsations, however, have complicated observations at auroral latitudes. The newly deployed mid-latitude Wallops radar provides measurements of the spatiotemporal behavior of the ionospheric plasma drift at sub-auroral latitudes where the weak wave signature can be the dominant signal.

[3] In this paper we present the first sub-auroral observations of Pi2 pulsations simultaneously in the ionosphere by the new Wallops HF radar and on the ground at the Ottawa ground magnetometer station.

2. Data

[4] We utilize line-of-sight observations obtained by the Wallops HF radar. This mid-latitude radar provides an extension of the global SuperDARN network from the sub-auroral zone down to ~50° magnetic latitude. The SuperDARN radars detect coherent scatter from electron-density irregularities that are extended along the geomagnetic field. Figure 1 shows the measured line-of-sight (LOS) velocities obtained between 03:22:00 and 03:30:22 UT on 15 March, 2006. The ~35 sec gap between each panel is primarily due to the radar scanning at higher beam numbers (eastward pointing) that did not provide any echoes. The velocities are weak and fairly constant in the first two panels until 03:24:00 UT when the flows intensify. The velocities then began to fluctuate with an approximate period of 2 times the 1-min FOV scanning rate. Blue indicates flows towards the radar while red indicate flows away from the radar. Although Wallops does not have a interferometer we find it exceedingly unlikely that the LOS observations are due to ground scatter. Note that the backscatter follows constant magnetic latitude not distance to radar and as we shall see the LOS variations from beam to beam are highly correlated with the ground magnetic field perturbations.

[5] As seen in Figure 1 Ottawa (OTT, 45.4°N, 284.4°E, geographic) is located at the western edge of the Wallops field-of-view. Figure 2 shows 1 Hz Ottawa vector magnetic field perturbation data band-pass filtered in the Pi2 band (6–15 mHz) using a standard Hanning filter. Pulsations are present with a maximum amplitude in the geographic north-south direction. The frequency is ~8.5 mHz (~118 sec period) in apparent agreement with the period of the ionospheric LOS fluctuations.

[6] Solar wind IMF Bz and dynamic pressure measured by ACE (r = [228, 41, 7] Re GSM) are shown in Figures 3a and 3b. Under an assumption that IMF features are planar with normals in the x-direction, these ACE observations have been propagated 61 min from the point where they were observed to the Earth using the X-distance and observed solar wind speed (~410 km/s). The propagated

---

[1] Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland, USA.

[2] School of Mathematical and Physical Sciences, University of Newcastle, New South Wales, Australia.

[3] Laboratory for Extraterrestrial Physics, NASA/Goddard Space Flight Center, Greenbelt, Maryland, USA.

0094-8276/07/2007GL030492$05.00

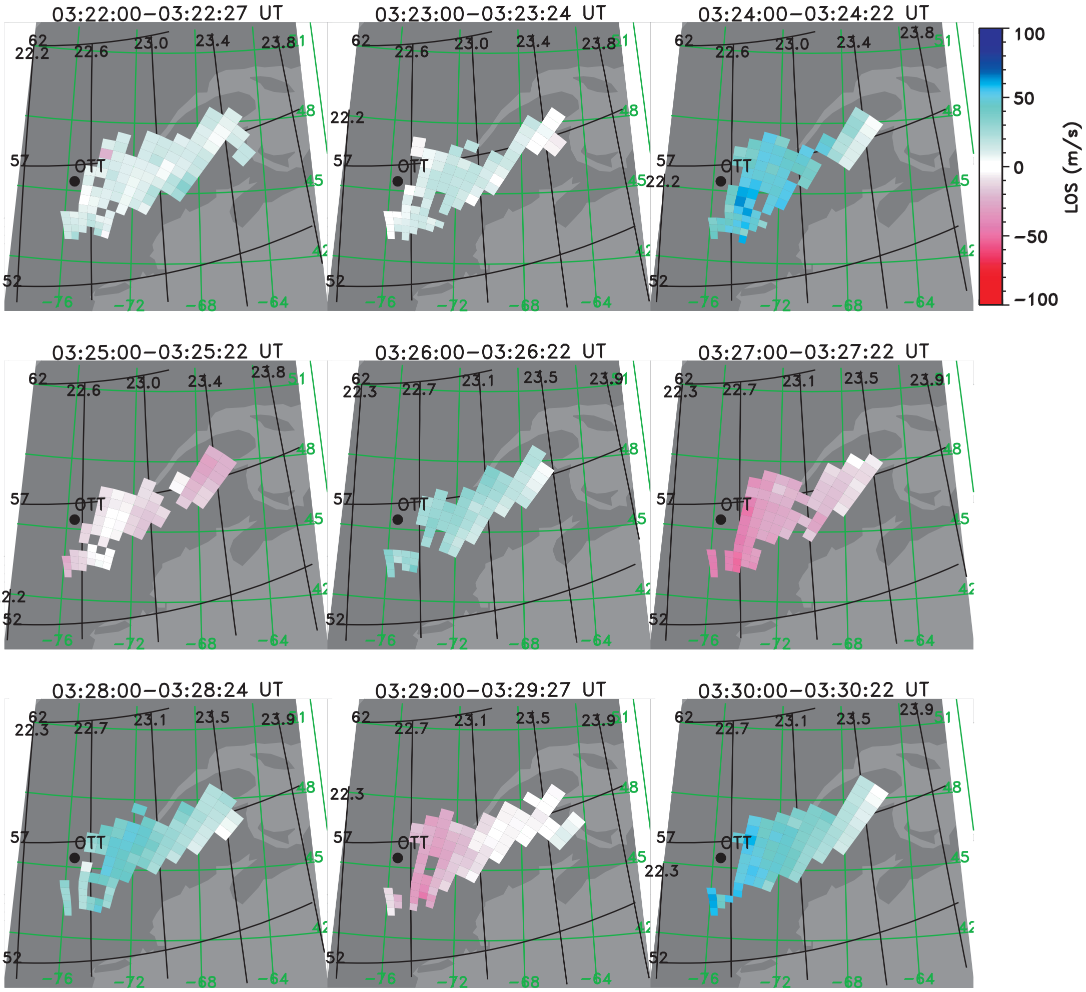

Figure 1. LOS velocities obtained by the Wallops radar (positive velocities are towards the radar (blue) and negative velocities are away from the radar (red)). Corrected geomagnetic latitude – magnetic local time (black) and geographic coordinates (green) are indicated. Finally, the location of Ottawa (OTT) ground magnetic station is shown. Starting at 03:24:00 the typical FOV velocities fluctuates with roughly the same frequency as the FOV sampling frequency.

Bz component is negative at the time of the fluctuations following a period of vanishing Bz and a prior southward period. The solar wind pressure is fairly constant although a minor increase is seen at 03:21:00 UT due to an enhancement in the solar wind speed.

[7] Within the magnetosphere GOES 12 was located at pre-midnight local times, (r = [−6, 3, 0] Re GSM) where it observed a weak but clear dipolarization at ~03:18:30 UT (Figure 3c). GOES 10 was located near dusk and observed a weakening of the magnetic field at 03:15:00 UT (not shown). Unfortunately, none of the LANL spacecraft were not well-situated to observe this event. Nevertheless, LANL-01A, located near 0400 LT observed a weak energetic electron injection at 0330 UT. The cloud of injected electrons had drifted to LANL-02A at 0830 LT by 0400 UT. None of the LANL spacecraft observed any significant ion injection.

[8] On the ground a weak magnetic bay was observed, indicating a weak isolated substorm. Figure 3d shows the magnetograms from Narsarsuaq (magnetic longitude and latitude of 66° and 43°) where this bay reached a modest −100 nT. We investigated all available ground magnetom-

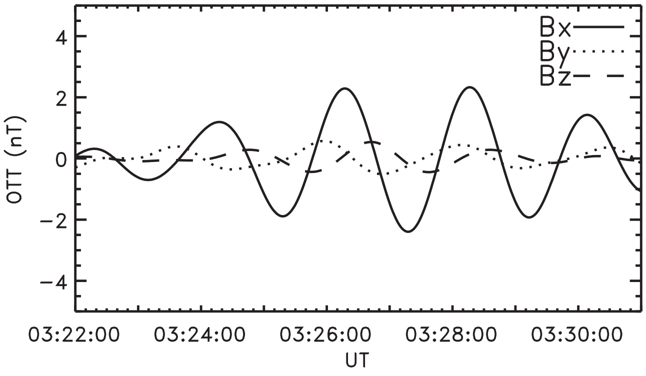

Figure 2. Ground vector magnetic field perturbations in the 6–20 mHz band. Standard geographic coordinates are used (X-north, Y-east, Z-down).

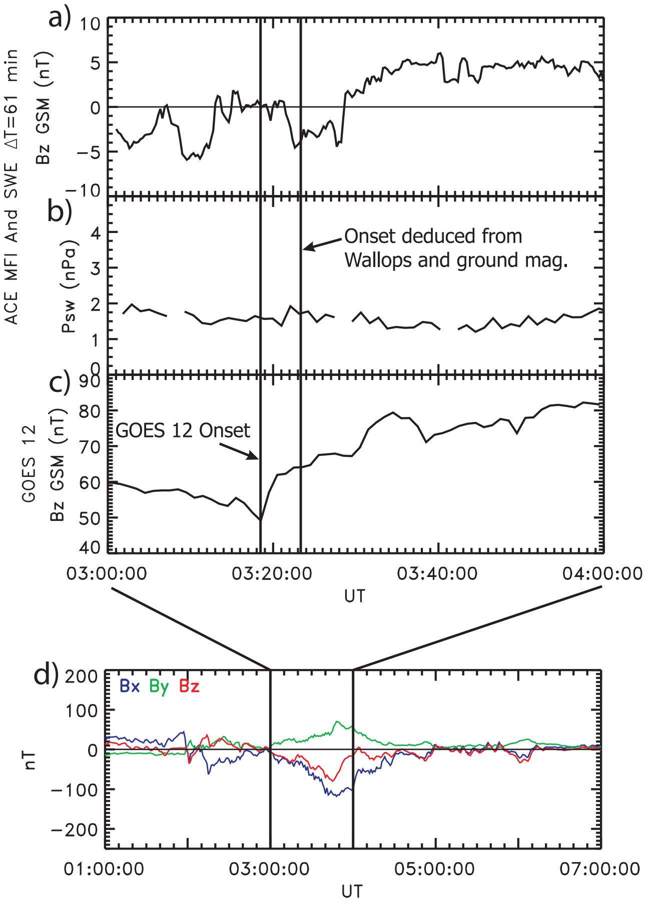

Figure 3. (a) and (b) Propagated solar wind parameters measured by ACE. In determining the solar wind dynamic pressure we assume charge neutrality; that the ions and electrons have identical flow velocities; and the ions in the solar wind consist of 96% H+ and 4% He++ ions. (c) Magnetic field data obtained by the GOES 12 spacecraft in GSM coordinates. (d) Narsarsuaq ground magnetometer data.

eter data and found evidence of this disturbance throughout on the nightside indicating that it was not a localized pseudo onset.

3. Discussion

[9] The data indicate oscillations in both the ground magnetic field and the ionospheric LOS measurements. Before addressing the properties of a wave explaining both sets of observations above we should point out that the analysis is complicated by four factors: 1) Wallops does not provide measurements of the full horizontal wave electric field ($\bar{e}_\perp$) or of the associated horizontal drift $\bar{u}_\perp$. While the ground magnetic field data are vector data the Wallops radar measures the Doppler shift of the reflected HF wave and hence we only obtain information of the line-of-sight drift. We will make the assumption that these are associated with $\bar{e}_\perp \times \bar{B}$ plasma drift (where $\bar{B}$ is the main field). Hence, we ignore any slowly varying contributions to the drift such as neutral winds. 2) The individual Wallops LOS measurements are separated in space and time within a large FOV while the ground magnetic field data are obtained at the same location and hence data are only separated in time. This is not a problem if the wave propagation across the radar FOV is sufficiently fast that the delay is negligible. Unfortunately, several studies have found the so-called azimuthal wave number $m \equiv (360^\circ \cdot \Delta T)/(T \cdot \Delta\phi)$ [*Yumoto*, 1986] (where T is the period of the Pi2 pulsations, ΔT is the phase lag, and $\Delta\phi$ is the longitudinal separation of two separated observations) to be $\sim 2-4$ for the latitudes in question. This corresponds to an appreciable $\sim 7-14$ s delay across the radar FOV which must be included in our analysis. 3) The LOS data are obtained at ionospheric altitudes (likely $\sim 200-300$ km) while the magnetic field data are measured on the ground. The ionosphere and neutral atmosphere influences the incoming ULF wave thereby complicating the analysis of these altitude separated measurements. 4) Our observations are made at latitudes of $\sim 57^\circ$ magnetic latitude where the main field inclination angle is $\sim 72^\circ$. *Sciffer et al.* [2004] showed that the complex interaction of the incoming wave with the conducting ionosphere depends on the dip angle. For non-vertical magnetic fields the field-aligned current associated with the wave will produce magnetic field perturbations measurable on the ground.

[10] Historically, simplistic assumptions have been used in interpreting the observations associated with ULF waves (for example vertical main magnetic field). Instead we will utilize the more realistic solutions developed recently in a series of papers [see *Sciffer et al.*, 2004, and references therein] which focused on ULF wave (1–100 mHz) propagation through the ionosphere. They determined a solution for the reflection and wave mode conversion coefficients for latitudes where the main field is non perpendicular to the conducting ionosphere, which includes Hall current effects and allows for a mixture of shear Alfven and fast mode ULF waves. We refer to their papers for an extensive discussion of the theory. In the context of the present paper it should, however, be mentioned that the modeling is constrained by a 1-dimensional approximation. The atmosphere and ionosphere are defined by the thermosphere model based on satellite mass spectrometer and ground-based incoherent scatter data (MSISE90) and the International Reference Ionosphere (IRI2001) model. The wave solutions are computed in the vertical direction, assuming constant values for the horizontal wave numbers, k_x and k_y. The value for k_y is derived from the observed *m*-number. For low-m events, the azimuthal structure is preserved from the ionosphere to the ground [e.g., *Ponomarenko et al.*, 2001]. The model allows for a complex k_y, based on the magnetometer data amplitude variation with longitude. The value for k_x is chosen to be consistent with the condition that $\nabla \times \mathbf{b} = 0$ in the atmosphere, i.e. $k_x b_y = k_y b_x$. These points are discussed in more detail by *Waters et al.* [2007].

[11] The Wallops observations are separated in time and space which presents a minor complication. From a cross correlation analysis of the observed ground magnetic field perturbation b_x (north component) and LOS observations we can determine an azimuthal wave delay of 0.75 deg/sec or m $\sim$ 2.3 in good agreement with published results [e.g., *Lester et al.*, 1984] and onset to be at $\sim$22.6 MLT also in good agreement with published results [e.g., *Gjerloev et al.*, 2007]. Taking this azimuthal delay into account Figure 4

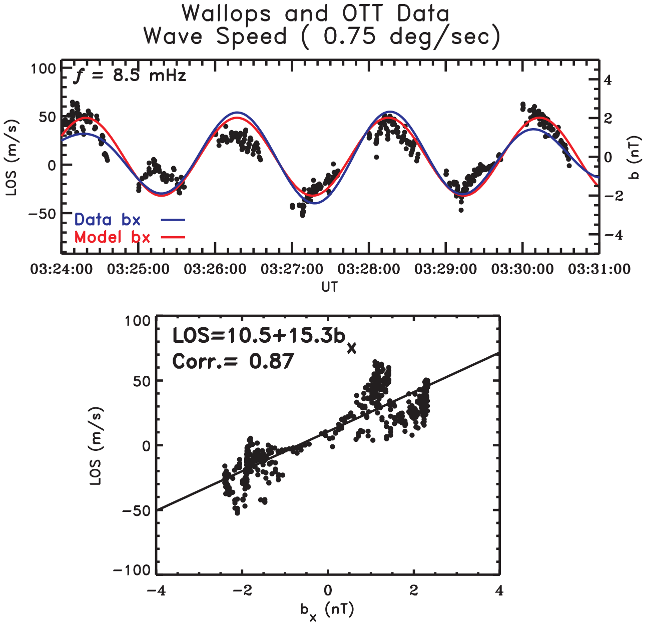

Figure 4. (top) Wallops LOS drift velocities (black dots), measured ground magnetic field perturbation, b_x, (blue line), and modeled ground level magnetic field perturbation, b_x, (red line) as a function of time. (bottom) LOS velocities as a function of observed b_x. Note that a relative delay has been included in the LOS measurements to account for the finite azimuthal wave velocity.

(top) shows the observed LOS data and measured b_x as a function of time. The high correlation between the two separate datasets is apparent. Figure 4 (bottom) shows the LOS as a function of measured b_x and a correlation coefficient of 0.87. Importantly, there is no phase shift between the two datasets and they fluctuate at the same frequency.

[12] The modeling requires the input wave mode mix (shear/fast) to be specified at 1000 km altitude, the top boundary. In order to match both the measured ionospheric LOS drift measurements (assumed 300 km altitude) and the ground magnetic field measurements the input wave consisted of 99.8% shear mode and 0.2% fast mode. Although this appears to be an insignificant fast mode contribution it should be kept in mind that the LOS measurements are obtained at an assumed altitude of 300 km where the amplitudes of the reflected MHD modes are defined by the 2 by 2 mode conversion coefficient matrix [*Sciffer and Waters*, 2002]. The four coefficients are functions of the dip angle, conductivity tensor, ULF wave number and frequency and the height of the infinitely thin ionospheric current sheet. Hence, the relative amplitudes of the input wave refer to the mix at 1,000 km and not where the radar probes. Figure 4 shows the modeled b_x (red line) in excellent agreement with the observed where the correlation between the modeled b_x and the measured LOS is 0.92.

[13] When comparing the observations with the model we make the assumption that the only source of ionospheric convection is the wave electric field. Consequently, we assume that the variations in the LOS observations are purely temporal (except for the azimuthal wave delay). The excellent agreement between model and data appear to support this assumption. However, the minor 10.5 m/s offset in the convection data is likely due to the presence of sources other than the wave itself as there is some evidence of in the LOS observations before 03:27:00 UT (Figures 1 and 4 (top)). Neutral winds can provide a possible explanation for this weak offset.

[14] *Sutcliffe and Nielsen* [1990, 1992] presented observations of Pi2 pulsations using the STARE radar system. However, the STARE observations were made with a 20s temporal resolution, they had a lower threshold of 15 mV/m (~300 m/s), and the observations were made in the auroral zone during active conditions thereby making the Pi2 pulsations only marginally observable. In fact they noted that in most cases it was impossible to discern oscillations in the STARE data with the same period as those observed in ground magnetic field data. The data used in the present study do not suffer from these complications and the signal is clear and unambiguous. Nevertheless, it is noteworthy that their observations indicate wave amplitudes in the ionosphere of ~50 mV/m and on ground ~30 nT. This, however, was in the auroral zone around 70 deg magnetic latitude while the subauroral ground station HER (magnetic longitude and latitude of 81° and −42°) indicated amplitudes of ~2.5 nT. They converted the observed ionospheric drift vectors to ionospheric electric fields and used the Biot-Savart law to obtain ground level magnetic field perturbations. In our solution we get $|\bar{e}_\perp| \sim 4$ mV/m. The difference in amplitude between Sutcliffe and Nielsen and our result is likely due to the latitudinal dependence of the wave amplitude. *Yeoman et al.* [1991] and *Bradshaw and Lester* [1997] reported observations of Pi2 pulsation using the SABRE coherent radar and MEASURE ground magnetometers. They averaged the LOS data within a subsection of the FOV and found velocity fluctuations with a magnitude of up to 200 m/s. The Pi2 pulsations were less ambiguous than the Sutcliffe and Nielsen observations which may be explained by the fact that the SABRE LOS observations were obtained at lower latitudes (~60–66 AACGM latitude).

[15] The cause of the observed pulsations could be a substorm onset or a solar wind pressure pulse. While the latter seems unlikely (see Figure 3) the ground magnetometer data and the GOES 12 observations point to the onset of the weak isolated substorm. From the Wallops data we can clearly identify the onset time to be within the data gap 03:23:24–03:24:00 UT. On the other hand the onset in the ground magnetometer data is somewhat ambiguous. From the first "significant" peak in the wave power we get onset around 03:24:00 UT for OTT in good agreement with Wallops data. The GOES 12 data on the other hand indicate an onset at 03:18:30 UT with an apparent propagation time from the magnetosphere to the ionosphere of a substantial ~6 minutes. OTT observed Pi2 pulsations starting around 03:14 UT, 03:24 UT, 03:37 UT, 03:43 UT. Wallops show clear pulsation signatures in agreement with these four onsets (03:37 UT and 03:43 UT are superposed onto a background of flows towards the radar). For both datasets the 03:24 UT pulsation is clearly the strongest. We still argue that it is a fairly isolated substorm based on the GOES 12 and westward electrojet observations. This is further supported by geosynchronous electron data observed by

LANL-01A (not shown). It was located near dawn (~04 LT) showing a nearly dispersionless injection at 03:30 UT. Of the four Pi2 pulsation onsets we picked the 03:24 UT to be associated with the substorm onset. The 03:14 UT precedes the GOES onset and the 03:37 UT and 03:43 UT results in unrealistic delays between the GOES 12 data and the ionospheric signature.

[16] It should be noted that the exact onset time based on measured ground level magnetic field Pi2 pulsations is somewhat ambiguous. *Liou et al.* [2000] presented a statistical study of Pi2 pulsation onset timing and concluded that Pi2 pulsations do not provide a reliable substorm onset time. In fact they found that in 29% of the events there was no sign of an auroral breakup within 10 min of the Pi2 pulsation burst. They further concluded that Pi2 pulsation delays are a function of the relative location of the ground magnetometer station with respect to the auroral onset. They suggested a linear relationship between the delay and the distance to the onset with a slope of ~7 (sec/hour relative MLT) or ~2.1 (deg magnetic longitude/second) somewhat faster than our result. The difference may be due to a latitudinal dependence of the wave delay.

[17] Images unquestionably provide the best means for the determination of the onset of the auroral substorm. However, space-borne imagers have a relative low sampling rate (~1 min) and are not always in a position to view the onset. Ground based all-sky cameras do provide high time resolution but have a limited field of view and are vulnerable to weather and moonlight/sunlight. The onset time of the auroral substorm is of significant importance and we have shown that SuperDARN type HF radars can provide an additional way for its determination. Naturally, LOS measurements of Pi2 pulsations will suffer from the same complications as the ground magnetometer Pi2 pulsations [*Liou et al.*, 2000; *Rostoker*, 2002]. However, the radar observations provide a cleaner signal compared to ground based magnetometers since ground based magnetometers are sensitive to many time varying near and distant current systems while there are very few sources of plasma convection at subauroral latitudes. Our results are obtained from a scanning mode in which ~35 second data-gaps are present thereby limiting the timing accuracy. However, other standard modes are run routinely for which the onset can be determined with a precision of ~3 seconds as defined by the beam integration period.

4. Summary and Conclusions

[18] Pi2 pulsations are observed by the use of both ground based magnetometer stations and Wallops radar ionospheric LOS measurements. These two very different data-sets are shown to be highly correlated. The observations represent the first sub-auroral observations of Pi2 pulsations using a ground based SuperDARN type HF radar. Modeling the event indicates that an incident wave at 1,000 km altitude wave comprised of mostly input shear Alfven mode with only a minor fast mode contribution provide amplitudes and phase relations in agreement with the observations. Cross correlation analysis show a delay of 0.75 deg/sec corresponding to an m-value of ~2.3. The solar wind dynamic pressure is fairly stable but the IMF Bz is highly variable thereby preventing an unambiguous identification of for a solar wind trigger of the substorm onset associated Pi2 pulsation. Instead magnetotail observations of a clear dipolarization and an intensification of the auroral westward electrojet producing a modest ground magnetic bay indicate that the wave is associated with the onset of a weak substorm. The Wallops LOS observations demonstrate the utility of using mid-latitude SuperDARN type HF radars to time Pi2 pulsation onset.

[19] **Acknowledgments.** We gratefully acknowledge CANMOS, the Danish Meteorological Institute, project scientist Jurgen Watermann; Intermagnet; the ACE team; the GOES team; and LANL energetic particle team. The study was supported by NSF grant ATM-0418101. K. T. wishes to acknowledge NASA NAG5-13119.

References

Bradshaw, E. G., and M. Lester (1997), SABRE observations of Pi2 pulsations: Case studies, *Ann. Geophys.*, *15*, 40–53.

Gjerloev, J. W., R. A. Hoffman, J. B. Sigwarth, and L. A. Frank (2007), Statistical description of the bulge-type auroral substorm in the far ultraviolet, *J. Geophys. Res.*, *112*, A07213, doi:10.1029/2006JA012189.

Lester, M., W. J. Hughes, and W. J. Singer (1984), Longitudinal structure in Pi2 pulsations and the substorm current wedge, *J. Geophys. Res.*, *89*, 5489–5494.

Liou, K., C. I. Meng, P. T. Newell, K. Takahashi, S. I. Ohtani, A. T. Y. Lui, M. Brittnacher, and G. Parks (2000), Evaluation of low-latitude Pi2 pulsations as indicators of substorm onset using Polar ultraviolet imagery, *J. Geophys. Res.*, *105*, 2495–2505.

Ponomarenko, P. V., C. L. Waters, M. D. Sciffer, B. J. Fraser, and J. C. Samson (2001), Spatial structure of ULF waves: Comparison of magnetometer and Super Dual Auroral Radar Network data, *J. Geophys. Res.*, *106*, 10,509–10,517.

Rostoker, G. (2002), Identification of substorm expansive phase onsets, *J. Geophys. Res.*, *107*(A7), 1137, doi:10.1029/2001JA003504.

Rostoker, G., S.-I. Akasofu, J. Foster, R. A. Greenwald, Y. Kamide, K. Kawasaki, A. T. Y. Lui, R. L. McPherron, and C. T. Russel (1980), Magnetospheric substorms: Definition and signatures, *J. Geophys.Res.*, *85*, 1663–1668.

Sciffer, M. D., and C. L. Waters (2002), Propagation of ULF waves through the ionosphere: Analytic solutions for oblique magnetic fields, *J. Geophys. Res.*, *107*(A10), 1297, doi:10.1029/2001JA000184.

Sciffer, M. D., C. L. Waters, and F. W. Menk (2004), Propagation of ULF waves through the ionosphere: Inductive effect for oblique magnetic fields, *Ann. Geophys.*, *22*, 1155–1169.

Sutcliffe, P. R., and E. Nielsen (1990), STARE observations of Pi2 pulsations, *Geophys. Res. Lett.*, *17*, 603–606.

Sutcliffe, P. R., and E. Nielsen (1992), The ionospheric signature of Pi2 pulsations observed by STARE, *J. Geophys. Res.*, *97*, 10,621–10,636.

Walker, A. D. M., R. A. Greenwald, W. F. Stuart, and C. A. Green (1979), Stare auroral radar observations of Pc 5 geomagnetic pulsations, *J. Geophys. Res.*, *84*, 3373–3388.

Waters, C. L., T. K. Yeoman, M. D. Sciffer, P. V. Ponomarenko, and D. M. Wright (2007), Modulation of radio frequency signals by ULF waves, *Ann. Geophys.*, *25*, 1113–1124.

Yeoman, T. K., M. Lester, D. K. Milling, and D. Orr (1991), Polarization, propagation and MHD wave modes of Pi2 pulsations: SABRE/SAMNET results, *Planet. Space. Sci.*, *39*, 983–998.

Yumoto, K. (1986), Generation and propagation mechanisms of low-latitude magnetic pulsations–A review, *J..Geophys.*, *60*, 79–105.

Ziesolleck, C. W. S., F. E. Fenrich, J. C. Samson, and D. R. McDiarmid (1998), Pc 5 field line resonance frequencies and structure observed by SuperDARN and CANOPUS, *J. Geophys. Res.*, *103*, 11,771–11,786.

J. Baker, R. Barnes, J. W. Gjerloev, R. A. Greenwald, K. Oksavik, J. M. Ruohoniemi, and K. Takahashi, Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723, USA. (jesper.gjerloev@jhuapl.edu)

C. L. Waters, School of Mathematical and Physical Sciences, University of Newcastle, NSW 2308, Australia.

D. Sibeck, Laboratory for Extraterrestrial Physics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.