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LETTER

Letter to the editor

CUTLASS observations of a high-*m* ULF wave and its consequences for the DOPE HF Doppler sounder

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Abstract. The CUTLASS (Co-operative UK Twin Located Auroral Sounding System) Finland HF radar, whilst operating in a high spatial and temporal resolution mode, has measured the ionospheric signature of a naturally occurring ULF wave in scatter artificially generated by the Tromsø Heater. The wave had a period of 100 s and exhibited curved phase fronts across the heated volume (about 180 km along a single radar beam). Spatial information provided by CUTLASS has enabled an *m*-number for the wave of about 38 to be determined. This high-*m* wave was not detected by the IMAGE (International Monitor for Auroral Geomagnetic Effects) network of ground magnetometers, as expected for a wave of a small spatial scale size. These observations offer the first independent confirmation of the existence of the ground uncorrelated ULF wave signatures previously reported in measurements recorded from an HF Doppler sounder located in the vicinity of Tromsø. These results both demonstrate a new capability for geophysical exploration from the combined CUTLASS-EISCAT ionospheric Heater experiment, and provide a verification of the HF Doppler technique for the investigation of small scale ULF waves.

Key words. Ionosphere (ionosphere–magnetosphere interactions) · Magnetospheric physics (magnetosphere–ionosphere interactions; MHD waves and instabilities)

1 Introduction

Pulsations with large azimuthal wave numbers (small azimuthal scale size), *m*, are a topic of considerable interest at present, in both theoretical and experimental studies. It is now widely accepted that a source of these ULF waves exists in drifting energetic particle fluxes. Particles of this type entering the Earth's near geospace from the geotail will undergo gradient curvature drift and thus move around the Earth constituting part of the global ring current. The drifting particles can drive MHD wave modes through wave-particle interactions, leading to perturbations in the electric and magnetic fields in the ionosphere (*e.g.* Hughes, 1983). Recently there have been a number of studies attempting to explain the occurrence and characteristics of high-*m* field line resonances in HF radar observations (Fenrich *et al.*, 1995; Fenrich and Samson, 1997). These waves exhibit similar characteristics to low-*m* field line resonances, occurring at the same wave frequency and on similar *L*-shells but westwards of the low-*m* resonance location. A non-linear Kelvin-Helmholtz instability has been proposed (Allan and Wright, 1997; Mann, 1998) as a coupling mechanism between the low-*m* wave guide modes and the high-*m* resonances.

In this paper we will present high spatial and temporal resolution data from the Finland part of the CUTLASS (Co-operative UK Twin Located Auroral Sounding System; Milan *et al.*, 1997) bistatic HF radar. A new experiment, SP-UK-OUCH (Observations of ULF waves with CUTLASS and the Heater) was specifically designed for CUTLASS measurements of ULF wave signatures in the ionosphere. The experiment utilises the high power HF Heating facility in Tromsø to generate artificial field-aligned ionospheric density striations. The CUTLASS observations presented here indicate that a high-*m* wave was detected in the radar backscatter which was not observed on the ground but was observed in the ionosphere by the DOPE (Doppler Pulsation Experiment) sounder. Simultaneously, magnetometers recorded a low-*m* pulsation. Subsequent to this, a longer period, low-*m* wave was apparent in the radar backscatter which correlated with the one observed on the ground.

Wright and Yeoman (1999) reported HF Doppler observations of so-called *uncorrelated* waves, that is to say those which had an ionospheric signature without a corresponding ground magnetic signature. These authors suggested that these observations were a result of waves with small spatial scale sizes which were not visible to other instruments with a lower spatial resolu-

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tion. This hypothesis is confirmed in the work presented here.

2 Instrumentation

The ionospheric convection velocities presented in this paper were measured by the CUTLASS Finland radar. CUTLASS is a frequency agile bistatic HF coherent radar consisting of stations at Thykkvibær, Iceland and Hankasalmi, Finland. They form part of the Super-DARN chain of HF radars (Greenwald *et al*., 1995). A detailed description of the CUTLASS mode of operation is given by Yeoman *et al*. (1997). In the OUCH mode, the Finland radar sounded on only 10 of its 15 beams (0–9), dwelling on each for 1 s, with a range cell length of 15 km. In this study only data from beam 5 of the Finland radar will be illustrated as this beam overlays Tromsø, the location of the EISCAT Heater.

The Doppler technique utilises the fact that variations in the refractive index or bulk motion of the plasma along the path of the radio wave cause small shifts in the received frequency, due to changes in the phase path of the wave. In the case where the phase path is not affected by changes in refractive index, this can be interpreted as an equivalent vertical bulk motion of the reflection point (plasma) with a velocity, v, using, for a vertical incidence sounder, the relation

$$\Delta f = -2\frac{v}{c}f \tag{1}$$

where c is the speed of light and f is the sounding frequency. Thus, any wave propagating through the ionosphere may leave a signature which can be detected by the sounder. The DOPE sounder makes routine HF continuous wave (CW) soundings of the ionosphere over Tromsø with high spatial and temporal resolution. The spatial resolution of the DOPE sounder has been shown (Wright *et al*., 1997) to be of the order of 3–4 km for an F-region reflection height of 250 km at this sounder frequency. It has been demonstrated that the sounder can make measurements of both low-*m* (Wright *et al*., 1998) and high-*m* (Wright and Yeoman, 1999) ULF wave signatures. A full description of the DOPE system is available in Wright *et al*. (1997). The temporal resolution of the DOPE data presented here is 12.8 s.

The EISCAT high-power HF facility or Heater is located at Ramfjordmoen, in the vicinity of Tromsø, Norway. It consists of 12 transmitters feeding a 6 by 6 array (the so-called *array 2*; which was employed during SP-UK-OUCH) of crossed dipole antennas which can be phased to transmit O-, X- or linear mode signals on frequencies in the range 3.9–5.6 MHz. The Heater is capable of radiating over 1 MW of continuous wave power. Further technical details of the Heating facility are given by Rietveld *et al*. (1993). During this experiment only half of the transmitters were utilised, each having an output of 75 kW. This had two-fold benefits: a reduction in the Heater power consumption, which is acceptable since significant backscatter powers are detected by CUTLASS for less than full Heater powers; the Heater beam width was increased (since each transmitter drives a row of six dipole antennas), which generated a larger patch of CUTLASS scatter. The transmitted Heater frequency was 4.54 MHz.

In addition to the HF Doppler and HF coherent radar data presented in this paper, data from the Tromsø (TRO) IMAGE (Lühr, 1994) ground magnetometer are included. These data are given in a geographic (XYZ) coordinate system and have a time resolution of 10 s. Data from additional IMAGE stations were also utilised in order to determine the latitudinal and azimuthal phase change of the ULF wave.

3 Observations

A run of SP-UK-OUCH occurred on 15 October 1998 from 1200 to 1623 UT facilitating a region of continuous high power backscatter on CUTLASS to be generated. Figure 1a displays a section of data from the CUTLASS radar during the experiment. The plot shows line of sight velocity data for beam 5 of the Finland radar for the interval 1300–1400 UT, where positive velocities represent flow *towards* the radar. The broad colourful band is the backscatter artificially generated by the Tromsø Heater, whose ground range from the radar locates it in the centre of the band (approximately at range gate 31). This remarkably continuous and uniform band has a spatial extent along the beam of about 12 range gates (180 km). The mean backscatter power during the interval exceeded 30 dB and the data also exhibited very narrow spectral widths which were typically less than 20 ms^{-1}. The data shown were recorded at CUTLASS sounding frequencies in the range 19.4–19.7 MHz. The line of sight flows observed by CUTLASS were modulated by a ULF wave signature which appears as a series of bands or stripes during this interval. These measurements represent a data set with an unprecedented spatial, temporal and velocity resolution for HF radar observations of a ULF wave.

Simultaneous X- and Y-component data from the TRO magnetometer over the same interval as displayed in Fig. 1a are given in Fig. 1d. It is clear that ULF wave activity is occurring throughout the interval and this is most apparent in the X-component data. Figure 1b shows the velocity observed by the Finland radar in beam 5 at range 30. This is simply a slice taken through the scatter in Fig. 1a at range 30 and plotted as a function of time. The middle panel of this figure (Fig. 1c) illustrates the DOPE signal frequency shift (Doppler shift, Δf) throughout this interval. The data in this panel have been filtered to exclude periods outside the range 60–200 s in order to remove high frequency noise and low frequency changes resulting from long period atmospheric gravity waves. A series of wave cycles of similar period are clearly visible in both time series particularly from 1315–1345 UT. The amplitude of these two signals both maximise in the interval 1333–1343 UT. The signature has peak-to-peak magnitudes of 170 m s^{-1} and 27 m s^{-1} for the line of sight CUTLASS

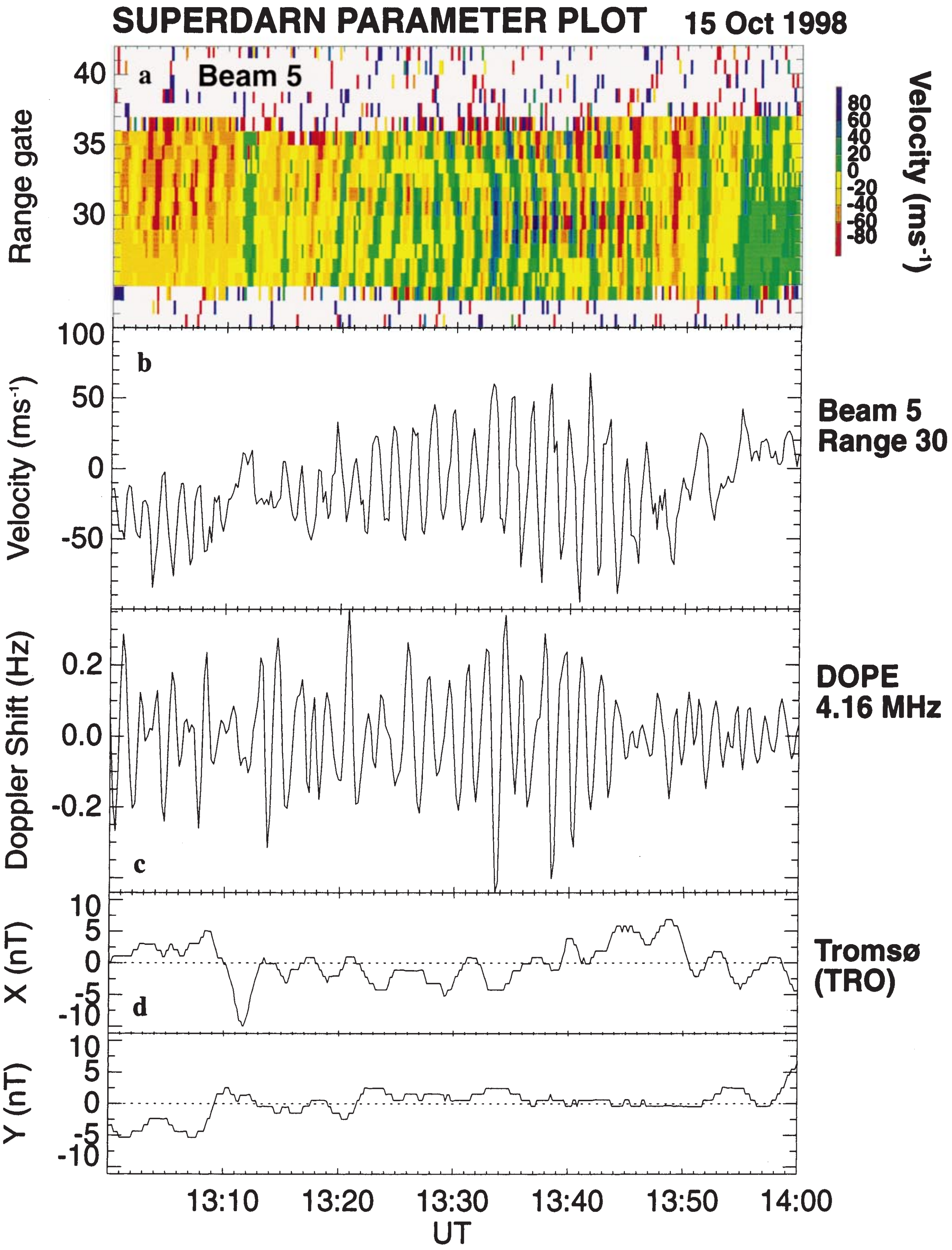

Fig. 1. **a** Line of sight velocity data from beam 5 of the CUTLASS Finland radar as a function of range and time for the interval 1300–1400 UT on 15 October 1998. Also shown are the time series for **b** CUTLASS Finland beam 5, range 30, **c** DOPE frequency shift and **d** Tromsø (TRO) X- and Y-component magnetic field. The data from the DOPE sounder has been filtered to exclude periods outside the range 60–200 s

velocity and the DOPE equivalent vertical velocity respectively (using Eq. 1). The component of the CUTLASS line of sight velocity (which is measured perpendicular to the local magnetic field) when resolved vertically as a result of the local field line tilt is 35 ms^{-1}, which agrees closely with the DOPE measurement. The TRO X-component data (Fig. 1d) offers no evidence of an oscillation at the same frequency as that observed in the ionospheric data. To determine the spectral components present in each time series in Fig. 1b–d they were all subjected to an FFT having been filtered beforehand (see Fig. 2 for details). The power spectra produced in this analysis are reproduced in Fig. 2. The signatures in the CUTLASS (Fig. 2a) and DOPE (Fig. 2b) data exhibit the same frequency of 10 mHz (100-s period). However, the TRO data (Fig. 2c) displays a peak spectral component at about 3.7 mHz (270-s period).

The Heater generated scatter was observed in several adjacent beams in the CUTLASS Finland radar. The spatial separation of these measurements enabled the calculation of the azimuthal wave number, *m*, of the 10 mHz wave which was found to be 38 ± 6. This corresponds to a wavelength of approximately 360 km at an F-region altitude of 200 km. The curvature of the phase fronts in Fig. 1a suggests a latitudinal scale length of the wave which is of the order of the width of the patch of backscatter (~180 km) and is a value similar to that of 60 km determined by Yeoman *et al.* (1997) for the wave signature previously reported in artificially generated CUTLASS backscatter. The *m*-number of the longer period wave observed on the IMAGE stations was calculated to be about 4. After about 1345 UT the 10 mHz wave ceased to be visible in the CUTLASS data and another ULF wave signature became apparent which had a frequency similar the wave measured on the ground. The *m*-number of this wave calculated from the radar backscatter was also found to be in the range 3–4 and is thus assumed to be related to the pulsation observed at the ground.

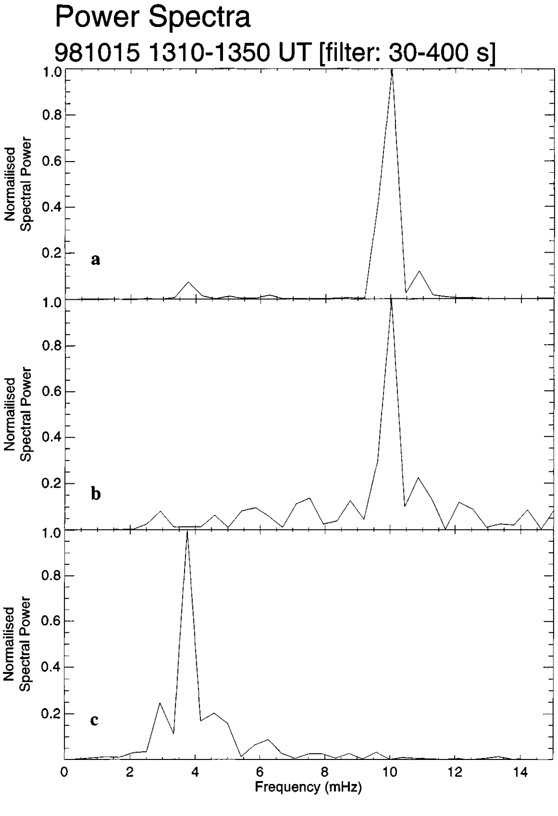

Fig. 2. Normalised power spectra for the interval 1310–1350 UT of the time series plotted in Fig. 1. **a** CUTLASS Finland beam 5, range 30, **b** DOPE and **c** TRO X-component. All data were filtered in the range 30–400 s before being passed through the fast Fourier transform

4 Discussion

Wright and Yeoman (1999) reported HF Doppler observations of the ionospheric signatures thought to be related to ULF waves with small spatial scale sizes using the DOPE sounder. They called this class of wave "uncorrelated" since there was no associated pulsation recorded by ground magnetometers in the vicinity. Until now, there were no direct simultaneous observations from other instruments (such as ground based radars or orbiting satellites) which could support the DOPE measurements and confirm the reliability of the sounder as a high spatial and temporal resolution monitor of the high-latitude ionosphere.

Wright and Yeoman (1999) estimated that the *m*-numbers associated with the DOPE observations of small scale ULF waves were in the range 37–159. The attenuation of the pulsation magnetic perturbation below the ionosphere is proportional to e^{-kz} (*e.g.* Hughes and Southwood, 1976) where k is the field perpendicular component of the wave number and z is the E-region height. Thus, applying this in the longitudinal and latitudinal directions between the high-*m* and low-*m* wave packets observed in this study the wave attenuation factors are calculated to be approximately 5.5 and 20 respectively. The small scale wave described in this study had an *m*-number of 38 and, thus, confirms the fact that DOPE can observe small scale wave structures in the ionosphere, which are effectively screened from the ground.

Recently, there have been reports of observations of resonant high-*m* ULF waves in data from SuperDARN HF radars similar to the CUTLASS system, which exhibit characteristics and morphology common to low-*m* field line resonance signatures occurring in the same local time sector, with the same wave frequency and latitudinal phase structure (Fenrich *et al.*, 1995; Fenrich and Samson, 1997). The velocity shear of the low-*m* resonant wave is thought to drive the instability which sets up a spectrum of high-*m* waves, one of which begins to grow in amplitude. Unstable distributions of westward drifting ions can then provide the energy to amplify the high-*m* seed waves which are expected (Allan and Wright, 1997; Mann, 1998) and observed (*e.g.* Fenrich *et al.*, 1995) to occur in the dawn and dusk sectors. The theory also avails the possibility that a harmonic of the low-*m* mode might arise, which would be consistent with the observations described here, where the high-*m* wave observed by CUTLASS and DOPE had a frequency which was three times that exhibited by the low-*m* wave on the ground. The high-*m* wave is observed near noon, then as the instruments move towards the region which maps to the dusk flank of the magnetosphere, the low-*m* wave becomes apparent. This could be the first direct evidence of the seeding effect described above, although if so a harmonic seems to be generated in this case. Further studies need to be carried out with instrumentation such as that described here.

5 Summary

A recent run of a new experiment called OUCH has provided a high resolution observation of a high-*m* ULF wave with the CUTLASS radar. The wave modulated background F-region flows observed in artificially generated radar backscatter and exhibited curiously curved phase fronts. The wave had an azimuthal wave number (*m*) of 38 and a frequency close to a harmonic of a low-*m* wave observed at the ground throughout the experiment and in the radar data immediately after the high-*m* wave had manifested itself in the radar backscatter.

The measurements of this wave provide the first definite confirmation that the DOPE HF Doppler sounder is capable of measuring ULF waves with small spatial scale sizes (as suggested by Wright and Yeoman, 1999) which do not have a corresponding ground magnetic signature due to screening of the ULF wave signal.

In addition, this event supports other recent observations of high-*m* resonant waves and low-*m* field line resonance signatures in SuperDARN F-region radar data which share many common features including occurrence location, frequency and phase characteristics. The observation is also consistent with a non-linear Kelvin-Helmholtz instability which has been proposed as a generation mechanism for this type of phenomenon.

The recent extension of the DOPE sounder to provide spatially separated (four paths instead of the original one) high resolution measurements of the ionospheric signature of such waves will offer a means to determine their scale sizes more routinely. This feature of the sounder and the apparently curved phase fronts of the wave observed in the CUTLASS data will be topics of discussion in forthcoming papers.

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