

High resolution bistatic HF radar observations of ULF waves in artificially generated backscatter

Darren M. Wright and Timothy K. Yeoman

Department of Physics and Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, UK

Abstract. High resolution HF radar observations of ULF waves in the ionosphere are possible by artificially generating irregularities using the EISCAT heater at Tromsø, Norway. The line-of-sight velocities from the CUTLASS radars have been combined for the first time to form bistatic flow vectors during a ULF wave, generating ionospheric electric field measurements with a higher accuracy than ever previously recorded by any instrument. A high- m wave observed in the ionosphere exhibits a frequency which is a harmonic of that of a low- m field line resonance which is observed simultaneously in the ionosphere and at the ground. The high- m pulsation resembles a class of particle driven wave previously recorded on VHF radars. These results are consistent with recent HF radar observations of small scale waves possessing similar characteristics to field line resonances and with the theory that the low- m wave may be driving the high- m wave through a non-linear Kelvin-Helmholtz instability.

1. Introduction

Small azimuthal scale size (high- m) ULF waves are currently the subject of interest in several theoretical and experimental studies. Drifting energetic particles are believed to drive these MHD wave modes through wave-particle interactions, leading to electric and magnetic field perturbations in the ionosphere (*e.g.* Hughes, 1983). A number of recent studies have attempted to explain the occurrence and characteristics of high- m field line resonances in HF radar observations (*e.g.* Fenrich *et al.*, 1995; Fenrich and Samson, 1997). These waves exhibit some of the characteristics of low- m field line resonances, occurring at the same wave frequency and on similar L -shells but westwards of the low- m resonance location. It has been proposed (Allan and Wright, 1997; Mann, 1998) that a coupling mechanism between the low- m wave guide modes and the high- m resonances might exist in a non-linear Kelvin-Helmholtz instability.

The ionospheric convection velocities presented in this paper were measured by the CUTLASS (Co-operative UK Twin Located Auroral Sounding System; Milan *et al.*, 1997) bistatic HF radar. The current experiment utilises the EISCAT high power HF Heating facility at Tromsø to generate artificial field-aligned ionospheric density striations (*e.g.* Robinson *et al.*, 1997) and represents a data set with extremely high spatial and temporal resolution with

ionospheric electric fields recorded with an unprecedented accuracy. This technique was first demonstrated by Yeoman *et al.* (1997), but in that case the Heater operated intermittently generating non-continuous radar backscatter. Their observations indicated the evolution of a impulsive cavity mode oscillation into a driven field line resonance which had a latitudinal scale size of only 60 km. A new experiment, SP-UK-OUCH (Observations of ULF waves with CUTLASS and the Heater) has been specifically designed for CUTLASS measurements of ULF wave signatures in the ionosphere. The CUTLASS observations presented here indicate that a high- m wave was detected in the radar backscatter. 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. Examination of the polarisation of the wave derived from the radar data has demonstrated similar characteristics with the VHF radar observations of particle driven high- m waves reported by Allan *et al.* (1982).

2. Instrumentation

CUTLASS is a frequency agile bistatic HF coherent radar consisting of stations at Thykkvibær, Iceland and Hankasalmi, Finland. They form part of the SuperDARN chain of HF radars (Greenwald *et al.*, 1995). A detailed description of the high resolution mode of operation of CUTLASS 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. The Iceland East radar operated on beams 11-15 with a dwell time of 2 s for each. A range cell length of 15 km was employed on both. The beam separation was 3.24° . In this study data from beam 5 of the Finland radar and beam 15 of Iceland East will be illustrated as these beams overlay Tromsø, the location of the EISCAT heater.

Detailed technical information on the EISCAT high power HF Heating facility are given by Rietveld *et al.* (1993). During this experiment only half of the transmitters (6 out of a possible 12) were utilised, each having an output of 75 kW. This reduced the overall power consumption and was possible since significant backscatter powers are detected by CUTLASS for less than full Heater powers. A further advantage of this mode was that the Heater beam width was increased (since each transmitter drives a row of 6 dipole antennas), which generated a larger patch of CUTLASS scatter. The transmitted Heater frequency was 4.54 MHz.

In addition to the HF coherent radar data presented in this paper, data from the Tromsø (TRO) IMAGE (International Monitor for Auroral Geomagnetic Effects; 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

Between 1200 and 1623 UT on 15 October 1998 the OUCH mode was in operation on both CUTLASS and the EISCAT Heater, facilitating the generation of a region of continuous backscatter. The heated patch extended 12 range gates (180 km) along beam 5 of Finland and 6 range gates (90 km) along beam 15 of Iceland East, which looks approximately azimuthally. The artificial scatter was also detected in beams 4-7 and beams 13-15 of the Finland and Iceland East radars respectively. Stack plots of line of sight velocities (V_{l-o-s}) for several range gates inside the artificially generated scatter along Finland beam 5 and Iceland East beam 15 are reproduced in respectively in Figs. 1a and 1b for the interval 1200-1600 UT. The ranges selected in these panels are centred on the middle of the heated volume (footpoint position 66.8°N 104°E geomagnetic) and have 15 km range cell lengths. Iceland East beam 15 points almost azimuthally eastwards and Finland beam 5 looks almost meridionally. All

data in these panels have an MLT=UT+2. Figure 1c displays the X- and Y-component TRO magnetic field variation for the same interval for comparison. A pulsation signature is clearly visible in the TRO data throughout the interval. A similar oscillation is observed in the radar data in the interval 1310-1530 UT on Iceland East and 1410-1530 UT on Finland. Although it is less clear there also appears to be a related signature between 1200-1230 UT in the Finland data. Spectral analysis of the time series indicates that the frequency of the oscillation in the radar and magnetometer data is about 3.8 mHz (260 s period). However, from 1230 to 1350 UT a wave signature is visible in the Finland V_{l-o-s} data alone which has a much higher frequency, confirmed to be 10 mHz (100 s period) by spectral analysis. No sign of this oscillation is evident in the Iceland East or TRO time series. Since the wave signatures were visible in several adjacent beams of the Finland radar, it is possible to determine the azimuthal wave numbers, m , of the ULF waves observed. They are calculated to be about 38 ± 6 for the high frequency wave and about 3-4 for the 3.8 mHz wave. An m -value of 4 was associated with the wave observed by the ground magnetometers for both intervals examined in the Finland data and was calculated using longitudinally separated IMAGE magnetometer

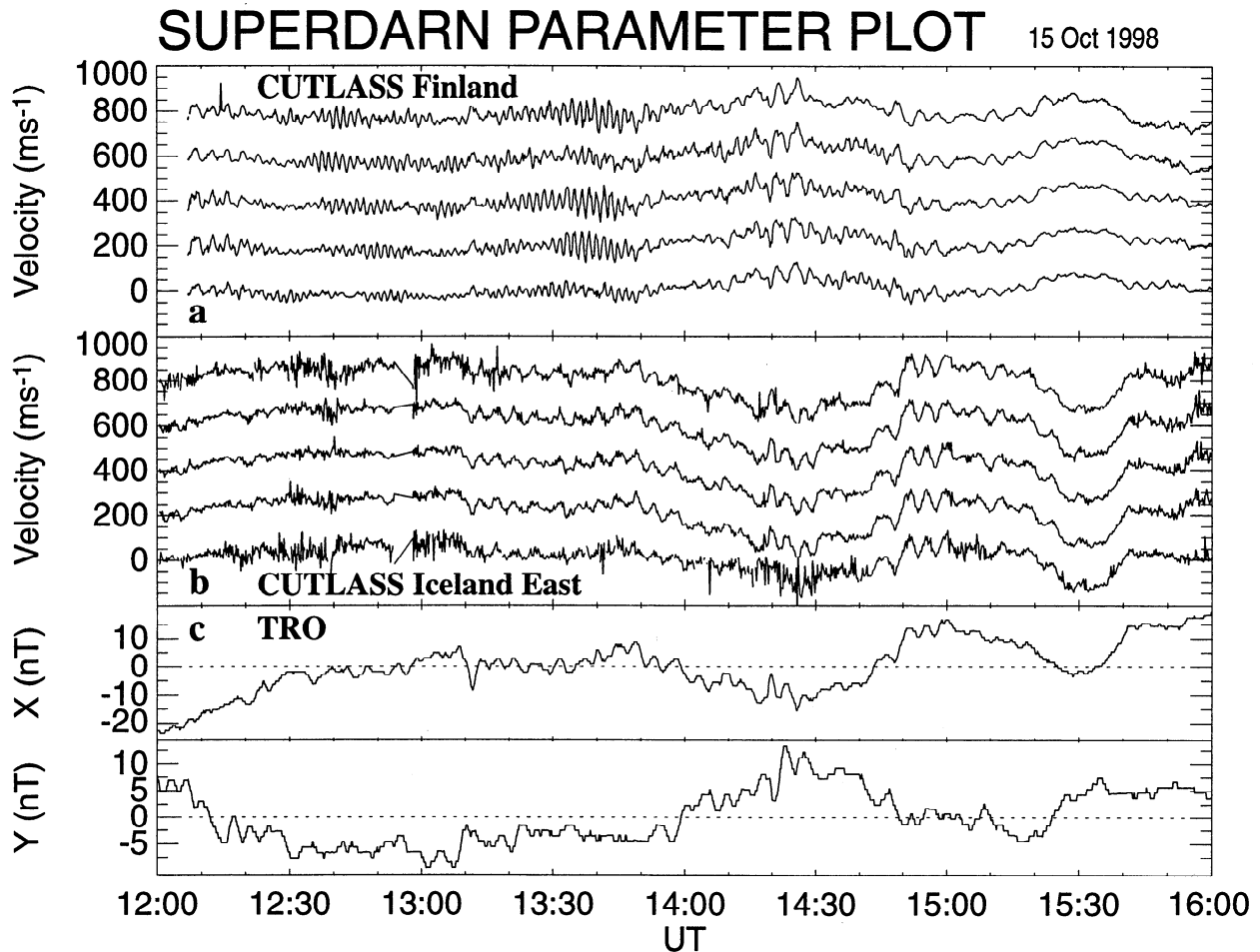


Figure 1. Line of sight velocity time series from the CUTLASS radar for the interval 1200-1600 UT on 15 October 1998: (a) Finland beam 5, range gates (from bottom) 26, 28, 30, 32 and 34; (b) Iceland East beam 15, range gates 34, 35, 36, 37 and 38. Each time series has been offset by 200 ms^{-1} for clarity and the ranges are centred on the middle of the heated volume (footpoint position 66.8°N 104°E geomagnetic). The range cell length is 15 km and all data were measured at an MLT=UT+2 hours. (c) TRO X- and Y-component magnetometer data for the same interval.

stations. The high- m wave observed in the ionosphere is typical of a new class of waves identified in HF Doppler sounder data at Tromsø (Wright and Yeoman, 1999).

It has been possible to combine the line of sight velocities measured by the CUTLASS radars in order to obtain bistatic flow vectors. V_{l-o-s} for Finland beam 5, range 28 and Iceland East beam 15, range 36 were employed for this study since they are close to the centre of their respective patches of artificial scatter and are collocated. The resulting data set represents high temporal and spatial resolution electric field measurements with unprecedented accuracy (exhibiting typical spectral widths less than 20 m s^{-1}). In addition, the “merged” data can be resolved into north-south (N-S) and east-west (E-W) geographic components and this information has been utilised to determine the polarisation characteristics of the high- m and low- m ULF waves observed in the CUTLASS data. Figure 2 displays the polarisation ellipses or *hodograms* for these two waves. The hodogram plots the N-S component of velocity as a function of the E-W component. The respective timeseries displayed having previously been narrow bandpass filtered in the range $P_w \pm 20 \text{ s}$, where P_w is the wave period. The sense of rotation and ellipticity of the hodograms indicate respectively the relative phases and amplitudes of the N-S and E-W components. The high- m wave is almost linearly polarised and N-S oriented (Fig. 2a), whereas the low- m wave has a larger phase difference between the N-S and E-W components and has a significant azimuthal component of velocity in the ionosphere. Both exhibit an anti-clockwise sense of rotation (N-S component of velocity leads in phase), indicating that these observations are equatorward of the locations of the maximum amplitudes of the respective resonances.

4. Discussion

The 10 mHz wave observed in the artificial scatter by the Finland radar is not observed by the ground magnetometers as a consequence of its small spatial scale length. 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. This implies the high- m wave was attenuated between the ionosphere and the ground by a factor of 5.5 more than the low- m wave as a consequence of the m -number. A point worth noting is that the phase fronts along the Finland radar beam exhibited a curved appearance as they evolved with time. This suggests that the latitudinal scale size of the wave was of the order of the size of the heated patch along the beam ($\sim 180 \text{ km}$). Applying the attenuation factor in this direction suggests that the high- m wave was attenuated at the ground by a factor of 20 relative to the low- m pulsation. A highly attenuated ULF wave with a latitudinal scale size of 60 km has also been reported by Yeoman *et al.* (1997) in heater generated backscatter.

There have been reports of observations of resonant high- m ULF waves in data from 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

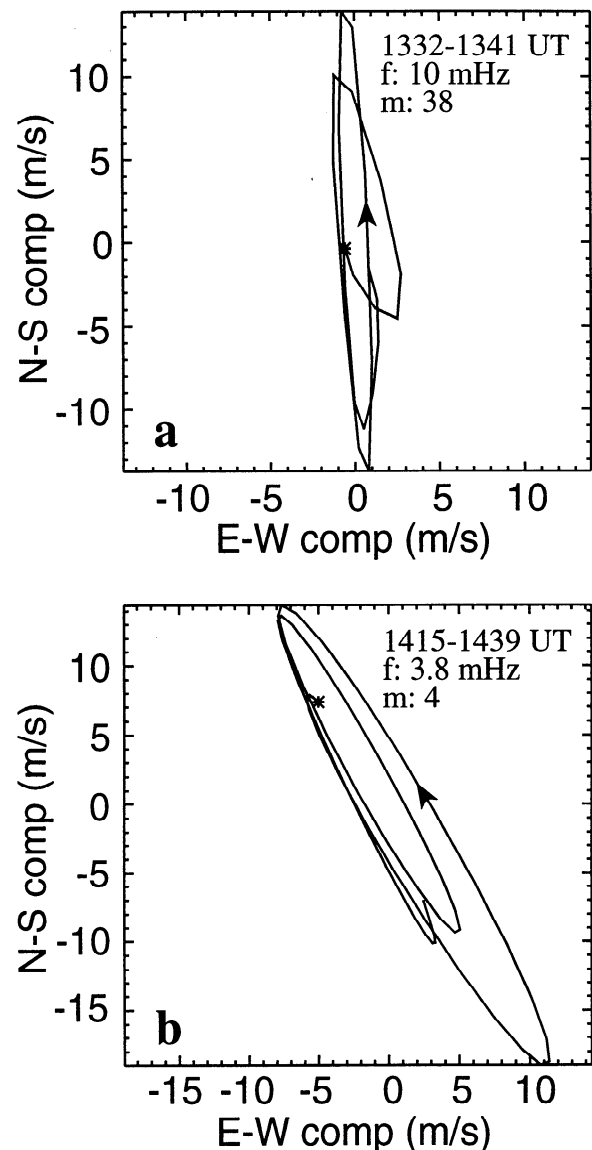


Figure 2. Hodograms derived from CUTLASS bistatic flow vectors and resolved into North-South (N-S) and East-West (E-W) geographic components: (a) the high- m 10 mHz wave in the interval 1332-1341 UT; (b) the low- m 3.8 mHz wave in the interval 1415-1439 UT. The arrows indicate the sense of rotation and the start of an ellipse is marked by 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 had a frequency which was three times that exhibited by the low- m wave on the ground. The high- m wave, which exhibits the westward phase propagation expect to be associated with particle driven waves, 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. The low-

m wave also appears to have a westward phase propagation. If this instability is responsible for the observations presented here then 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. In addition, the ratio of observed frequencies for the high- m and low- m waves is found to be 2.6, which is close to the theoretical ratio for second harmonic to fundamental frequencies (Cummings *et al.*, 1969) and supports the possibility that the occurrence of the high- m wave may be explained by the ring current instability theory (*e.g.* Southwood, 1976).

The high resolution measurements of the ionospheric electric fields associated with the ULF wave signatures presented here are considered to be the most accurate yet recorded by an HF radar as a result of the very narrow spectral widths associated with the heater generated backscatter, indeed they are probably the most accurate ionospheric electric field measurements from any technique to date. The hodograms which have been derived from the combined radar data are the first ever obtained from HF radar data. The characteristics of the high- m polarisation ellipse (Fig. 2a), especially its near linear polarisation, closely resemble those calculated for the "Storm-time" Pc5s observed with the STARE VHF radar (*e.g.* Allan *et al.*, 1982). A resonant structure is implied by the subsequent low- m hodogram (Fig. 2b) the anti-clockwise rotation of the ellipse indicating that the observations are equatorward of the resonance region. These polarisation characteristics are, then, also consistent with the seeding theory discussed above.

5. Summary

A new experiment has been developed with the aim of observing the ionospheric signatures of ULF waves in CUTLASS radar backscatter artificially generated by the EISCAT Heater. It has provided the first opportunity, under controlled conditions, to make high spatial and temporal resolution measurements of the waves where HF radar backscatter was not already present. Currently the experimental arrangement described here is unique, however the imminent deployment of the Kodiak Island SuperDARN radar, which has the HAARP facility (*e.g.* Rodriguez *et al.*, 1998) in its field of view, will present new opportunities for this type of experiment. The resulting electric field data exhibit unprecedented accuracy for an HF radar due to the narrow spectral widths associated with the artificial irregularities. A high- m wave was observed in the ionosphere at a frequency which was close to a harmonic of a low- m resonant wave occurring simultaneously and measured in the ionosphere and at the ground. The bistatic flow vectors derived from CUTLASS were transformed into hodograms (polarisation ellipses) for the two waves. The high- m signature displays similarities to the polarisation characteristics of non-resonant particle driven waves previously recorded by the STARE VHF radar and the low- m wave is consistent with the phase profile of a field line resonant structure. The results described are not inconsistent with the theory that low- m waves may, under appropriate conditions, drive high- m waves via a non-linear Kelvin-Helmholtz instability in the magnetosphere. In this case, however, the instability appears to have stimulated a harmonic of the driving wave.

Acknowledgments. The authors wish to extend their gratitude to the Particle Physics and Astronomy Research Council (PPARC) for support during the research presented in this paper. In addition, we would like to thank Mike Rietveld and the staff of the EISCAT site at Ramfjordmoen, Norway for their assistance in operating the Tromsø heating facility; Mark Lester, the CUTLASS PI, for facilitating our employment of CUTLASS; the Finnish Meteorological Institute and Børre Holmeslet of the Tromsø Auroral Observatory for magnetometer data. Also, we are grateful to Mark Lester, Steve Milan and Jackie Davies for their assistance with various aspects of this study.

References

- Allan, W., E. M. Poulter and E. Nielsen, STARE observations of a Pc5 pulsation with large azimuthal wave number, *J. Geophys. Res.*, 87, 6163, 1982.
- Allan, W. and A. N. Wright, Large- m waves generated by small- m field line resonances via the nonlinear Kelvin-Helmholtz instability, *J. Geophys. Res.*, 102, 19927, 1997.
- Cummings, W. D., R. F. O'Sullivan and P. J. Coleman, Standing Alfvén waves in the magnetosphere, *J. Geophys. Res.*, 74, 778, 1969.
- Fenrich, R. C., J. C. Samson, G. Sofko and R. A. Greenwald, ULF high- and low- m resonances observed with the Super Dual Auroral Network, *J. Geophys. Res.*, 100, 21535, 1995.
- Fenrich, R. C. and J. C. Samson, Growth and decay of field line resonances, *J. Geophys. Res.*, 102, 20031, 1997.
- Greenwald, R. A. *et al.*, DARN/SUPERDARN A global view of the dynamics of high-latitude convection, *Space Sci. Rev.*, 71, 761, 1995.
- Hughes, W. J., Hydromagnetic waves in the magnetosphere, *Solar Terrestrial Physics* (edited by Carovillano, R. L. and Forbes, J. M.), Reidel, Dordrecht, 1983.
- Hughes, W. J. and D. J. Southwood, The screening of micropulsation signals by the atmosphere and ionosphere, *J. Geophys. Res.*, 81, 3234, 1976.
- Lühr, H., The IMAGE magnetometer network, *STEP International Newsletter*, 4, 4, 1994.
- Mann, I. R., An MHD model for driven high m field line resonances, *Geophys. Res. Lett.*, 25, 1515, 1998.
- Milan, S. E., T. K. Yeoman, M. Lester, E. C. Thomas and T. B. Jones, Initial backscatter occurrence statistics from the CUTLASS HF radars, *Ann. Geophys.*, 15, 703, 1997.
- Rietveld, M. T., H. Kohl, H. Kopka and P. Stubbe, Introduction to ionospheric heating at Tromsø – I. Experimental overview, *J. Atmos. Terr. Phys.*, 55, 577, 1993.
- Robinson, T.R., A.J. Stocker, G. E. Bond, P. Eglitis, D. M. Wright and T.B. Jones, O- and X-mode heating effects observed simultaneously with the CUTLASS and EISCAT radars and low power HF diagnostics at Tromsø, *Annales Geophysicae*, 15, 134, 1997.
- Rodriguez, P. *et al.*, The WIND-HAARP experiment: Initial results of high power radio wave interactions with space plasmas, *Geophys. Res. Lett.*, 25, 257, 1998.
- Southwood, D. J., A general approach to low-frequency instability in the ring current plasma, *J. Geophys. Res.*, 81, 3340, 1976.
- Wright, D. M. and T. K. Yeoman, High-latitude HF Doppler observations of ULF waves: 2. waves with small spatial scale sizes, *Ann. Geophys.*, in press, 1999.
- Yeoman, T. K., D. M. Wright, T. R. Robinson, J. A. Davies and M. T. Rietveld, High spatial and temporal resolution observations of an impulse-driven field line resonance in radar backscatter artificially generated with the Tromsø heater, *Annales Geophysicae*, 15, 634, 1997.

D. M. Wright and T. K. Yeoman, Department of Physics & Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, UK. (email: dmw7 or yxo@ion.le.ac.uk).

(Received June 10, 1999; accepted July 20, 1999.)