Drift resonance and drift-bounce resonance energy sources for ULF waves observed in artificially-induced radar backscatter

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Abstract. HF radar backscatter which has been artificially-induced by a high power RF facility such as the EISCAT heater at Troms¿ has been demonstrated to provide ionospheric electric field data of unprecedented temporal resolution and accuracy. Here such data are used to investigate ULF wave processes observed by the CUTLASS HF radars. Within a short period of time three distinct wave types are observed, with differing periods, and latitudinal and longitudinal phase evolution. Combining information from the three waves allows the drift-bounce resonance interactions which cause the waves to be determined.

1. Introduction

In the SP-UK-OUCH (**O**bservations of **U**LF waves with **C**UTLASS and the **H**eater) artificial backscatter experiment the CUTLASS (Co-operative UK Twin Located Auroral Sounding System; Milan *et al.*, 1997) bistatic HF radars run in a high temporal and spatial resolution mode. The EISCAT heater is in continuous operation at 50% power, at a frequency of 4 MHz for 4 hours. The heater produces artificial electron density striations in the F region ionosphere, and these irregularities act as targets for the HF radar. This is shown schematically in Figure 1a. The artificial targets have been demonstrated to accurately track the natural ionospheric convection velocity, and the backscatter obtained is of very high power, and very narrow spectral width (Yeoman *et al.*, 1997; Eglitis *et al.*, 1998; Wright and Yeoman, 1999a,b). This allows short integration time to be run on the radar, providing higher time resolution than is normally available. The narrow spectral widths also produce ionospheric electric field measurements of unprecedented accuracy. Sample coherent and incoherent scatter spectra from natural and artificial irregularities are illustrated in Figure 1b,c.

In general magnetospheric Ultra Low Frequency (ULF) waves which have an energy source external to the Earth, such as an impulse in the solar wind, solar wind buffeting, or the Kelvin-Helmholtz instability on the magnetopause, are characterised by small effective azimuthal wavenumbers, *m*, (or equivalently a large scale size in the azimuthal direction). Conversely, it is now widely accepted that an energy source for small-scale, high-*m* ULF waves exists in drifting energetic particle fluxes, through drift and drift-bounce resonance interactions. Such high-*m* waves are a topic of considerable importance in both theoretical and experimental studies at present. Energetic particles entering the Earth's inner magnetosphere from the magnetotail will experience 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 magnetosphere and ionosphere when free energy is available to the wave via a non-Maxwellian particle distribution function, with a positive slope at an appropriate energy (e.g. Hughes, 1983, Figure 2). Such wave-particle interactions are a process of fundamental importance in collisionless astrophysical plasmas.

2. Observations

For the interval under study the artificial backscatter technique has provided an interval of bistatic electric field data during a complex period of wave activity. Unprecedented spatial, temporal and electric field resolution is achieved. During the 18th October 1999 artificial backscatter was obtained from both the

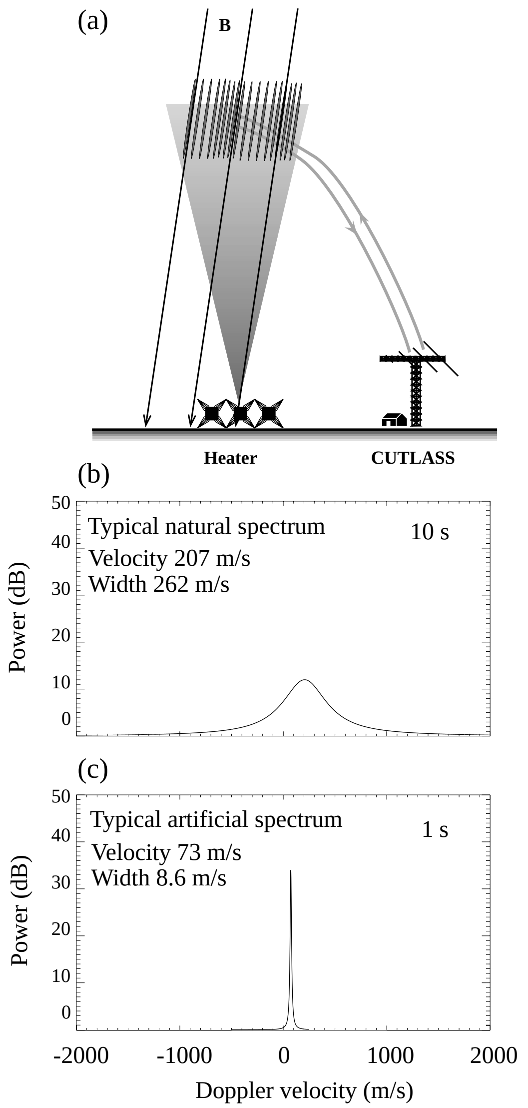

Figure 1. (a) A schematic of the artificial backscatter experiment, SP-UK-OUCH. The Tromsø heater continuously heats the F region ionosphere, creating artificial ionospheric irregularities. These are detected by the CUTLASS radars, operating in a high temporal and spatial resolution mode. (b) A typical HF radar spectrum, obtained from fitting to the autocorrelation function of backscatter from natural F region irregularities after an integration period of 10 s. (c) A similar spectrum, but this time obtained from a 1 s integration from a heated F region. A narrower spectrum results, even from a shorter integration time.

CUTLASS radars, allowing bistatic vector electric field data to be obtained. Here, for brevity, only data from Hankasalmi is presented. Figure 3 presents a colour-coded representation of the line-of-sight velocity measured by the CUTLASS Hankasalmi radar for several radar range gates over a half-hour sub interval (Interval 1, 1230-1300 UT) of the four-hour experiment. A region of the high latitude ionosphere of roughly one degree in both latitude and longitude is illuminated by the EISCAT heater at Troms¿. Complex and variable wave activity is clear in the data.

The wave characteristics in three different intervals are examined. For Interval 1 the clearest wave signature in this interval is between 1450 and 1300 UT, although higher frequency waves are detectable before this. The wave has a frequency of 5.7 mHz and an azimuthal wavenumber, *m*=+6–3. It is a large scale wave which is also observed by the IMAGE magnetometer at Troms¿. This *m* value is calculated by examining the wave phase variation between Hankasalmi beams 4 and 5, and is also measured by similarly comparing azimuthally spaced magnetometers from the IMAGE array. This wave is interpreted as a fundamental, large-scale toroidal field line resonance.

Interval 2 (1300-1330 UT; Figure 4) has a wave of frequency of 3.8 mHz and an azimuthal wavenumber, *m*=-35–5, and shows clear equatorward phase motion. The wave thus has azimuthal phase propagation opposite to the solar wind flow, but in the direction of gradient-curvature drifting protons. This frequency is close to that predicted from Interval 1 for a fundamental poloidal resonance. Such waves, with equatorward phase propagation, are generally assumed to be generated by drift resonance with westward drifting protons (e.g. Allan *et al.*, 1983; Grant *et al.*, 1992). They have a weak or non-existent signature in ground magnetometer data, as small-scale waves suffer attenuation through the ionosphere. The attenuation of the pulsation magnetic perturbation below the ionosphere is proportional to e^{-kz} (*e.g.* Hughes and Southwood, 1976) where $\boldsymbol{k}$ is the field perpendicular component of the wave number and z is the E-region height.

A fundamental mode drift resonance with westward moving, large pitch angle protons could provide the energy as illustrated schematically in Figure 2a. Using the drift resonance equation (*e.g.* Hughes, 1983)

$$\omega_{wave\,\#2} = m_{wave\,\#2}\,\omega_{drift}.$$

$$\text{So,}\quad \omega_{drift} = \left(\frac{\omega}{m}\right)_{wave\,\#2}.$$

Protons of energy 47–10 keV and large pitch angle are predicted to provide the wave energy source. Interval 3 (1330-1400 UT; Figure 5) has a wave of frequency of 14.3 mHz and an azimuthal wavenumber, *m*=-35–5. This frequency is close to that predicted from interval l for a second harmonic poloidal resonance.

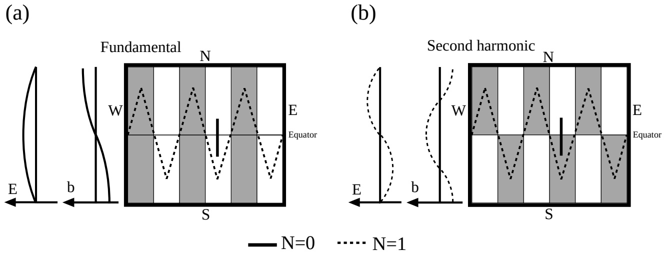

Figure 2. Trajectories of two ions (solid and dashed lines) in the wave rest frame. Shaded and unshaded regions represent positive and negative electric field respectively. The ions indicated with a solid line are in resonance with the *N*=0 drift mode, and the ions represented by the dashed line with the *N*=1 drift-bounce resonance (after Southwood and Kivelson, 1982).

A second harmonic mode drift-bounce resonance with westward moving, small pitch angle protons (as illustrated in Figure 2b) of similar energy (37–10 keV) could provide the energy. Such particles fit the bounce-resonance condition (*e.g.* Hughes, 1983)

$$\omega_{wave\,\#3} - m_{wave\,\#3}\omega_{drift} = N\omega_{bounce}$$

for the wave parameters deduced here and *N*=1. Such small pitch angle particles drift slightly slower than the large pitch angle particles, and thus are expected to reach the dayside slightly later than the population driving the Interval 2 wave.

3. Summary

- The artificial backscatter technique has provided an interval of bistatic electric field data during a complex period of wave activity. Unprecedented spatial, temporal and electric field resolution is achieved
- A large scale (low *m*) field line resonance is observed, and gives the fundamental toroidal eigenfrequency as 5.7 mHz
- Small scale (high m) particle-driven waves are also observed, near the expected frequencies of the fundamental and second harmonic (3.8 and 14.3 mHz)
- These two waves are consistent with a drift wave and a bounce-resonance energy source, respectively, with a driving particle population at 35-45 keV. It appears that the postnoon sector can support both drift resonance and a drift-bounce resonance interactions for waves with *m*~-35.

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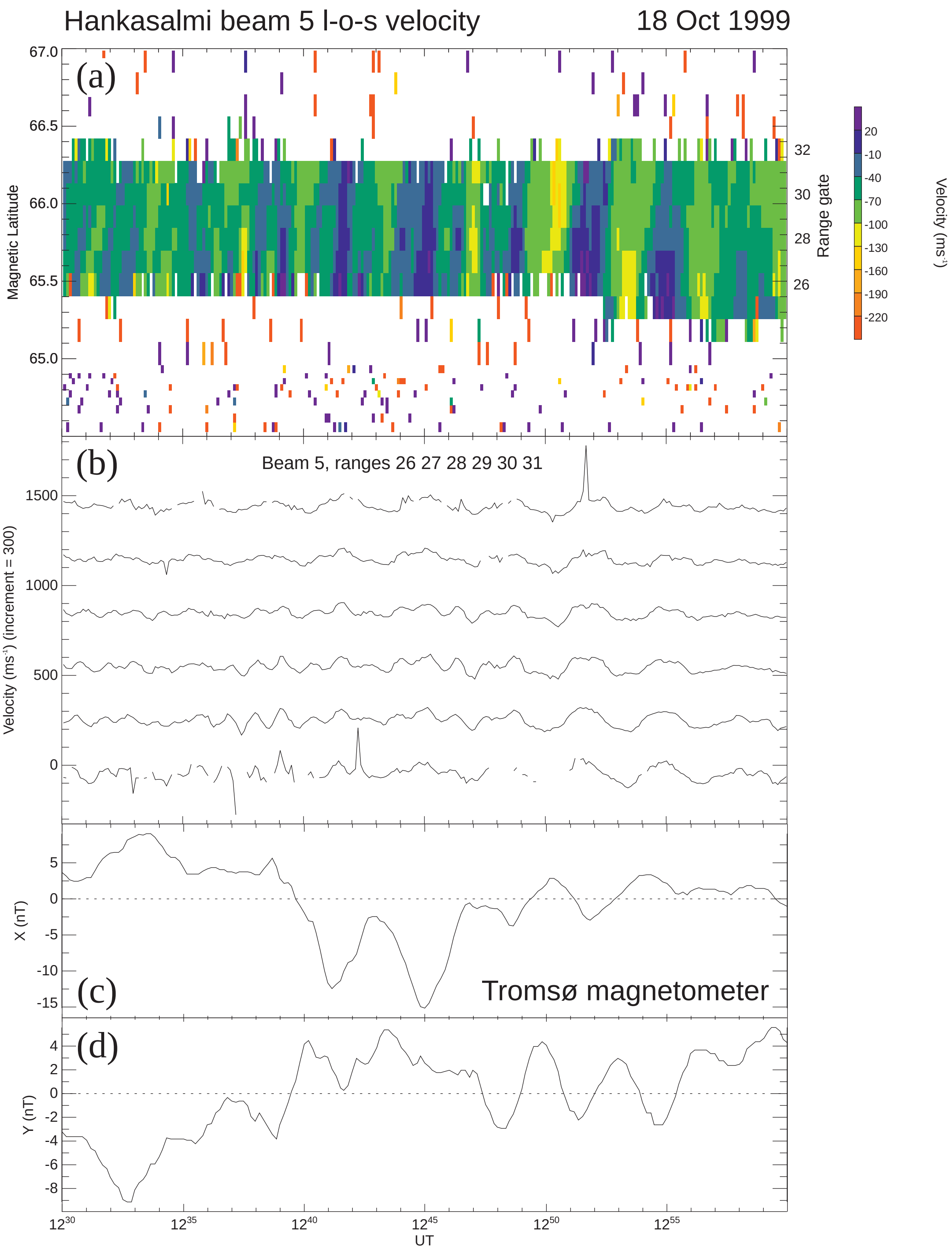

Figure 3. Interval 1, 1230-1300 UT: (a) Beam 5 velocities from Hankasalmi, Finland as a function of geomagnetic latitude. The velocities are colour-coded such that flow away from the radar (negative velocities) are indicated in red and flow toward the radar (positive velocities) are indicated in blue. Radar range gate is also indicated on the right. (b) a timeseries representation of the velocity measurements in (a). (c) X and (d) Y component magnetograms from the TRO magnetometer. The magnetometer lies under range gate 32.

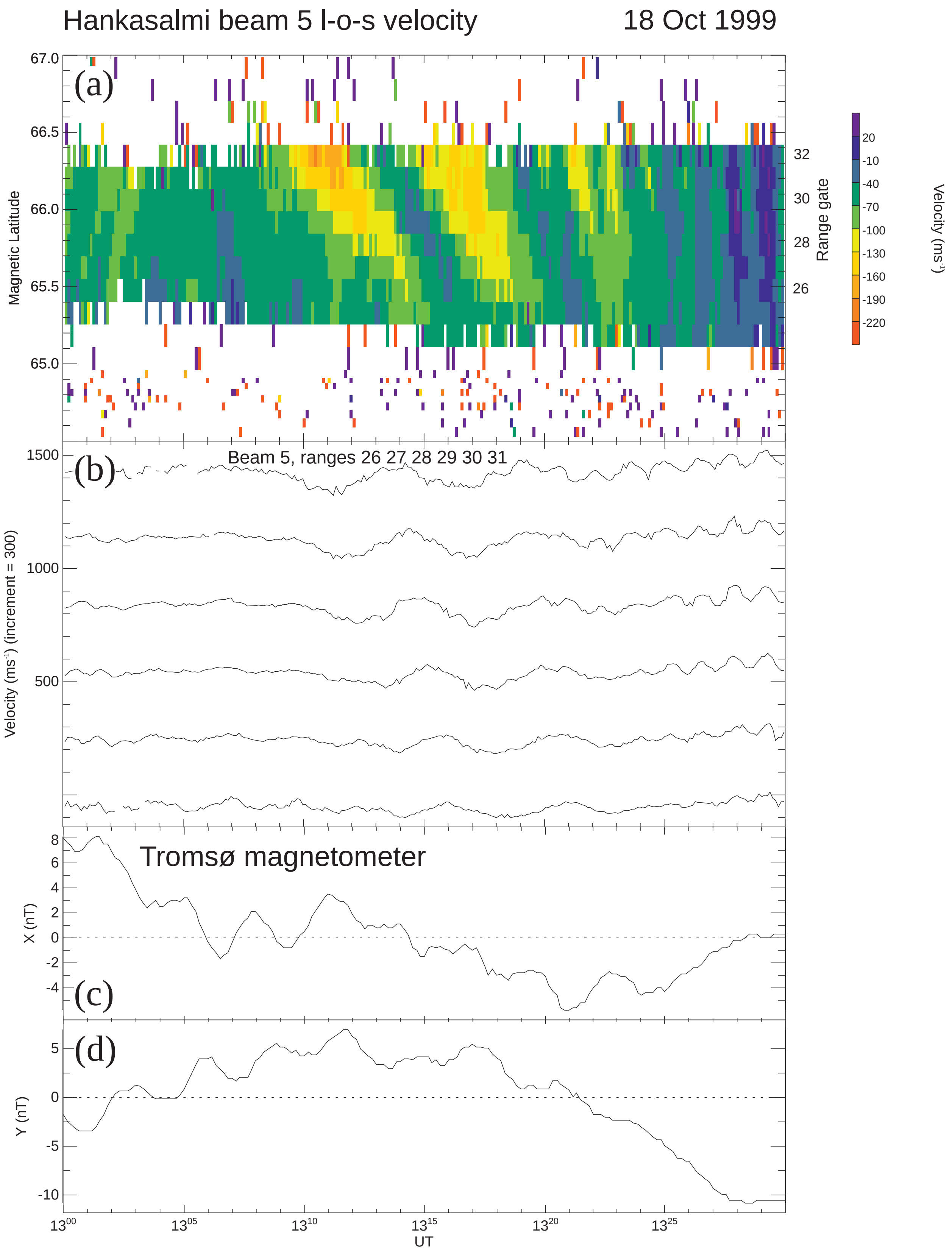

Figure 4. Interval 2, 1300-1330 UT. Format as for Figure 3.

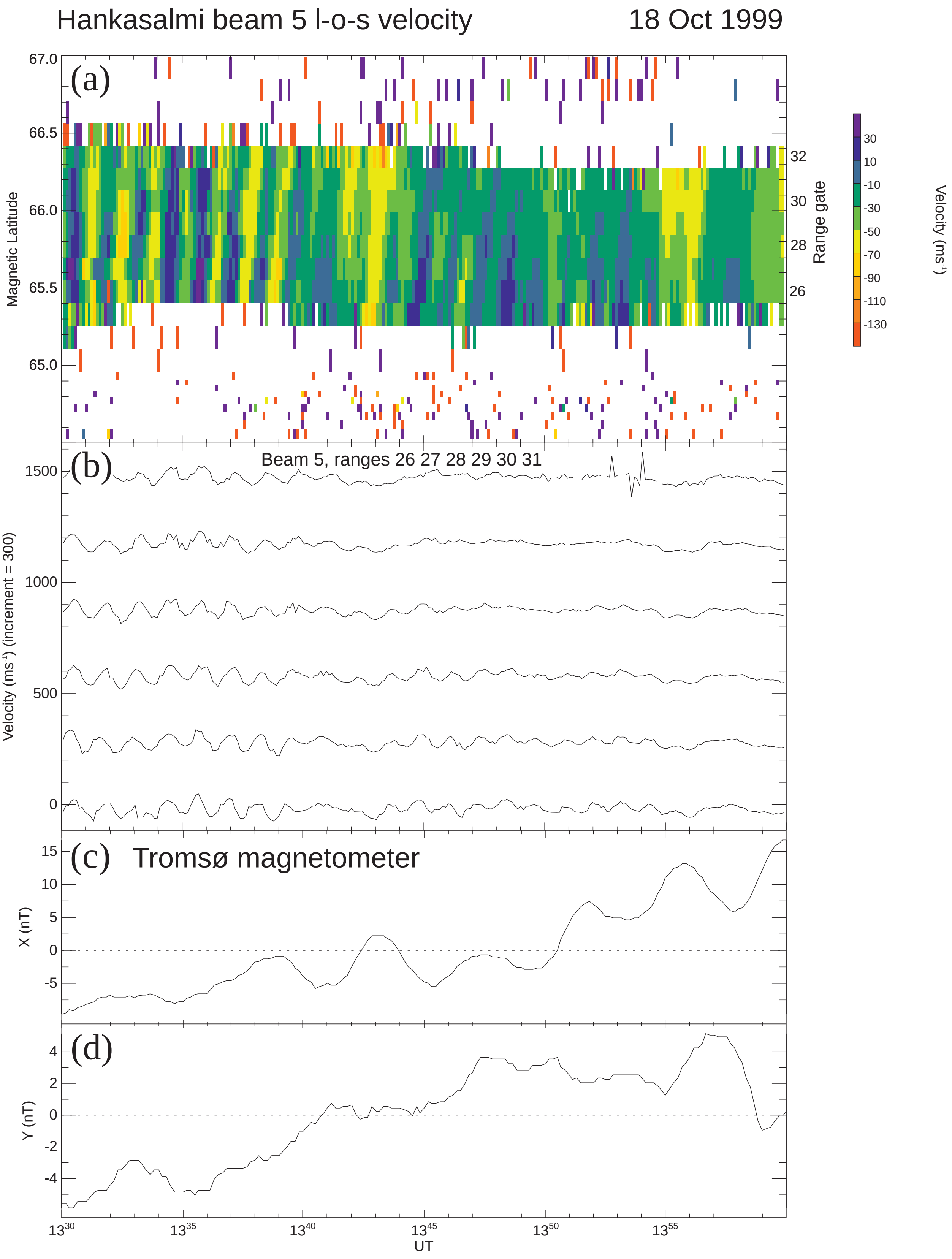

Figure 5. Interval 2, 1300-1330 UT. Format as for Figure 3.