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Cluster spacecraft observations of a ULF wave enhanced by Space Plasma Exploration by Active Radar (SPEAR)

S. V. Badman, D. M. Wright, L. B. N. Clausen, R. C. Fear, T. R. Robinson, and T. K. Yeoman

Department of Physics & Astronomy, University of Leicester, Leicester LE1 7RH, UK

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Abstract. Space Plasma Exploration by Active Radar (SPEAR) is a high-latitude ionospheric heating facility capable of exciting ULF waves on local magnetic field lines. We examine an interval from 1 February 2006 when SPEAR was transmitting a 1 Hz modulation signal with a 10 min on-off cycle. Ground magnetometer data indicated that SPEAR modulated currents in the local ionosphere at 1 Hz, and enhanced a natural field line resonance with a 10 min period. During this interval the Cluster spacecraft passed over the heater site. Signatures of the SPEAR-enhanced field line resonance were present in the magnetic field data measured by the magnetometer on-board Cluster-2. These are the first joint ground- and space-based detections of field line tagging by SPEAR.

Keywords. Ionosphere (Active experiments; Ionosphere-magnetosphere interactions)

1 Introduction

High power radio facilities have been used for many years to investigate the terrestrial ionosphere (see e.g. the review by Stubbe, 1996, and references therein). Absorption of radiowave energy by electrons in the lower ionosphere causes the electron temperature to increase, a process which has a very short characteristic timescale, e.g. ∼1 ms at 90 km altitude (Stubbe et al., 1982). Over longer heating intervals (of order 10 s at similar altitude) the electron density can also be increased (Stubbe et al., 1982). The effect of these increases in temperature and density in the collisional lower ionosphere is to increase the local conductivity, which subsequently affects the existing currents flowing in the ionosphere. When the heater output is modulated at a certain frequency the ionospheric parameters will also be modulated at this frequency such that an oscillating current is set up. The active region becomes a virtual antenna radiating an electromagnetic wave at the modulation frequency both up into the magnetosphere and down to the ground. For this process the heating occurs in the collisional plasma of the ionospheric D- and E-regions at altitudes of ∼70–100 km. Modulated heating experiments have been carried out using various frequencies in the ULF, ELF and VLF ranges i.e. $\sim 10^{-3}$–10^{4} Hz (e.g. Stubbe, 1996; Bösinger et al., 2000). In these experiments the presence of the modulated wave was usually looked for in ground magnetometer data. The success of such experiments is highly dependent on the prevalent conditions, e.g. Maul et al. (1990) detected pulsations at frequencies $\sim 10^{-3}$ Hz–10 Hz under both quiet and disturbed geomagnetic conditions, while Bösinger et al. (2000) found evidence of artificial magnetic pulsations (at frequencies of 0.1–3 Hz) in ∼10% of their experiment intervals. In the case of heating closed geomagnetic field lines, when the modulation frequency matches a field line eigenfrequency (typically ∼mHz frequencies, e.g. Fenrich et al., 1995) then energy can be pumped into a field line resonance and the observed field perturbations will be strong.

Artificial enhancement of field line resonances is useful to explore characteristics of the field line such as the harmonic structure, and the plasma mass loading along the field line (e.g. Orr, 1984; Chisham and Orr, 1991). "Tagging" a field line in this way also provides a means of constraining magnetic field models because the position of the field line footprint in the ionosphere is known. This is applicable to spacecraft orbiting through a resonant flux tube, and is particularly useful at high latitudes where the field configuration becomes very non-dipolar. Higher frequency (∼Hz) artificially-enhanced waves can interact with the Ionospheric Alfven Resonator (IAR), a vertical cavity bounded by Alfvén wave reflectors (e.g. Lysak, 1993), and generate secondary effects such as field-aligned electron acceleration (Robinson

Correspondence to: S. V. Badman
(svb4@ion.le.ac.uk)

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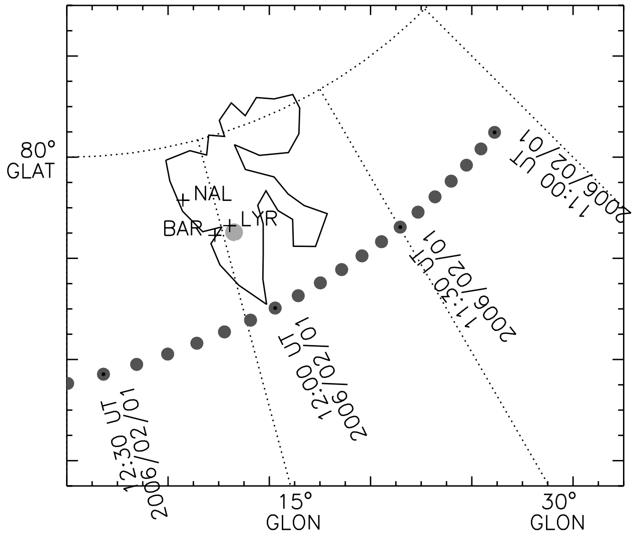

Fig. 1. A map showing the locations of the SPEAR heater patch at 100 km altitude (light grey circle), the IMAGE and Barentsburg magnetometer sites used in this study (labelled crosses), and the mapped ionospheric footprint at 100 km altitude of the Cluster-2 spacecraft (dark grey circles) during 11:00–12:30 UT on 1 February 2006, in geographic coordinates.

et al., 2000). In the experiment described by Robinson et al. (2000) the FAST spacecraft (Carlson et al., 1998) detected artificially-modulated electric field and electron flux intensities. Studying these ionospheric and magnetospheric processes under known experimental conditions provides insight into naturally-occurring phenomena such as the aurora.

Space Plasma Exploration by Active Radar (SPEAR) is a high-power radio facility located on the island of Spitsbergen at geographic coordinates 78.15° N and 16.05° E, shown in Fig. 1. SPEAR is capable of transmitting a steerable beam of radio waves at frequencies between 4 and 6 MHz, with a wide range of modulation frequencies. A full description of SPEAR and its operational capabilities is given by Wright et al. (2000) and Robinson et al. (2006). Among many results from SPEAR experimental heating campaigns run so far, ground magnetometer data have provided evidence of stimulation of the local IAR at Hz frequencies (Scoffield et al., 2006), and excitation of open field lines at mHz frequencies (Clausen et al., 2008). This paper describes a similar experiment when SPEAR modulated ionospheric currents at 1 Hz and 1.67 mHz, and enhanced a field line resonance at 1.67 mHz on closed field lines. The modulations were detected by ground magnetometers and evidence of related disturbances at 1.67 mHz was found in magnetic and electric field measurements taken by the Cluster spacecraft conjugate to SPEAR. This is the first spacecraft detection of field line-tagging by SPEAR.

2 Instrumentation

SPEAR is located in the region of various ground-based instruments used to study magnetosphere-ionosphere interactions. Several spacecraft including the Cluster satellites orbit over its high-latitude site. The ground- and space-based instruments used in this experiment will now be described.

2.1 Ground instrumentation

During the interval 11:30–12:30 UT on 1 February 2006 SPEAR transmitted 1 Hz modulated X-mode polarised wave at 4.9 MHz, with a 5 min on–5 min off (1.67 mHz) cycle. The 1 Hz modulation was intended to stimulate the IAR, while the 10-min on-off period could enhance an existing field line eigenmode at that frequency. The beam was centred on the local field-aligned direction with a half-power width of ∼20°, which mapped to a heated patch of ∼35 km diameter at 100 km altitude in the ionosphere. This patch is indicated in Fig. 1 by the larger light grey shaded circle. The antenna gain was ∼22 dB at the frequency employed and the effective radiated power was ∼15 MW. The SPEAR site is adjacent to that of the EISCAT Svalbard Radar, which is capable of measuring ionospheric parameters such as electron density and temperature, but unfortunately was not operating during the interval of interest in this study.

A Canadian Digital Ionosonde (CADI) is co-located with SPEAR. The CADI uses radio pulses to probe the ionospheric structure at a 4 min cadence. When SPEAR is transmitting it saturates the ionosonde signal, but essential features are still discernable in the ionograms produced as will be seen in Sect. 3.1 below.

The International Monitor for Auroral Geomagnetic Effects (IMAGE) magnetometer network (Lühr, 1994) currently has 30 stations distributed throughout Scandinavia covering a range of geographic latitudes from 58° to 79°. In this study we use data from the two stations located closest to SPEAR: Ny Ålesund (NAL) at 78.92° N, 11.95° E (geographic coordinates) and Longyearbyen (LYR) at 78.20° N, 15.82° E, the locations of which are marked in Fig. 1 by the labelled crosses. NAL and LYR are at a ground distance of 125 km and 8 km, respectively, from SPEAR. The ground magnetometer data were resolved into three mutually perpendicular components X, Y and Z where X and Y point towards geographic north and east along the ground, respectively, and Z is the vertical component. The IMAGE station data were sampled at a time resolution of 10 s, which was too low to identify the 1 Hz modulation signal, but was sufficient to detect effects related to the 5 min on-off cycle. The Barentsburg pulsation magnetometer (BAR), located at 78.09° N and 14.21° E (at a ground distance of 43 km from SPEAR) as indicated in Fig. 1, samples the magnetic field data at a much higher rate of 40 Hz and was therefore capable of detecting any artificial modulation of ionospheric currents at 1 Hz. Investigation of data from these magnetometer stations during past campaigns indicates that they do not experience direct coupling with the SPEAR transmissions, therefore any modulated signals received are valid representations of modulated ionospheric currents.

2.2 The Cluster spacecraft

The Cluster mission consists of four spacecraft orbiting the Earth in a tetrahedral formation (Escoubet et al., 2001). On 1 February 2006 at ∼12 UT the Cluster spacecraft were at a position ∼(5,7,6) R_E in Geocentric Solar Ecliptic (GSE) coordinates i.e. sunward and duskward of the north pole. (The GSE coordinate system is defined with X directed from the Earth to the Sun, Y is positive towards dusk in the ecliptic plane and Z completes the set pointing northward from the ecliptic.) The spacecraft were at relatively large separations from each other at this time (up to ∼2 R_E separation across the whole tetrahedron), so they magnetically mapped to different locations in the ionosphere. The ionospheric footprint of Cluster-2 was found to pass closest of the four spacecraft to the SPEAR heated flux tube during the heating experiment. The Cluster-2 footprint at 100 km altitude is marked at 5 min intervals from 11:00 to 12:30 UT on 1 February 2006 by the line of dots in Fig. 1. The mapping of the spacecraft orbit to the ionosphere was performed using the Tsyganenko (1996) model of the Earth's magnetic field. The interplanetary magnetic field (IMF) inputs to the model were the averages calculated over the corresponding hour-long interval of data from the magnetometer onboard the Advanced Composition Explorer (ACE) spacecraft (Stone et al., 1998; Smith et al., 1999) located upstream of the Earth. (The solar wind travel time from ACE to the Earth has been accounted for.) Specifically, the values for the GSE Y and Z components were B_Y=0.9 nT and B_Z=−3.3 nT. No solar wind dynamic pressure data were available from ACE so the standard input of P_{dyn}=2 nPa was used. This value is comparable to the average measurement of P_{dyn}=1.7 nPa made by the Solar Wind Experiment on the WIND spacecraft (Ogilvie et al., 1995) located upstream 30 R_E dawnward and 70 R_E sunward of ACE over the same interval. The value for the geomagnetic index D_{st}=−10 nT was taken from the World Data Service for Geomagnetism, Kyoto archives. Uncertainties in these values input to the model do not significantly alter the footprint output.

Each Cluster spacecraft carries a fluxgate magnetometer (FGM), capable of providing vector measurements of the magnetic field at up to 67 Hz in burst mode (Balogh et al., 2001). The data used in this study were high resolution (22 Hz) obtained from the Cluster Active Archive. Electric field measurements were made by the Electric Field and Wave (EFW) investigation (Gustafsson et al., 1997) onboard the Cluster spacecraft. The duskward and sunward electric field components (corresponding to GSE Y and X respectively) were available at spin (∼4 s) resolution. The third mutually perpendicular component of the electric field is not measured by the instrument (although it can be deduced by assuming **E.B**=0), therefore we consider only the two available components and their resultant ($E_{\text{res}}=[E_{\text{dusk}}^2+E_{\text{sun}}^2]^{1/2}$) here.

3 Observations

To artificially enhance a field line resonance the heater needs to be on closed field lines. Although the high-latitude SPEAR site is often located in the polar cap on open field lines, particle data from the Defense Meteorological Satellites Program (DMSP) F13, F15 and F16 spacecraft showed that SPEAR was located equatorward of the auroral oval i.e. on closed field lines during the heating interval. This was confirmed by a statistical model of the auroral oval location (Holzworth and Meng, 1975) using the value for the K_p index (obtained from the World Data Service for Geomagnetism, Kyoto archives) of K_p=1, and also by electron data measured by the Plasma Electron and Current Experiment (PEACE) instruments onboard the Cluster spacecraft (Johnstone et al., 1997) which identified hot trapped electron populations indicative of closed field lines.

3.1 Ionospheric conditions

Successful X-mode modulated heating experiments require the presence of an absorbing D- or E-region at the heater transmit frequency (Borisov and Stubbe, 1997). A sample of the CADI ionograms returned during both heater "on" and "off" intervals is shown in Fig. 2. At 11:26 UT, before the heating began, the ionosonde indicated the presence of a patchy E-region extending to frequencies of ∼4.5 MHz i.e. just below the SPEAR transmit frequency of 4.9 MHz. The returns from the F-region are a further indication that the E-region was weakly absorbing because some signal had transmitted through to higher altitudes. The next ionogram shown, obtained at 11:34 UT, demonstrates the saturation of the ionosonde during SPEAR transmission, resulting in gaps in the ionogram, although some reflections from both E and F-region altitudes were still detected. Subsequent ionograms indicate the variability of the ionospheric conditions throughout the interval. Evidence of a suitable E-region was detected at 11:54 UT (SPEAR on), 12:10 UT (SPEAR on) and 12:18 UT (SPEAR off) but not at 11:58 UT (SPEAR off). Overall therefore it seems that ionospheric conditions appropriate for X-mode heating occurred intermittently throughout this interval, owing at least in part to the presence of a sporadic E-layer, improving and becoming more steady after ∼12:10 UT.

3.2 Ground magnetometer measurements

The X and Y components of the magnetic field measured on the ground are plotted for IMAGE stations Ny Ålesund (NAL) and Longyearbyen (LYR) over the time interval

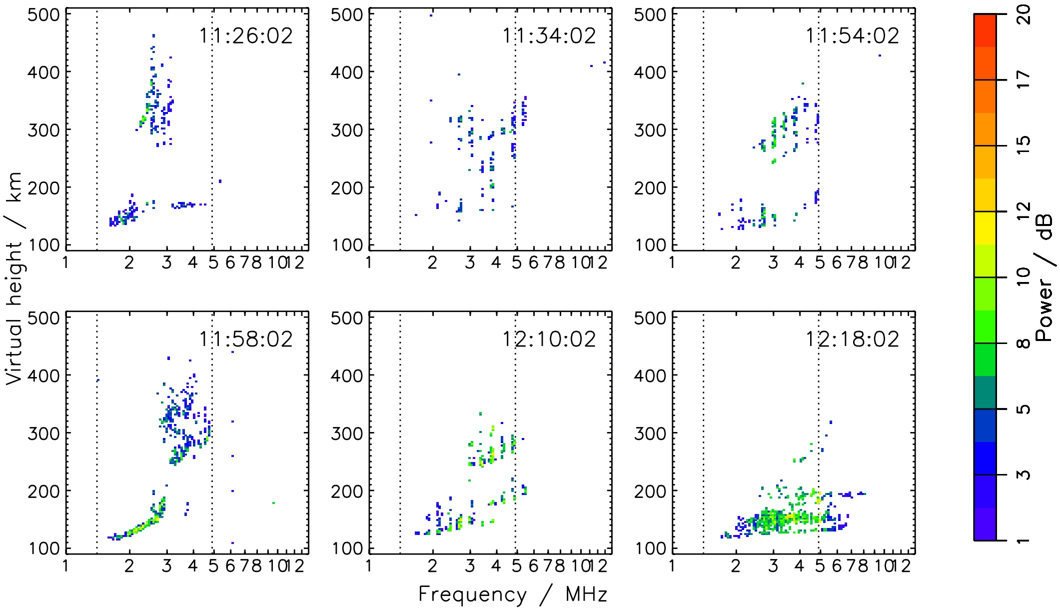

Fig. 2. Sample ionograms measured by the ionosonde co-located with SPEAR on 1 February 2006. The returned powers are colour coded in dB according to the scale at the right hand side and plotted against frequency (on a log scale) and virtual height. The vertical dashed line toward the left of each ionogram shows the minimum sampling frequency of the ionosonde, and the line at 4.9 MHz marks the SPEAR transmit frequency during the experiment. The time (UT) of each ionogram is given in the top right hand corner.

11:00–13:00 UT in Fig. 3. The data have had the day mean subtracted and grey shaded regions indicate the SPEAR on times, each lasting 5 min. Fluctuations on few-minute timescales are distinguishable by eye in most of the data panels shown. A spectral analysis was performed on the data using a sliding window of length 4000 s. This length of data window was required to obtain a suitable spectral resolution of 0.25 mHz. The resulting spectral powers in the frequency band encompassing 1.67 mHz (the frequency of the SPEAR 10 min on-off cycle) are plotted against time for the X and Y data components in the third and fourth columns of Fig. 3. These plots show enhanced power at 1.67 mHz in the Y (eastward) component of the field data at NAL and LYR during the SPEAR heating interval 11:30–12:30 UT, demarcated by the vertical dashed lines. The few minute delay between the start time and the power increase could be a physical effect attributed to the varying ionospheric conditions, the timescale for the ionospheric electron density to respond to the heating, or it could be a smearing effect of the long sampling window used in the analysis technique. The variability of the power at 1.67 mHz during the heating interval is attributed to the varying ionospheric conditions e.g. the sporadic E-layer. Under ideal conditions with a modulated westward ionospheric current, the ground magnetic field would exhibit modulations in the north-south (X) component, whereas here we observe modulations of the east-west field component, implying a north-south ionospheric current. Observations of modulations in both the north-south and east-west components of the ground magnetic field have previously been made (e.g. Scoffield et al., 2006), so our results are not unusual for non-ideal experimental conditions.

A cross phase analysis has been undertaken between the NAL and LYR ground magnetometer data and the SPEAR output signal, modelled as a square wave with a 10 min period, to identify resonant frequencies between the signals. A sliding window of length 1000 s was used in the analysis, with a data point collected every 100 s. The results of the cross phase analysis for NAL Y component are plotted in Fig. 4a and those for LYR Y component are in Fig. 4b. The output obtained from analysis windows wholly within the heating experiment is marked by the vertical dashed lines on each plot, and the horizontal dashed line marks the frequency 1.67 mHz. The right hand panels show the spectral power between the two signals in each case plotted versus time and frequency. The power has been log scaled and plotted according to the colour scale above the plot. The scale was saturated at both ends to highlight significant power relationships. It is evident that significant cross powers were present in bands encompassing 1.67 mHz between the SPEAR signal and the Y component of the ground magnetometer data at both NAL and LYR. The power was maximum during ~12:00–12:30 UT, which is when the most substantial E-region was detected by the CADI (see Fig. 2), and a large deflection in the Y component of the field at the ground was measured. The plots indicate that a weak signal was present at 1.67 mHz before the experiment interval, interpreted as an existing eigenmode, which was subsequently enhanced by SPEAR. The cross phase values plotted in the left hand

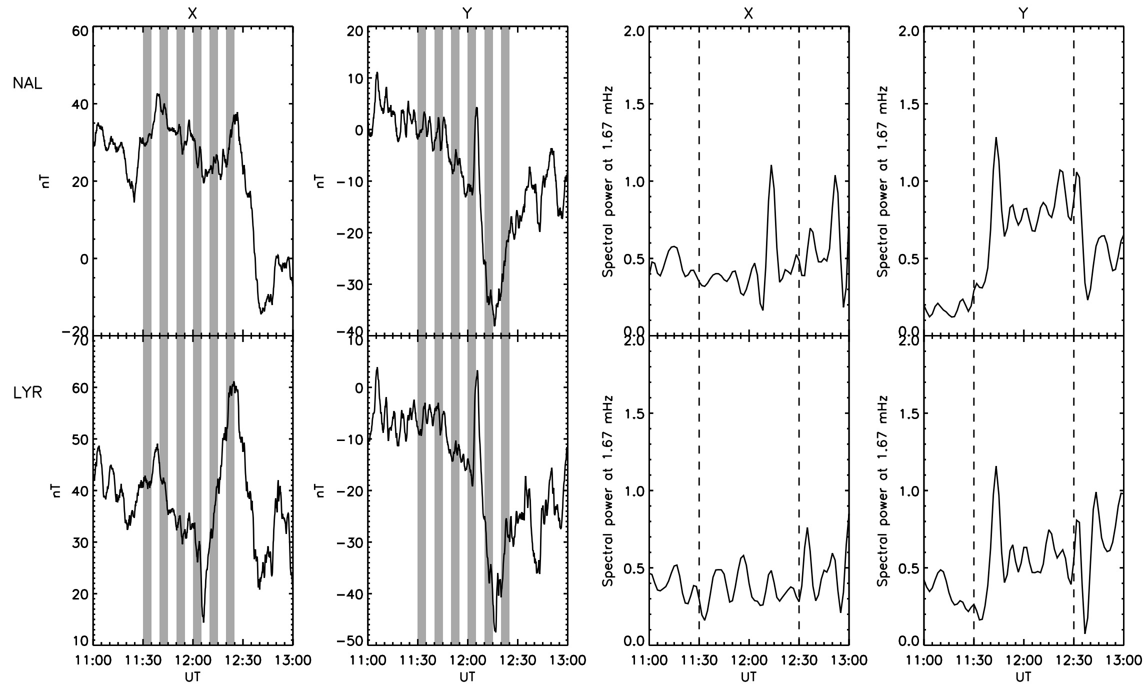

Fig. 3. Magnetic field data from ground magnetometers at (top) Ny Ålesund (NAL), and (bottom) Longyearbyen (LYR) during 11:00–13:00 UT on 1 February 2006. The X (geographic north) and Y (geographic east) components of the field are plotted in the first and second columns respectively. These data have had the day mean value subtracted. The grey shaded regions indicate the SPEAR on times, each lasting 5 min. The third column shows the spectral power at 1.67 mHz in the X component at each station, obtained using a sliding window of 4000 s length as described in the text. The vertical dashed lines mark the interval of SPEAR heating from 11:30–12:30 UT. The plots in the fourth column similarly show the spectral power at 1.67 mHz in the Y component of the data.

panels were variable across the entire interval, but remained steadier at ∼100° (±60°) during the centre of the heating interval. The relative steadiness of the phase value further implies that the magnetometer data were being driven at the artificial modulation frequency of 1.67 mHz for at least part of the heating interval.

To investigate the 1 Hz modulation the higher time resolution data from the Barentsburg (BAR) magnetometer were examined. Spectral analysis of the hour long segments of the data showed that the spectral power at 1 Hz was increased by a factor of 3 during the experiment time 11:30–12:30 UT compared to the powers in the preceding and subsequent hours (not shown). No other spectral resonance structures characteristic of the IAR (e.g. Belyaev et al., 1987, 1999) were identified at this time, indicating that the resonant cavity was weak overall. Therefore we do not expect to detect substantial effects of artificial stimulation of the IAR, such as accelerated electrons described by Robinson et al. (2000). In summary, the ground magnetometer data indicate that SPEAR modulated currents in the local ionosphere at both 1 Hz and 1.67 mHz and also enhanced a field line resonance at 1.67 mHz.

3.3 Cluster spacecraft magnetic and electric field measurements

On 1 February 2006 at ∼12 UT the Cluster spacecraft were at a position ∼(4, 8, 5) R_E GSE i.e. sunward and duskward of the north pole. The mapped spacecraft footprints indicated that Cluster-2 passed closest to the SPEAR site at ∼12:05 UT (shown in Fig. 1) at an altitude of ∼11 R_E, followed by Cluster-3 at 12:20 UT and Cluster-1 at 12:30 UT. According to this mapping, Cluster-4 did not reach its closest approach to the heated patch until ∼12:40 UT, i.e. after the experiment ended. Taking into account uncertainties in the model inputs and the model itself, the mapped footprints pass sufficiently close to the SPEAR-heated ionospheric patch to encourage investigation of any correspondencies, as will be studied below.

The high-resolution magnetic field magnitude, $|B|$, data recorded by the FGM onboard each spacecraft are plotted in Fig. 5, resampled at a rate of 10 Hz. The shaded regions on each panel represent the 5 min intervals when SPEAR was transmitting. The vertical dashed line in each panel marks the time of closest approach of the spacecraft to the SPEAR. In general, the data from spacecraft 1, 2 and 3 exhibited fluctuations over a total range of ∼20 nT. Smaller (∼nT) variations were also detected on timescales of seconds and sub-seconds.

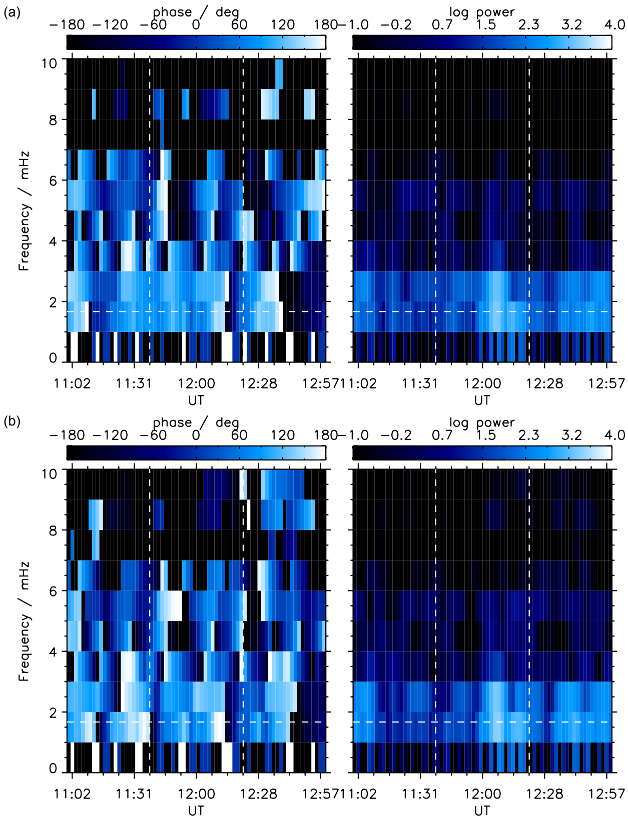

Fig. 4. Cross-phase analysis of ground magnetometer data with the SPEAR output signal, modelled as a square wave with a 10 min period. A sliding analysis window of length 1000 s was used, with a data point collected every 100 s. **(a)** NAL Y component data with model SPEAR signal and **(b)** LYR Y component with model SPEAR signal. The right hand panel of each shows the spectral power between the two signals plotted versus time and frequency. The power has been log scaled and plotted according to the colour scale above the plot. The scale was saturated at both ends to highlight significant power relationships. The left hand panel shows the cross-phase as a function of time and frequency, between ±180°, colour-coded according to the scale at the top. The horizontal line marks 1.67 mHz frequency and the vertical dashed lines mark the limits of output obtained from windows wholly within the heating experiment.

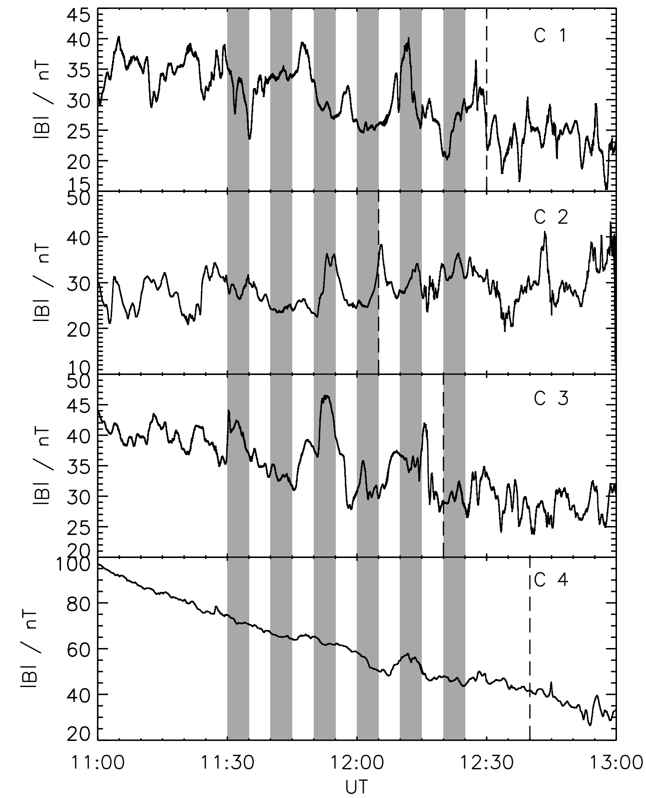

Fig. 5. Magnetic field magnitude in nT measured by the four Cluster spacecraft during 11:00–13:00 UT on 1 February 2006. The grey shaded regions indicate the 5 min SPEAR on times, as before. The vertical dashed line on each panel marks the estimated time of closest approach to the SPEAR flux tube to the nearest 5 min.

The Cluster-4 data displayed a more linear trend due to its location closer in to the planet, decreasing from ∼80 nT to ∼25 nT over the 2 h interval, with some smaller-scale variations superposed. Three large increases ($\Delta|B|\sim$10 nT) were measured in the field magnitude at Cluster-2 during SPEAR on times 11:50–11:55, 12:00–12:05 and 12:10–12:15 UT. These times were centred on the projected time of closest approach of Cluster-2 to SPEAR i.e. 12:00 UT.

A Fourier analysis applied to hour-long segments of the Cluster-2 $|B|$ data revealed that the spectral power at 1.67 mHz (10 min period) was enhanced by a factor of 4–5 during the SPEAR experiment at 11:30–12:30 UT. These results are shown in Fig. 6. The spectral power obtained from the hour of data after the heating ended (12:30–13:30 UT) was again reduced, although this spectrum may be contaminated as it contains data from when the spacecraft entered into the magnetosheath at ∼13:00 UT. Although only the results of the field magnitude analysis are shown, power was present in both the compressional and transverse (Alfvénic) components of the field during the interval. The strongest spectral powers were present in the field components with a north-south orientation at the spacecraft, indicating a rotation of the wave polarization between the ground (where the power was in the east-west component) and magnetosphere, as expected due to the currents in the ionosphere (Hughes and Southwood, 1976). Similar spectral analysis applied to the data from the other three spacecraft did not yield any enhancement at 1.67 mHz during the heating interval. A cross-phase analysis was performed between the Cluster-2 field magnitude data and the Y component of the magnetic field measured at both NAL and LYR. The power of the cross-phase analysis was maximum in the frequency band encompassing 1.67 mHz in the results for both stations (not shown). In addition, the cross-phase values determined

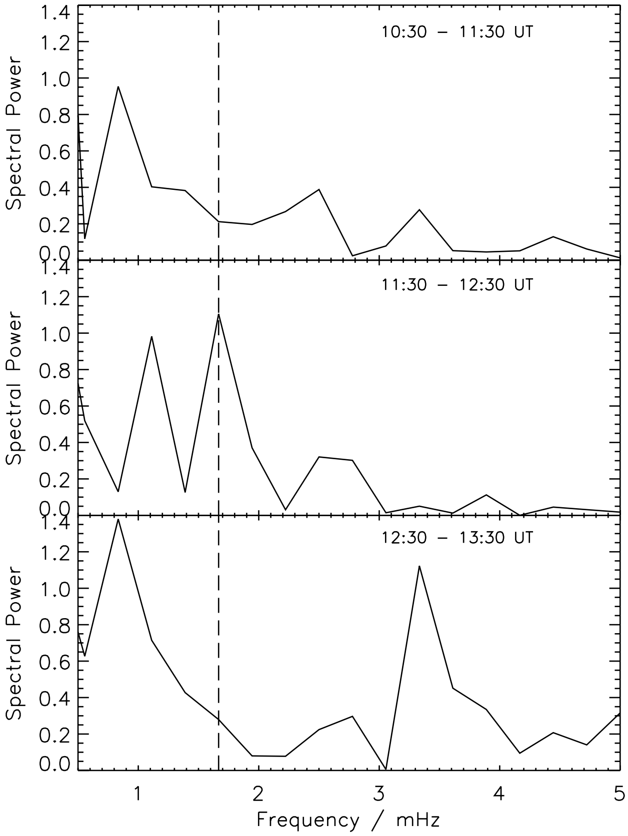

Fig. 6. Fourier analysis of three hour-long segments of magnetic field magnitude data from Cluster-2 FGM, corresponding to before, during and after the SPEAR heating interval. The vertical dashed lines mark the 1.67 mHz modulation frequency.

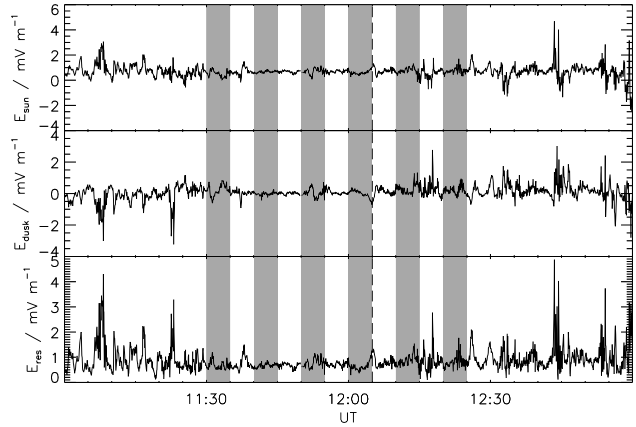

Fig. 7. Electric field measurements in mV m^{-1} made by Cluster-2 EFW experiment during 11:00–13:00 UT on 1 February 2006. The sunward and duskward components plotted in the top and middle panels, respectively, correspond to GSE X and Y. Their resultant ($[E_{\rm dusk}^2+E_{\rm sun}^2]^{1/2}$) is plotted in the third panel. The grey shaded regions indicate the 5 min SPEAR on times, and the vertical dashed lines mark the estimated time of closest approach of Cluster-2 to the SPEAR flux tube, as in Fig. 5.

for both stations became steadier during the middle of the heating interval compared to during the times before and after the experiment. These results indicate that the signals detected at both ground magnetometers and at Cluster-2 were related to each other, and hence that the Cluster-2 observations were linked to the heating by SPEAR. The magnetic field fluctuations detected by Cluster-2 were likely signatures of large-scale heating effects on the flux tube, i.e. enhancement of a field line resonance at 1.67 mHz.

To investigate the harmonic structure of the field line resonance, the electric field measurements were also examined. The duskward and sunward electric field components (corresponding to GSE Y and X respectively) and their resultant ($[E_{\rm dusk}^2+E_{\rm sun}^2]^{1/2}$) from Cluster-2 are plotted in Fig. 7. The data were at spin resolution i.e. ∼4 s. Small perturbations in the electric field, of magnitude up to ∼2 mV m^{-1} overall, were measured throughout the heating interval. One distinct feature was identified in both the sunward and duskward components during 12:00–12:05 UT. The sunward component first decreased to ∼0.4 mV m^{-1}, then increased to ∼1 mV m^{-1}. The dawn-dusk component decreased during the 5 min interval from ∼0 to −0.7 mV m^{-1}. These variations occurred at the same time as the strong increase in magnetic field magnitude identified by Cluster-2 FGM shown in Fig. 5. Deflections of the electric field components were also measured during 11:50–11:55 UT and 12:10–12:15 UT (the remaining intervals when large increases in the magnetic field were measured), but these cannot confidently be distinguished from the ongoing fluctuations in the rest of the data. Spectral analysis of the EFW data revealed very weak spectral powers at 1.67 mHz in the $E_{\rm sun}$ and $E_{\rm dusk}$ components and their resultant during the heating interval 11:30–12:30 UT. Overall, these electric field data show some small magnitude features corresponding to the significant features identified in the magnetic field data during the interval of interest, but only weak signatures of a wave of frequency 1.67 mHz were identified by the spectral analysis technique employed.

4 Discussion

The observations presented above indicate that a SPEAR-enhanced ULF wave was detected both on the ground and in space during 11:30–12:30 UT on 1 February 2006. Spectral analysis of the NAL and LYR ground magnetometer data has shown that the spectral power at 1.67 mHz, corresponding to SPEAR's 10 min on-off heating cycle, was enhanced in the Y (east-west) component during the experiment interval. This indicates that the SPEAR heating successfully generated an oscillating current system in the ionosphere, which in turn induced the field perturbations detected in the ground magnetometer data. These observations are validated by the ionosonde measurements which revealed that suitable ionospheric conditions existed intermittently during the interval.

The Cluster-2 spacecraft detected significant increases in the magnetic field spectral power at 1.67 mHz around the closest approach of Cluster-2 to the SPEAR flux tube. These features in the data suggest that the on-off cycle of heating was modulating the geomagnetic field lines at 1.67 mHz. A much weaker signature was seen in the measurements of the electric field. The difference in the strength of the wave signatures in the electric and magnetic field could be attributed to the harmonic mode of a standing wave on a field line, where the magnetic and electric field perturbations are out of phase with each other (Orr, 1984). At the spacecraft location, some distance along the field line, the amplitude of the wave magnetic field could therefore be close to a maximum while the wave electric field amplitude is small.

Modulation of ionospheric currents at 1 Hz was also enhanced during the hour long SPEAR heating interval, as measured by the ground magnetometer at Barentsburg. However, the resonant characteristics of the IAR were not present during this interval, so strong interactions with the resonator are not expected. Features such as modulated enhancements in field-aligned electron fluxes detected in the modulated heating experiment described by Robinson et al. (2000) would therefore not be detected by the Cluster instruments during this experiment. The Cluster-2 PEACE data were in fact examined for this interval but no modulated electron fluxes were identified. Wright et al. (2000) presented results from a study of ionospheric ULF wave ray-tracing in a proton-electron plasma, and showed that a 1 Hz wave would not propagate beyond where the wave frequency approaches the local proton gyrofrequency, which occurs at $\sim 5\,R_E$. This distance is below Cluster's altitude of $\sim 11\,R_E$, therefore the electric and magnetic field components of the 1 Hz wave would not be detected at Cluster.

These observations constitute the first joint space- and ground-based detections of artificial enhancement of a field line resonance at high latitudes. As discussed in the introduction above, experiments such as these provide a way of investigating the field line characteristics such as the harmonic structure of the eigenmode and plasma mass loading along the field line. Using modulated heating to "tag" a field line also facilitates study of the field line configuration when a spacecraft at a known location encounters the tagged flux tube. The conjugate spacecraft detection identified here is particularly interesting because at these high latitudes the field lines are non-dipolar and difficult to model. More quantitative estimates of the field model accuracy obtained using field line tagging require more detailed investigation of the experiment parameters than is presented in these first results. Similar modulated heating experiments have been carried out by SPEAR during campaigns in 2005–2008 using different modulation and transmission frequencies, and with conjugate spacecraft at higher and lower altitudes than those used here. Results from these other experiments will be compared in future studies with the initial results presented here to learn about the field line characteristics mentioned above, and to determine the effects of these different experiment parameters on the observations obtained.

5 Conclusions

We have presented evidence that the Cluster-2 spacecraft, orbiting at an altitude of $\sim 11\,R_E$ detected signatures of wave activity stimulated by SPEAR modulated heating on 1 February 2006. A large-scale modulation of the field lines at 1.67 mHz was identified in the spacecraft magnetic field measurements, corresponding to the 5 min on–5 min off heating by SPEAR. This modulation was also enhanced in the east-west component of the ground magnetometer data in the vicinity. Data from the Barentsburg magnetometer showed that 1 Hz modulation of currents in the local ionosphere was also enhanced during the SPEAR transmission times. These observations form the first joint ground- and space-based evidence of field-line "tagging" by SPEAR.

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