

First results of artificial stimulation of the ionospheric Alfvén resonator at 78°N

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[1] On 2 December 2005 a modulated X-mode ionospheric modification experiment was carried out using the Space Plasma Exploration by Active Radar (SPEAR) high power facility on Svalbard (78.15°N, 16.05°E), with the intention of artificially stimulating the Ionospheric Alfvén Resonator (IAR). A modulation frequency of 3 Hz was superimposed on a 20 minute on/off cycle. Local ionograms showed an E region ionosphere of sufficient plasma density for the SPEAR beam to strongly interact with the low-altitude ionospheric plasma. The Barentsburg pulsation magnetometer monitored the resulting wave activity in the 0.5–5 Hz frequency range. Clear enhancements of the spectral power at 3 Hz were observed in the D component data, when SPEAR was transmitting and there was little natural Pc1 wave activity. During part of the interval, when high power substorm-associated Pc1 waves occurred, the polarisation of the artificially-stimulated wave rotated from the D to the H component. **Citation:** Scofield, H. C., T. K. Yeoman, T. R. Robinson, L. J. Baddeley, R. S. Dhillon, D. M. Wright, T. Raita, and T. Turunen (2006), First results of artificial stimulation of the ionospheric Alfvén resonator at 78°N, *Geophys. Res. Lett.*, 33, L19103, doi:10.1029/2006GL027384.

1. Introduction

[2] The existence of the Ionospheric Alfvén Resonator (IAR) was first proposed by Polyakov [1976]. The IAR is a vertical structure bounded at either end by partial reflectors of Alfvén waves. The lower boundary lies at around 100 km altitude, where the Alfvén wave frequency matches the ion-neutral collision frequency [Borisov and Stubbe, 1997]. Strictly speaking the IAR has no definite upper boundary, but rather a rapid, but smooth increase in Alfvén speed (peaking at ~7000 km altitude on the nightside and 13000 km on the dayside [Chaston et al., 2003]) due to a swift decrease in plasma density above the ionospheric F layer density peak. This region plays an important role in particle acceleration processes. The characteristic frequencies of the IAR scale as $V_{AI}/2h$, where V_{AI} is the characteristic ionospheric cavity Alfvén speed, and h is the scale height of the cavity (400–1200 km [Hebden et al., 2005]). Much theoretical work has been carried out recently in order to understand the behaviour and significance of this

resonant cavity [e.g., Lysak, 1993; Trakhtengerts et al., 2000; Chaston et al., 2003]. The theoretical model of the IAR of Lysak [1993] has been compared with observations of the resonance signatures in the IAR [e.g., Odzimek et al., 2004; Hebden et al., 2005].

[3] The eigenfrequencies of the IAR were first observed in 1985, at Nizhny Novgorod, Russia ($L \sim 2.6$), in the form of multiple, horizontally banded spectral resonance structures (SRS) in frequency-time plots of mid-latitude magnetic background noise (0.1–10 Hz) in pulsation magnetometer data [Belyaev et al., 1987]. The observations were later extended to higher latitudes [Belyaev et al., 1999]. Natural IAR resonance features appear as multiple maxima and minima in magnetic power spectra, which are stable for several hours and usually end by fading out or being masked by more intense wave activity of magnetospheric origin.

[4] At auroral latitudes SRS features are regularly observed in high resolution magnetometer data, especially at night, however the signatures are often masked by intense wave activity associated with auroral processes. Belyaev et al. [1990] showed that the frequency and spacing of the resonance peaks are inversely related to the critical frequency of the F2-layer of the ionosphere (f_oF_2). They are also related to the size of the resonance cavity and the local Alfvén speed [Trakhtengerts et al., 2000].

[5] Recently natural SRS have also been observed in pulsation magnetometer data from Barentsburg, Svalbard at $L = 15$ [Semenova et al., 2005]. It was found that the characteristics of SRS at the polar cap were similar to those observed in the auroral zone and that they could be explained by IAR theory.

[6] Several attempts have been made to create artificial magnetic pulsations using high power radio waves in so called heating experiments [e.g., Gulielmi et al., 1985; Stubbe, 1996]. Modulating the frequency of a high power pump wave will result in the launching of an Alfvén wave from the upper edge of the ionosphere, if certain conditions are satisfied. A significant portion of the HF wave energy must be absorbed by the ionosphere and there must be a DC electric field in the absorption layer [Kolesnikova et al., 2002]. The pump wave modifies the ionospheric electron temperature and hence collision frequencies in the absorption layer, which leads to a local perturbation of the ionospheric conductivity, at the modulation frequency. The magnetic field variations caused by the modulated ionospheric current may be detected at the ground [e.g., Rietveld et al., 1984]. The presence of the DC electric field results in the generation of a current system, with both field tangential and field parallel components. If the parallel current is of sufficient magnitude, relative to the other currents in the system, the associated electric and magnetic field perturba-

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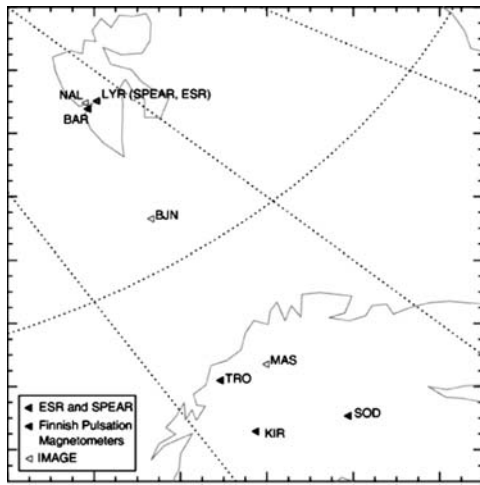


Figure 1. A map showing the locations of the IMAGE magnetometer stations (grey triangles), the Finnish pulsation magnetometers (solid black triangles), SPEAR and the ESR (grey and black triangle), in magnetic coordinates.

tions result in the formation of an Alfvén wave, with the same frequency as the modulation of the pump wave. Such magnetic field variations in the ULF/ELF/VLF frequency range have been generated by the high power facility at Tromsø, Norway ($L = 6-7$) [Stubbe, 1996].

[7] It is possible to inject Alfvén waves into the IAR, when ionospheric conditions are favourable, using modulated X-mode heating. The resulting wave may be observed as an enhancement at the modulation frequency in the dynamic spectra of pulsation magnetometer data. If the modulation frequency matches an eigenfrequency of the cavity, resonance will be achieved and the power of the observed enhancement will be significantly larger [Trakhtengerts *et al.*, 2000]. Evidence for the artificial excitation of the IAR using the Tromsø heater has been reported by Börsinger *et al.* [2000] and Robinson *et al.* [2000]. Börsinger *et al.* [2000] attempted to excite waves in the 0.1–3 Hz range, and observed the ground signatures of artificial waves during 10% of the heating time. They used a variety of stepwise frequency sweeps at modulation frequencies between 0.1 and 2 Hz. This method helped to identify the resonant frequencies of the cavity, which showed a higher power response.

[8] Robinson *et al.* [2000] injected a 3 Hz ULF wave into the IAR, using the Tromsø heater. The wave was detected for a short interval by the FAST satellite, as it passed the flux tube which mapped to the heater site, at an altitude of 2550 km. This event has been studied in detail and has been reported by Kolesnikova *et al.* [2002] and Wright *et al.* [2003]. To date it is the only instance of the successful detection of an artificially generated ULF wave at typical IAR frequencies in spacecraft data.

[9] Motivation for the artificial stimulation at the natural eigenfrequencies of the IAR are threefold. Firstly, stimulating IAR resonance provides an excellent opportunity to characterise the behaviour of the resonant cavity. Secondly, when combined with other diagnostics such as spacecraft particle detectors, it enables an exploration of the particle acceleration processes which occur at the upper boundary of the IAR, where the very high Alfvén velocity leads to the generation of parallel electric fields [Robinson *et al.*, 2000;

Lysak, 1993]. Finally, waves injected into the IAR will escape from the upper boundary of the resonator into the magnetosphere, where they may be detected by higher altitude spacecraft. At very high latitudes such experiments may reveal the magnetic field geometry in regions of the magnetosphere which are strongly coupled with the interplanetary medium [Wright *et al.*, 2000].

[10] On 2 December 2005, from 1800–1940 UT, the Space Plasma Exploration by Active Radar (SPEAR) high power facility, located near Longyearbyen, Svalbard was used to transmit an X-mode 3 Hz modulated square wave, at 4.45 MHz with a 20 minute on/off cycle. Observations from the Barentsburg Pulsation Magnetometer (BAR), show enhancements in spectral power at 3 Hz during heating. Ionosonde data show that ionospheric conditions were favourable during this time. These results, which are presented in full in section 3 of this paper, are the first observations of heater induced ULF waves at $L \sim 15$. The operation of the instruments is briefly described in section 2.

2. Instrumentation

2.1. SPEAR

[11] The SPEAR facility, described in full by Robinson *et al.* [2006], is a versatile high-power radar system located in the polar cap, at 78.15° N and 16.05° E geographic, around 10 km from Longyearbyen, Svalbard (Figure 1), adjacent to the EISCAT Svalbard Radar site. The SPEAR antenna system comprises a 6×4 array of full-wave, rhombically-broadened, crossed dipoles, with a distributed high power transmitter system, capable of transmitting a steerable beam of radio waves in the frequency range 4.0 to 6.0 MHz with up to ~ 0.2 MW of RF power at arbitrary polarisation, and with a wide variety of modulation frequencies. Each dipole is connected to a 4 kW transmitter which is capable of continuous operation, with an antenna gain of ~ 22 dB and an effective radiated power of up to 30 MW. The transmitted beam is steered by digitally phasing the transmitters. A Canadian Digital Ionosonde (CADI) system is collocated with SPEAR. The ionosonde is a pulsed system providing 500 W of RF power.

2.2. Magnetometers

[12] The BAR Magnetometer has been in operation since July 2005. At 78.09° N latitude and 14.21° E longitude, geographic, it forms the highest latitude station of the Finnish Pulsation Magnetometer Chain. The magnetometer is a three-component search coil magnetometer. It is timed by a GPS system and the sampling rate of the data is 40 Hz. The IMAGE (International Monitor for Auroral Geomagnetic Effects) [Lühr, 1994] magnetometer network consists of 27 magnetometer stations located throughout Scandinavia, covering a geographical latitudinal range of 58° to 79° . Each station uses fluxgate magnetometers to take measurements in three orthogonal directions with a sampling interval of 10 s, and a resolution of 1 nT. The locations of the stations used here are marked on Figure 1.

3. Observations

3.1. Heating Experiment

[13] On 2 Dec 2005, between 1800–1940 UT, SPEAR was operated in X-mode in a modulated heating experiment.

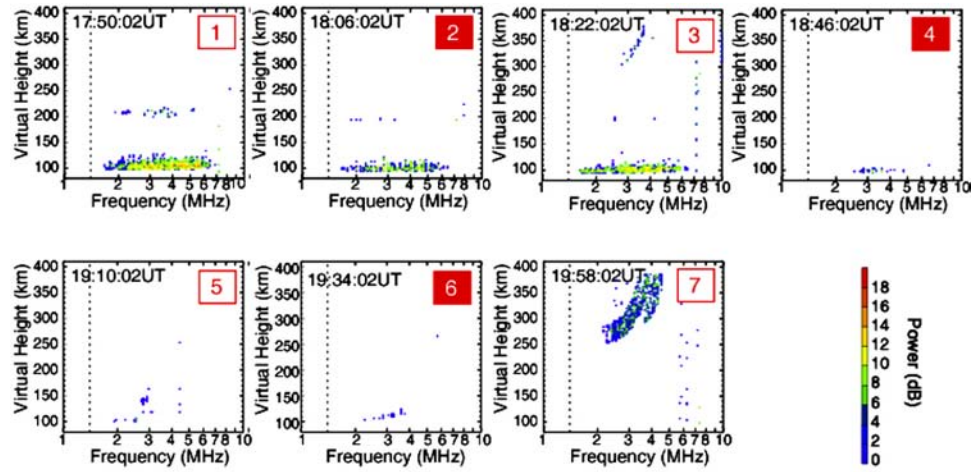


Figure 2. Summary plot of ionograms from the SPEAR Ionosonde. In each plot the x-axis is a logarithmic scale of frequency in MHz, covering the range 1–10 MHz, and the y-axis shows virtual height, covering 80–410 km. The colour scale shows power in dB, ranging from 0 (blue) to 33 (red) dB. One ionogram is taken for each SPEAR ‘on’ and ‘off’ interval, as numbered, corresponding to the intervals defined in Figure 3.

44 of the 48 SPEAR transmitters were radiating at 4.45 MHz, each with a power of ~ 2 kW. A 3 Hz modulated square wave was transmitted, with a 20 minute on/off cycle, and an effective radiated power of 12 MW. Due to the poor weather conditions personnel were not available to run the EISCAT Svalbard Radar (ESR). However, the ionospheric conditions were observed by the ionosonde.

3.2. Ionosonde

[14] Figure 2 illustrates a series of ionograms from the SPEAR ionosonde, which show the changing ionospheric conditions during the heating experiment. Each panel presents a sample ionogram from sequential SPEAR ‘off’ and ‘on’ intervals, with the time of each measurement annotated at the top. The actual cadence of the ionograms was 8 min. At the start of the interval in panels one and two, the horizontal band of high power returns, between 90–130 km virtual height, indicates a substantial E region is detected, extending up to 6 MHz, which is ideal for modulated SPEAR heating, since E region plasma density must be large enough to absorb sufficient HF power to launch an Alfvén wave. The ionogram indicated that the E region critical frequency exceeded the SPEAR transmit frequency until 1846 UT, after which the ionosonde signal suffered significant absorption, making it impossible to tell what the ionospheric conditions were, in the absence of the ESR (i.e., the ionosonde beam was totally absorbed, rather than being reflected back to the receiver. As a result there are no measurements marked on the graphs). This sudden absorption is consistent with the disturbed conditions at that time, which are discussed later. During the final SPEAR ‘on’ evidence of an E region was again present, but by 1950 UT, during the final SPEAR ‘off’ interval, the enhanced E region had disappeared.

3.3. Pulsation Magnetometer

[15] Data from the BAR magnetometer are presented in dynamic spectral form in Figure 3. H and D component data are plotted in Figures 3a and 3b respectively. Each data point plotted represents the mean of 20 Fourier

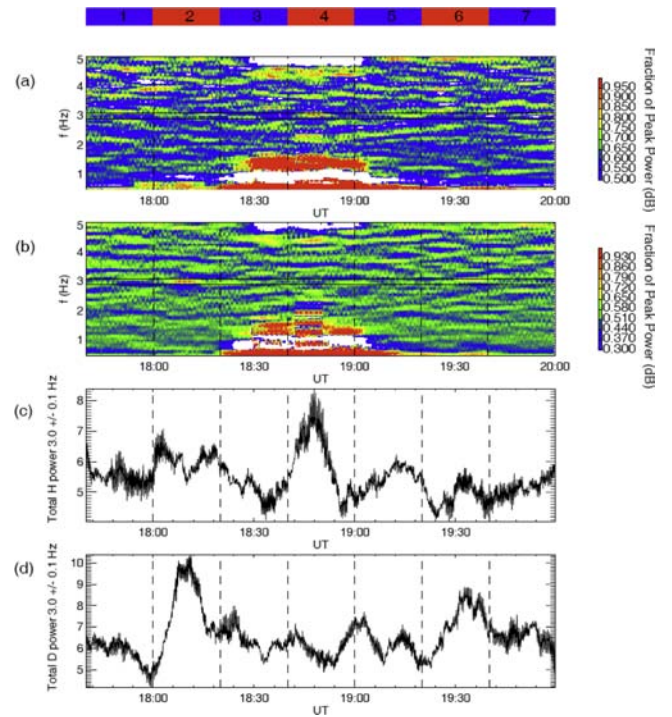


Figure 3. A summary plot of BAR pulsation magnetometer data. (a and b) Fourier power of data at frequencies between 0.5 and 5.0 Hz as a fraction of the peak power at 3 Hz as it varies with time. Each pixel represents an average of 20 unique spectra, each calculated from a 1024 point (25.6 seconds) window with a 256 point (6.4 seconds) slip between pixels. This gives a time resolution of 6.4 seconds and a frequency resolution of 0.04 Hz. Figure 3a shows H component data while Figure 3b shows D component data. The D component peak was 1.6 times the magnitude of the H component peak. The bar at the top of the figure and the vertical dashed lines indicate when the heater was turned on (red). (c and d) Variation of Fourier power, summed between 2.9 and 3.1 Hz, with time. Figure 3c shows H component data and Figure 3d shows D component data.

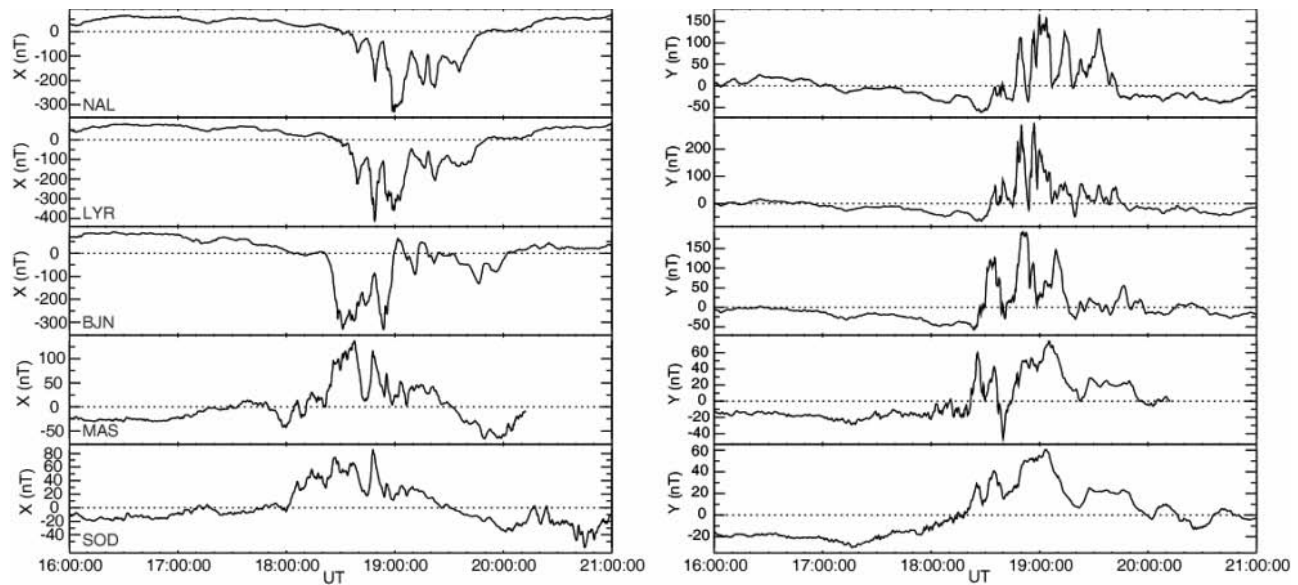


Figure 4. Summary plot of IMAGE data: (right) X-component (northward) data and (left) y-component (eastwards) data. The data are plotted in order of descending magnetic latitude.

spectra, created from consecutive, independent 25.6 second (1024 point) spectral windows centred at that time. The slip distance between data points is 6.4 seconds (256 points). Taking such an average of 20 spectrum helps to eliminate uncorrelated noise in the individual spectra, whilst highlighting the persistent features such as SRS. The frequency resolution of the dynamic spectra is 0.04 Hz. Dynamic spectra are often dominated by Pc 1 wave activity which masks SRS in the IAR. In order to draw out SRS features each spectrum was filtered in the frequency domain. The mean power of each spectrum was removed and a Lanczos squared filter, with a high frequency cutoff of 1.0 Hz and a low frequency cutoff of 0.2 Hz was used. The colour scale shows the Fourier power as a fraction of the maximum power observed at 3 Hz during the interval. The bar at the top of Figure 3 and the vertical dashed lines indicate the times when SPEAR was turned on. The red shading of the bar indicated on and the blue shading indicates off, with the intervals labelled 1 to 7. The horizontal white lines mark the frequencies 2.9 Hz and 3.1 Hz. If the ionospheric conditions are favourable one might expect to see an enhancement in power at 3 Hz during the times when SPEAR is turned on (intervals 2, 4, and 6). Indeed there is an enhancement of the D component during interval 2 between 1800–1820 UT and also during interval 6 between 1920–1940 UT. However during interval 4 (1840–1900 UT) the conditions become quite disturbed and the spectra are swamped by Pc 1 wave activity. This coincides with the total absorption of the ionosonde beam noted above. No D component enhancement at 3 Hz is observed during this interval, but such an enhancement is seen in the H component.

[16] Figures 3c and 3d show time series calculated from the sum of the Fourier power between 2.9 and 3.1 Hz (i.e., between the horizontal black lines in Figures 3a and 3b). Figure 3c shows the H component data and Figure 3d shows the D component data. The shaded bars and vertical lines again indicate the intervals where SPEAR is turned on. Enhancements in the $3 \text{ Hz} \pm 0.1 \text{ Hz}$ power occur during the

heated intervals, in the D component for intervals 2 and 6 and in the H component for interval 4. Natural enhancements also occurred outside these times, although they were of lower spectral power.

3.4. Fluxgate Magnetometers

[17] Figure 4 presents data from selected stations of the IMAGE fluxgate magnetometer network. All stations show a sudden magnetic field disturbance, indicative of substorm activity, occurring first in the lower latitude stations, at 64° geomagnetic latitude at 1800 UT, and subsequently propagating poleward up to and beyond the latitude of BAR (76° geomagnetic) at ~ 1830 UT. This corresponds to the absorption of the ionosonde signal and the increase in Pc 1 activity observed by the BAR magnetometer.

4. Discussion and Conclusions

[18] During the interval under investigation there were three periods of 20 minutes duration when modulated ionospheric modification was carried out, separated by 20 minute intervals. During the first SPEAR “on” (interval 2) the ionospheric conditions were favourable for a strong interaction between the SPEAR pump wave and the D and E regions of the ionosphere (60 km–130 km altitude), resulting in a 3 Hz modulation of the ionospheric current systems. An enhancement of the 3 Hz spectral power is observed in the pulsation magnetometer data D component at this time. This enhancement may indicate artificial stimulation of the ionospheric Alfvén resonator at or near one of the harmonics of its resonant frequency, however improved stimulation efficiency may also be due to improved ionospheric conditions. No enhancement is observed in the H component [e.g., Molchanov *et al.*, 2004]. This however, is not entirely unexpected since previous observations have suggested that SRS signatures typically have a larger amplitude in the D component than in the H component [e.g., Molchanov *et al.*, 2004].

[19] During the second SPEAR “on” (interval 4) the ionospheric conditions were more disturbed. The ionograms from this period show that the ionosonde signal has been completely absorbed, suggesting a sudden increase in D and E region plasma density. Such conditions should also be favourable for a strong interaction between the SPEAR pump wave and the lower ionosphere, although no measurement of the critical frequency in the lower ionosphere is available. The IMAGE magnetometer data show a disturbance in the geomagnetic field at all stations, indicative of substorm activity. The dynamic spectra of the pulsation magnetometer data (Figures 3a and 3b) show an increase in natural Pc 1 wave activity at frequencies between 0.5–1.5 Hz, which is likely to be related to the disturbances observed in the IMAGE data. It is common for such activity to obscure natural SRS signatures in the Fourier power spectra, due to the comparatively low power of SRS. No enhancement is observed in the spectral power of the D component pulsation magnetometer data at this time, however there is a small enhancement in the H component at 3 Hz, visible in Figure 3a. There are also enhancements at other frequencies during this heater interval, at ~ 2.25 Hz and ~ 3.75 Hz, and to a lesser extent at ~ 1.5 Hz and ~ 0.75 Hz. This may suggest some short term excitement of waves at the IAR eigenfrequencies by a broadband source. If so, then they are short-lived. Such enhancements in the ionospheric plasma density might also be expected to change the resonant frequencies of the IAR. Banded structures are also observed in the D component during this interval, however they are at frequencies of 0.9 Hz, 1.25, 1.6, and 1.95 Hz and are of lower amplitude.

[20] During the 3rd SPEAR “on” (interval 6) the ionospheric conditions have returned to something more similar to those observed during interval 2. An enhancement is again observed in the spectral power of the D component of the pulsation magnetometer data, at 3 Hz. Figures 3c and 3d show that there is also a small enhancement in the 3 Hz spectral power in the H component, which may indicate resonance in the IAR.

[21] Although several other X-mode modulated heating experiments were carried out during the same two-week SPEAR heating campaign, the interval presented here was the only one where ionospheric conditions appeared favourable and where stimulation of the IAR was successful. It should be noted that for this interval there is some power in the dynamic spectra (Figure 3b) at, or around, 3 Hz during interval 1, prior to the heating, perhaps indicating that 3 Hz was a favourable frequency for the modulation experiment, being close to an existing eigenfrequency of the IAR. However, no signatures clear enough to have been independently identified as natural SRS were observed.

[22] It is also not clear why the polarization of the artificially stimulated wave should shift from D to H during intervals 3–5. For natural waves it is thought that polarization is related to the source of the resonance. However in this case the source is the same. It is possible that the polarization of the oscillation is related to the background ionospheric electric fields, which have been altered by the disturbed conditions during intervals 3–5. The magnetic field changes measured by IMAGE (a sharp change in the X component indicating a rotation of the ionospheric electric field as a westward electrojet is established) are

consistent with this interpretation, but further study of similar events is required to clarify this matter.

[23] The results presented here have shown for the first time that it is possible to artificially excite ULF waves at 3 Hz, through artificial stimulation of the IAR with modulated X-mode heating, at 78° N ($L \sim 15$). However it is not clear whether the artificial waves were at an eigenfrequency of the cavity. In future real time processing of the BAR data will enable the selection of heater frequencies, which correspond to the eigenfrequencies of the IAR, as observed from natural SRS signatures. Coordination of such experiments with satellite overpasses and operation of the ESR, should then allow the investigation of the injection of such artificially-stimulated waves into the magnetosphere, hence a determination of the magnetic field geometry of the overlying magnetosphere and exploration of associated particle acceleration processes.

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