FAST observations of ULF waves injected into the magnetosphere by means of modulated RF heating of the auroral electrojet

T.R. Robinson[1], R. Strangeway[2], D.M. Wright[1], J.A. Davies[1], R.B. Horne[3], T.K. Yeoman[1], A.J. Stocker[1], M. Lester[1], M.T. Rietveld[4], I.R. Mann[5], C.W. Carlson[6] and J.P. McFadden[6].

Abstract. Results are reported from an experiment in which the HF high power facility at Tromsø was utilised to inject artificial ULF waves into the magnetosphere by means of modulated heating of the auroral electrojet. Local electric field oscillations associated with the artificially stimulated ULF waves were detected on board the FAST spacecraft, at an altitude of 2550 km. In addition, a modulated downward flux of electrons was also detected. The artificially excited waves, together with these energised downward electrons, were observed in a narrow region only a few tens of km across the geomagnetic field, which mapped down the geomagnetic field line to the heated volume in the ionosphere. Furthermore, the downward flux exhibited energy dispersion in a manner that was consistent with the artificially excited waves having followed the geomagnetic field line out beyond the spacecraft, where they appear to have stimulated electron precipitation back down the field line.

1. Introduction

The EISCAT high power facility (heater) at Tromsø, Norway, has been used extensively to generate both VLF and ULF electromagnetic radiations by means of modulated heating of the ionospheric conducting layers [Stubbe et al., 1982, 1985; Stubbe, 1996]. The EISCAT heater operates in the HF band between 3.9 and 8 MHz. VLF and ULF waves are generated in the ionosphere by modulating the heater power with the desired frequency. This has the effect of modulating the electron temperature in the ionosphere, through the strong heating effect of the electromagnetic waves [Stubbe and Kopka, 1977]. Because of its dependence on electron temperature, this in turn causes the value of the electrical conductivity of the ionosphere to oscillate at the desired frequency. Thus, natural currents (the ionospheric electrojet) are also modulated at the desired rate. As a result, the oscillating ionospheric current acts as a giant antenna that transmits the VLF and ULF electromagnetic waves out into space as well as back down to the ground.

[1]University of Leicester, Leicester LE1 7RH, UK
[2]University of California, Los Angeles, California 90024-1567, USA
[3]British Antarctic Survey, Cambridge CB3 0ET, UK
[4]EISCAT, N-9027, Ramfjordmoen, Norway (also at Max-Planck Institut für Aeronomie D-37191, Katlenburg-Lindau, Germany)
[5]University of York, Heslington, York YO10 5DD, UK
[6]University of California, Berkeley, California 94720, USA

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Although the resulting artificially stimulated radiations have been commonly observed by ground based instruments, only a few spacecraft observations, all at VLF, have so far been reported [e.g. James et al., 1990 and Kimura et al. 1994]. The aim of the experiments reported below was to test the feasibility of identifying or 'tagging' a narrow magnetic flux tube, threading the ionosphere and magnetosphere, by injecting a field guided ULF wave (by means of modulated electrojet heating) and detecting the injected wave on board a spacecraft, as it traversed common field lines out in the magnetosphere. This aim considerably limited the choice of ULF frequencies that could be used. The frequency had to be low enough to ensure Alfvénic (field guided) characteristics, but also high enough so that several oscillations could be observed by a rapidly moving spacecraft in traversing a region of scale size similar to that of the heated patch in the ionosphere. These considerations lead to the choice of wave frequencies of a few Hz.

An opportunity to test the feasibility of such a field line 'tagging' scheme arose on 8 October, 1998, when the FAST (Fast Auroral SnapshoT) satellite [Carlson et al., 1998] was due to transit the site of the Tromsø heater. This site is situated just inside the Arctic Circle (69.58N, 19.22E geographic) and is within the zone where the auroral electrojet commonly occurs. The FAST satellite, which orbits the Earth at altitudes of between 350 and 4175 km, carries on board electric field and charged particle detectors, in addition to other instrumentation.

2. Experimental Arrangement

ULF waves with a frequency of 3 Hz were continuously excited by modulated heating, using the Tromsø heater, between 20:15 UT and 20:45 UT on 8 October, 1998. This period occurred after local sunset and thus in the absence of any solar illumination. The input power to the heater transmitters was 960 kW. However, only half of this was available for the ULF excitation, because the other half of the power was consumed by a VLF modulation of 1 kHz, which was applied simultaneously with the ULF modulation. The purpose of this second modulation was to allow a spatially broad, unguided VLF signal to be injected into the magnetosphere. This signal could, in principle, be detected by the spacecraft when far from the field line through Tromsø and constituted a separate experiment which will not be referred to further in this report.

During the period of modulated heating, the heater transmitted a 4.04 MHz, X-mode, radio beam with a half-width of 7°, centred on a direction along the local geomagnetic field. This produced a circular heated layer in the ionosphere of diameter 25 km, approximately 100 km above the ground, which is the source of the ULF waves. Figure 1 depicts the ionospheric source region (indicated by the 25-km diameter circle) together with the ionospheric footprint of the FAST satellite track, mapped down the field line passing through the spacecraft. The IGRF model appropriate for 8 October 1998 was used for this mapping. The satellite altitude during this transit was approximately 2550 km. The resulting uncertainly in the position of the magnetic field line mapping over this distance is of the order of 50 km on the ground plane.

3. FAST Observations

The shaded portion of the FAST track, in Figure 1, approximately indicates the time (and location) when strong effects caused by the artificially injected 3 Hz ULF waves were observed at the spacecraft. A much larger portion of the FAST data was examined than is actually displayed here, but only this short, approximately 4 second, period between 20:16:19 and 20:16:23 UT exhibited a 3 Hz signature. As can be seen from Figure 1, the size of the disturbed patch itself, along the FAST orbit, is approximately 20 km long when mapped down the field line. This distance is very close to the estimated diameter of the heated patch. Also, the region of disturbance detected by FAST lies within about 30 km of the heated patch. Magnetometer data from the IMAGE array indicated that there was a deflection of the geomagnetic field lines from the quiet condition directions, due to a local current system, at this time. The sense of this deflection was to bring the two regions, indicated in Figure 1, even closer together.

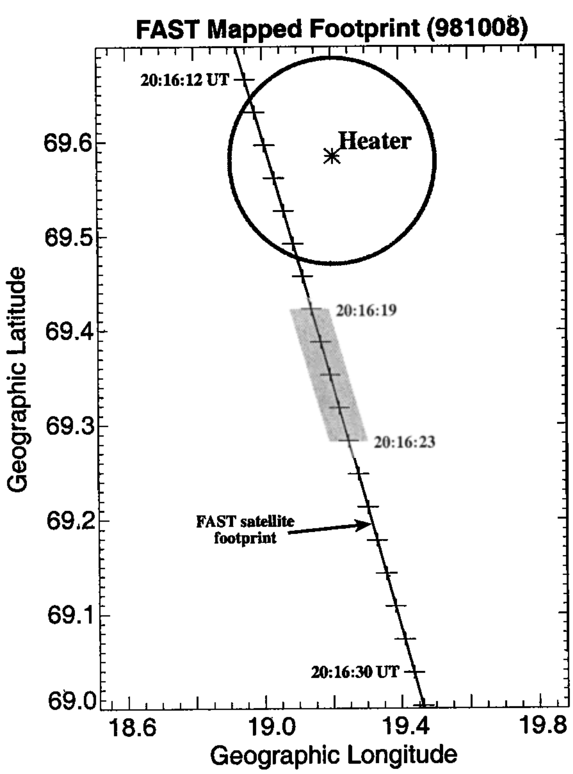

Figure 1. The ionospheric heated patch (circle with 25 km diameter) and the ionospheric footprint, mapped along the geomagnetic field, of the disturbance seen in the satellite data, for 4 seconds, between 20:16:19 and 20:16:23 UT (shaded portion of the footprint).

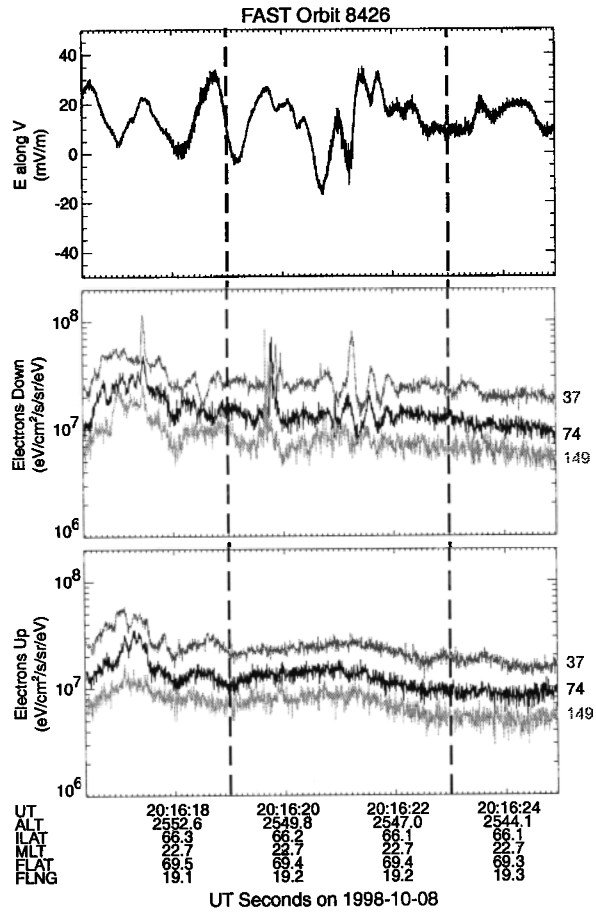

Figure 2. FAST observation data. Upper panel is the perpendicular electric field, $E_{\perp}$; lower two panels are the downward and upward, magnetic field aligned electron fluxes, respectively. The vertical dashed lines delineate the same interval as the shaded portion of the FAST footprint in fig. 1.

This result demonstrates the remarkable nature of the mapping of the ionospheric disturbance out to the spacecraft altitude, along the geomagnetic field line, with little detectable lateral spreading across the field line.

The spacecraft data, observed in situ, are illustrated in Figure 2. The upper panel shows the strength of the electric field, which is predominantly in a direction perpendicular to the geomagnetic field. The centre panel is the downward, field aligned, electron flux and the lower panel is the upward, field aligned electron flux. These flux data are averages over angles within 30° of the field line. Three separate energy channels (37, 74 and 149 eV) are illustrated, for both the upward and downward fluxes. All of the parameters are displayed as functions of universal time. The electric field data clearly exhibit an oscillation with a frequency close to 3 Hz (the mean period is actually 0.34 s rather than 0.33s) with an amplitude of approximately 10 mVm^{-1} and lasting for around 4 seconds duration, as depicted in Figure 1. These are probably local oscillations associated with the ULF wave at the spacecraft. Also clearly illustrated is the 3 Hz oscillation in the downward electron flux. It is noticeable that this disturbance, although it lies within the same time window as that of the electric field oscillations, is of somewhat shorter duration (approximately 1.5 seconds, from 20:16:20.5 to

20:16:22 UT) than that in the electric field and is also biased towards the second half of the 4 second window. This may be significant, as discussed below. A much smaller amplitude fluctuation is just discernible in the upward flux. It is important to note that the oscillations in the different energy channels of the downward flux are all out of phase, the fastest, highest energy electrons leading with the slower lower energy electrons falling behind. Closer analysis of this energy dispersion has revealed that the phase shifts are all consistent with an acceleration source region for the electrons approximately 530± 160 km above the spacecraft.

4. Discussion

Artificially stimulated ULF waves, with a frequency of 3 Hz, have been injected into the ionosphere by means of modulated heating and the electric field oscillations associated with them, at a frequency very close to 3 Hz, have been directly detected by the FAST spacecraft. The ionospheric source region mapped almost exactly along the geomagnetic field into the region of the detected oscillation. This observation is consistent with an interpretation involving the excitation of field guided Alfvénic ULF waves injected from the ionosphere and propagated along the field line with negligible lateral dispersion, as predicted by ideal MHD theory [e.g. Landau and Lifshitz, 1960]. A flux of downward electrons, on virtually the same field lines as these injected ULF waves, with an almost identical frequency signature was also detected by the FAST spacecraft. However, the energy dispersion present in this flux strongly suggests that the electrons were not locally energised in the near vicinity of the spacecraft, but rather were accelerated from a relatively small region, several hundreds of km beyond the orbit of the spacecraft, albeit on the same geomagnetic field line. What is less obvious is how the electrons were accelerated and why only from above the spacecraft. An electric field with a significant component parallel to the geomagnetic field within the acceleration region and oscillating at 3 Hz would explain our observations. However, as is well known, the ideal MHD theory of Alfvén waves excludes any components of the electric field parallel to the background magnetic field. This is because electron inertia is neglected in ideal MHD. As is explained below, when electron inertial effects are included, parallel electric field components associated with field guided ULF waves can become significant [Clemmow and Dougherty, 1969].

A detailed quantitative analysis of the observations above is beyond the scope of this short report. However, they may be understood, in a semi-quantitative manner, in terms of a generalised Ionospheric Alfvén Resonator (IAR) model due to Lysak [1993] (see the schematic in Figure 3). The 3 Hz ULF waves are launched as described above and propagate out of the ionosphere at the Alfvén speed, V_A. According to Lysak's model, V_A has a value of the order of 10^3 km s^{-1} at ionospheric altitudes but increases quasi-exponentially as the density of the ionised gas falls with altitude, reaching a peak at approximately 0.5 R_E above the Earth where its value is of the order 10^5 km s^{-1}. This peak also marks the upper boundary of the IAR. In the ionosphere the waves carry an electric field entirely perpendicular to the geomagnetic field, as seen in the spacecraft data. This electric field clearly cannot accelerate electrons along the magnetic field direction. However, for waves confined to a narrow region across the geomagnetic field, the effect of the increasing Alfvén speed, according to magneto-ionic theory [Clemmow and Dougherty, 1969], is to change the polarisation of the electric field so that it acquires a component parallel to the geomagnetic field. Waves confined to a narrow region across the geomagnetic field necessarily contain a spatial spectrum of wave vectors with large components perpendicular to the geomagnetic field. Then, the ratio of the parallel, $E_\parallel$, to perpendicular, $E_\perp$, components of the electric field is given by [Clemmow and Dougherty, 1969]

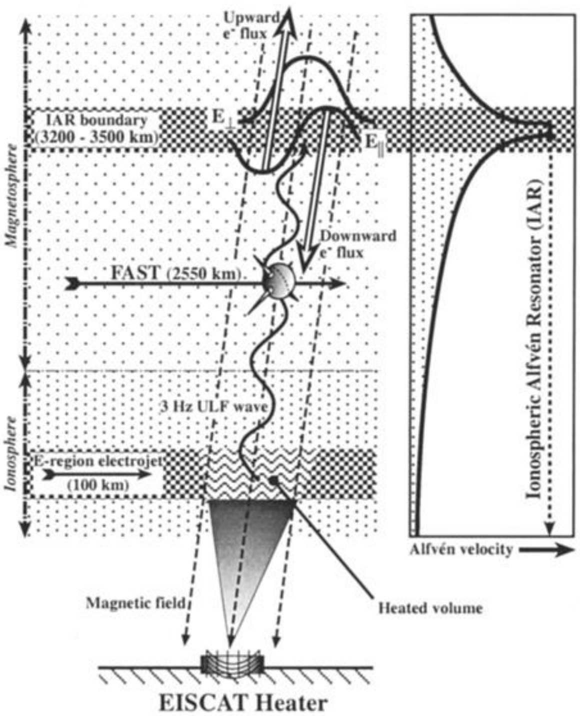

Figure 3. Schematic of the artificial 3 Hz ULF wave injection from the ionospheric source region, along the geomagnetic field line, beyond the spacecraft to the Ionospheric Alfvén Resonator boundary at about 1.5 R_E. Here the wave acquires a significant electric field component parallel to the geomagnetic field and can accelerate electrons down past the spacecraft towards the ionosphere, as well as away from the spacecraft, out into space.

$$E_\parallel/E_\perp = \omega^2(k_\perp/k_\parallel)/(\Omega_i\Omega_e) \tag{1}$$

where ω is the angular frequency of the wave, $k_\parallel$ and $k_\perp$ are, respectively, the components of the wavevector, parallel and perpendicular to the geomagnetic field and Ω_i and Ω_e are the ion and electron gyro-frequencies, respectively.

It is reasonable to assume that the heated patch is a gaussian shape of width L, across the geomagnetic field, then the characteristic width of the spatial spectrum normal to the geomagnetic field, will be $1/L$. Further, the value of $k_\parallel$ is just ω/V_A, as long as $L >> V_A/(\Omega_i\Omega_e)^{1/2}$. This inequality is well satisfied for the heated patch under consideration. Hence, relation (1) can be written

$$E_\parallel/E_\perp = V_A\omega/(L\Omega_i\Omega_e) \tag{2}$$

From relation (2) it is not difficult to appreciate that the parallel electric field is only significant near the peak of the V_A profile, at the upper boundary the IAR. Indeed, using the very approximate values of V_A, from Lysak's model, and allowing also for the reduction of the geomagnetic field strength by a factor of around 3.5 in moving from the Earth's surface to a point 0.5 R_E above it, the ratio in relation (2) increases by around three orders of magnitude at the upper boundary of the IAR, compared to its value in the ionosphere. It should also be noted that this region of higher parallel electric field strengths lies at a distance of around 700-1000 km above the position of the FAST satellite and therefore coincides well with the estimated position of the electron acceleration region as determined by the observed energy dispersion in the downward electron flux.

The gaussian spatial distribution may also be attributed to the perpendicular electric field component. Thus, the factor of $k_\perp$ in relation (1) implies that the spatial distribution of the parallel electric field component will be a derivative of the gaussian with respect to a displacement normal to the geomagnetic field. Then, the parallel field will be upward in one half of the disturbed region and downward in the other. Consequently, the downward flux of accelerated electrons will only be intercepted by the spacecraft in one half of the disturbed region, where the parallel electric field is directed upwards. Similarly, when the electric field is in the downward half of its distribution it accelerates the electrons away from the spacecraft and out along the field line into the outer magnetosphere. This picture is certainly consistent with the present observations and may explain the differences in distributions of the electric field and downward electron flux data, noted above.

The motion of the spacecraft does not have a large effect on the frequency of the wave observed by its instruments. As in the present circumstances $k_\parallel << k_\perp$, only the component of the spacecraft's velocity $V_\perp$, perpendicular to the geomagnetic field will cause any Doppler shift at all. Then, the frequency seen by the spacecraft is ω-$k_\perp V_\perp$. However, since the heated patch is stationary, the spatial spectrum perpendicular to the geomagnetic field will contain a spread of values of $k_\perp$, approximatelybetween $\pm 1/L$. Further, the value of $V_\perp$ is approximately $2L/T$, where T is the time the spacecraft takes to traverse the disturbed region. Thus, the spacecraft will observe the wave frequency broadened by $\pm 2/T$ (radians per sec.). Given that T is of the order of 4 seconds, this results in a broadening of the 3 Hz spectrum by only ±0.1 Hz. Furthermore, this Doppler broadening is precisely what naturally leads to the spacecraft detecting a finite wave packet with a 3 Hz carrier lasting just 4 seconds, rather than the continuous monochromatic signal which would be detected by a stationary observer within the disturbed patch.

Although we have proposed an electron precipitation mechanism that involves man-made ULF waves, it is not difficult to see that a similar process could also easily occur naturally. Any disturbance in the lower ionosphere, localised in a few km across the geomagnetic field and exhibiting time variations with scale times of seconds to tenths of seconds, could launch field guided ULF waves which would produce accelerating parallel electric fields when they reached the IAR boundary. This constitutes a powerful feedback process, since the precipitated electrons will enhance the original ionospheric disturbance, which will in turn enhance the upgoing wave amplitudes. Furthermore, the upgoing electrons produced by the mechanism described can, in principle, travel unimpeded to very great distances out along the field line, beyond the IAR boundary. This implies that it may be possible to tag field lines by detecting these electrons with satellites orbiting at several Earth radii.

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