GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L16101, doi:10.1029/2006GL026462, 2006

DEMETER observations of ELF waves injected with the HAARP HF transmitter

M. Platino,[1] U. S. Inan,[1] T. F. Bell,[1] M. Parrot,[2] and E. J. Kennedy[3]

Received 30 March 2006; revised 12 June 2006; accepted 27 June 2006; published 17 August 2006.

[1] Modulated HF heating of the auroral electrojet is used to inject ELF signals into the magnetosphere that are observed on the low altitude DEMETER spacecraft. The HF heater is a component of the High-Frequency Active Auroral Research Program (HAARP) facility in Gakona, Alaska, (located at L ~ 4.9). Simultaneous observations of all six components of the ELF electromagnetic fields on the DEMETER spacecraft are used to estimate the total ELF power radiated downward into the Earth-ionosphere waveguide. ELF signals generated by the HAARP heater are also simultaneously observed at a nearby ground-based site, allowing a comparison of the ELF power in the Earth-ionosphere waveguide versus that detected on DEMETER. The estimated values of power onboard DEMETER at different frequencies range from 0.32W to 4W, while the values of power estimated from a ground receiver at a distance of 36 km from HAARP range from 2.71W to 4.22W. **Citation:** Platino, M., U. S. Inan, T. F. Bell, M. Parrot, and E. J. Kennedy (2006), DEMETER observations of ELF waves injected with the HAARP HF transmitter, *Geophys. Res. Lett.*, *33*, L16101, doi:10.1029/2006GL026462.

1. Introduction

[2] *Generation of ELF/VLF waves* by modulating the *D* region conductivity in the vicinity of the auroral electrojet using a powerful High Frequency (HF) heater is by a now well established technique [*Stubbe and Kopka*, 1977; *Rietveld et al.*, 1989; *Inan et al.*, 2004, and references therein]. The mechanism involves the periodic modification of the electron temperature in the D and lower E regions of the ionosphere, which leads to periodic changes in the Pedersen and Hall conductivities, resulting in periodically changing electric current density in the electrojet and thus radiation. Under such circumstances, the heated ionospheric area with its immediate surroundings acts as a huge 'polar-electrojet' antenna, radiating primarily at a frequency corresponding to the modulation frequency of the HF carrier.

[3] Spacecraft observations of ELF/VLF waves generated by different HF heating facilities have been carried out on both low [*Lefeuvre et al.*, 1985; *James et al.*, 1984; *Inan and Helliwell*, 1985], and high-altitude spacecraft [*James et al.*, 1990*; Bell et al.*, 2004*; Platino et al.*, 2004]. Nevertheless, the degree to which modulated HF heating can be consistently used to inject ELF/VLF waves upward into the overlying magnetosphere, and the total ELF power radiated by such a source is not understood at a quantitative level.

[4] In this paper, we present recent observations on the DEMETER spacecraft of electromagnetic ELF waves produced through modulation of auroral electrojet currents, and use the simultaneously observed multiple field components to estimate the total ELF power radiated into the Earth-ionosphere waveguide by the electrojet current modified by the HAARP HF heater. The observations reported herein were carried out over the ELF frequency range of 118 Hz to 1197 Hz on the 3-axis stabilized DEMETER satellite, at an altitude of ~730 km in an orbit of 98.3° of inclination. Ground observations of the HAARP ELF transmitted signals are also provided and compared to the DEMETER observations. A numerical raytracing model was used to simulate the propagation of ELF whistler mode waves from the ionospheric generation regions up to the spacecraft and to estimate the spatial extent of the region in the ionosphere illuminated by ELF waves.

2. HAARP-DEMETER Campaign

[5] The DEMETER spacecraft is a low altitude satellite, with two sets of antennas, one set to measure the three components of the plasma wave electric field using the electric sensors of the Electric Field Instrument (ICE) and one set to measure the three components of the plasma wave magnetic field using the magnetic sensors of the Instrument Magnetometer Search-Coil (IMSC), operating over a frequency range of 10 Hz to 1.25 kHz in the burst mode [*Parrot*, 2002]. Attempts to observe the HAARP ELF signals on DEMETER were carried out during passes close to the HAARP facility, on spacecraft trajectories whose subsatellite points on the ground were at a distance no larger than 200 km from HAARP at the closest point. The HAARP HF heater is located near Gakona, Alaska, at a site with geographic coordinates of 62.4° (North) latitude, 145.2° (West) longitude and geomagnetic coordinates of 63.1° (North) latitude and 92.4° (West) longitude. At HAARP, an HF phased – array transmitter is used to heat small, well-defined volumes of the ionosphere with high power radio signals in the 2.8 to 10 MHz frequency range. At the time these experiments were performed, the HAARP HF transmitter had a total maximum radiated power capability of 960 kW. The ELF/VLF signal format shown in Figure 1 was impressed upon a 3.3 MHz carrier through sinusoidal amplitude modulation, with a modulation index of 0.95. The HF carrier frequency was chosen to provide maximum heating in the *D* region of the ionosphere [*James et al.*, 1984], taking into account the allocated frequencies at which HAARP can transmit at its highest

---

[1] Space, Telecommunications and Radioscience (STAR) Laboratory, Stanford University, Stanford, California, USA.

[2] Laboratoire de Physique et Chimie de l'Environnement, Centre National de la Recherche Scientifique, Orléans, France.

[3] Naval Research Laboratory, Washington, D. C., USA.

0094-8276/06/2006GL026462$05.00

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE
DEMETER observations of ELF waves injected with the HAARP HF transmitter

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Space, Telecommunications and Radioscience (STAR) Laboratory,Stanford University,Stanford,CA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**6**	

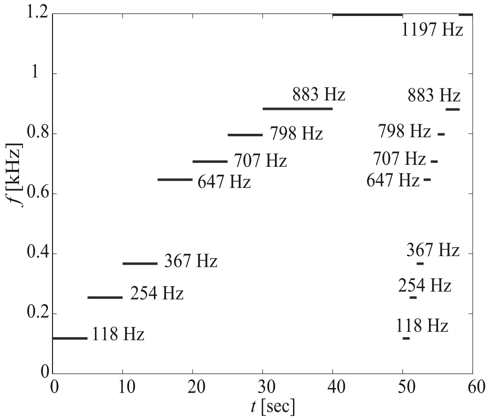

Figure 1. Schematic spectrogram (to scale) of the transmission pattern used by the HAARP HF facility to heat the ionosphere. The ELF waves were AM modulated onto a carrier frequency of 3.3 MHz. The transmitted HF wave was in the X mode.

power, using HF waves polarized in the extraordinary (X) mode to provide the maximum ELF radiated power [*Kapustin et al.*, 1977; *Stubbe et al.*, 1981, 1982]. The HF beam was oriented vertically in order to have a transmitted HF wave with a **k**-vector as perpendicular as possible to the *D* layer of the ionosphere. The modulation pattern consists of pulses of 2 sec, 4 sec, 5 sec and 12 sec, duration at frequencies located in the ELF frequency range. These ELF modulation frequencies are below the range of frequencies which were found in the past to be more efficiently generated via modulated HF heating [*Stubbe et al.*, 1981], but all lie in the range for which DEMETER can record in the burst mode the three components of both electromagnetic fields for frequencies below 1.25 kHz. The actual numerical values were chosen to avoid possible interference from harmonics of 60 Hz generated by power grids [*Helliwell et al.*, 1975].

3. Determination of the Illuminated Region

[6] The raytracing program used for the computations presented here is described by *Inan and Bell* [1977], with a geomagnetic field model based on a centered dipole with electron gyrofrequency of 880 kHz at the ground on the magnetic equator. The model of the magnetospheric electron and ion densities is the same as used by *Platino et al.* [2004]. Nevertheless, ray paths at these low altitudes are not was not very sensitive to the magnetospheric electron density model.

[7] Figure 2 shows a schematic of the DEMETER pass over HAARP. The propagation path of the wave energy is calculated using raytracing, as described in the previous paragraph. The region of space illuminated by HAARP is determined from the maximum distance at which the HAARP signal is observed on the spacecraft (430 km lateral distance from HAARP). DEMETER receivers are routinely

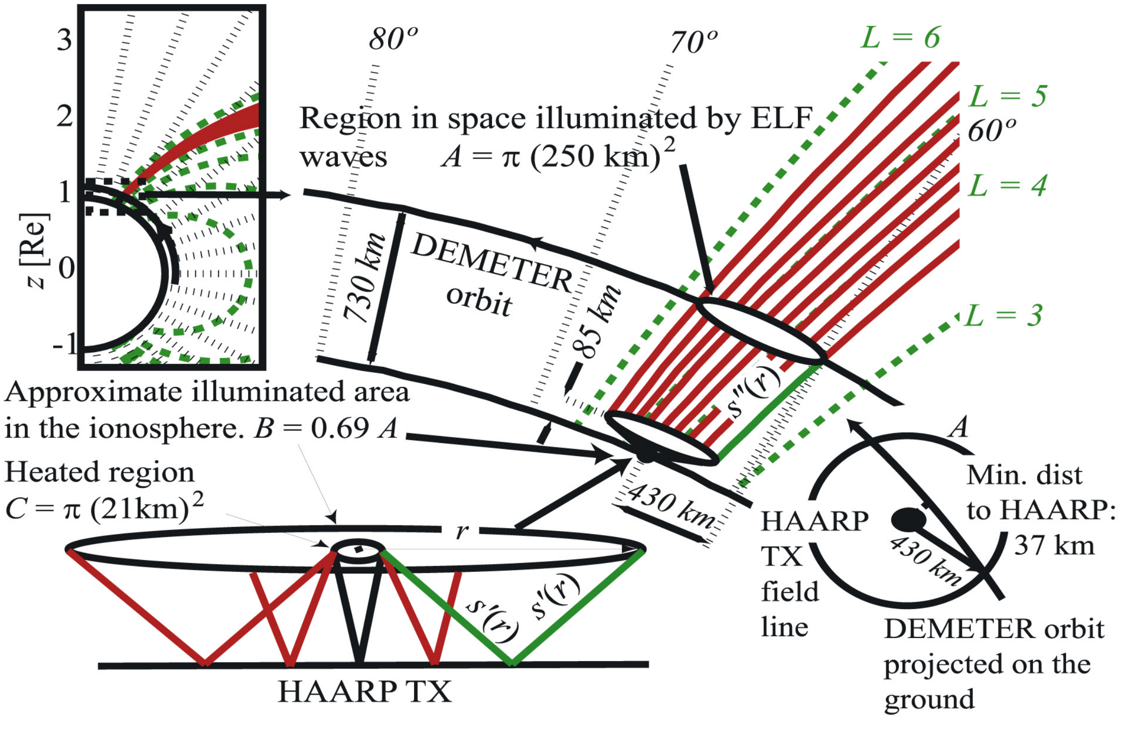

Figure 2. Raytracing simulation of the wave propagation path for the date studied. Shown are the ray paths from the simulation. The raypaths were injected into the magnetosphere at very low wave normal angles and the difference in paths for the different frequencies observed was not noticeable at these low attitudes. Included in the plot are a scheme of the satellite path during February 10, 2005 at around 06:52:30 UT, and different views of the illuminated regions from the ground in the bottom left panel and from space in the bottom right panel.

shut off at invariant latitudes larger than 65°, so that no observations exist beyond that latitude. We assume azimuthal symmetry around the magnetic field line intersecting HAARP to estimate the area A of the region of space illuminated by HAARP. Using backwards raytracing we can then determine the area B of the *D*-region in the ionosphere illuminated by HAARP. We also know the region C in the ionosphere heated by the HF transmitter, using the known beamwidth of the HAARP array. Since ELF waves tend to propagate predominantly along the Earth's magnetic field lines, upward propagating ELF radiation produced in and near the heated spot will not spread significantly in the horizontal direction as it propagates to the DEMETER altitude. The large difference between regions B and C, is due to the fact that waves generated by the modulated electrojet are produced over an altitude range which spans the lower ionospheric reflection height (~85 km at night) and not only propagate upward, but also downward. The downward propagating waves are then reflected from the ground and escape into the magnetosphere as they propagate in the Earth-ionosphere waveguide to larger lateral distances away from the source. This effect produces an ELF illumination region which is much larger than the actual HF-heated ionospheric spot. Modulation of the ionospheric conductivity in the presence of the auroral electrojet electric fields can also lead to horizontal currents which flow in loops outside of region C, producing an effective radiating region that will be larger than the actual heated one. To take into account these looping currents requires a model of the entire heating process, which is beyond the scope of the present discussion.

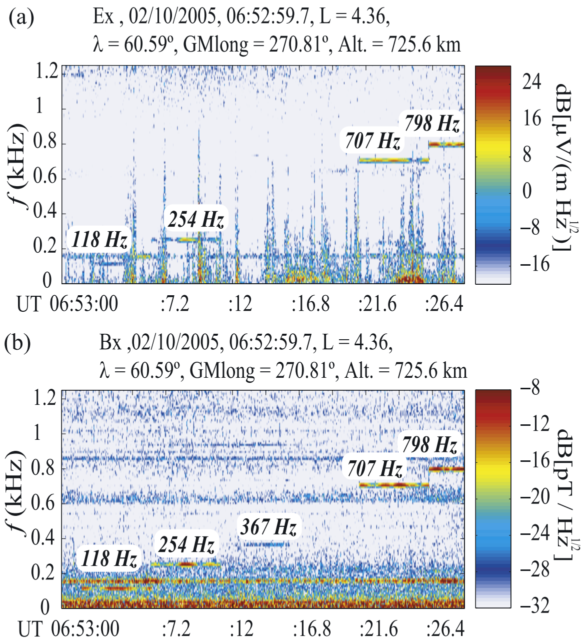

Figure 3. Detailed ICE and IMSC spectrograms from the DEMETER satellite pass during February 10, 2005. (a) An overview of the detected HAARP signal in one of the electric field components. The transmitted pattern at frequencies up to 798 Hz is observed. (b) An overview of the detected HAARP signal in one of the magnetic field components. The transmitted pattern at frequencies up to 798 Hz is observed.

4. Observations: HAARP-Generated ELF Signals Observed at DEMETER and on the Ground

[8] ELF/VLF waves generated by HAARP – modulated electrojet currents were observed on one fourth of the DEMETER satellite passes over HAARP (3 times of 12 passes). This low probability may be due to the variability of the intensity of the electrojet [*Lefeuvre et al.*, 1985; *James et al.*, 1984; *Inan and Helliwell*, 1985], as well as the ambient ELF noise levels at the DEMETER orbit. However we also have to consider the fact that DEMETER does not record data above the invariant latitude of 65°, which, given the fact that HAARP is located at 62.4° and that the ELF raypaths have the tendency to move towards higher latitudes, may significantly limit the chances of observing the HAARP-generated ELF signal to those occasions when the emitted ELF fields are relatively intense.

[9] Figure 3 shows an overview spectrogram of data recorded using the ICE and IMSC instruments on DEMETER during February 10, 2005, where the HAARP-transmitted signal (Figure 1) is clearly observed during a 30 second period. Pulses at all of the ELF modulation frequencies are observed except the one at 647 Hz and the ones above 800 Hz. Between 600 Hz and 650 Hz, a strong noise band is seen which corresponds to the local proton gyrofrequency, representing the upper band limit for left hand mode propagation. The 647 Hz signal from HAARP may be strongly absorbed (attenuated) due to its proximity to the upper cutoff since the 647 Hz signal is observed on the ground at the same levels as the other ELF pulses. Pulses at frequencies higher than 800 Hz are not observed because the DEMETER receiver stopped recording at 06:53:27 UT. These pulses were in fact also produced and launched downward, as evidenced by the fact that they are observed on the ground. Similar pulses in this frequency range were actually detected on DEMETER during other passes, where the termination of the data recording (at the 65-degree invariant latitude point) was at a later time in the course of the transmission sequence. It can be seen that many pulses exhibit deep fading, especially those at 707 Hz and 798 Hz. This fading is possibly due to multi–path effects produced by ionospheric irregularities [*Sonwalkar et al.*, 1984]. Natural impulsive emissions are observed in the electric field instrument below 600 Hz. A resonance at the proton gyrofrequency is observed between 600 Hz and 650 Hz. Other artificial emissions are observed like continuous narrow band observed around 180 Hz, most likely produced by power line harmonics. The spectral lines observed above 800 Hz and the narrow band noise observed below 50 Hz in the magnetic field instrument are due to instrumental noise onboard the satellite.

[10] Figure 4a shows simultaneous data recorded on the ground near Chistochina, Alaska, at a distance of ~36 km from the HAARP HF heater. These data also show ELF signals generated by HAARP. Displayed in this figure is the wave magnetic field detected with one of the two loop antennas on the ground. This type of data provides an indication of the strength of the ELF/VLF signal radiated downward by the auroral-electrojet antenna. Since the extent of the generation region is believed to encompass the upper

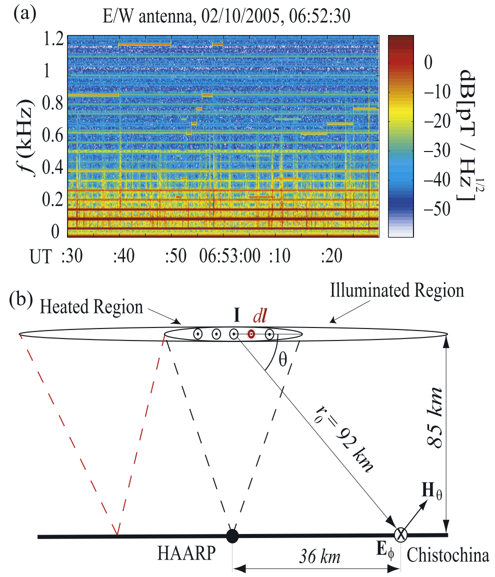

Figure 4. (a) Ground observations of the ELF HAARP generated signal at Chistochina, on February 10, 2005, starting at 06:52:30 UT. The panel shows data from a vertical magnetic loop antenna, oriented to the geographic East-West line. The magnitude scale refers to magnetic field intensity in pT / Hz$^{-1/2}$. (b) Scheme used for the calculation of the radiated power toward the ground. Indicated are the electrojet currents, moving outside the page, and the location of the HAARP heater, as well as the receiver in Chistochina.

boundary of the Earth-ionosphere waveguide, it is not clear as to whether efficient coupling of ELF wave energy upward (to DEMETER altitudes) is indicative of efficient coupling to ground-based sites (and/or vice versa). The ELF radiation directed upward from the heated spot into the magnetosphere may be significantly different from that directed into the Earth-ionosphere waveguide. Figure 4b shows a schematic of the heated region and illuminated region, with respect to the ground receiver at Chistochina. The vector **I** represents the electrojet current, while *dl* is a differential vector length along **I**. Also plotted are $\mathbf{H}_\theta$ and $\mathbf{E}_\varphi$ the electric and magnetic field vectors observed at the ground receiver.

5. Calculation of the ELF Power Radiated by HAARP

[11] To estimate the total ELF power radiated as a result of modulated HF heating by HAARP, we use the expression below [*Jasna Ristic-Djurovic,* 1993, pp. 40–41] to calculate the time average Poynting flux vector $\langle \mathbf{S}_\mathrm{D} \rangle$, using local cold plasma parameters (as measured on DEMETER) as well as the value of the total wave magnetic field $\mathbf{B}_\mathrm{D}$, for arbitrary values of wave normal angle ψ:

$$\langle \mathbf{S}_D \rangle = \frac{c}{2\mu_0}\left\langle |\mathbf{B}_D|^2 \right\rangle \cdot \frac{\sqrt{(\tan\psi - \rho_1\rho_2 X)^2 + \left(1+\rho_2^2 X\right)^2}}{\left(\rho_2^2 X^2 n\cos\psi\right)\left[1 + (1+\tan^2\psi)\left[D\frac{\left(n^2\sin^2\psi - P\right)}{P(n^2-S)}\right]^2\right]} \quad (1)$$

where $\langle \ldots \rangle$ symbol denotes averaging in time over the duration of each ELF/VLF pulse, where:

$$\rho_1 = i\frac{E_z}{E_y} = \frac{(n^2-S)n^2\sin\psi\cos\psi}{D\left(n^2\sin^2\psi - P\right)} \qquad \rho_2 = i\frac{E_x}{E_y} = \frac{(n^2-S)}{D}$$
$$\text{and } X = \frac{P}{\left(P - n^2\sin^2\psi\right)} \quad (2)$$

The refractive index n as well as the values of the auxiliary variables D, P, and S are obtained from *Stix* [1962, p. 10]. These values depend on Π_e, Π_i, the electron and ion plasma frequency and Ω_e, Ω_i, the electron and ion gyrofrequency as well as the wave angular frequency ω. The gyrofrequency values are calculated using a DGRF/IGRF Geomagnetic Field model with $\mathbf{B}_0 = 40.804$ μT at the HAARP geographic coordinates. The plasma frequency values are determined from measurements onboard DEMETER of electron and ion (mostly O^+) density using the Langmuir Probe Instrument (ISL) and the Plasma Analyzer Instrument (IAP), for an electron density of $n_e \sim 4750$ cm^{-3} and an ion density of $n_i \sim 5352$ cm^{-3}. The refractive index n also depends on ψ, the wave normal angle.

[12] As shown in Figure 2, the HAARP-generated ELF signal is observed on DEMETER at a distance for which the subsatellite point on the ground is 430 km away from HAARP. The signal is observed during a 30 second period, after which the DEMETER receiver is shut off. Therefore our observations are representative of only the outer part of the illuminated region. In order to integrate $\mathbf{S}_\mathrm{D}$ over the total area and obtain an estimate for the radiated ELF power, we must assume a model of the distribution of ELF wave power over the illuminated area B. We assume that the variation of $\mathbf{S}_\mathrm{D}$ is symmetrical around the magnetic field line intersecting HAARP and we define a function $g(r)$ which represents the radial variation of the Poynting vector with r, the radial perpendicular distance from the HAARP magnetic field line. We define a function $s_m(r) = 2\mathrm{m}\sqrt{(r/2\mathrm{m})^2 + (85\mathrm{km})^2}$ as the total ray path from the heated region to the injection point in the ionosphere at a radial distance r, for a ray reflecting m times in the Earth-ionosphere waveguide, highlighted in green in Figure 2 for $m = 1$. Assuming that the power varies as s_m^{-2}, were s is the distance to the source, the radiated power P_D is:

$$P_D = \int_B \langle \mathbf{S}_D \rangle \cdot d\mathbf{S} = \langle S_D \rangle \iint\limits_{r,\,\phi} g(r) r\, dr\, d\phi$$
$$= \langle S_D \rangle \left[\rho_S \int_0^{r_1} 2\pi r\, dr + \rho_S \sum_{m=1}^{\infty} \int_0^{r_2} 2\pi r \sigma_t (1-\sigma_t)^{m-1} \cdot \left(\frac{s_1(r_2(f))}{s_m(r)}\right)^2 dr\right] \quad (3)$$

where φ is the angle around the HAARP magnetic field line, the radial distance from the r_1 is the radius of the illuminated region C, ($r_1 \sim 21$ km). It should be noted that during the 30 seconds of observation of the HAARP signal, DEMETER moves a distance of approximately 6.7 km/sec 30 sec = 200 km over the illuminated region. Therefore it

Table 1a. Results From the Calculations of the Estimated ELF Power Radiated From the Electrojet Virtual Antenna Into the Magnetosphere, P_D, Using Equations (1)–(3) Using $\psi = 0°$, at Each of the Transmitted Step Frequencies, for the Distribution Model Adopted

	s_m^{-2} Distribution	
f [Hz]	$\langle S_D\rangle$, pW/m^2	$\langle P_D\rangle$, W
118	n/a	n/a
254	9.4	2.7
367	1.13	0.32
707	17.5	4
798	18.4	3.4

should be noted that the observations at different frequencies occur a different locations inside the illuminated region. We assume that the size of this region is the same for all frequencies, but the change in location of the spacecraft must be taken into account when calculating g(r). This is achieved introducing the parameter $r_2(f)$, the distance of the satellite footprint to HAARP at the beginning of the ELF pulse of frequency f. ($r_2(f)$ = 207 km @ 118 Hz, 205 km @ 254 Hz, 197 km @ 367 Hz, 159 km @ 707 Hz and 125 km @ 798 Hz). The first term of the sum on the right hand side of (3) represents the wave energy radiated directly upward from the heated spot. The second term represents the energy leaked upward from the Earth-ionosphere waveguide. The quantity σ_t represents the fraction of wave power transmitted upward into the ionosphere as the waves in the Earth-ionosphere waveguide reflect from the upper boundary. We assume that σ_t is constant for each ray. The ionosphere wave power transmission coefficient σ_t at the time of the observation is unknown, since the ionospheric density profile in the D-region at that time is not known. Nevertheless we can use (3) to determine a lower bound to the amount of power that HAARP is radiating into the waveguide, if we choose a value of σ_t that maximizes the term $\sum_{m=1}^{\infty}\sigma_t(1-\sigma_t)^{m-1}\left(\frac{s_1(r_2)}{s_m(r)}\right)^2$. It is found that this term is maximum for σ_t approaching 1. The factor ρ_S is the spread of power as the rays propagate in the magnetosphere from B to A and is equal to the surface ratio A/B, that is $\rho_S = (0.69)^{-1}$.

[13] Shown in Figure 4a are the measurements of one of the components of the horizontal magnetic field at Chistochina, which we denote as $\mathbf{B}_\theta$. If we assume that the electrojet virtual antenna can be described to first order as a dipole with current $\mathbf{I}$ in the East–West direction and a moment $\mathbf{I}\,dl$ (Refer to Figure 4b), we can use the measurements of $\mathbf{B}_\theta$ from the ground station to estimate the time average Poynting flux $\langle\mathbf{S}_{CH}\rangle$ of the wave propagating towards the ground and the power radiated towards the ground P_{CH} as:

$$\langle \mathbf{S}_{CH}\rangle = \frac{1}{2}\langle \mathbf{E}_\phi \times \mathbf{H}_\theta\rangle = \frac{\eta_0}{2\mu_0^2}\frac{\left\langle |B_\theta|^2\right\rangle}{(1+F^2)(1+R)^2}\breve{\mathbf{e}}_r \text{ and}$$

$$P_{CH} = \int_S \langle \mathbf{S}_{CH}\rangle \cdot d\mathbf{S} = \iint_{\theta,\,\phi} \langle S_{CH}\rangle r_0^2 \sin\phi \, d\phi d\theta \tag{4}$$

where θ is the angle around the electrojet antenna dipole and r_0 = 92 km, as shown in Figure 4b. Chistochina is in the far field of the modulated electrojet currents at frequencies greater that ~600 Hz, and in the near field for lower frequencies. At these lower frequencies the near field terms must be subtracted from the measured fields at Chistochina before it can be used for power calculations. This subtraction was carried out assuming that the modulated electrojet currents represent a dipole current, resulting in the term $(1 + F^2)$ in (4), where $F = c/(\omega\, r_0)$. The magnetic field observed on the ground receiver at Chistochina is actually a factor of $(1 + R)$ greater than the actual value emitted by the electrojet antenna, due to the reflection on the ground, where R is the reflection coefficient of the ground. For dry soil ($\sigma \sim 10^{-5}$ S/m and $\varepsilon_r \sim 4$) we estimated the value of R as $R = \mathrm{Re}[(n_{CH} - 1)/(n_{CH} + 1)]^2$ where n_{CH} is the refractive index of the ground, $n_{CH} = (\varepsilon_r + i\sigma/(\varepsilon_0\,\omega))^{1/2}$.

6. Results

[14] Results of the power calculations are summarized in Tables 1a and 1b. In calculating the power, ionospheric losses were neglected since these are generally <1 dB for the frequencies of interest here [*Helliwell*, 1967]. Table 1a show the results for the power calculations using the distribution of S_D along the region B explained in section 5 by equation (3). The values of S_D are obtained from equations (1) and (2) using $\psi = 0°$. Observed values of magnetic field on the ground B_θ and B_φ are obtained using the N/S and E/W oriented antennas at Chistochina (Table 1b). The values of the magnetic field for each component are averaged over the pulse duration. S_{CH} and P_{CH} are the Poynting vector and radiated power at each frequency, respectively, estimated using equation (4). From the simple model used to determine the total ELF power radiated by HAARP, we arrive at results which resemble those of similar previous experiments [*James et al.*, 1990], with a minimum estimated value of radiated power of 5.9 W at 707 Hz. Results reported in *James et al.* [1990] were performed with an ionospheric heater located at a similar latitude as HAARP, the MPAe facility, near Tromsø, Norway (~69.6° invariant latitude), radiating with an effective HF power of 270 MW, using an X and O mode, AM modulated ELF/VLF signal that consisted of a series of pulses ranging in frequency between 525 Hz and 5925 Hz. The DE 1 spacecraft, which observed the signals during this experiment, was located at an altitude of ~11000 km, ten times the altitude of DEMETER in the present experiment. Nevertheless the power estimate of ~4W is comparable to the estimates presented in this report. The values of power

Table 1b. Results of Radiated Power Into the Earth-Ionosphere Waveguide, P_{CH}, Obtained From Equation (4)[a]

F, Hz	$\langle B_\theta\rangle$, pT	$\langle B_\varphi\rangle$, pT	$\langle S_{CH}\rangle$, pW/m^2	$\langle P_{CH}\rangle$, W
118	n/a	n/a	n/a	n/a
254	1.54	1.23	50.7	2.71
367	1.25	0.87	52.7	2.82
707	0.92	0.91	78.8	4.22
798	0.87	0.78	69.7	3.73

[a] Also included are the averaged values of the two magnetic field components measured by the E/W and N/S antennas at Chistochina.

estimated using DEMETER wave amplitudes are generally lower than the estimated power based on ground observations. In particular, the power estimated using DEMETER at 367 Hz and 647 Hz, reveals a strong attenuation that is not observed on the ground receiver. The pulses at frequencies below the local proton gyrofrequency are subject to mode conversion from the right handed to the left handed mode, which may be affecting the pulses at 647 Hz and 367 Hz. It can be seen that there is a modest frequency dependence of the radiated power, which can be interpreted as an increase with frequency of the efficiency of the generation of ELF waves by modulation of the electrojet (in space: *James et al.* [1984], on the ground: *Rietveld et al.* [1989]). However this dependence is less than the f^2 dependence which would be expected from a dipole antenna of fixed length in free space.

[15] **Acknowledgments.** This work was supported, in part, by the High Frequency Active Auroral Research Program (HAARP), under grant N00014-03-0631 from the Office of Naval Research (ONR). We thank J. J. Berthelier for providing the ICE and IAP data. We also thank M. J. McCarrick for setting up the transmissions schedule and time-frequency patterns in the HAARP HF heater and P. A. Kossey for the support in this experiment.

References

Bell, T. F., U. S. Inan, M. Platino, J. S. Pickett, P. A. Kossey, and E. J. Kennedy (2004), CLUSTER observations of lower hybrid waves excited at high altitudes by electromagnetic whistler mode signals from the HAARP facility, *Geophys. Res. Lett.*, *31*, L06811, doi:10.1029/2003GL018855.

Helliwell, R. A. (1967), A theory of discrete VLF emissions from the magnetosphere, *J. Geophys. Res.*, *72*(19), 4773–4790.

Helliwell, R. A., J. P. Katsufrakis, T. F. Bell, and R. Raghuram (1975), VLF line radiation in the Earth's magnetosphere and its association with power system radiation, *J. Geophys. Res.*, *80*, 4249–4258.

Inan, U. S., and T. F. Bell (1977), The Plasmapause as a VLF wave guide, *J. Geophys. Res.*, *82*, 2819–2827.

Inan, U. S., and R. A. Helliwell (1985), Active experiments from ground, in *Results of the Arcad 3 Project and of Recent Programmes in Magnetospheric and Ionospheric Physics Toulouse*, vol. 84, pp. 599–607, Cepadues-Ed., Toulouse, France.

Inan, U. S., M. Golkowski, D. L. Carpenter, N. Reddell, R. C. Moore, T. F. Bell, E. Paschal, P. Kossey, E. Kennedy, and S. Z. Meth (2004), Multi-hop whistler-mode ELF/VLF signals and triggered emissions excited by the HAARP HF heater, *Geophys. Res. Lett.*, *31*, L24805, doi:10.1029/2004GL021647.

James, H. G., R. L. Dowden, P. Rietveld, P. Stubbe, and H. Kopka (1984), Simultaneous observations of ELF waves from an artificially modulated auroral electrojet in space and on the ground, *J. Geophys. Res.*, *89*, 1655–1666.

James, H. G., U. S. Inan, and M. T. Rietveld (1990), Observations on the DE 1 spacecraft of ELF/VLF waves generated by an ionospheric heater, *J. Geophys. Res.*, *95*, 12,187–12,195.

Jasna Ristic-Djurovic, L. (1993), Gyroresonant scattering of radiation belt electrons by oblique whistler waves, Ph.D. thesis, Dep. of Electr. Eng., Stanford Univ., Stanford, Calif.

Kapustin, I. N., R. A. Pertsovsky, A. N. Vasil'ev, V. S. Smirnov, O. M. Raspopov, L. E. Solov'eva, A. A. Ul'yachenko, A. A. Arykov, and N. V. Galakhova (1977), Generation of radiation at combination frequencies in the region of the auroral electrojet, *JETP Lett.*, *25*(5), 248–251.

Lefeuvre, F., J. L. Rauch, V. I. Dee, E. E. Titova, and V. E. Yurov (1985), Detection from Aureol-3 of the modulation of auroral electrojet by HF-heating from ELF signals in the upper atmosphere above Tromsoe, in *Results of the Arcad 3 Project and of Recent Programmes in Magnetospheric and Ionospheric Physics Toulouse*, vol. 84, pp. 609–619, Cepadues-Ed., Toulouse, France.

Parrot, M. (2002), The micro-satellite DEMETER, *J. Geodyn.*, *33*(4–5), 535–541.

Platino, M., U. S. Inan, T. F. Bell, J. S. Pickett, E. J. Kennedy, J. G. Trotignon, J. L. Rauch, and P. Canu (2004), Cluster observations of ELF/VLF signals generated by modulated heating of the lower ionosphere with the HAARP HF transmitter, *Ann. Geophys.*, *22*(7), 2643–2653.

Rietveld, M. T., P. Stubbe, and H. Kopka (1989), On the frequency dependence of ELF/VLF waves produced by modulated ionospheric heating, *Radio Sci.*, *24*, 270–278.

Sonwalkar, V. S., T. F. Bell, R. A. Helliwell, and U. S. Inan (1984), Direct multiple path magnetospheric propagation: A fundamental property of nonducted VLF waves, *J. Geophys. Res.*, *89*, 2823–2830.

Stix, T. H. (1962), *The Theory of Plasma Waves*, McGraw-Hill, New York.

Stubbe, P., and H. Kopka (1977), Modulation of the polar electrojet by powerful HF waves, *J. Geophys. Res.*, *82*, 2319–2325.

Stubbe, P., H. Kopka, and R. L. Dowden (1981), Generation of ELF and VLF waves by polar electrojet modulation: Experimental results, *J. Geophys. Res.*, *86*, 9073–9078.

Stubbe, P., H. Kopka, M. T. Rietveld, and R. L. Dowden (1982), ELF and VLF wave generation by modulated heating of the current carrying of the lower ionosphere, *J. Atmos. Terr. Phys.*, *44*, 1123–1125.

T. F. Bell, U. S. Inan, and M. Platino, Space, Telecommunications and Radioscience (STAR) Laboratory, Stanford University, Stanford, CA 94305, USA. (platinum@stanford.edu)

E. J. Kennedy, Naval Research Laboratory, 4555 Overlook Avenue SW, Washington, DC 20375, USA.

M. Parrot, Laboratoire de Physique et Chimie de l'Environnement, Centre National de la Recherche Scientifique, 3 A avenue de la Recherche Scientifique, F-45071 Orléans cedex 02, France.