Orientation of the HAARP ELF ionospheric dipole and the auroral electrojet

M. B. Cohen,[1] M. Gołkowski,[1] and U. S. Inan[1]

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[1] The HF heating facility of the High Frequency Active Auroral Research Program (HAARP), located near Gakona, Alaska, generates ELF (300 Hz - 3 kHz) waves via modulated HF (2.7–10 MHz) heating of the auroral electrojet. Using two ELF/VLF receivers at ~700 km from HAARP, the orientation of the equivalent ELF radiating ionospheric dipole is inferred from the relative strength and Earth-ionosphere waveguide modal content of signals received. In several cases analyzed the effective HAARP electric dipole orientation is generally along magnetic east-west direction. A new metric is introduced to evaluate the validity of the determination of source characteristics with medium and long-range ELF/VLF measurements. Results are put into context of the auroral electrojet, indicating the possibility of studying small-scale electrojet structure not observable with magnetometers.
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1. Introduction

[2] Modulation of natural ionospheric currents to generate ELF (300 Hz–3 kHz) radiation has been investigated theoretically and experimentally since the first observations by *Getmantsev et al.* [1974]. Since efficient ELF radiating antennae require prohibitively large physical sizes, harnessing the natural ionospheric currents (~75–100 km) at high latitudes by modulated heating with HF (2.7–10 MHz) waves is an attractive alternative. Nonlinear HF to ELF conversion occurs via absorption-induced changes in the electron temperature and thus the ionospheric conductivities. The effectiveness of such an ELF radiator is a function of the ambient current distribution and electron density, as well as electron heating and cooling rates, which are highly variable [*Moore*, 2007].

[3] The European Incoherent Scatter (EISCAT) Association HF heating facility near Tromsø, Norway generates ELF/VLF signals with ground-based amplitudes of up to 1 pT. The Tromsø data, and corresponding theoretical interpretations, are reported in a long series of papers [e.g., *Stubbe and Kopka*, 1983]. The 1 MW radiated, 200–300 MW ERP Tromsø HF heater was typically 100% square wave amplitude modulated at HF frequencies from 2.75 to 8 MHz.

[4] HF ionospheric heating facilities at Arecibo, Puerto Rico, and the High Power Auroral Stimulation (HIPAS), near Fairbanks, Alaska, have done similar experiments. At Arecibo, the equatorial dynamo current was modulated with 800 kW to produce 500 Hz - 5 kHz waves [*Ferraro et al.*, 1982]. At HIPAS, ELF/VLF waves were produced most successfully when the electrojet was overhead, when there was low D region absorption, and when visible aurora were not present [*Villaseñor et al.*, 1996].

[5] The HAARP heating facility in Gakona, Alaska (62.39°N, 145.15°W) injects ELF/VLF waves in the Earth-ionosphere wave-guide as far as 4400 km [*Moore et al.*, 2007] and also into space [*Inan et al.*, 2004]. HAARP has recently been upgraded to a total radiated power of 3.6 MW, and an ERP capability of ~400 MW at 3.25 MHz. In this paper, we present a new method to determine the effective ELF dipole characteristics using observations at medium distances (~700 km).

2. Description of Data

[6] ELF/VLF data are taken with the AWESOME receiver. These broadband, high-sensitivity ELF/VLF receivers consist of two orthogonal air-core loop antennae, measuring the two horizontal components of the magnetic field as low as a few femtotesla. Data is synchronized to GPS. The three relevant receivers are shown in Figure 1a.

[7] Near field ELF measurements (within ~50 km of HAARP) show high variability, making decoupling of effects of various dependencies difficult. Furthermore, the cavity resonator formed by the Earth and ionosphere dominates the frequency response, producing strong resonances at multiples of ~2 kHz [*Stubbe and Kopka*, 1983]. However, the Earth-ionosphere waveguide allow only certain modes to propagate to longer distances, facilitating easier decoupling.

[8] On the other hand, subionospheric propagation is also intrinsically variable. Numerical models of the propagation of ELF/VLF signals in the Earth-ionosphere waveguide require as input the electron density profiles all along the propagation path, which are highly variable and typically not known. There may therefore be an optimal distance, long enough for properties to be dominated by waveguide modes, but short enough to minimize effects of ionospheric variations over the propagation path. Observed signals may then be more directly linked to the source current geometry.

[9] At frequencies <3 kHz, the three basic propagating Earth-ionosphere wave-guide modes are the quasi-transverse electromagnetic mode (qTEM), with magnetic field horizontal and transverse to propagation path, existing at all frequencies but with higher attenuation with increasing frequency [*Inan and Inan*, 2000, p. 255]. The quasi-transverse magnetic mode (qTM) has magnetic fields aligned in the same way but propagates only above the first order ionospheric cutoff (~1.8 kHz). The quasi-

[1]STAR Lab, Stanford University, Stanford, California, USA.

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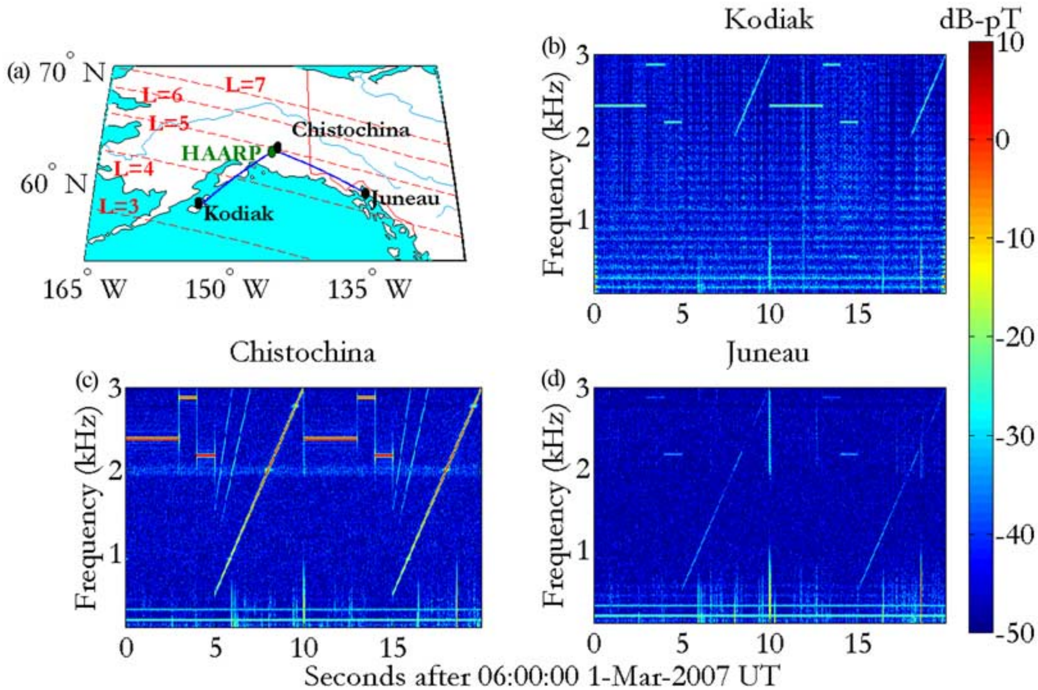

Figure 1. (b)–(d) Spectrograms from sites in Figure 1a. During this period, the transmitted pattern consisted of tones at 2375 Hz (3 sec), 2175 Hz (1 sec), and 2875 Hz (1 sec), followed by a 500 Hz/s ramp between 500 Hz and 3 kHz.

transverse electric (qTE) mode is subject to the same cutoff, but has a transverse electric field and a radial magnetic field. Though the TE and TM modes exist in higher orders, at <3 kHz only the lowest mode of each propagates.

[10] Polarization is defined as B_r/B_θ, where B_r is the radial magnetic field phasor (i.e., in the direction from HAARP to receiver), and B_θ is the horizontal azimuthal magnetic field phasor. Polarization is also discussed in this context by *Barr et al.* [1986] and *Moore et al.* [2007]. Polarization provides a measure of relative contributions of the qTE (which is dominated by B_r) and qTM modes (dominated by B_θ). Rapid changes in the electrojet strength would likely scale B_r and B_θ roughly equally [*Barr et al.*, 1986]. Polarization is therefore intrinsically insulated from these rapid changes.

3. Observations

[11] The strength of HAARP-generated ELF signals show high variability minute-to-minute and day-to-day (up to 80 dB) as a result of local ionospheric electron density and electrojet variations. Nevertheless, HAARP-generated ELF is detected, even on the weakest days, at a receiver located in Chistochina, Alaska (62.61°N, 144.62°W, 37 km from HAARP) with signal intensities typically between 10 fT and 10 pT. Amplitudes at Chistochina of > ~100 fT are often indicative of reception also at Juneau (58.59°N, 134.90°W, 704 km magnetic ESE of HAARP), and Kodiak (57.87°N, 152.88°W, 661 km magnetic SSW of HAARP). The heading from HAARP to Juneau and Kodiak, respectively, differ by nearly 90°, i.e., the sites sense nearly orthogonal directions in the HAARP radiation pattern.

[12] We consider periods of consistent strong reception at Juneau and Kodiak. Figures 1b–1d show samples of HAARP ELF signals (transmitted format was a 10-second long sequence of three tones and a frequency-time ramp) observed at the three sites for two hours, during ionospheric nighttime on 01 March 2007. All format elements are seen at Chistochina, while Kodiak data does not exhibit any signals below ~2 kHz, and the Juneau spectrogram shows variable fading with frequency.

[13] The lack of signal <~2 kHz at Kodiak is consistent with absence of qTEM mode, whereas the Juneau data with qTEM and some combination of other modes. Figure 2 shows signal amplitude and polarization (B_r/B_θ) for three different frequencies at Juneau and Kodiak for a 30 minute period. Each observed tone is 1–3 seconds long, and is integrated over the entire pulse for the polarization measurement. At Kodiak, the polarization indicates a stronger radial component for all three frequencies, consistent with qTE1 mode. At Juneau, the polarization for the 2375 Hz and 2875 Hz components suggest an additional azimuthal magnetic component. Furthermore, at Kodiak, all three frequencies' intensities are very closely correlated, consistent with a single dominant mode, while the highly variable intensities at Juneau evidence modal interference.

[14] Signals are stronger at Kodiak by ~5–10 dB, which (since both sites are at ~700 km) could not be attributed to ionospheric attenuation unless the HAARP-Juneau path exhibited 7–14 dB/Mm higher attenuation than the HAARP-Kodiak path, unreasonable in view of typical nighttime attenuation rates of <4 dB/Mm (J. Galejs as cited by *Davies* [1970]). However, this difference is a natural result of a generally magnetic east-west orientation of the effective electric dipole radiator as shown below.

[15] These observations were repeated for two more daytime cases, covering the same 30-minutes on consecutive days with good ELF reception at Juneau and Kodiak, 28 and 29 April 2007 (not shown). These data show similar

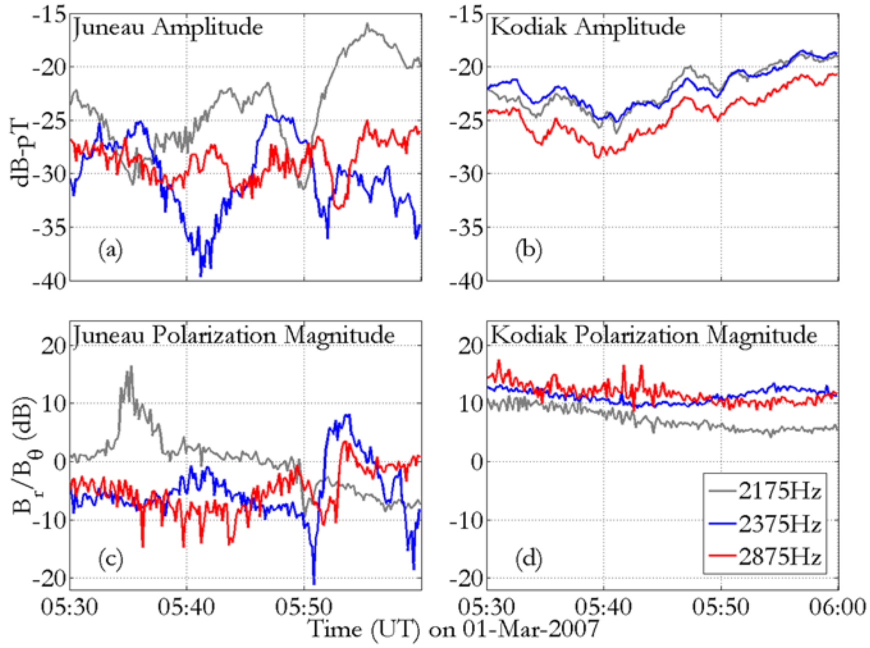

Figure 2. (a) Amplitude at Juneau, (b) amplitude at Kodiak, (c) polarization at Juneau, and (d) polarization at Kodiak.

results to 01 March 2007, i.e., qTE1 content at Kodiak, qTE1+qTM1 content at Juneau with weaker signals.

4. Discussion

[16] We utilize a numerical method to evaluate the degree to which modal content is preserved at these distances, and therefore, the viability of the orientation determination, for the four different ionospheres in Figures 3b and 3c. The D-region electron density is represented with a reference height and steepness parameter [*Wait and Spies*, 1965], which work well in linking VLF observations with ionospheric profiles [e.g., *Thomson*, 1993]. The four models represents low and flat (Profile A, h' = 80 km β = 0.50 km^{-1}), low and sharp (Profile B, h' = 80 km β = 0.75 km^{-1}), high and flat (Profile C, h' = 80 km β = 0.5 km^{-1}), and high and sharp (Profile D, h' = 80 km β = 0.5 km^{-1}). The E-region is represented as an exponential decay,

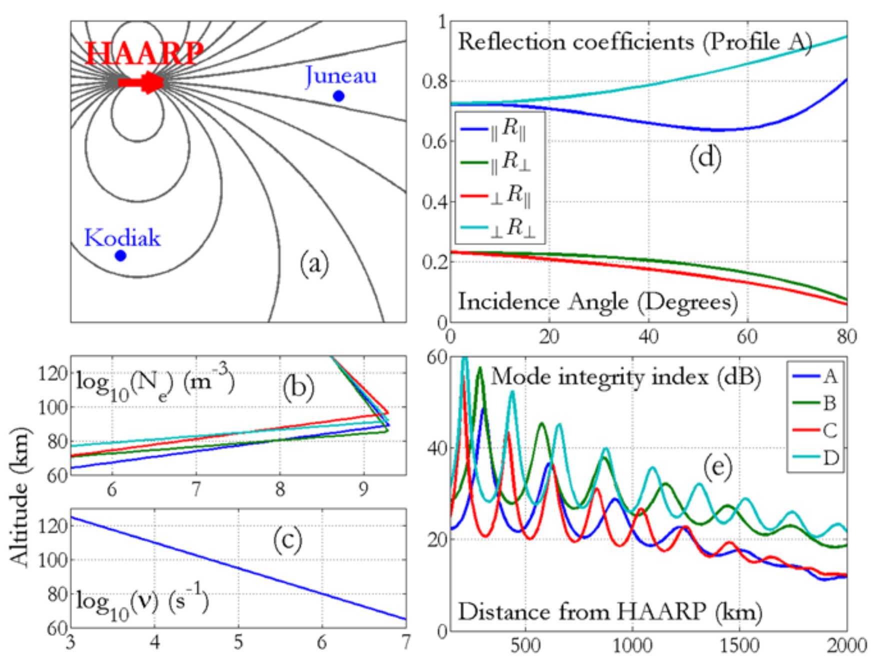

Figure 3. (a) Schematic showing how the field lines for an electric dipole affect the modal content at Juneau and Kodiak. (b)–(c) Electron density and collision frequency profiles for four different ionospheric D and E regions as defined in the text. The four reflection coefficients from the ionosphere for profile as a function of angle of incidence with respect to vertical (d), Ξ for 2375 Hz (e).

beginning at the altitude where electron density reaches a fixed maximum value (2×10^9 el/m^3), ending at a minimum value (4×10^7 el/m^3) at 130 km. The collision frequency profile is exponentially decreasing through 130 km, similar to that used by *Cummer and Inan* [2000].

[17] We first calculate the 2×2 ionospheric reflection coefficient tensor

$$R(\theta_i) = \begin{pmatrix} {}_{\|}R_{\|} & {}_{\|}R_{\perp} \\ {}_{\perp}R_{\|} & {}_{\perp}R_{\perp} \end{pmatrix}$$

as a function of angle of incidence [*Budden*, 1955]. The diagonal terms are the ratios of reflected and incident waves that are polarized with electric fields parallel to, and perpendicular to, the plane of incidence, respectively. The off-diagonal terms represent conversion from parallel incidence to perpendicular reflection ($\|R_{\perp}$), and vice versa ($_{\perp}R\|$). This method implicitly takes into account the lossiness and anisotropy of the ionosphere, which manifest themselves as attenuation and mode conversion of the propagating signals.

[18] The tensor R is calculated as outlined by *Budden* [1955]. Two initial solutions satisfying conditions at high altitude are separately integrated downward through the ionosphere until a free space point below the ionosphere is reached. The two resulting solutions are separated into upward and downward propagating waves, and normalized. Figure 3d shows the magnitude of the components of R, as a function of incidence angle, for Profile A, at 2375Hz, and for a magnetic field along the HAARP-Juneau path, based on the IGRF-10 model.

[19] We assume modal configurations as in an ideal (i.e., perfectly conducting plates) parallel plate waveguide with a plate separation of 80 km, and then apply the reflection tensor as a correction factor. At 2375 Hz, waves traveling in a 80 km thick parallel plate wave-guide can be decomposed into a pair of plane waves traveling at an angle $\theta_i \simeq 38°$ with respect to the boundary normal [*Inan and Inan*, 2000, p. 269] implying an ionospheric reflection every ~205 km.

[20] Since R refers to a single reflection, we let $A = R^n(\theta_i)$ be a 2×2 matrix where n is the estimated number of ionospheric reflections (including fractions), proportional to distance from source. As a broad measure of the modal content of the subionospheric wave on a given propagation path, we therefore define the mode integrity index in terms of the diagonal (preserved modes) terms, and the off-diagonal (converted modes), of A, as

$$\Xi = \frac{A_{11}A_{22}}{A_{12}A_{21}}$$

[21] The value of Ξ will decrease with distance. Values of Ξ well above unity are indicative that mode content is a strong function of source generation characteristics, indicating that the link between received polarization and source orientation is valid without applying a theoretical model with its inherent uncertainties, as described earlier. This method does not implicitly take into account the Earth curvature (which is not a dominant factor at these distances).

[22] Figure 3e shows the magnitude of Ξ as a function of distance. At 700 km, all four ionospheres exhibit mode integrity above 20 dB, indicating that excited modes are at least a factor of 10 greater than converted modes, therefore our polarization measurements are reliable to within ~10%. Since our observed polarizations are often >10 dB, a 10% variability would not affect our observations, and orientation measurements would be reliable to ~10°. Additional receivers at other azimuths from HAARP may improve the reliability further.

[23] Having established the viability of polarization measurements, we now determine the effective HAARP ELF electric dipole orientation, for the cases illustrated. Figure 3a shows the effect of dipole orientation on polarization measurements at Juneau and Kodiak. The electric field lines are stronger at Kodiak than Juneau, and are transverse to the HAARP path at Kodiak, but are parallel to the path at Juneau. The results for 01 March 2007, are consistent with an ELF electric dipole oriented perpendicular to the path from HAARP to Kodiak preferentially exciting qTE modes towards Kodiak and qTM (including qTEM) towards Juneau. Since Juneau is ~10° E of magnetic North from HAARP, the dipole orientation is likely within 10° of magnetic EW. We assume here that the fields do not rotate as they exit the ionosphere, as described by *Werner and Ferraro* [1991], because the peak altitude of generation is near or below where the ambient Hall conductivity becomes dominant at higher altitudes.

[24] In general, the orientation of the ionospheric ELF radiating dipole above HAARP is due to a combination of three separate modulated conductivities. The parallel conductivity is along $\mathbf{B}_0$, the Hall conductivity is orthogonal to $\mathbf{B}_0$ but parallel to the driving electric field (i.e. the auroral electrojet), and the Pedersen conductivity is orthogonal to both. For far-field ELF radiation due to heating at the HF frequencies used here, the Hall conductivity change plays a dominant role [*Barr et al.*, 1986; *Moore et al.*, 2007], though possible contributions of Pedersen conductivities cannot be discounted. Therefore, for these three independent cases, clear differences in modal content at two medium distance sites indicate that the ambient electrojet electric-field above HAARP is roughly in the North-South direction (i.e. perpendicular both to the vertical magnetic field and the EW dipole) Our observations are consistent with general understanding of typical electrojet currents and fields [*Baumjohann*, 1983]. Although the electrojet current is typically in the east-west direction (i.e., circumpolar), the currents are driven by electric fields that are in the north-south direction (i.e., polar) [*Baumjohann*, 1983], due to the fact that the ambient Hall conductivity between 70 and 100 km is larger than the Pedersen conductivity.

[25] *Rietveld et al.* [1983], *Carroll and Ferraro* [1990], and *Payne et al.* [2007] have discussed the connection between measured field properties and the auroral electrojet direction at the altitudes of the HF heating (which determines the radiation pattern). *Rietveld et al.* [1983] found close correlations between polarization ellipses observed within 20 km of the heated region to auroral radar measurements. Payne et al. (submitted manuscript, 2007) determines orientation with receivers in the near field (i.e. <50 km), through detection of a null in the vertical electric field as the HF heated region was scanned slowly in a circular pattern, and the result compared with a theoretical HF-ELF conversion models. The method described in this paper does not

require beam scanning or independent measurements (such as radar), and requires as few as two receivers detecting the signals at mid-distances from the source.

[26] Empirical determination of the structure of the ionospheric electrojet currents is difficult and is conventionally approached with magnetometer measurements [*Baumjohann*, 1983]. Data from a north-south chain of magnetometers in Alaska were examined for the dates and times of the ELF observations. A first order inversion of the magnetometer readings suggests that the main electrojet currents flow primarily in the magnetic East-West direction but are at least 100 km north of HAARP and therefore preclude a direct comparison to the ELF observations here. In addition, the magnetometer measurements are likely dominated by the strongest electrojet altitudes (100–120 km), which are usually above the altitudes of HF heating (70–90 km). The currents at these altitudes may not necessarily be in the same direction [*Werner and Ferraro*, 1991].

[27] Since magnetometer readings are inherently single point measurements [*Kamide and Kokubun*, 1996], the method of determination of the ELF dipole orientation presented here is a potential diagnostic of small scale electrojet current structure above the HF heater, or of weaker portions of the electrojet at the edge, which cannot be measured with the magnetometer array, or with VLF remote sensing as described by *Cummer et al.* [1996]. Such a diagnostic may be particularly useful during periods of substorms of high geomagnetic activity, when the auroral electrojet is more variable, and may demonstrate complicated small-scale spatial structures [*Kamide and Kokubun*, 1996].

5. Conclusion

[28] Having established that ELF modal content at distances ~700 km is a strong function of the source characteristics, we have used measurements at two sites to determine the effective electric ELF dipole generated by the HAARP HF heater. Our results show that the dipole is directed primarily magnetic East-West with variations of 10s of degrees. Further studies will be necessary to evaluate the consistency of this observation. Particularly interesting would be a comparison of pre and post midnight sectors, and a comparison across varying geomagnetic conditions. The inferred magnetic north-south electrojet direction (based on the dominance of the Hall conductivity in HF modulated heating experiments) are generally in agreement with past studies, and magnetometer readings, though the latter lack the spatial resolution for a direct comparison. Future efforts may utilize these results to investigate small-scale spatial structures in the electrojet not measurable with magnetometers.

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M. B. Cohen, M. Gołkowski, and U. S. Inan, STAR Lab, Electrical Engineering Department, 350 Serra Mall Room 356, Stanford, CA 94305, USA. (mcohen@stanford.edu)