# DEMETER Observations of a Column of Intense Up-going ELF/VLF Radiation Excited by the HAARP HF Heater

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## Abstract

The regions of ELF fields generated by the recently upgraded HAARP HF heater (3.6 MW) and observed on the DEMETER satellite are classified according to signal intensity and lateral distance from HAARP. The region closest to HAARP contains waves of relatively high intensity (E = 350 uV/m, B = 20 pT) within a narrow cylindrical column of ~ 10 - 20 km radius coming from the source at 75 km. It is shown that the observed intense columnar radiation is consistent with predictions of a recent full-wave model [1] of ELF radiation induced by HF-heater.

## Summary

ELF signals are known to be generated via modulated HF heating of lower ionospheric D region within which naturally occurring ionospheric currents flow. The presence of the ionosphere not only enables the generation of ELF waves but also determines the propagation characteristics of these waves. For ground-based observations at distant points the ELF signals propagate within the Earth-ionosphere waveguide, and exhibit maxima near multiples of 2 kHz which are attributed to waveguide resonance effects. As the ELF waves propagate within the Earth-ionosphere waveguide, some wave energy penetrates through the ionosphere into the overlying magnetosphere. Previous in-situ measurements of HF-heating-generated ELF/VLF signals have included those at low altitudes observing signals propagating from the source to the satellite without reflection from the ground [2] and those at laterally distant locations – involving propagation in the Earth-ionosphere waveguide and continuous penetration through the ionosphere upward to higher altitudes [3]. However, there exist relatively few spacecraft observations of ELF waves generated via HF heating, with many remaining unknowns. One important parameter concerns the amount of ELF power propagating upward from the heated region. In the work [2] the *E*-field measured aboard the ISIS 1 spacecraft at 1200 km altitude was sustained at the level of 200 uV/m for 525 Hz, 1575 Hz and 1725 Hz in the close region of $d < 50$ km (where *d* is defined as the lateral distance at the altitude of the source between magnetic footprint of the satellite at this altitude and the center of the source). It even reached the value of 2.6 mV/m for 525 Hz at one data point, which was disregarded by the authors as a possible measurement anomaly. The effective source currents deduced from ISIS data were 1 to 2 orders of magnitude larger than currents calculated from ground-based measurements for the same event. On the other hand, in the work [4] the results of [2] were questioned. Measurements on the Akebono satellite over HIPAS [4] showed maximum fields of $E = 15$ uV/m and $B = 0.25$ pT for 2.5 kHz signal. Maximum fields in Akebono measurements over Tromso HF heater [5] were found to be $E = 4$ uV/m and B = 2 pT at 2.5 kHz. For these lower fields in space the effective source currents were calculated to be consistent with ground observations.

In this work the ELF signals (~ 100 Hz to 2.5 kHz) generated in the D region of the ionosphere by the HAARP HF ionospheric heater are observed on the DEMETER spacecraft as it passes through the region above HAARP, and also by ground-based VLF receivers near HAARP. The High Frequency (HF) ionospheric heater used herein is a component of the High-Frequency Active Auroral Research Program (HAARP) facility located near Gakona, Alaska, at geographic position of 62.39° N, 145.15° W, corresponding to L ~ 4.9. The recently upgraded HAARP HF heater consists of a 180-element phased array antenna fed by distributed transmitters at each antenna element with total maximum continuous power of 3.6 MW. HAARP can operate at HF ranging from 2.8 MHz to 10 MHz, and in our experiments was used at 3.25 MHz to provide maximum heating in the D region of the ionosphere.

DEMETER is a low-earth-orbit satellite with an altitude of approximately 670 km, inclination of 98.3° and horizontal velocity of about 7.6 km/s. For HAARP campaigns DEMETER operated in the burst mode, in which broadband waveforms of 3 components of both $E$ and $B$ fields up to 1.25 kHz and one component of each field up to 20 kHz are recorded. Electron and ion densities were measured by a Langmuir probe and thermal plasma analyzer. We also use ELF/VLF (~100 Hz to 40 kHz) data from the Stanford ground-based receiver in Chistochina, located 37 km to the North-East from HARRP at 62.6° N, 144.6° W. For this latest round of HAARP experiments, DEMETER burst recordings were specially extended beyond the normal termination at invariant latitude of 65°.

DEMETER observations of HAARP-induced ELF signals over long polar tracks allows us to recognize three distinct spatial regions, classified simply on the basis of signal strength and distance $d$ of the DEMETER magnetic footprint at 75-km from the HAARP heated spot. The first and relatively large region is characterized by relatively low field magnitudes ($E$ < 10 uV/m), extending from $d$ ~ 200 - 300 km to $d$ ~ 900 km. Within this region, the signal observed is likely that which is launched from the source region into the Earth-ionosphere waveguide, within which it propagates while continually leaking upward and reaching the satellite as a whistler mode wave propagating close to the zenith direction. The outer boundary of this region may substantially differ from day to day and depends on the magnitude of the originally launched signal and its attenuation within the waveguide and during trans-ionospheric transmission to satellite altitudes.

The second region of relatively higher fields (10 uV/m < $E$ < 100 uV/m) extends to d ~ 200 - 300 km. The region is usually slightly displaced southward with respect to the field line of the source. This region is likely characterized by the fact that the waves arriving at the satellite without reflection from the ground dominate over those which are at least once reflected from the ground. Direct waves are stronger in amplitude but fall off faster with the distance from the source than waves propagating in the waveguide. Thus, the outer boundary of this region can be defined as the location at which the direct waves become weak enough to be comparable with those leaking upward from the waveguide.

The third region is characterized by extremely high fields ($E$ = 367 uV/m, $B$ = 19.2 pT as observed on 01 March 2007), has a spatial extent of the order of ten kilometers, and is located within d < 100 km from the source field line. It thus appears that there exists a cylindrical column (with radius of 10 - 20 km) of the waves emanating from the source region (i.e., the HF heated region at 75 km) propagating upward along magnetic field lines or slightly displaced from the field line. 100 km is the maximum lateral distance between the magnetic footprint of the satellite and the center of the source at 75 km within which such column can occur, because in no pass beyond this distance have high fields ever been observed. Also it may turn out that such a column is actually not displaced from the field line of the source and therefore is larger in radius so that we observe only a part of the column. Our review of the literature indicates that up to now this region (i.e., the column) has been traversed by a spacecraft only once before, by the ISIS 1 spacecraft on 09 December 1981 [2]. The discrepancy between the electrojet current strength as deduced from the ground measurements and space observation has led to doubts [4] about the ISIS 1 measurements; however, DEMETER observations of extremely high fields in-situ and moderate fields on the ground provide the support of their validity.

In this work we also compare the results of DEMETER observations with recently developed full-wave model [1] of ELF radiation produced by HF-heater modulation of electrojet currents and we show that observations of three ELF field regions and field strengths are generally consistent with model predictions.

## References

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