First demonstration of HF-driven ionospheric currents

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[1] The first experimental demonstration of HF driven currents in the ionosphere at low ELF/ULF frequencies without relying in the presence of electrojets is presented. The effect was predicted by theoretical/computational means in a recent letter and given the name Ionospheric Current Drive (ICD). The effect relies on modulated F-region HF heating to generate Magneto-Sonic (MS) waves that drive Hall currents when they reach the E-region. The Hall currents inject ELF waves into the Earth-Ionosphere waveguide and helicon and Shear Alfven (SA) waves in the magnetosphere. The proof-of-concept experiments were conducted using the HAARP heater in Alaska under the BRIOCHE program. Waves between 0.1–70 Hz were measured at both near and far sites. The letter discusses the differences between ICD generated waves and those relying on modulation of electrojets. **Citation:** Papadopoulos, K., C.-L. Chang, J. Labenski, and T. Wallace (2011), First demonstration of HF-driven ionospheric currents, *Geophys. Res. Lett.*, *38*, L20107, doi:10.1029/2011GL049263.

1. Introduction

[2] A recent letter [*Papadopoulos et al.*, 2011] presented theoretical/computational results of a new concept that uses ionospheric HF heating to generate waves in the ULF/ELF range without requiring the presence of electrojet currents as in the so called Polar Electrojet (PEJ) antenna concept [*Rietveld et al.*, 1987, 1989; *Belyaev et al.*, 1987; *Barr and Stubbe*, 1991; *Papadopoulos et al.*, 1990, 2003, 2005; *Zhou et al.*, 1996]. The new concept termed, Ionospheric Current Drive (ICD), can operate in any geographic region, as well as in electrojet regions under conditions of no or low electrojet. The objective of this letter is to present the first experimental proof of principle of the ICD concept.

[3] A series of experiments were conducted using the HAARP ionospheric heater in Alaska to test and validate the ICD concept, and determine its constraints and scaling properties with ELF frequency, HF power and polarization. An additional objective of the experiments was to determine the features that distinguish ICD from PEJ generation for experiments conducted in electrojets regions. Before describing the experiments we briefly remind the reader [*Papadopoulos et al.*, 2011] that to zero order ICD and its ground signature involve two steps (Figure 1): (a) The generation of an oscillatory diamagnetic current ***J*** in the heated F-region given by

$$\vec{J} = \frac{\vec{B_0} \times \nabla \delta p}{B^2} \exp(i\omega t) \quad (1)$$

Here δp is the modified F-region pressure due to the HF electron heating, $B = |\mathbf{B}_o|$ is the ambient magnetic field, and ω is the modulation frequency of the HF power. The diamagnetic current integrated over the heated volume creates an oscillatory magnetic moment **M** anti-parallel to the ambient magnetic field $\mathbf{B}_o$ that drives the isotropically propagating MS mode; (b) A Hall current driven by the interaction of the electric field associated with the downward part of MS wave Poynting flux [*Lysak*, 1997] with the Hall conductivity of the lower ionosphere. The Hall current acts as a secondary antenna, and generates both ground magnetic field signatures and upward propagating helicon and SA waves in a fashion similar to the PEJ. In essence while the PEJ antenna relies on D/E oscillatory Hall currents driven by HF modulation of the conductivity when an *ionospheric electric field is present*, the ICD generates a Hall region *virtual antenna* by imposing an oscillatory electric field originated from the F-region pressure modulation and interacting with the ionospheric Hall region. Since the primary modulation that drives the MS wave occurs in the F-region the maximum excitation frequency lies in the low ELF region (< 50–70 Hz) consistent with the relatively slow F-region response to heating and cooling sequences.

2. Experimental Observations

[4] The ICD concept and its distinction from PEJ generated events were demonstrated in a set of experiments conducted between August 2009 and November 2010 using the HAARP heater in Gakona, Alaska. An example of ICD and PEJ generation obtained on Sep. 9, 2009, 02:00:00–12:00:00 UT is shown in Figure 2. During the test the heater operated at 3.20 MHz and 3.85 MHz, O-mode and full power (3.6 MW). Individual ULF (.2, .8, 1.4 and 3.8 Hz) and ELF (12, 18, 24, 28, 36 and 44 Hz) frequencies were generated and sampled one at a time. One kHz signals were transmitted every 10 minutes as a proxy of the electrojet strength. Previous work [*Rietveld et al.*, 1987; *Papadopoulos et al.*, 2005] has shown that during PEJ operation the amplitude of the one kHz signals is 2–3 times or more larger than the ULF/ELF amplitude. Figure 2a shows the time evolution of the foF2 and foE as given by the local digisonde, while Figures 2b and 2c show the amplitude of the ELF/ULF signals along with amplitude of the one kHz signal (marked by a black dot) at times (02:30–05:15) and (05:15–12:00). It is clear that during the first period (Figure 2b) the amplitude of the kHz signal dominates that of the ULF/ELF. This is consistent with PEJ operation and HF coupling to the E-region facilitated by the

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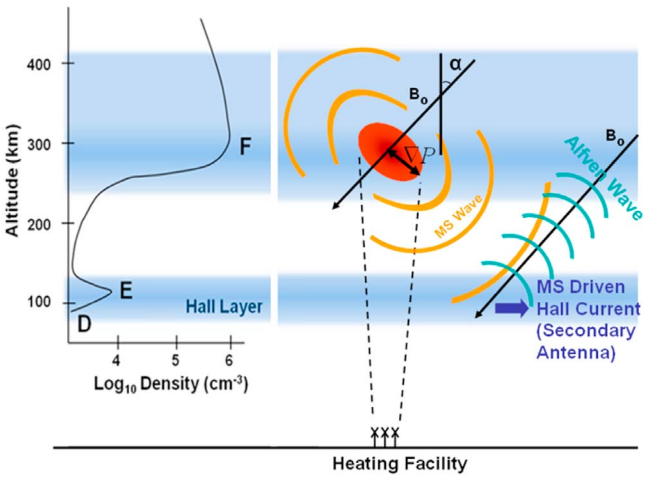

Figure 1. Schematic of the Ionospheric Current Drive (ICD) concept. Periodic F-region heating leads to a diamagnetic current $\nabla \delta p \times B$ and an oscillatory field aligned magnetic moment M that radiates isotropic MS waves. The E-field of the MS wave drives Hall currents in the E-region, resulting in a virtual antenna that injects waves in the earth-ionosphere waveguide and SA waves in the magnetosphere.

presence of densities approximately 4×10^4#/cm^3 that result in significant absorption at 3.2 MHz, and prevent any significant F-region heating. During the second period (Figure 2c) the 1 kHz signal disappears while the amplitude at the ULF/ELF frequencies dominates. As seen in Figure 2a during the second period we expect very weak D/E region absorption and thus significant F-region heating. Furthermore the data indicate under-dense probably collisional F-region heating similar to the one discussed by *Gustavsson et al.* [2010]. Figure 2c also shows maximum amplitude at 12 Hz, and 1/f behavior at higher frequencies as seen in the amplitude of the ELF triplets (12-18-24) and (28-36-44). Notice that the difference in amplitude for ULF frequencies (.2, .8, 1.4 and 6.0 Hz) is due to fact that they were tested first at half and then at full power in order to test the scaling with power. All of the above scaling was consistent with many other experiments and will be further discussed later in the letter.

[5] Figure 3 presents a summary of measurements obtained during the period of Oct. 14–23, 2009, when the HAARP heater operated at 2.75 MHz, X-mode, 3.6 MW, and on-off power modulation cycles at frequencies from 12 Hz to 20 kHz. Figure 3a shows the fluxgate magnetometer trace onsite HAARP during the experiment period. One can see that there was very weak electrojet activity ($\ll$50 nT) during the entire 10/14–10/22 period and moderate to strong electrojet activity during 10/22–10/23. Experiments were performed for approximately 5 hours daily for a total of 51 hours. While ELF signals below 50 Hz were recorded at all times, significant VLF signals were recorded only on 10/22 and 10/23 for approximately 6 hours and were correlated with occurrence of strong electrojet activity. The ICD vs. PEJ operating periods can be clearly distinguished in a diagram that plots the ratio of the ELF amplitude over the electrojet proxy test signal at 2.02 kHz taken at the time of the ELF measurement vs. the synchronously measured 2.02 kHz amplitude shown in Figure 3b. One can see that the data are organized in a step-like fashion; a vertical strip for values of the 2.02 kHz amplitude smaller than .2 pT that corresponds to the extremely weak or no electrojet during the Oct. 14–21 period on the upper left corner and a horizontal strip for values of 2.02 kHz amplitude larger than .2 pT that marks the presence of an electrojet current during Oct. 22–23, on the lower right corner. The latter behavior is consistent with the well-known amplitude vs. frequency scaling for PEJ generated waves measured both at HAARP and EISCAT [*Rietveld et al.*, 1987, 1989; *Papadopoulos et al.*, 2005]. Figures 3c and 3d compare the temporal waveforms measured on the ground for ICD and PEJ correspondingly at a frequency 32 Hz and at the times marked as (c) and (d) in Figure 3a. They are time-averaged waveforms over many cycles, constructed by averaging over time series of magnetometer measurements made at 48 kHz sample rate and adjustment for DC bias. The left half before the red vertical line corresponds to heater ON, while the right half to heater OFF. The PEJ waveform (Figure 3d) exhibits a major overshoot with a value of 3 pT at about 0.6–0.7 msec while the average amplitude is approximately .8 pT. This PEJ behavior has been previously observed [*Rietveld et al.*, 1987; *Papadopoulos et al.*, 2005] and attributed to the electron temperature saturation for D/E region heating with a timescale of approximately .2 msec. The additional time of approximately .5 msec is due to HF

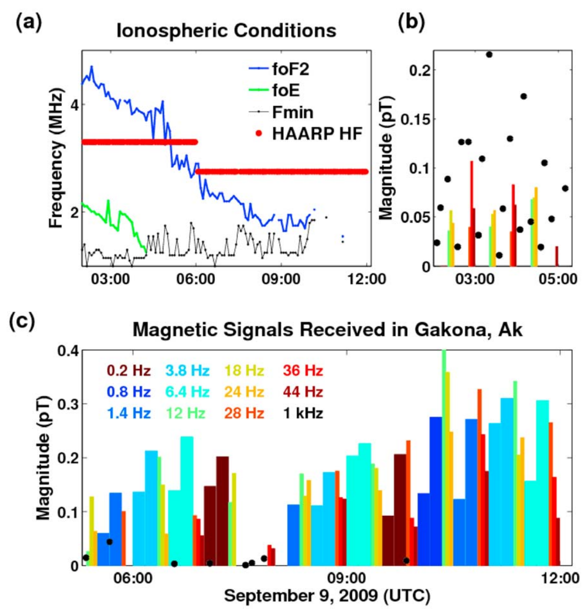

Figure 2. (a) Digisonde parameters foF2 (blue), foE (green), Fmin (black), and HAARP HF (red) on Sep. 9, 2009 02:00–12:00 UT. Notice two events: First the foE decays after 04:30 UT; Second the heating becomes underdense at approximately 05:15. (b) ULF/ELF and 1 kHz test signal (black dot) amplitude at Gakona during 02:00–5:15 UT. (c) Same as Figure 2b but during 05:15–12:00 UT. Notice that during the first period, when there is strong foE layer the 1 kHz signals are dominant, ELF signals moderate to marginal and ULF completely absent. Following the fading of the foE and the beginning of underdense F-region heating the 1 kHz signals disappear while the ULF/ELF signals dominate. We associate the first period with PEJ and the second with ICD Notice also that the amplitude of the ELF triplets (12-18-24 Hz) and (28-36-44 Hz) decreased with increasing frequency indicating a 1/f scaling.

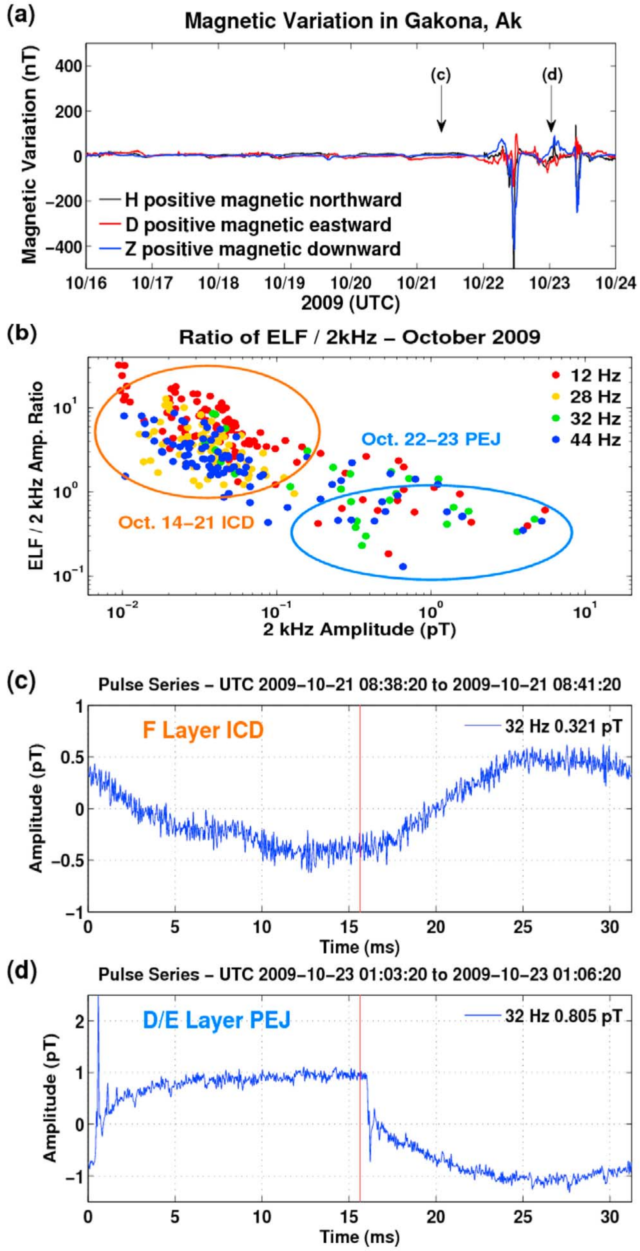

Figure 3. (a) HAARP fluxgate magnetometer traces for the Oct. 14–23, 2009 period. Time dependent magnetic amplitude at various frequencies measured under quiet-day without electrojet currents, 10/14–10/22 and active-day with electrojet currents 10/23–10/24. (b) Plot of the ratio of the ELF to the test 2.02 kHz amplitude vs. the synchronously measured 2.02 kHz amplitude results in a step like diagram with ICD generation points concentrated in the upper left corner (orange circle) and PEJ in the lower right corner (blue circle). (c) Temporal waveforms of NS magnetic signals at 32 Hz recorded on the ground during no electrojet period [taken at the arrow marked (c) in Figure 3a]. (d) Same as in Figure 3c for disturbed day D/E region PEJ case [taken at the arrow marked (d) in Figure 3a]. Notice that the waveform exhibits a sharp overshoot at ~ 0.6–0.7 msec after heater turned ON at zero time and OFF at the time marked by the red line. The sharp 3 pT overshoot feature is typical for D/E region heating. Lack of overshoot and reflection features in Figure 3c indicate F-region heating that occurs at much slower time scales.

signal propagation to 75 km and ELF signal propagation to the ground at the speed of light. Ground reflections of the overshoot also appear at subsequent .5 msec time intervals in the waveform. The overshoot reappears at the switch OFF time. Notice that there are no similar overshoots in the ICD waveform of Figure 3c because the temperature saturation time is controlled by F-region heat loss, which is by at least two orders of magnitude slower than the D/E region.

[6] Figure 4 shows key properties of ICD as compared with PEJ. The experiments were conducted between 07:00–08:00 UT on 11/3/10 and focused on amplitude dependence on ELF frequency, HF polarization, and HF power. During this time the magnetometer trace was below 10 nT and the 2 kHz amplitude was below noise indicating complete absence of electrojet currents. Figure 4a indicates very stable ionospheric conditions and under-dense heating during the experimental time. Two significant dependences are evident from Figure 4b. (i) Contrary to PEJ that favors X-mode heating, the ICD amplitude is independent of the polarization of the HF heating wave. (ii) Maximum amplitude occurs at 11 Hz and has 1/f dependence at higher frequencies up to 70 Hz. Similar scaling is evident in numerous tests as well as in the results of Figure 2b. The physics underlying the 1/f behavior is similar to the one that explains the 1/f dependence above approximately 6 kHz for the PEJ case; namely temporal pulse length shorter than the heating time required to reach saturation [*Rietveld et al.*, 1989; *Papadopoulos et al.*, 2005]. Finally Figure 4c shows the relative ELF/ULF amplitude for four frequencies taken at 50% and 100% of HF power, indicating that the amplitude of the ELF/ULF signals scaled linearly with power, similar to the PEJ generation. Similar scaling is show for all ICD measurements.

3. Summary: Implications for Mid and Low Latitude Heaters

[7] We have presented the first experimental evidence for generating currents in the lower ionosphere by HF modulated

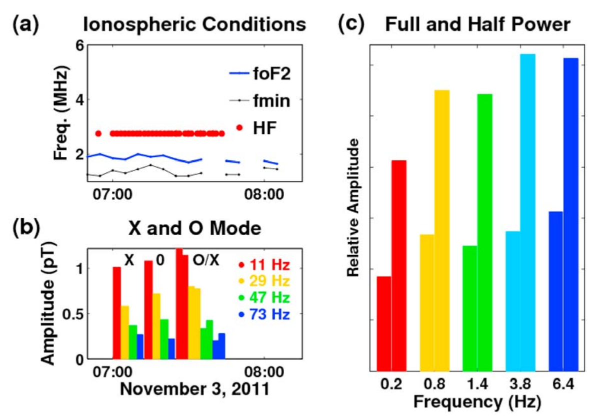

Figure 4. (a) Ionosonde data indicating very stable conditions and under-dense heating. (b) Sequences of X, O, and O/X mode indicating that the ICD amplitude does not depend on the HF polarization. The results also show the 1/f scaling with frequency. (c) Scaling with power for several frequencies indicating ELF amplitude proportional to HF power. The first (second) part of the cycle is taken at 50% (100%) of the power and results in approximately half the signal amplitude.

F-region heating without requiring the presence of electrojet currents for frequencies up to 70 Hz. As discussed above the current drive and the creation of a virtual ELF antenna is accomplished in two steps. First, F-region heating generates a diamagnetic current with a field-aligned magnetic moment. Second, the electric field of the magnetosonic wave radiated by the F region magnetic moment drives a Hall current when it reaches the bottom of the ionosphere. This new technique allows location of modulating HF heaters to sites closer to applications as well as to middle and low latitude regions using the Arecibo and SURA heaters. (Following our suggestion Dr. Kotik reported in the RF Interaction Workshop, April 17–19, 2011 Santa Fe NM, experimental confirmation of ICD using the SURA heater.) The current results provide a natural explanation of the puzzling Arecibo ELF generation experiment of *Ganguly et al.* [1986]. Although the present paper focused on ground measurements the physics described by *Papadopoulos et al.* [2011] and illustrated in Figure 1 predicts that simultaneously with the ELF injection into the ground SA and MS waves will be injected in the magnetosphere and the radiation belts. In fact such waves have been detected by the DEMETER satellite crossing the HAARP magnetic zenith and will be presented elsewhere. It is our intention to test the magnetospheric SA and MS injection using the Arecibo heater currently under construction, complemented by measurements at its conjugate region in Argentina and satellite measurements using the RBSP satellites and the Air Force DSX mission. Application of the ICD concept at Arecibo will allow us for the first time to test wave-particle interactions in the inner radiation belt under controlled conditions.

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