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ELF/VLF wave generation via ionospheric HF heating: Experimental comparison of amplitude modulation, beam painting, and geometric modulation

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[1] Generation of ELF/VLF radio waves (300 Hz to 10 kHz) is achievable via modulation of natural currents in the lower ionosphere with high-power HF (2–10 MHz) heating. Recently, Cohen et al. (2008b) put forth an alternative to conventional amplitude HF power modulation, therein referred to as geometric modulation, in which the HF ionospheric heating beam is geometrically steered at the desired ELF/VLF frequency, and found 7–11 dB enhanced amplitudes, and ~14 dB directional dependence for the thus generated ELF/VLF waves, compared to vertical amplitude modulation. In this paper, we quantitatively compare amplitude modulation, geometric modulation, and a previously proposed technique known as beam painting, wherein the HF beam is rapidly moved over a wide area during the on portion of amplitude modulation in order to create a larger heated region in the ionosphere. We experimentally analyze both the total generation and the directionality, i.e., the suitability of each technique to direct signals along a chosen azimuth. Among the three methods, geometric modulation is found to be uniquely well suited for both goals. We also conduct experiments to investigate two particular physical effects and their role in generation efficacy: that of heat-cool duty cycle and the oblique angle of the HF heating beam. It is found that both duty cycle and the oblique angle of the beam have small but counteracting impacts, consistent with the notion that the primary physical process responsible for generation enhancement in geometric modulation is that of formation of an effective multielement phased array.

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1. Introduction

[2] Radio waves of extremely low frequency (ELF, 300–3000 Hz) and very low frequency (VLF) (3–30 kHz) have for decades been widely studied due to their associations with various geophysical phenomenon (see review by *Barr et al.* [2000]). Because ELF/VLF waves are highly reflected by the ionospheric *D* region, they can be guided by the so-called Earth-ionosphere waveguide to global distances, with attenuation rates of only a few dB/Mm [*Davies*, 1990, p. 389], and have thus emerged as a practical method for long-distance communication, and navigation via phase coherent triangulation [*Swanson*, 1983]. In addition, ELF/VLF waves can propagate via the whistler mode in the magnetosphere, where they can undergo interaction with energetic >1 keV particles in the radiation belts. Although a number of high-power ground based VLF transmitters regularly operate in the 10–30 kHz band (with no directional control), generation below 10 kHz is a significant challenge. The extremely long wavelengths, along with the high conductivity of the Earth at these frequencies, yield an opposite (cancelation) image current well within a wavelength of any physically realizable antenna. Achieving even a ~3% radiation efficiency requires massive structures and unique geography as was shown with the Siple Station ELF/VLF transmitter [*Helliwell and Katsufrakis*, 1974; *Raghuram et al.*, 1974] that consisted of a 33.5 km long horizontal dipole antenna elevated above the conducting Earth by a 2 km thick Antarctic ice sheet.

[3] In recent decades, ELF/VLF waves have been generated via modulated high frequency (HF) (2–10 MHz) heating of the ionospheric *D* and *E* regions (50–100 km altitudes). Due to the temperature-dependent conductivity of the lower ionosphere, radiation at ELF/VLF is generated when the HF heating is modulated at ELF/VLF rates in the presence of natural ionospheric currents. The first observations by *Gemantsev et al.* [1974] were followed by the construction of a number of HF antenna array "ionospheric heater" facilities, in part for quantitative investigation of this process. The ionospheric observatory near Arecibo, Puerto Rico [*Ferraro et al.*, 1982], and the observatory at Jicamarca,

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Peru [*Lunnen et al.*, 1984], were both used to generate weak (<1 fT) ELF signals utilizing the equatorial dynamo current. However, high-latitude facilities utilizing the auroral electrojet have thus far had more success at stronger (>1 pT) ELF/VLF generation. The High-Power Auroral Stimulation (HIPAS) facility near Fairbanks, Alaska, utilizes eight 150 kW transmitter array operating at 2.85 MHz, generating ELF/VLF waves with phase modulation, double-frequency excitation, and amplitude modulation (AM) [*Villaseñor et al.*, 1996]. The EISCAT facility near Tromsø, Norway, has been utilized for a wide variety of ELF/VLF experiments [e.g., *Stubbe et al.*, 1981]. The 1 MW radiated, 200–300 MW effective radiated power (ERP) Tromsø HF heater was typically amplitude modulated with 100% depth square waves at HF frequencies from 2.75 to 8 MHz. Signals were also detected at distances from Tromsø of 550 km [*Barr et al.*, 1986], and 2200 km [*Barr and Stubbe*, 1991].

[4] More recently, the High Frequency Active Auroral Research Program (HAARP) phased array HF facility near Gakona, Alaska (62°22′N, 145°9′W), has been used to generate ELF signals that have been observed at distances along the Earth as far as 4400 km [*Moore et al.*, 2007], as well as injected into the magnetosphere and observed in the geomagnetic conjugate region [*Inan et al.*, 2004; *Gołkowski et al.*, 2008]. The first observations of a saturation mechanism have also been realized [*Moore et al.*, 2006]. In 2007, an upgrade of HAARP was completed, increasing its capacity from 48 active elements, 960 kW input power, and 175 MW ERP (at 3.25 MHz), to 180 active elements, 3.6 MW input power, and ~575 MW ERP (at 3.25 MHz). *Cohen et al.* [2008a] observe that the ELF/VLF amplitudes at distances of ~700 km vary by at least 5–10 dB as a function of direction from HAARP, due at least in large part to an effective dipole orientation resulting primarily from the direction of the electrojet fields.

[5] Although modulated HF heating remains one of the only reliable means for ELF/VLF wave generation, efficiencies are still quite low, on the order of ~0.001% [*Moore et al.*, 2007]. Substantial efforts have been made to maximize resulting signal generation from ELF/VLF modulated HF heating. We focus here on two particular efforts to provide an alternative to conventional amplitude modulation, in which the HF power is modulated in time with no HF beam motion. We review some of these efforts here.

1.1. Continuous HF Heating

[6] Some efforts have been made to generate enhanced ELF/VLF waves with a continuous wave (CW) HF heating process, which has the advantage of injecting more total HF power into the ionosphere compared to amplitude modulated HF (and will therefore produce stronger ELF/VLF signals for the same HF-ELF/VLF conversion efficiency). *Barr et al.* [1987] report an alternating HF beam between two locations in the ionosphere (spending half the ELF/VLF period on each), displaced by a controllable zenith angle. They therefore reported results which resembled two independent ionospheric sources operating 180° out of phase, demonstrated via interferences observed at a distant receiver. *Barr and Stubbe* [1997] report having split the Tromsø HF array into two halves and driving them with two different CW HF frequencies, differing by 565 Hz and 2005 Hz, respectively, but find that this CW method produced ~11 dB weaker signals. However, calculations by *Barr and Stubbe* [1997] suggest that the generation might increase above 2 kHz, specifically in the direction of the array half with a lower HF frequency, though it would decrease in the opposite direction. *Villaseñor et al.* [1996] tried a similar arrangement (referred to therein as double-frequency excitation) and also found weaker signals compared to traditional AM generation below ~2 kHz, but comparable signals at times between ~3 kHz and 14 kHz. This CW technique was also found to be more stable in time than the AM method. *Villaseñor et al.* [1996] also attempted the so-called "demodulation mode," where the beam heated vertically for half the ELF/VLF period, and heated two regions on either side of vertical for the second half of the cycle. The demodulation mode is similar in concept to the two-location technique reported by *Barr et al.* [1987], and signal strengths about half compared to AM are reported therein, measured within 150 km of the HIPAS facility. *Papadopoulos et al.* [1994] and *Borisov et al.* [1996] theoretically describe a coherent sweep, with a source moving along a line at rates close to the phase velocity of propagating waves, in order to generate Cerenkov radiation.

1.2. Beam Painting

[7] *Papadopoulos et al.* [1989, 1990] suggest a so-called "beam painting" technique, where the HF heating beam scans rapidly over a large area during the on portion of the ELF/VLF period, returning to each location before the electrons have cooled. Although still possessing the on-off pattern to the HF power as amplitude modulation, beam painting enables a much larger area of the ionosphere to be heated, potentially enabling stronger ELF/VLF generation, particularly at the lowest frequencies. *Barr et al.* [1999] experimentally determined that beam painting would likely not be effective at the Tromsø facility, as the technique of beam painting requires high-ERP HF heating so that the characteristic heating rates can be much faster than the cooling rates. Also, the Tromsø facility possessed a beam scanning ability along one dimension (first reported by *Rietveld et al.* [1984]) but not rapid enough to fully implement the beam painting technique in two dimensions. It is found that the ERP of the Tromsø heater was not sufficiently high. The upgraded HAARP facility was specifically designed to combine the highest ERP among worldwide HF heating facilities with the ability to very rapidly (i.e., 100 kHz rates) steer the beam over a cone within ~30° of vertical. As such, HAARP is uniquely suited to investigate ELF/VLF wave generation with this beam painting technique.

1.3. Geometric Modulation

[8] *Cohen et al.* [2008b] implement a technique referred to therein as "geometric modulation," which involves the HF beam moving in a geometric pattern at ELF/VLF rates, with no power modulation. The period of traversing the geometric pattern dictates the fundamental ELF/VLF frequency generated, since a given location within the pattern will undergo modulated on-off heating at that rate. Due to the rapid (100 kHz) beam steering rates possible with HAARP, nearly arbitrary geometric patterns are possible. A "circle sweep" (where the HF beam sweeps along a circular pattern at ±15° angle) is found by *Cohen et al.* [2008b] to result in

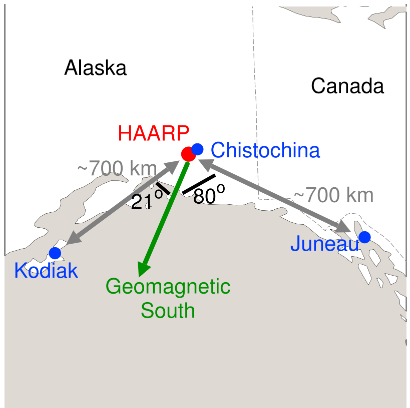

Figure 1. Map showing the HAARP facility and the locations of the three receivers used. The red dot indicates the location of HAARP, near Gakona, Alaska. The blue dots show the locations of the receivers utilized here, in Chistochina (~37 km distance from HAARP), Kodiak, and Juneau (both ~700 km distance from HAARP).

7–11 dB increased signal amplitudes compared to vertically directed amplitude modulation. The "sawtooth sweep" (where the HF beam traverses a line in one direction at ±15° angle over one ELF/VLF period) is found to have a ~14 dB amplitude difference between a sawtooth sweep azimuth oriented toward, or orthogonal to, a receiver path (measured at ~700 km distance from HAARP). On the other hand, changing the sense of rotation of the circle sweep had little or no impact on the observed amplitudes.

[9] *Cohen et al.* [2008b] conclude that the amplitudes and directionality associated with geometric modulation are due at least in some part to the effective creation of an ELF/VLF phased array, i.e., a generalized extension of the two-element array demonstrated by *Barr et al.* [1987]. *Barr et al.* [1988] also show that an oblique AM HF beam acts somewhat as a directional array, due largely to the varying propagation delays of the HF waves from ground to ionosphere, albeit one without the experimental control inherent to geometric modulation. In this paper, we report the first direct comparison between amplitude modulation, beam painting, and geometric modulation.

2. Experimental Setup

[10] ELF/VLF data are taken with the Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME) receiver, which is described in detail by *Cohen et al.* [2010]. The AWESOME receivers consist of two orthogonal air core loop antennas, sensitive to the horizontal magnetic field between ~0.3 and 47 kHz. A third channel, which can be used for the vertical component of either the magnetic field or electric field, is not utilized in these observations. Data are sampled at 16 bits at 100 kHz, and synchronized to GPS and provide <100 ns absolute timing accuracy. Receiver noise levels vary depending on antenna size and frequency but are in the range of ~0.001 pT per $\sqrt{Hz}$ in the passband. Calibration is performed by injection of a signal reference into the front end of the receiver, which enables the recorded digital values to be directly related to magnetic field values at all frequencies. The data can be rotated in post processing, so that the magnetic field can be obtained both in the radial direction (parallel to the source-to-receiver path), and the azimuthal direction (orthogonal).

[11] Figure 1 shows a map with the three receiver locations utilized in this work: Chistochina (62.62°N, −144.62°W, 37 km from HAARP), Juneau (58.59°N, 134.90°W, 704 km from HAARP), and Kodiak (57.87°N, 152.88°W, 661 km from HAARP). Chistochina is located near to the HAARP facility, while Juneau and Kodiak are located in roughly orthogonal directions from HAARP, but at similar distances.

[12] In designing an experiment to compare various modulation techniques, it is important to take into account the rapidly varying natural generation conditions (namely, the auroral electrojet strength and direction, and the ionospheric density profile), which can drastically change the generated amplitudes by as much as 40 dB on the order of tens of seconds (although at other times they can remain remarkably steady), and can additionally be radically different from day to day. To compare the effect of various modulation techniques, we transmit a series of tones at several different frequencies for each technique. The tones are typically only a few seconds long to minimize the effect of naturally changing conditions, while still allowing unambiguous detection in the receivers.

[13] To further mitigate changing conditions, and to enable meaningful long-term averages, the transmission format is repeated for long periods (typically an hour or more), after which the following averaging technique is applied (also utilized by *Cohen et al.* [2008b]). For each received single-frequency tone, the complex phasor amplitudes of both the radial and azimuthal magnetic fields are calculated by integrating the demodulated data in the baseband over the duration of the tone. The phasors over the many repetitions of the format can then be averaged, separately for the radial and azimuthal fields, and the final results then summed in quadrature.

[14] Averaging the signals in complex phasor form instead of just their amplitudes has the advantage of significantly improving signal-to-noise (SNR) ratio. When averaging a large number of complex phasors, incoherent noise destructively interferes, whereas coherent signals with the same phase add constructively, thereby enabling detection of weaker signals. The same process can then be repeated at neighboring frequencies without HAARP transmissions, to determine comparative noise levels (and therefore the uncertainties via the SNR). We note that if this technique is applied during periods when the polarization or phase of the received signals change substantially over time (for instance, when the ionospheric conditions or auroral electrojet orientation change), the averaged phasor values may not accurately represent the average signal amplitudes, since the signals would not maintain constant complex phase. We therefore repeat this experiment on multiple days, to confirm that the comparative results shown here hold consistently, although only one representative example is shown here.

[15] All HF heating experiments described here are carried out with X-mode heating at 2.75 MHz or 3.25 MHz, the lowest HF frequencies available with HAARP, and also those that have been observed to produce the strongest ELF/

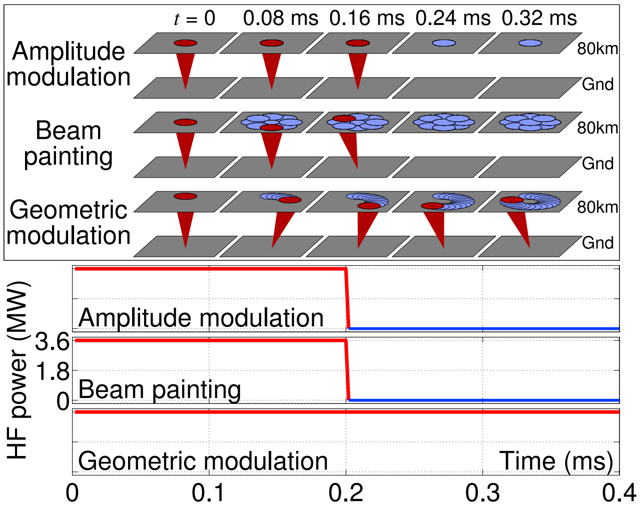

Figure 2. Schematic comparison of amplitude modulation, beam painting, and geometric modulation. (top) The progression of the HF beam at five points within the ELF/VLF cycle (assuming 2.5 kHz, so the total ELF/VLF period is 4 ms). (bottom) The HF power as a function of time. The beam is stationary for amplitude modulation and goes off for the second half of the period. Beam painting shows the same amplitude modulation but also involves beam motion within the on portion of the ELF/VLF cycle. Finally, geometric modulation involves no power modulation but instead a slower sweep of the signal along a geometric shape, in this case a circle.

VLF amplitudes on the ground (due to higher absorption in the *D* region). The ERPs at these frequencies are ~420 MW and ~575 MW, respectively.

[16] The geometric modulation and beam painting experiments involve changing the phase of the HF signal radiating from each antenna element, in order to change the HF beam's direction at each of the many discrete steps. In principle, this may effect the beam shape at these steps and thereby affect the comparison between geometric modulation, beam painting, and amplitude modulation. Though not shown here, it is observed with an HF receiver at the HAARP facility that the antenna array undergoes a transition period, a few μs long, at each step of the beam motion. During this period, the beam location may slew back and forth slightly, however the shape of the HF beam and its side lobes remain largely intact, with the ERP likely not reduced by any more than 1 dB. Hence, the transition period between each beam steps likely has a small, if any, impact on the HF power densities delivered to the ionosphere, as compared to amplitude modulation with a stationary beam.

3. Modulation Schemes

[17] We utilize three techniques of modulated HF heating: amplitude modulation, beam painting, and geometric modulation. Figure 2 schematically shows how the HF beam evolves over the ELF/VLF period (at 2.5 kHz, or 0.4 ms period) for each of the three techniques. In Figure 2 (top), the three rows correspond to amplitude modulation, beam painting, and geometric modulation, with the row showing the position of the beam (or no beam if HF power is off) at five points in the ELF/VLF period. The HF energy can be seen to begin at the ground, reach the ionosphere, and heat a region of the ionosphere shown in red. The light blue elliptical regions represent where the beam had previously heated during the ELF/VLF cycle. Animation 1 shows the animation of the beam motions for each technique over 80 frames.[1]

[18] In amplitude modulation, the HF beam orientation is kept constant during the experiment, but the HF power is multiplied by an envelope function (in this case, a square wave with 50% duty cycle) at the desired ELF/VLF frequency. During beam painting, the HF power is also multiplied by a square wave envelope function, but the beam is additionally steered very rapidly (i.e., 10 μs dwell times) between a number of locations during the on portion of the ELF/VLF period. For geometric modulation, the HF power is left on continuously, but the beam is slowly (i.e., in 40 steps) swept along a geometric pattern, so that the geometric pattern is traversed in one ELF/VLF period.

[19] For each of the three techniques, we utilize either an axially symmetric implementation (where the beam locations do not favor a particular direction) or a directed implementation (where the beam locations are arranged so as to favor a particular direction), as shown in Figure 3. For AM, the HF beam can be directed vertically (symmetric, referred to here as "vertical AM") or at an oblique angle along some azimuth (directed, referred to here as "oblique AM"). The beam paint locations may be organized with 9 points to fill a grid area (symmetric, referred to here as "grid paint"), or a 3-point paint to illuminate an azimuthal line (directed, referred to here as "line paint"). The geometric modulation pattern may be a circle (symmetric, referred to here as circle sweep), or a line traversed in only one direction (directed, referred to here as sawtooth sweep).

[20] The axially symmetric implementations are useful for understanding the total wave generation achieved with a particular format, since those implementations do not have an intrinsic directionality, and thus can be more directly compared to vertical AM. The directed implementation is useful for characterizing the directionality of the modulation technique, which can be inferred by varying the azimuth chosen. The HAARP array capabilities enable beam locations within ±15° angular region to be included in these formats, so that this specification dictates the radius and length of the geometric modulation sweeps and the spacing of the beam paint locations.

[21] A comparison between beam painting and geometric modulation is of particular interest, since the techniques illuminate an area of the ionosphere of roughly the same size, whereas amplitude modulation illuminates a smaller region corresponding to a single beam width. However, an important differentiating characteristic between geometric modulation and beam painting is that for the latter, the heated region of the ionosphere radiates ELF/VLF roughly in phase, whereas for geometric modulation, the slower scanning dictates a progressive phase. For instance, the elements on oppo-

[1] Animation 1 is available in the HTML.

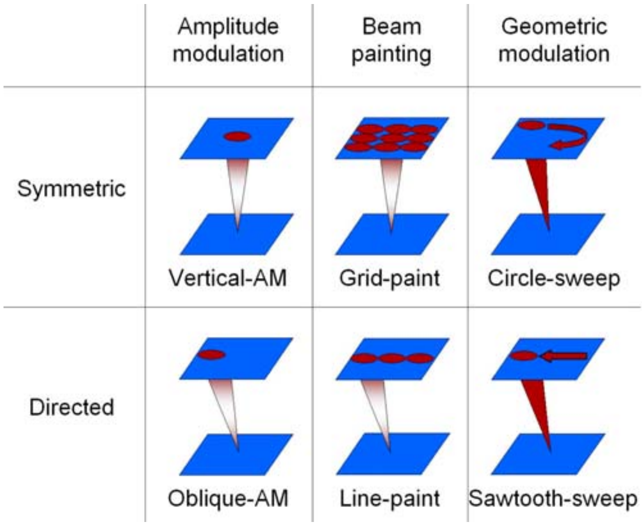

Figure 3. Classification of modulation techniques. We implement each amplitude modulation, beam painting, and geometric modulation technique in a symmetric fashion and a directed fashion and designate a reference name for each of the six types.

site sides of the circle illuminated by the circle sweep radiate ELF/VLF roughly 180° out of phase.

4. Comparative Frequency Responses

[22] A single experiment which quantitatively compared the above six modulation schemes was conducted on 16 March 2008, between 1300 UT and 1600 UT. Figure 4 shows the magnetic field amplitude as a function of frequency for each of the three modulation techniques (geometric modulation, beam painting, and amplitude modulation, shown in green, blue and red, respectively). Each technique is implemented in symmetric form (Figure 4, top) and directed form (directed to Juneau (Figure 4, middle) and Kodiak (Figure 4, bottom)). The observed fields with error bars calculated as discussed above are shown at Chistochina (Figure 4, left), Juneau (Figure 4, middle), and Kodiak (Figure 4, right), although the error bars at Chistochina are too small to be visible. We note again that since Juneau and Kodiak are at close to orthogonal azimuths from HAARP, they sense nearly orthogonal elements of the radiation pattern from the HAARP ELF/VLF ionospheric source region. The locations of the receivers in Alaska, with respect the HAARP, are shown in the map in the bottom left panel of Figure 4. The observations of

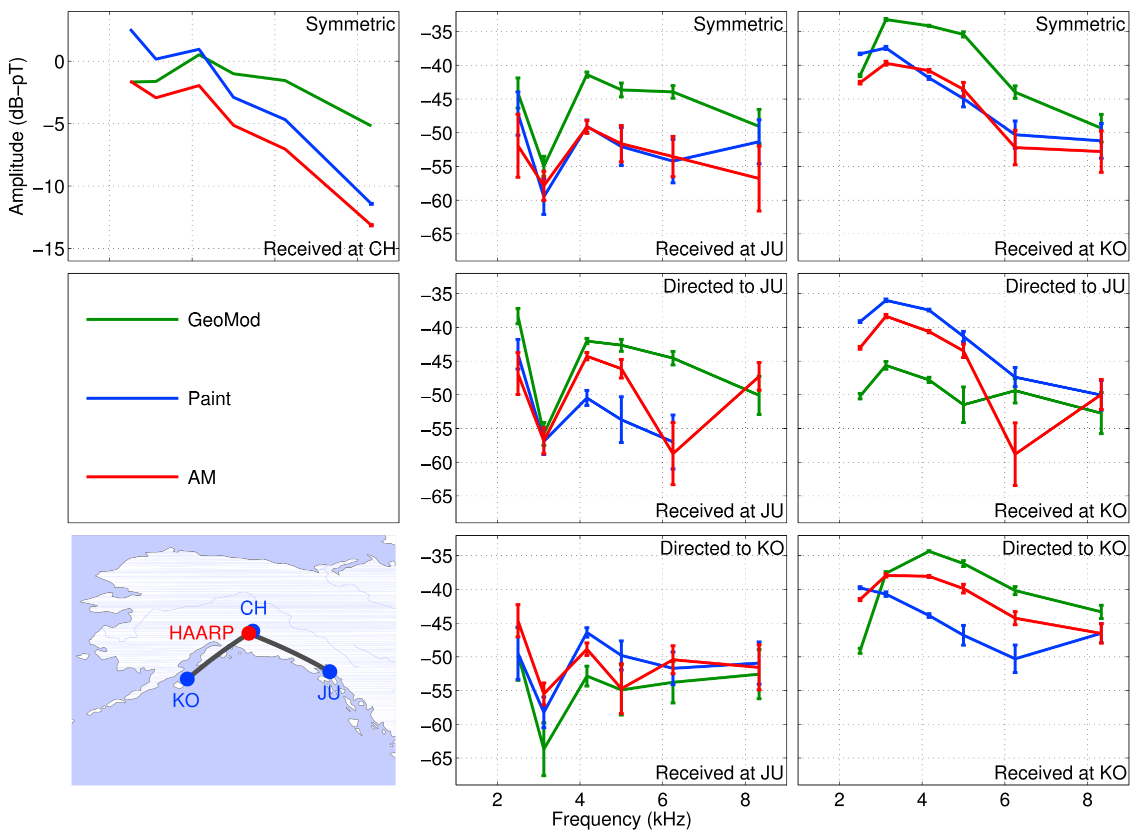

Figure 4. Observed frequency response. The ELF/VLF signal amplitude as a function of ELF/VLF frequency for geometric modulation (green), beam painting (blue), and amplitude modulation (red). We show the signal at each of the three receivers ((left) Chistochina, (middle) Juneau, and (right) Kodiak) and implement each in both (top) a symmetric form and a directed form to both (middle) Juneau and (bottom) Kodiak.

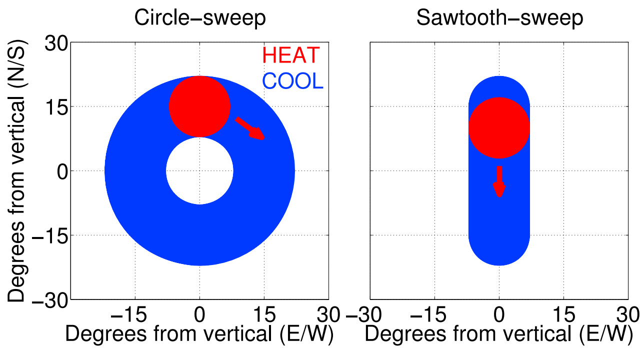

Figure 5. The area illuminated by (left) the geometric modulation format circle sweep and (right) the north-to-south sawtooth sweep. The red spot shows the 3 dB beam width (where heating occurs), which moves in the direction of the arrow. The blue patch shows the shape of the rest of the illuminated region (where the cooling occurs).

signals near the HAARP facility (at Chistochina) reveal the following.

[23] 1. The grid paint (the symmetric implementation of beam painting) yields signals ~2 dB stronger and ~4 dB stronger than vertical AM at 2.5 kHz and 8.3 kHz, respectively.

[24] 2. The circle sweep (the symmetric implementation of geometric modulation) yields nearly the same amplitudes as vertical AM at 2.5 kHz but yields ~8 dB stronger signals at 8.3 kHz.

[25] However, at longer distances from HAARP, the behavior of the received amplitudes is different. In particular, the observed signals at Juneau or Kodiak, (~700 km away) are as follows.

[26] 1. The grid paint yields little or no measurable enhancement in amplitude compared to vertical AM.

[27] 2. The circle sweep yields 7–11 dB stronger signals compared to vertical AM (and to grid paint). This is consistent with the observations of *Cohen et al.* [2008b], although the experiments here were run on a different day.

[28] 3. Changing the azimuth of the line paint between directed to Kodiak and directed to Juneau affects the received ELF/VLF amplitudes by 4–6 dB, at least above ~3 kHz where error bars are sufficiently small. In particular, directing the line paint azimuth toward Kodiak generates stronger signals at Juneau, and vice versa, so that the line paint generates directionality orthogonal to its azimuth.

[29] 4. Changing the azimuth of the sawtooth sweep between directed to Kodiak and directed to Juneau affects the received ELF/VLF amplitudes by 11–15 dB, at least above ~3 kHz where error bars are sufficiently small. In particular, directing the sawtooth sweep toward Kodiak generates stronger signals at Kodiak, and vice versa, so the sawtooth sweep generates directionality parallel to its azimuth. This is consistent with the observations of *Cohen et al.* [2008b], although the experiments here were run on different days.

[30] 5. Comparison between the circle sweep and oblique AM directed to either Juneau or Kodiak indicates that the circle sweep yields 2–6 dB stronger signals at that receiver, particularly in the frequency range between 3 and 6 kHz. Similarly, comparison between the sawtooth sweep directed to either Juneau or Kodiak and oblique AM directed to the same receiver indicates that the sawtooth sweep yields 2–6 dB stronger signals at that receiver, particularly in the frequency range above 4 kHz, at least as high as 8 kHz. Hence, the geometric modulation appears to produce at least some amplitude gains at a distant receiver that cannot be explained strictly by the tilted beam nature.

[31] There are also consistent features to the frequency response of all the formats, like the null at 3 kHz observable at Juneau on all forms of modulation. The more general frequency response of ELF/VLF wave generation via ionospheric heating is a function of ionospheric conditions, both above HAARP, and along the propagation path to the receiver, both of which vary greatly in time. More complete discussions of this behavior can be found in other works.

[32] It is worth noting that the behavior at the nearby sites is substantially different at the nearby site (Chistochina) compared to the more distant sites (Juneau and Kodiak). In particular, the relative advantage of the geometric modulation schemes are not apparent when near to HAARP. This observation likely arises from the phased nature of geometric modulation. For instance, since opposite sides of the circle sweep radiate ELF/VLF out of phase from each other, the radiation from the circle sweep would produce a null at the center, if its elements were all ideal point sources. The lack of a complete null at Chistochina is likely due to nonidealities of the sources, namely, the finite size of the HF beam, and the effects of its side lobes. Chistochina is also displaced from the center of the circle by ~37 km.

5. Physical Mechanisms

[33] We now discuss the role of two physical mechanisms that may distinguish geometric modulation from the conventional AM technique: Heat-cool duty cycle, and phasing from oblique heating. Relative degrees to which these two mechanisms impact the observations of geometric modulation could be important in the application of geometric modulation in the context of other HF arrays (for instance, one at the geomagnetic equator), or for different HF frequencies. We therefore separately discuss the role of each.

5.1. Duty Cycle

[34] Duty cycle refers to the fraction of the ELF/VLF period during which heating occurs, as opposed to cooling. In the amplitude modulation experiments conducted here, the on portion (heating) of the ELF/VLF period corresponded to 50% of the ELF/VLF period. However, due to the continuous-heating nature of geometric modulation, the fraction of the ELF/VLF period during which heating occurs at a given location is not the same, and is not arbitrarily controllable. Rather, the duty cycle is more generally set by the ratio of the area of the heated region to the total area illuminated during the geometric modulation format. Figure 5 shows a schematic of the size of the beam (red) where heating is occurring and the area covered by the rest of the beam motion (blue), where electron in cooling occurs, for both the circle sweep (Figure 5, left) and the sawtooth sweep. For instance, at 3.25 MHz, the 3 dB width of the HF heating beam is ~15.8° and ~12.7° in the two directions, respectively, or

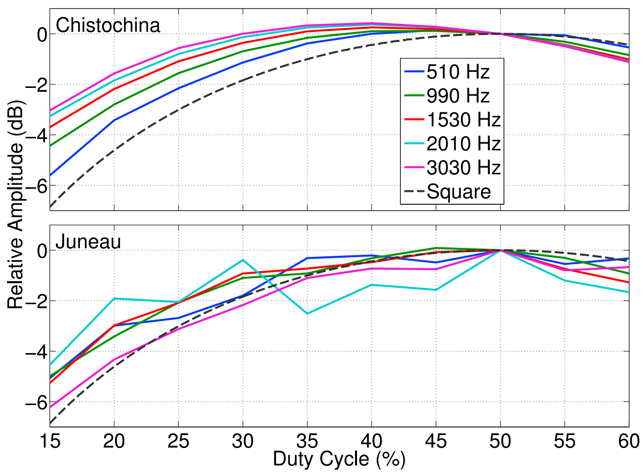

Figure 6. The ELF/VLF amplitude received at (top) Chistochina and (bottom) Juneau, shown as a function of the duty cycle for square wave amplitude modulated HF heating. We show separate curves for five different frequencies. The dashed line shows the amplitude of the first harmonic that would result from a square wave with varying duty cycle.

~360 km^2. The total area covered by the beam if circled at a 15° angle from vertical is ~3000 km^2, so the average duty cycle is ~12%. For the sawtooth sweep, the total area covered by the beam is ~1360 km^2, so the average duty cycle is ~26%. For most amplitude modulation experiments run previously with square wave modulation (as opposed to sinusoidal modulation), however, the duty cycle has been 50%, to maximize the harmonic content of the fundamental frequency.

[35] To distinguish the importance of the substantially different duty cycle intrinsic to geometric modulation, we conduct an experiment in which the duty cycle of AM heating is varied between 15% and 60%, at several different ELF frequencies. The HF beam is square wave amplitude modulated and directed vertically. ELF/VLF signals received at the nearby Chistochina receiver. These data are presented in Figure 6, for five different ELF/VLF frequencies, observed at both the Chistochina and Juneau receivers. The analytical harmonic content of a square wave with varying duty cycle is also shown with a dashed line (which would be the expected result if the ionosphere responded much faster than ELF/VLF time scales). The data from the two locations demonstrate similar results, although the Juneau receiver detects the signals with lower SNR as a result of the ~700 km distance from HAARP to Juneau, so the differing characteristics between the ELF frequencies are not as reliable there as the Chistochina observations.

[36] For all ELF/VLF frequencies shown in Figure 6, the peak amplitude occurs for duty cycles between 30% and 50%. These results can be explained in the context of the ionospheric response to heating, and recovery back to ambient conditions. Earlier workers [*Rietveld et al.*, 1986; *Barr et al.*, 1999] have approximated the ionospheric changes as resembling an exponential approach toward a steady state value (for heating) or ambient value (for cooling) with characteristic heating and cooling time constants, and these past studies have been able to empirically determine these time constants with ELF/VLF data generated with HF heating of the ionosphere.

[37] If the ionospheric temporal response is considered as such, then a duty cycle below 50% would be more effective at maximizing the amplitude if the cooling time constant were substantially longer than the heating time constant, since the HF beam need not waste time heating the electrons beyond steady state, but does need to allow time for the electron temperatures to return closer to the ambient values. Hence, in these experiments, the cooling rate appears to be significantly longer than the heating rate, which is the main condition under which beam painting is proposed to be effective.

[38] The optimal duty cycle also decreases with increasing ELF/VLF frequency, where the off times are too short to allow sufficient recovery of ionospheric electron temperatures On the other hand, at the lowest frequency, 510 Hz, the temporal evolution of the electron temperatures most resembles a square wave (shown in gray), since the on and off durations are the longest (compared to the characteristic heating and cooling time constants).

[39] We are particularly interested in the role of the reduced duty cycle in the observations presented earlier. Although duty cycle variations between 30% and 55% are associated with only small (i.e., <1.5 dB) changes in the received ELF/VLF amplitude at Chistochina, duty cycles substantially lower (i.e., <20%) result in a 2–6 dB loss in the received amplitude, with the loss being smaller at the highest ELF/VLF frequencies. At Juneau, however, the frequency dependence of the duty cycle variation does not appear to be present, and the amplitude losses at 15% duty cycle is ~4–6 dB. Therefore, for the 3.25 MHz circle sweep, where the duty cycle is only ~12%, generation strength may be adversely affected by the lower duty cycles, particularly at the lowest ELF/VLF frequencies or when detected at more distance receivers. This frequency-dependent loss from lower duty cycle is similar to the frequency dependence observed by *Cohen et al.* [2008b] where geometric modulation becomes increasingly more effective (compared to vertical AM) above 3 kHz.

5.2. Phasing From Oblique Heating

[40] The effect of phasing from oblique heating is explored by *Barr et al.* [1988]. When the beam is tilted at an angle from vertical, the finite extent of the beam results in a propagation delay to a given altitude being shorter for the component of the HF beam closest to vertical than that furthest from vertical. As such, the HF heating at the outer parts of the beam begins slightly later than the inner parts. The resulting phase gradient appearing across the heated region causes the radiation to be directed toward the beam tilt. *Moore and Rietveld* [2009] suggest that the observations by *Cohen et al.* [2008b] may possibly be attributed in large part to the tilted beam nature inherent to geometric modulation. On the other hand, *Cohen et al.* [2009] suggest that this effect more likely responsible for only a small portion of the amplitude enhancement and directionality associated with geometric modulation.

[41] To experimentally determine the effect of phasing from oblique heating with HAARP, we tilt the beam at an angle of 15°, and separately measure the received signal

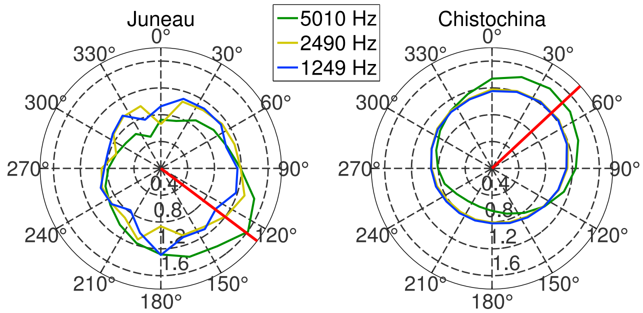

Figure 7. The amplitude received at (left) Juneau and (right) Chistochina as the azimuth of the beam is steered in a circle. The red line indicates the direction to the receiver from HAARP. At each azimuth, the beam is tilted 15° from vertical and is amplitude modulated. The plots show the received signal strengths at 3 ELF/VLF frequencies.

with this tilt at different azimuths around the circle (in 18° increments). We note that ±15° is currently the largest angle over which HAARP can perform geometric modulation (or other rapid beam motion experiments), although the HF beam can be more generally steered over a 30° angle from vertical. For this reason, AM with a ±15° oblique tilting is helpful in addressing the role that this phase gradient plays in the 7–11 dB amplitude gain compared to vertical AM, and 11–15 dB directionality, observed by *Cohen et al.* [2008b] and confirmed here.

[42] In the absence of receivers at all azimuths in a circle surrounding HAARP, we effectively rotate the source region in order to derive the directional radiation pattern of oblique heating based on observations at a single receiver site. We once again measure the signals both at the nearby Chistochina receiver, and the more distant Juneau receiver. Figure 7 shows plots of the amplitudes received, as a function of the azimuth of the off-vertical tilt. The red line indicates the direction toward the receiver. A ~3–4 dB enhancement in the amplitude is observed when the AM beam is directed toward the receiver. It should be noted, however, that the amplitude enhancement observed at Chistochina (unlike that at Juneau) is largely a function of proximity to the heated region, which changes noticeably with azimuth of the oblique heating angle. The observations at Juneau are consistent with the amplitude observations of *Barr et al.* [1988], despite the somewhat different HF array properties between HAARP and the Tromsø heater. This difference is small compared to the 7–11 dB enhancement (compared to vertical AM), and 11–15 dB azimuthal dependence, observed in association with the circle sweep and sawtooth sweep, respectively.

[43] In addition, the enhancement at Juneau from phasing from oblique heating is strongest at the highest ELF/VLF frequencies, consistent with the explanation of *Barr et al.* [1988] that a phase gradient across the heated region results from the propagation delays of the HF signal to the ionosphere. At the highest frequencies, the difference in speed-of-light propagation time between vertical propagation to 80 km altitude, and propagation at 30° oblique angle, is ~0.04 ms. At 5 kHz, this difference begins to approach a significant fraction of the 0.2 ms period. An alternative explanation is that the horizontal extent of the heated region begins to approach the ELF wavelength (60 km at 5 kHz).

[44] The magnitude of the amplitude changes associated with the phasing from oblique heating is roughly equal and opposite to the size and frequency dependence of the amplitude changes associated with a low (<20%) duty cycle, if not a few dB smaller. For this reason, the adverse impact of the low duty cycle present in the circle sweep appears to be at least compensated by the enhancement resulting from the phasing from oblique heating. Furthermore, changing the angle of tilt (i.e., the radius of the circle sweep) reduces the effect of both. While the duty cycle increases with a smaller tilt angle, closer to 50%, the effect of the oblique tilting is also reduced.

[45] We also note that although the 15° oblique angle tilt enables a more direct comparison with geometric modulation, the current hardware limitations of HAARP actually allow oblique AM heating at up to 30° from vertical, whereas geometric modulation and beam painting is currently restricted to a ±15° cone from a given location. It is possible, however, to conduct geometric modulation and beam painting experiments with the center point located 15° off vertical (whereas in this paper the center point is strictly vertical. Such a strategy may capture additional directionality and amplitude gains. For example, a future experiment may compare oblique AM HF heating at 30° from vertical with a circle sweep in which the center of the circle is inclined by 15° from vertical.

6. An ELF/VLF Phased Array

[46] Since the effect of duty cycle and phasing from oblique heating appear to be small and counteracting, these experiments appear to be consistent with the notion that geometric modulation is able to produce stronger and directable signals in significant part due to the effective creation of a large-element ELF/VLF phased array. Individual beam locations create separate and independently radiating regions, whose phases can be controlled by the order in which those regions are heated, as discussed by *Cohen et al.* [2008b, 2009].

[47] Geometric modulation and beam painting share two important features: that the region of the ionosphere heated by the HF beam is substantially larger than that of either vertical or oblique amplitude modulation, and that the beam motion invariably involves heating with a beam that is off vertical. Despite this feature, the two techniques act quite differently from each other, in that the amplitude enhancement associated with beam painting appear to be present only near to HAARP, whereas that of geometric modulation is observable also at larger distances. Additionally, the directionality inherent in the sawtooth sweep is opposite to that of the line paint, in that it directs radiation along its azimuth, rather than orthogonal.

[48] The reason for these differences likely arises from the fact that the radiating ionosphere associated with the sawtooth sweep and the line paint may be characterized as line sources [e.g., *Stutzman and Thiele*, 1998, chapter 4], or an array of point sources aligned along an azimuth. The line paint acts as a broadside antenna, since there is no phase shift along the line source [e.g., *Stutzman and Thiele*,

1998, p. 37]. However, the sawtooth sweep has an associated phase shift of ~8.7° per km, since the total phase shift along the line is 360°, and the length of the sawtooth sweep at ±15° is ~43 km at an altitude of 80 km. The sawtooth sweep, acts in a manner than tends toward an end-fire antenna array. The 43 km length corresponds to a free-space wavelength at ~7 kHz, so near this frequency, the sawtooth sweep likely acts closest to an ideal end-fire array.

[49] At 7 kHz, the horizontal motion of the beam in the sawtooth sweep will also closely match phase velocities of propagating waves in the Earth-ionosphere waveguide (which are close to the speed of light, particularly for the lower-order modes). This is another way of saying that the phase of a propagating wave in the Earth-ionosphere waveguide in the direction of the sawtooth sweep will show the same spatial phase variation as the radiating ELF/VLF from the sawtooth sweep, which is ideal for producing Cerenkov radiation as suggested by *Borisov et al.* [1996]. At the lower frequencies, the phase variations do not line up, because the HF beam moves slower than the speed of light. This may also explain in part why geometric modulation appears to provide a smaller advantage compared to vertical AM at the lower frequencies we consider.

[50] Furthermore, in point 5 in the experimental comparison above, the frequency range where the sawtooth sweep provides an advantage compared to oblique AM is upshifted compared to the frequencies where the circle sweep provides an advantage over oblique AM, which may be due in part to the speed of the ELF/VLF source as compared to the speed of light. In particular, the ELF/VLF source moves at a faster spatial rate for the circle sweep than it does for the sawtooth sweep at the same ELF/VLF frequency, since the circumference of the circle is longer than the length of the sawtooth sweep. Hence, the speed of the source in the circle sweep matches the speed of light at a lower ELF/VLF frequency as compared to the sawtooth sweep.

[51] It is important to note that unlike the line paint, the phases of the ionospheric sources of geometric modulation can be more generally controlled by the sequential order in which the HF beam heats the ionosphere, which dictates the relative phases of each beam location. In essence, the end result is a much larger extension of the two-element array reported by *Barr et al.* [1987]. *Cohen et al.* [2008b] therefore suggest that geometric modulation effectively creates a controllable large-element ELF/VLF phased array, and that this feature at least in part accounts for the amplitude enhancement and directionality associated with geometric modulation.

[52] In practice, however, it is impossible to control the phase of an infinite number of locations, because the finite size of the HF beam limits the spatial resolution of the phased radiating ionosphere, and the finite area it covers essentially limits the number of elements. For instance, the size of the beam at 3.25 MHz is ~360 km^2 at 80 km altitude, but the total area of the ionosphere covered during the 15° circle sweep is ~3000 km^2, or ~8 times larger. So with the 3.25 MHz beam at HAARP implementing a circle sweep, the maximum number of beam spots which can be independently controlled is ~8, since a larger number of locations will require that they overlap, in which case they cannot be independently controlled. Similarly, the sawtooth sweep at 3.25 MHz allows ~4 independent beam spots.

7. Conclusion

[53] We have conducted the first direct experimental comparison between amplitude modulation, beam painting, and geometric modulation, for ELF/VLF wave generation via ionospheric HF heating. We have implemented all three of these techniques in a form to both preserve azimuthal symmetry, and to generate a directionally controlled signal, utilizing beam tilting up to 15° from vertical. Beam painting, utilizing HF beam motion to widen the region of the ionosphere undergoing heating, provides stronger ELF/VLF signals (compared to vertical AM) nearby to HAARP, but less so at farther distances. On the other hand, geometric modulation provides about an order of magnitude higher ELF/VLF powers, particularly when measured at further distances from HAARP. Geometric modulation also generates a level of directionality (11–15 dB) that is matched by neither beam painting nor oblique AM heating.

[54] We have also separately investigated the role of two particular physical effects which are embedded in the technique of geometric modulation by virtue of the finite size of the HF beam. However, the impacts of heat-cool duty cycle and of oblique HF heating appear to be small and counteracting. We have then separately analyzed the radiating ionospheric region associated with geometric modulation in the context of a phased array of sources.

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References

Barr, R., and P. Stubbe (1991), ELF radiation from the Tromsø "super heater" facility, *Geophys. Res. Lett.*, *18*(6), 1035–1038.

Barr, R., and P. Stubbe (1997), ELF and VLF wave generation by HF heating: A comparison of AM and CW techniques, *J. Atmos. Sol. Terr. Phys.*, *18*, 2265–2279.

Barr, R., P. Stubbe, M. Rietveld, and H. Kopka (1986), ELF and VLF signals radiated by the "polar electrojet antenna": Experimental results, *J. Geophys. Res.*, *91*(A4), 4451–4459.

Barr, R., M. T. Rietveld, P. Stubbe, and H. Kopka (1987), Ionospheric heater beam scanning: A mobile source of ELF radiation, *Radio Sci.*, *22*(6), 1076–1083.

Barr, R., M. Rietveld, P. Stubbe, and H. Kopka (1988), Ionospheric heater beam scanning: A realistic model of this mobile source of ELF/VLF radiation, *Radio Sci.*, *23*(3), 379–388.

Barr, R., P. Stubbe, and M. T. Rietveld (1999), ELF wave generation in the ionosphere using pulse modulated HF heating: Initial tests of a technique for increasing ELF wave generation efficiency, *Ann. Geophys.*, *17*, 759–769.

Barr, R., D. Llanwyn Jones, and C. J. Rodger (2000), ELF and VLF radio waves, *J. Atmos. Sol. Terr. Phys.*, *62*, 1689–1718.

Borisov, N., A. Gurevich, K. Papadopoulos, and C. Chang (1996), Direct Cerenkov excitation of waveguide modes by a mobile ionospheric heater, *Radio Sci.*, *31*(4), 859–867.

Cohen, M. B., M. Gołkowski, and U. S. Inan (2008a), Orientation of the HAARP ELF ionospheric dipole and the auroral electrojet, *Geophys. Res. Lett.*, *35*, L02806, doi:10.1029/2007GL032424.

Cohen, M. B., U. S. Inan, and M. A. Gołkowski (2008b), Geometric modulation: A more effective method of steerable ELF/VLF wave generation with continuous HF heating of the lower ionosphere, *Geophys. Res. Lett.*, *35*, L12101, doi:10.1029/2008GL034061.

Cohen, M. B., U. S. Inan, and M. Gołkowski (2009), Reply to comment by R. C. Moore and M. T. Rietveld on "Geometric modulation: A more effective method of steerable ELF/VLF wave generation with continuous HF heating of the lower ionosphere", *Geophys. Res. Lett.*, *36*, L04102, doi:10.1029/2008GL036519.

Cohen, M. B., U. S. Inan, and E. W. Paschal (2010), Sensitive broadband ELF/VLF radio reception with the AWESOME instrument, *IEEE Trans. Geosci. Remote Sens.*, *48*, 3–17.

Davies, K. (1990), *Ionospheric Radio*, Peter Peregrinus, London.

Ferraro, A. J., H. S. Lee, R. Allshouse, K. Carroll, A. A. Tomko, F. J. Kelly, and R. G. Joiner (1982), VLF/ELF radiation from the ionospheric dynamo current system modulated by powerful HF signals, *J. Atmos. Terr. Phys.*, *44*, 1113–1122.

Gemantsev, G. G., et al. (1974), Combination frequencies in the interaction between high-power short-wave radiation and ionospheric plasma, *JETP Lett.*, *20*, 101–102.

Gołkowski, M., U. S. Inan, A. R. Gibby, and M. B. Cohen (2008), Magnetospheric amplification and emission triggering by ELF/VLF waves injected by the 3.6 MW HAARP ionospheric heater, *J. Geophys. Res.*, *113*, A10201, doi:10.1029/2008JA013157.

Helliwell, R., and J. Katsufrakis (1974), VLF wave injection into the magnetosphere from Siple Station, Antarctica, *J. Geophys. Res.*, *79*(16), 2511–2518.

Inan, U. S., M. Gołkowski, 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.

Lunnen, R. J., H. S. Lee, A. J. Ferraro, T. W. Collins, and R. F. Woodman (1984), Detection of radiation from a heated and modulated equatorial electrojet current system, *Nature*, *311*, 134–135.

Moore, R. C., U. S. Inan, and T. F. Bell (2006), Observations of amplitude saturation in ELF/VLF wave generation by modulated HF heating of the auroral electrojet, *Geophys. Res. Lett.*, *33*, L12106, doi:10.1029/2006GL025934.

Moore, R. C., U. S. Inan, T. F. Bell, and E. J. Kennedy (2007), ELF waves generated by modulated HF heating of the auroral electrojet and observed at a ground distance of ~4400 km, *J. Geophys. Res.*, *112*, A05309, doi:10.1029/2006JA012063.

Moore, R. C., and M. T. Rietveld (2009), Comment on "Geometric modulation: A more effective method of steerable ELF/VLF wave generation with continuous HF heating of the lower ionosphere" by M. B. Cohen, U. S. Inan, and M. A. Golkowski, *Geophys. Res. Lett.*, *36*, L04101, doi:10.1029/2008GL036002.

Papadopoulos, K., A. S. Sharma, and C. L. Chang (1989), On the efficient operation of a plasma ELF antenna driven by modulation of ionospheric currents, *Comments Plasma Phys. Controlled Fusion*, *13*(1), 1–17.

Papadopoulos, K., C. Chang, P. Vitello, and A. Drobot (1990), On the efficiency of ionospheric ELF generation, *Radio Sci.*, *25*(6), 1311–1320.

Papadopoulos, K., H.-B. Zhou, and C.-L. Chang (1994), Cerenkov excitation of whistler/helicon waves by ionospheric HF heating, *Geophys. Res. Lett.*, *21*(4), 1767–1770.

Raghuram, R., R. Smith, and T. Bell (1974), VLF Antarctic antenna: Impedance and efficiency, *IEEE Trans. Antennas Propag.*, *22*, 334–338.

Rietveld, M. T., R. Barr, H. Kopka, E. Nielsen, P. Stubbe, and R. L. Dowden (1984), Ionospheric heater beam scanning: A new technique for ELF studies of the auroral ionosphere, *Radio Sci.*, *19*(4), 1069–1077.

Rietveld, M. T., H. Kopka, and P. Stubbe (1986), *D*-region characteristics deduced from pulsed ionospheric heating under auroral electrojet conditions, *J. Atmos. Terr. Phys.*, *48*, 311–326.

Stubbe, P., H. Kopka, and M. T. Rietveld (1981), Generation of ELF and VLF waves by polar electrojet modulation: Experimental results, *J. Geophys. Res.*, *86*(A11), 9073–9078.

Stutzman, W. L., and G. A. Thiele (1998), *Antenna Theory and Design*, 2nd ed., John Wiley, Hoboken, N. J.

Swanson, E. R. (1983), Omega, *Proc. IEEE*, *71*(10), 1140–1155.

Villaseñor, J., et al. (1996), Comparison of ELF/VLF generation modes in the ionosphere by the HIPAS heater array, *Radio Sci.*, *31*(1), 211–226.

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