



Geometric modulation: A more effective method of steerable ELF/VLF wave generation with continuous HF heating of the lower ionosphere

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[1] ELF/VLF radio waves (300 Hz–30 kHz) are difficult to generate with practical antennae, because of their extraordinarily long (10–1000 km) wavelengths, and the lossy nature of the Earth's surface at these frequencies. ELF/VLF waves have been successfully generated via amplitude modulated (AM) HF (2–10 MHz) heating of the lower ionosphere. Through the temperature-dependent conductivity of the lower ionospheric plasma, a patch of the ionospheric current becomes a large radiating 'antenna'. We implement a new method of ELF/VLF wave generation, herein named 'geometric modulation', involving scanning the HF heating beam in a geometric pattern without modulating its power. Utilizing results from the upgraded 3.6 MW radiated HAARP HF antenna array, we show that geometric modulation can enhance ELF/VLF wave generation by up to ~ 11 dB over the conventional AM method. Geometric modulation also allows directional launching of the signal into the Earth-ionosphere waveguide, forming an unprecedented steerable large-element ELF/VLF ionospheric phased array. **Citation:** Cohen, M. B., U. S. Inan, and M. A. Golkowski (2008), 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.

1. Introduction

[2] The generation of radio waves of Extremely Low Frequency and Very Low Frequency (ELF/VLF, 0.3–30 kHz) has long been a challenge for scientists and engineers. With wavelengths of ~ 10 –1000 km, acceptably efficient radiating antennae require similar length scales. This problem is exacerbated by the good conductivity of the Earth's surface at these frequencies ($\sim 10^{-4}$ S/m), so that a horizontal radiating antenna along the ground suffers the hindrance of an image current just below the ground plane.

[3] ELF/VLF frequencies have important scientific and practical uses, due to the efficient propagation of ELF/VLF signals in the Earth-ionosphere waveguide (EIW). ELF/VLF waves impact the physical processes at play in the ionosphere and magnetosphere (see *Barr et al.* [2000] for a review) and can be an effective diagnostic tool. HF heating of the lower ionosphere in the presence of natural currents constitutes one of the few effective means of ELF/VLF wave generation, and thus has remained a subject of active research since the first demonstration by *Getmantsev et al.* [1974].

[4] The ionospheric observatories near Arecibo, Puerto Rico [*Ferraro et al.*, 1982], and Jicamarca, Peru [*Lunnen et al.*, 1984], generated weak (< 1 fT) ELF signals utilizing the equatorial dynamo current. High latitude facilities utilizing the auroral electrojet have generated stronger (> 1 pT) ELF/VLF signals. The HIPAS facility near Fairbanks, Alaska, utilizes a 150 kW transmitter array operating at 2.85 MHz [e.g., *Villaseñor et al.*, 1996]. The 1 MW radiated EISCAT facility near Tromsø, Norway, has performed ELF/VLF experiments [e.g., *Stubbe et al.*, 1982], including an HF beam steering ability utilized by *Rietveld et al.* [1984] to observe electrojet spatial structure.

[5] More recently, the High Frequency Active Auroral Research Program (HAARP) phased-array HF facility near Gakona, Alaska ($62^{\circ} 22'N$, $145^{\circ} 9'W$), has generated ELF signals observed as far as 4400 km [*Moore et al.*, 2007], as well as in the geomagnetic conjugate region [*Inan et al.*, 2004; M. Golkowski et al., Magnetospheric amplification and emission triggering by ELF/VLF waves injected by the 3.6 MW HAARP ionospheric heater, submitted to *Journal of Geophysical Research*, 2008]. In 2007, an upgrade of HAARP was completed, increasing its HF radiated power from 960 kW to 3.6 MW [*Cohen et al.*, 2008]. The generation of ELF/VLF waves via HF heating is strongly affected by D-region electron density and auroral electrojet strength, however, HF heating parameter choice (frequency, beam direction, power, etc.) is quite important.

[6] *Papadopoulos et al.* [1990] suggest a so-called 'beam painting' technique, i.e., moving a high-power HF beam over a large area during the heating period at a rate faster than the electrons cool followed by HF OFF period to complete the AM cycle., though here we report a technique in which the beam moves at rates (a few kHz) substantially slower than the 10s of μ s cooling rates [*Barr et al.*, 1999], with a continuously ON beam. *Papadopoulos et al.* [1994] and *Borisov et al.* [1996] also theorized ELF/VLF injection into the EIW and magnetosphere via Cerenkov radiation from a source moving along a line at speeds near or above the phase velocity of propagating waves.

[7] Efforts to generate an ELF/VLF directional array have been very limited. *Barr et al.* [1987] alternate the HF beam between two regions using the Tromsø facility, with half the ELF/VLF cycle at each. The observations resembled those of an array with two antiphase elements. *Werner and Ferraro* [1987] theoretically investigated ionospheric ELF/VLF arrays.

[8] In this paper, we implement a new technique, hereafter referred to as 'geometric modulation' (and abbreviated GM), in which the beam scans in a geometric pattern at ELF/VLF rates, with no power modulation. The period of traversing the geometric pattern dictates the fundamental ELF/VLF modulation frequency, so that ON-OFF modulation is achieved

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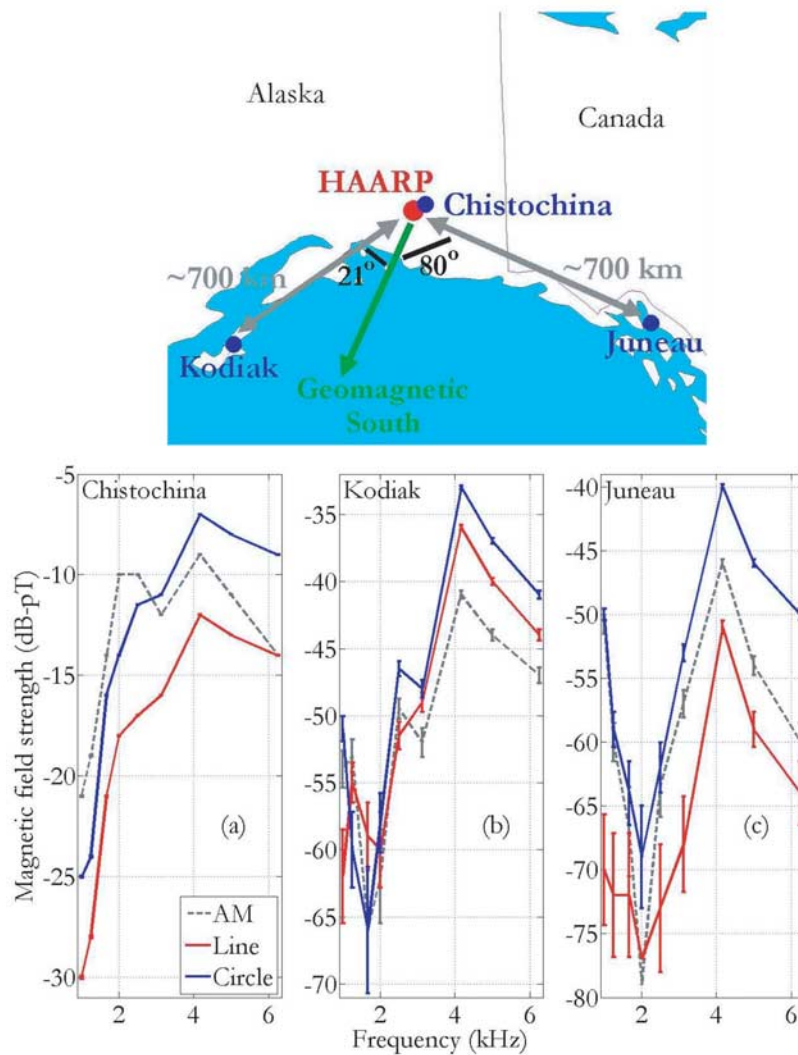


Figure 1. (top) Receiver locations. Chistochina ($62^{\circ} 37'N$, $144^{\circ} 37'W$, 37 km from HAARP), Kodiak ($57^{\circ} 52'N$, $152^{\circ} 53'W$, 661 km from HAARP), and Juneau ($58^{\circ} 35'N$, $134^{\circ} 54'W$, 704 km from HAARP), and directions shown compared to geomagnetic south. (bottom) The observed response of amplitude modulation, north-south line-sweep, and circle-sweep, measured at the indicated nine frequencies between 1 kHz and 6.25 kHz, at (a) Chistochina, (b) Kodiak, and (c) Juneau.

through beam motion, not power modulation. We demonstrate experimentally that GM enhances ELF/VLF amplitudes from modulated HF heating by as much as 7–11 dB, particularly above 3 kHz, and at longer (hundreds of km) distances from HAARP. We demonstrate that GM allows the directing of the signal in the EIW.

2. Experimental Setup

[9] ELF/VLF data are taken with the so-called AWE-SOME. These broadband, high-sensitivity (typically femto-teslas) ELF/VLF receivers consist of two orthogonal air-core loop antennae, measuring the two horizontal components of the magnetic field between 350 Hz and 47 kHz. Data is synchronized to GPS with inherent 200 ns accuracy. The receivers include RFI-suppression filtering at the input to reject HF signals.

[10] We utilize data from three receiver sites in Alaska. Chistochina, located quite close (~ 37 km) to HAARP, and Kodiak and Juneau, at longer distances (~ 700 km). Kodiak is

located at a direction from HAARP $\sim 21^{\circ}$ west of geomagnetic south, while Juneau is located at a direction from HAARP $\sim 10^{\circ}$ south of geomagnetic east. Figure 1, top panel, shows the locations of HAARP and the three receivers.

[11] The four modulation schemes discussed here are summarized in Figure 2, top panel. For amplitude modulation (AM), we utilize 50% duty cycle, 100% depth square wave modulation. Three types of GM ‘sweep’ schemes are introduced, each of which is compared to a typical AM scheme. The GM schemes are herein labeled line-sweep, where the heating beam scans back and forth along a chosen azimuth, completing a full back-forth scan (in this case $\pm 15^{\circ}$) in one ELF/VLF period); sawtooth-sweep, where the heating beam scans along one chosen azimuth, completing one sweep across the path in one ELF/VLF period and starting back at the initial end; and circle-sweep, where the heated beam follows a circular pattern with some radius (in this case 15°). In these experiments, we utilize an HF carrier frequency of 3.25 MHz, with X-mode polarization, and with ERP of ~ 575 MW.

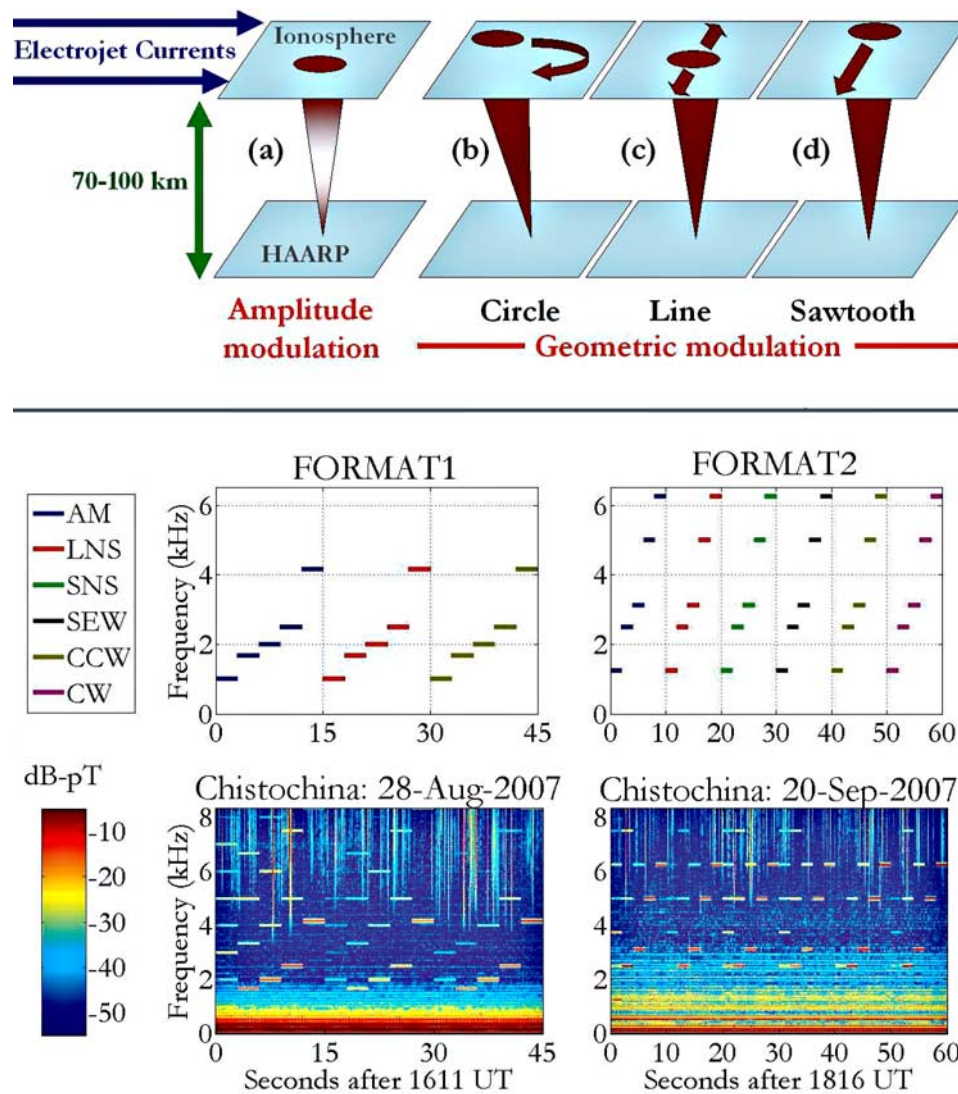


Figure 2. Experimental setup. (top) Modulation schemes, amplitude modulation, and geometric modulation with the CW beam moving in a pattern at ELF/VLF frequencies. Circle, line and sawtooth sweeps are shown. (bottom) Transmitted formats and Sample spectrograms. FORMAT1 includes AM, a geomagnetic north-south line-sweep (LNS), and a counterclockwise circle-sweep (CCW). FORMAT2 also includes sawtooth-sweeps north-to-south (SNS) and east-to-west (SEW), and a clockwise circle-sweep (CW).

[12] In a typical experiment, a frequency-time transmission format is repeated for many minutes. We discuss two particular formats designed to evaluate the effectiveness of AM and GM. Each format consists of a pattern of pulses, generated by each different modulation scheme for direct comparison. These 45–60 second long formats are repeated for periods of ~ 1 hour, and the received signal amplitudes are averaged to minimize the effect of ionospheric variations. While each format is transmitted at several different times, the comparative effectiveness of each modulation schemes is found to be consistent whenever SNR is sufficient (>10 dB) at all three receiver sites.

[13] The two transmission formats utilized, herein named FORMAT1 and FORMAT2, are illustrated in the lower plots of Figure 2, along with sample spectrograms. The received data show harmonics of the ELF/VLF frequencies from nonlinearities in the HF heating, though here we consider only the fundamental frequency. FORMAT1 consists of five

single-frequency 3-second pulses (1 kHz, 1.667 kHz, 2 kHz, 2.5 kHz, 4.167 kHz), for each of three modulation schemes: AM, line-sweep (in the geomagnetic north-south azimuth), and circle-sweep (with counterclockwise rotational sense, viewed from below). FORMAT2 includes the same modulation schemes as in FORMAT1, but also adds sawtooth-sweeps in both the geomagnetic north-to-south, and east-to-west azimuth, and an additional circle-sweep with clockwise rotational sense. FORMAT2 utilizes 2-second pulses with different ELF/VLF frequencies, (1.25 kHz, 2.5 kHz, 3.125 kHz, 5 kHz, 6.25 kHz).

[14] We rotate the data from each site to align with the great circle path from HAARP to receiver, and separately integrate the radial and azimuthal magnetic field amplitudes of each received pulse over its length, to provide a single horizontal magnetic field measurement. We then average these phasor quantities over the many (typically 60) repetitions of the format. Comparative noise measure-

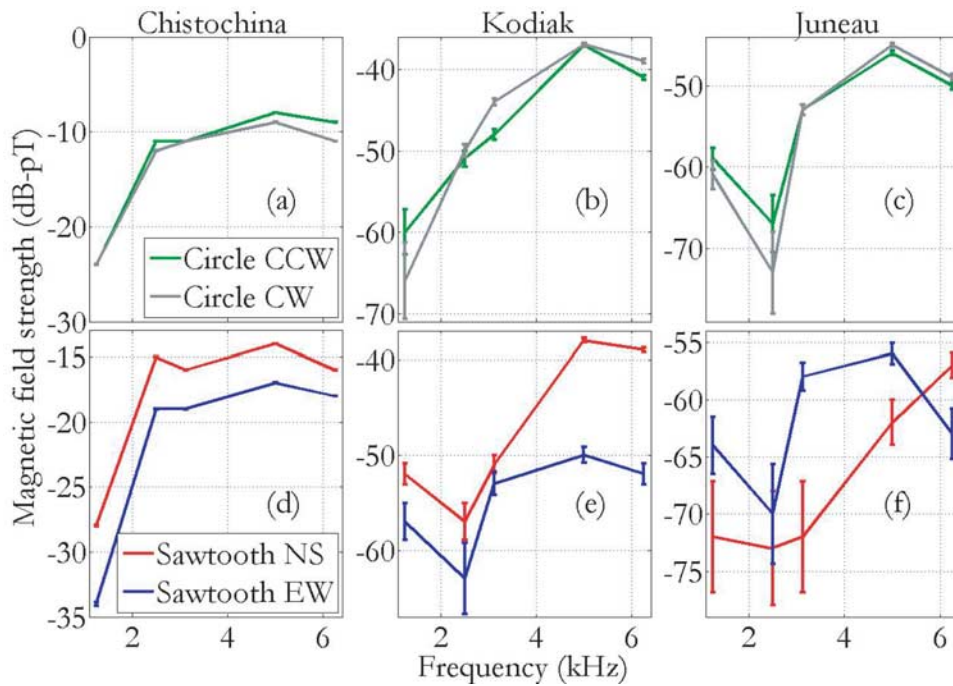


Figure 3. The frequency response of the two counterclockwise (CCW) and clockwise (CW) circle-sweeps, at (a) Chistochina, (b) Kodiak, and (c) Juneau, at five frequencies between 1.25 kHz and 6.25 kHz. (d–f) The frequency response of north-to-south (NS) and east-to-west (EW) sawtooth-sweeps.

ments are obtained by repeating the same procedure where no signal was transmitted, and are found to be and between -70 dB-pT and -75 dB-pT at Chistochina and Kodiak, and between -75 dB-pT -80 dB-pT at Juneau.

3. Observations

[15] Figure 1, bottom plots, shows the frequency dependent ELF/VLF amplitude measured at each of the three sites and for each of the three modulation schemes (labeled AM, LNS, and CCW) that were included in FORMAT1 and FORMAT2. We combine the results from the two formats after normalizing by the intensity of the 2.5 kHz pulse, which is common to both. GM schemes are shown with solid lines, while AM is shown as a dashed line. Error bars shown are based on the noise levels described above, though are small enough to be not visible for the stronger signals. FORMAT1 was transmitted on 28 August 2007, from 1600–1700 UT, and FORMAT2 on 20 September 2007, from 1717–1818 UT, both during ionospheric daytime and during periods of weak geomagnetic activity with k_p below 3.

[16] At Chistochina, AM produces higher ELF/VLF field amplitude compared to the circle-sweep by 2–4 dB, and to the line-sweep by 5–8 dB for signals below 3 kHz. Above 3 kHz, however, circle-sweep produces higher amplitudes than AM by 1–5 dB. At the longer distances, GM appears to provide a more distinct advantage, although specifically below ~ 2 kHz, comparison of these schemes is complicated by the fact that the signal propagates below the EIW cutoff frequency (~ 1.8 kHz), and so signal levels for the three modulation schemes cannot be unequivocally distinguished from measurement error. However, above 3 kHz, the circle-sweep leads to higher amplitude signals compared to AM

by 7–11 dB. In addition, above 3 kHz at Kodiak, the line-sweep produces amplitudes up to 5 dB higher than AM.

[17] From 3 kHz to 6.25 kHz, the decrease in amplitude with increasing ELF/VLF frequency common to all three modulation schemes at all three sites results from a combination of the conductivity modulation, waveguide resonance (i.e., reflections between the Earth and ionosphere observed nearby), and waveguide propagation (i.e. guiding along the EIW to longer distances), all of which are frequency dependent. At Chistochina (i.e. close to HAARP), where resonance effects dominate over propagation effects [Stubbe *et al.*, 1982], the amplitude of AM decreases with increasing ELF/VLF frequency faster than that of GM, so that GM schemes become increasingly advantageous, up to 6.25 kHz. However, at Kodiak and Juneau, where propagation effects dominate over resonance effects, the three schemes have the same dependence on increasing ELF/VLF frequency between 3 kHz and 6.25 kHz.

[18] GM inherently delivers 3 dB more HF power into the ionosphere compared to AM, yet provides a 7–11 dB enhancement, and is therefore more efficient by 4–8 dB, likely as a result of more efficient phasing of the heated region and utilization of the heating duty cycle. Furthermore, since amplitudes of ELF/VLF signals generated via modulated HF heating as observed on the ground are roughly proportional to total HF power delivered to the ionosphere [Barr and Stubbe, 1991], with some variations resulting from a saturation mechanism at these power levels [Moore *et al.*, 2006], the 7–11 dB enhancement exceeds the 6 dB enhancement that would be expected by simply doubling the power of HAARP. This represents a significant achievement given that ELF/VLF generation via modulated HF heating has efficiencies near 0.001% [Moore *et al.*,

2007], and especially since a similar increase of ELF/VLF radiated amplitudes through an array power or size upgrade would require another long and costly upgrade.

[19] Above 3 kHz, the line-sweep and AM have different relative effectiveness at Kodiak and Juneau (roughly equal distances from HAARP). The line-sweep is along the geomagnetic north-south azimuth, i.e., generally toward Kodiak and orthogonal to the HAARP-Juneau path. At Kodiak, the line-sweep generates stronger ELF/VLF than AM by 3–5 dB, whereas at Juneau, the north-south line-sweep produces 3–4 dB weaker ELF/VLF amplitudes than AM. These results suggest that the line-sweep may preferentially direct radiation roughly along the azimuth of the sweep, effectively acting as a directed antenna in addition to the 5–10 dB stronger radiation in the direction roughly orthogonal to the electrojet current direction [Cohen *et al.*, 2008].

[20] FORMAT2 includes sawtooth-sweeps with two orthogonal azimuths, and circle-sweeps with both rotational senses. The frequency response for different modulation schemes are shown in Figure 3, with measurements at the five ELF/VLF frequencies included in FORMAT2.

[21] The two circular sweep rotational senses produce amplitudes that are within a few dB, however the amplitudes of the two sawtooth-sweeps are very strong functions of direction from HAARP. For instance, the two sawtooth-sweep azimuths (north-to-south and east-to-west) impact ELF/VLF amplitudes at Kodiak and Juneau by as much as 14 dB, and up to 5 dB at Chistochina, and are higher when the sawtooth-sweep azimuth is pointed roughly toward the receiver. However, since Kodiak and Juneau are not precisely along the geomagnetic east and south directions from HAARP (being 21° and 10° off in bearing, respectively), they are also not precisely along the sawtooth-sweep azimuth, either. It is therefore possible that an even larger than 14 dB enhancement may be realized if the sawtooth-sweep azimuth is oriented directly toward a receiver.

[22] Rietveld *et al.* [1984] perform experiments in which the AM heating beam is moved slowly along a line in the north-south azimuth, and show that signal amplitudes at a nearby receiver may vary due to the spatial structure of the auroral electrojet. At least some of the 11 dB improved ELF/VLF amplitude associated with GM may therefore be due to such spatial structure, with the sweeps simply including regions with a stronger electrojet. However, this possibility is inconsistent with the signal amplitude's dependence on the sawtooth-sweep azimuth, and therefore cannot be the dominant explanation for the larger ELF/VLF amplitudes observed.

[23] It thus appears that the directionality associated with the sawtooth-sweep arises at least in part from the effective creation of an ELF phased array, producing constructive and destructive interference as a function of direction. The phase of each element within the array is determined by the phase within the ELF/VLF cycle at which the beam begins to heat that area. For instance, in the circle-sweep, the beam takes a full ELF/VLF period to traverse the circle, hence the circle-sweep can be treated as having a progressive phase variation of 2π around the circle. In the sawtooth-sweep in FORMAT 2, the number of distinct phases is simply the number of beam positions in the modulation scheme, i.e., 20 for the circle-sweeps in FORMAT2. Since the circumference of the circle is

~ 135 km, the inter-element phase shift is therefore $2\pi/20$, and the inter-element spacing is $\sim 135/20$ km. Since the sawtooth-sweep appears to direct radiation along its azimuth, it acts similar to an end-fire array, which may work best at directing the radiated signal when the phase shift between adjacent elements is comparable to the phase difference of propagating waves in that direction. In addition to the circle and sawtooth-sweep, other configurations of beam locations will create more general types of radiation patterns, for instance, four corners of a square. In general, full control of the phasing can be exercised via an arbitrary pattern of beam directions and dwell times in the order of the desired phasing, including a large number of beam positions spaced by arbitrary distances, which would be generalizable extension of the two-element array presented by Barr *et al.* [1987].

4. Conclusion

[24] A novel method of ELF/VLF wave generation via HF heating is implemented, herein named 'geometric modulation' (GM), whereby the HF heating beam is scanned along a geometric pattern with constant power. We have described three particular forms of GM, where the beam scans at a constant radius (circle-sweep), back and forth along an azimuth (line-sweep), or one way along an azimuth (sawtooth-sweep).

[25] Near HAARP, GM is less effective than AM below 2 kHz, but more effective above 3 kHz. For long distance observations, GM consistently produces substantially stronger signals than AM for ELF/VLF frequencies above 3 kHz, by as much as 7–11 dB. In addition, GM can lead to the creation of an unprecedented ELF phased array, capable of directed radiation at different azimuths within the EIW. Furthermore, additional improvements in both the resultant ELF/VLF amplitudes and the effective array directivity may yet be realized with further theoretical and experimental optimization.

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