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

ELF/VLF waves can be generated via amplitude modulated HF heating of the auroral electrojet, which turn a patch of ionospheric currents into a radiating antenna. We introduce a new, more powerful technique, "geometric modulation", involving scanning the HF beam in a geometric pattern with no power modulation. Utilizing results obtained from the HAARP facility, we show that geometric modulation enhances ELF/VLF wave generation by up to 7-11 dB over conventional AM methods, due to improved coupling to the Earth-ionosphere waveguide, and better utilization of the heating duty cycle. When beam motion is along an azimuth, an unprecedented ELF/VLF phased array is effectively formed.

***Cohen, M. B.*, Inan, U. S.**

Stanford University STAR Laboratory
350 Serra Mall, Room 356
Stanford, CA 94305, USA
mcohen@stanford.edu, inan@stanford.edu

Abstract

ELF/VLF waves can be generated via amplitude modulated HF heating of the auroral electrojet, which turns a patch of ionospheric currents into a radiating antenna. A new, more powerful technique, termed `geometric modulation', involves scanning the HF beam in geometric patterns with no power modulation. Utilizing results obtained from the HAARP facility, we show that geometric modulation enhances ELF/VLF wave generation by up to 7-11 dB over the conventional AM method, a significant achievement. When beam motion is along an azimuth, an unprecedented ELF/VLF phased array is effectively formed, allowing steerability of ELF/VLF waves. Quantitative theoretical modeling is also discussed.

1. Summary

The generation of radio waves of Extremely Low Frequency (ELF, 300-3000 Hz) and Very Low Frequency (VLF, 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 greatly exacerbated by the fact that the surface of the Earth is a good conductor at these frequencies ~10^{-4} S/m), so that the radiation efficiency of a horizontal antenna along the ground suffers the hindrance of an effective image current just below the ground plane [1]. For instance, the ELF facilities located in Wisconsin and Michigan utilized grounded horizontal wire to operated at 76 Hz, but even with a length of about 150 km, these sites managed to radiate only ~10 W [*2*].

ELF/VLF frequencies have important scientific and practical uses, due to the efficient propagation of ELF/VLF signals in the Earth-ionosphere waveguide (i.e., attenuation rates of a few dB/Mm), and the large skin depth for salt water (~4-5 m at 3 kHz). These properties enable communication with submerged submarines, accurate global navigation through phase triangulation from multiple transmitters. Because ELF/VLF waves interact with the D-region of the ionosphere, and also with trapped particles in the Van Allen radiation belts, ELF/VLF waves have important effects on the dynamics of the physical processes at play in the ionosphere and magnetosphere. Consequently, these low frequency waves are often effective tools for diagnostics of these remote regions [3]. Though lightning discharges radiate impulsive (~1 ms) ELF/VLF signals, known as radio atmospherics, which can be detected at global distances, modulated HF heating of the lower ionosphere in the presence of natural currents constitutes one of the few effective means of artificial ELF/VLF wave generation, and thus has remained a subject of active research since the first demonstration [4].

The generation of these ELF/VLF waves is strongly affected by two natural phenomena: D-region ionospheric electron density and the electrojet strength. These quantities are known to be highly variable, as geomagnetic conditions strongly affect both. However, the choice of HF heating parameters (frequency, beam size, beam direction, power, etc.) is also quite important.

In this paper, we introduce a new technique, hereafter referred to as `geometric modulation', in which the beam progressively scans in a geometric pattern at ELF/VLF rates, with no power modulation. The time period of traversing the geometric pattern dictates the fundamental ELF/VLF modulation frequency, so that ON-OFF modulation is achieved through beam motion, not through power modulation.

Experiments conducted at the HAARP facility in August and September, 2007, comprise the first tests of this new technique. We demonstrate that geometric modulation enhances ELF/VLF amplitudes from modulated HF heating by as much as 7-11 dB. This enhancement is particularly strong above 3 kHz, and at longer (hundreds of km) distances from HAARP. We also demonstrate that geometric modulation allows the directing of the signal in the Earth-ionosphere waveguide.

We note that in the field of ELF/VLF generation, with such long wavelengths, the only available means of radiating signals are financially expensive and resource intensive, and even still are electrically highly inefficient. For instance, ELF generation via modulated heating of the auroral electrojet radiates ELF power in the Earth-ionosphere waveguide on the order of 10s of Watts, despite injection of HF power in the MW range. ELF/VLF amplitudes generated with this technique scale roughly with total HF power [5], apart from the impediment of a saturation mechanism [6]. Therefore, upgrading the HAARP facility from 960 kW to 3.6 MW, which required years of construction and considerable resources and made HAARP the most powerful HF heating facility in the world, was completed in order to achieve generated ELF amplitude gains of no more than ~11.5 dB. In this sense, an additional improvement in signal generation of up to 11 dB strictly as a result of more effective utilization of existing resources constitutes a major achievement in the field of ELF generation.

In addition, the ability to direct ELF/VLF radiation along a chosen direction to substantial distances has heretoforth been an unachievable goal, due to the need for an array of phased ELF dipoles, themselves separated by distances comparable to a wavelength. We present here the first experimental verification that the technique of geometric modulation, in introducing this capability, has effectively formed the world's first ELF phased array.

Utilizing quantitative theoretical models of the HF-ELF/VLF conversion process, we explain the enhancement of ELF/VLF amplitudes observed in association with geometric modulation as a result of better utilization of the heating duty cycle, and a more effective size, shape, and phasing, of the HF heated ionosphere, enabling more efficient coupling to Earth-ionosphere waveguide modes.

Furthermore, since the method described herein has not yet been optimized, additional improvements to both the generated amplitudes and the effective array directivity may yet be possible with further theoretical and experimental investigations into the optimization of the varying parameters involved in geometric modulation.

2. References

1. A. D. Watt, (1967), *VLF radio engineering*. International Monographs in Electromagnetic Waves, Vol. 14. Pergamon, Oxford, England.

2. D. L. Jones, (1995) *ELF radio* in: 100 Years of Radio. IEE Conference Publication, Vol. 141. IEE, London, pp. 101-106.

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

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

5. R. Barr, and P. Stubbe (1991), ELF radiation from the Tromso ``super heater'' facility, *Geophys. Res. Lett., 18* (6), 1035-1038.

6. R. C. Moore, 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.