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

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1. Introduction

[1] *Cohen et al.* [2008] overlook observations presented by *Barr et al.* [1988], which have a direct and possibly significant impact on two of their primary conclusions. The two conclusions of interest are: 1) that 'geometric modulation' in the form of circle-sweeping is significantly more efficient than amplitude modulation at generating ELF/VLF waves, and 2) that the ELF/VLF beam generated using sawtooth format 'geometric modulation' indicates the creation of a controllable ELF phased array with an ''unprecedented'' level of directionality. Both conclusions impact the interpretation of physical processes responsible for ELF/VLF wave generation, and each is discussed, in turn, in light of the experimental observations presented by *Barr et al.* [1988].

2. ELF/VLF Wave Generation Efficiency

[2] We consider ELF/VLF wave generation efficiency in terms of the amplitude of the ELF/VLF wave observed at a single far-field receiver site as well as in terms of the integral ELF/VLF power injected into the Earth-ionosphere waveguide in all azimuthal directions. We first consider the wave amplitude observed at a single far-field receiver site.

[3] *Cohen et al.* [2008] show that the ELF/VLF radiation produced using the circle-sweep format 'geometric modulation' (CSGM) technique is higher in amplitude (by 7–11 dB) than that produced by vertical, amplitude-modulated HF (AM) beam. As stated, the increase in ELF/VLF wave generation efficiency is thus 4–8 dB due to the two-fold HF power consumption of the CSGM technique. The far-field experimental measurements presented by *Barr et al.* [1988] indicate that a possibly significant portion of the 4–8 dB increase in ELF/VLF wave generation efficiency observed by *Cohen et al.* [2008] is due to the 15° off-vertical heating angle employed during CSGM. It is therefore more appropriate to compare the GM experiments with oblique AM heating.

[4] *Barr et al.* [1988] present experimental and theoretical results concerning the amplitude of ELF/VLF waves between 1 and 6 kHz generated by AM heating of the auroral electrojet at the Tromsø HF heating facility in Norway. The 1 to 6 kHz range is the same as that explored by *Cohen et al.* [2008]. Observations were made at a receiver 550 km from the HF transmitter, comparable to the 700 km distances of the receivers used by *Cohen et al.* [2008]. Although the experimental results were first reported by *Barr et al.* [1987] (as cited by *Cohen et al.* [2008]), *Barr et al.* [1988] provide a more elegant and complete theoretical analysis of the observations and is more appropriate for comparison with GM. At Tromsø, when the HF beam was directed toward the receiver (up to 37 degrees off-vertical), a significant increase (sometimes by more than 10 dB, and on average by 6 dB) in the ELF/VLF signal amplitude was observed compared to vertical heating. We estimate, based on the experimental observations presented in the Figure 6 provided by *Barr et al.* [1988], that the difference between vertical heating and 15° off-vertical heating may result in a ~5 dB increase in ELF/VLF signal amplitude in the 3–6 kHz range, which is the range over which 'geometric modulation' is observed to produce the largest amplitudes [*Cohen et al.*, 2008].

[5] At HAARP, the ELF/VLF amplitude gain realized by oblique AM heating may be larger or smaller than previously observed at Tromsø, and this value should be determined by experiment. The claim that CSGM produces 7–11 dB higher ELF/VLF amplitude than does amplitude modulation appears to be unjustified in this regard, since about 5 dB of this gain may reasonably be attributed to the 15° off-vertical angle of the circle-sweep format. Of course, a full model would also account for the differences in duty cycle. Without experimental evidence to the contrary, however, and in light of the observations presented by *Barr et al.* [1988], an absolute ELF/VLF amplitude gain between 2 and 6 dB and an overall ELF/VLF wave generation efficiency (for single site observations) between −1 and 3 dB seem more appropriate. This result indicates that for single-site observations, 15° off-vertical AM heating may have essentially the *same* wave generation efficiency as CSGM, a result which starkly contrasts the conclusions presented by *Cohen et al.* [2008].

[6] Furthermore, based on the experimental observations by *Barr et al.* [1988], it appears possible that an amplitude-modulated HF beam aimed in the direction of the receiver at 30° off-vertical (which is currently the maximum 'safe' off-vertical deflection angle at HAARP for a standard AM beam) could produce an ELF/VLF amplitude that is comparable to that generated using CSGM, despite using a

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lower average HF power (and noting that a 15° angle is currently the largest 'safe' off-vertical angle at which HAARP may perform CSGM). While CSGM may be more efficient than oblique AM heating in this case, the experimental results presented by *Cohen et al.* [2008] unfortunately cannot address this issue. As a result, it is as yet unclear whether simple amplitude modulation is more or less efficient at ELF/VLF wave production than the more complicated 'geometric modulation' formats proposed by *Cohen et al.* [2008].

[7] It should be noted, however, that CSGM produces 7–11 dB amplitude gain over vertical AM heating over all azimuthal angles, a feat which cannot be matched by oblique AM heating. In this regard, the essentially azimuthally-uniform increase in ELF/VLF amplitude is, in fact, unprecedented and represents a significant contribution to the field of ELF/VLF wave generation. Despite this contribution, the observations presented by *Cohen et al.* [2008] cannot experimentally address whether circle-sweep format 'geometric modulation' injects more ELF/VLF power into the Earth-ionosphere waveguide than does oblique AM heating.

[8] The total ELF/VLF wave power injected into the Earth-ionosphere waveguide using the two formats may be compared theoretically, however. Assuming that vertical AM heating produces an ELF/VLF amplitude of −50 dB pT between 3 and 6 kHz, consistent with the amplitudes presented by *Cohen et al.* [2008], and assuming an azimuthally-uniform relative increase in amplitude of 7–11 dB for CSGM, the total ELF/VLF power injected into the Earth-ionosphere waveguide using CSGM may be estimated. The observations presented by *Barr et al.* [1988] indicate that oblique AM heating produces an amplitude gain of ∼4 dB when directed 15° off-vertical toward the receiver and ∼−4 dB when directed 15° off-vertical away the receiver. Assuming that the ELF/VLF amplitude varies sinusoidally with azimuth, the total ELF/VLF power injected into the Earth-ionosphere waveguide by oblique AM heating may similarly be estimated. Under these conditions, CSGM is more efficient than oblique AM heating by ∼3–7 dB, accounting for the 2-fold increase in power. Oblique AM heating at 30° off-vertical, however, may produce amplitude gains of up to 7.5 dB when directed toward the receiver and −7.5 dB when directed away the receiver [*Barr et al.*, 1988]. In this case, CSGM is more efficient than oblique AM heating by ∼0–4 dB. It thus appears possible that oblique AM heating at 30° off-vertical may result in approximately the same total ELF/VLF wave generation efficiency as CSGM. Such a possibility is not addressed by *Cohen et al.* [2008] and should be evaluated experimentally.

3. ELF/VLF Source Directionality

[9] *Cohen et al.* [2008] show that the ELF/VLF radiation produced using the sawtooth-sweep format 'geometric modulation' (STGM) technique is highly directional in that, depending on the direction of the sweep, the observed ELF/VLF amplitude may vary by as much or greater than 14 dB. They conclude that the observed directionality, produced by an ionospheric phased array, is unprecedented.

[10] Such observations are not "unprecedented" as claimed. If we consider only amplitude modulation as an alternative, the far-field directionality of the ELF/VLF source created by oblique heating with an amplitude-modulated HF signal is possibly on the same order of magnitude. Once again citing the results presented by *Barr et al.* [1988], the ELF/VLF amplitude generated for oblique AM heating at 37 degrees off-vertical in the direction of the receiver is observed to be as much as 15 dB higher than for heating at 37 degrees off-vertical away from the receiver in the 3 to 6 kHz range. Such an observation clearly indicates a directional ELF/VLF source region with a directionality approximately on the same order of magnitude as the STGM technique. Far-field observations of the amplitude and phase of the generated ELF/VLF signal could only accurately be predicted by employing a spatially-distributed set of properly phased dipoles [*Barr et al.*, 1988], which is entirely equivalent to the phased-array description presented by *Cohen et al.* [2008]. Although the observations presented by *Barr et al.* [1988] can be used to measure the difference between heating in directions with 180° difference in azimuth, the observations presented by *Cohen et al.* [2008] measure the difference between heating in directions with only 90° difference in azimuth. One might reasonably expect, however, that the ELF/VLF amplitude generated by STGM increases at heating azimuth angles larger than 90°. While further detailed observations may indicate that the STGM technique is indeed more directional than simple oblique heating with an AM beam, the observations presented by *Cohen et al.* [2008] do not support their rather dramatic conclusion.

[11] Furthermore, we estimate, based on the experimental observations presented in Figure 6 provided by *Barr et al.* [1988], that the difference between heating 15° off-vertical toward the receiver and away from the receiver is ∼6–10 dB in ELF/VLF signal amplitude in the 3–6 kHz range. It is therefore possible that as much as 6–10 dB of the observed 14 dB directionality is simply due to the 15° off-vertical heating portion of the STGM format. If the ELF/VLF amplitude gain produced by oblique AM heating is somewhat larger at HAARP than previously observed at Tromsø, it may be possible that the majority of the directionality observed by *Cohen et al.* [2008] can be attributed to the oblique heating angle. Such a possibility can be directly evaluated by experimental measurement.

4. Summary

[12] *Cohen et al.* [2008] do not account for the possibly significant effects of oblique HF heating in their comparison of ELF/VLF waves generated by 'geometric modulation' and those produced by standard amplitude modulation. We argue that the observations presented by *Cohen et al.* [2008] do not necessarily support the conclusion that CSGM is significantly more efficient at ELF/VLF wave generation than amplitude modulation, although this may be proven to be the case by future experiments. The azimuthally-uniform increase in ELF/VLF amplitude produced by CSGM is significant, however. With regard to STGM, it is possible that a large portion of the directionality observed may be attributed to oblique heating, rather than to the creation of an "unprecedented" steerable ELF/VLF phased array (which is not, in fact, unprecedented). Both issues, however, may be directly addressed by more detailed future experiments.

[13] Such future experiments may include, for instance, the comparison of ELF/VLF waves generated using CSGM and STGM with those generated by directed short-pulse modulation of the type used, for example, by *Rietveld et al.* [1986] and *Papadopoulos et al.* [2005]. HF pulse durations of several 10's of microseconds, corresponding to the effective pulse width experienced by each point in space using CSGM and STGM, may be used to approximate the magnitude and phase of ELF/VLF signals generated at different locations by CSGM and STGM, thereby assessing the distribution of the effective ionospheric ELF/VLF phased array.

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