GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L04102, doi:10.1029/2008GL036519, 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"

M. B. Cohen,[1] U. S. Inan,[1] and M. Gołkowski[1]

Received 29 October 2008; revised 12 January 2009; accepted 22 January 2009; published 18 February 2009.

Citation: 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.

1. Mechanisms of ELF/VLF Directionality

[1] We thank *Moore and Rietveld* [2009] (hereafter referred to as MR09) for their comments to *Cohen et al.* [2008] (hereafter referred to as CA08). MR09 consider the two following conclusions of CA08 concerning the generation of ELF/VLF (0.3–30 kHz) waves with typical amplitude modulation (AM) and geometric modulation of ionospheric High-Frequency (HF) heating: 1) "Geometric modulation can enhance ELF/VLF wave generation by up to ~11 dB over the conventional AM method", and 2) "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".

[2] MR09 refer to Figure 6 of *Barr et al.* [1988], which appears to show that 3–5 dB amplitude gains at long-distances can be achieved by tilting an AM HF beam by 15° toward that receiver (and conversely, a 3–5 dB reduction results from an HF beam tilted 15° away from the receiver), i.e., oblique AM HF heating. These observations are a straightforward consequence of phasing of ELF/VLF radiating currents across the heated region as a result of the variable propagation delay of the HF signal to the ionosphere [see *Barr et al.*, 1988, Figure 7]. MR09 therefore claim that 3–5 dB of the 7–11 dB amplitude gain, and 6–10 dB of the 14 dB directionality of geometric modulation reported by CA08, may result from the oblique nature of the HF beam.

[3] The experiment of *Barr et al.* [1988] is actually first reported by *Barr et al.* [1987], which was cited and described by CA08. The 1987 paper also discusses a related but more advanced experiment in which the HF beam alternates between two regions in the ionosphere, one directed toward a distant (~500 km) receiver, and one directed away, effectively creating two independent but anti-phase ELF/VLF sources. The distance between these two sources is controlled by the two oblique HF beam angles. The amplitude at the distant receiver is found to be dependent on the distance between the two sources, and varying (due to constructive and destructive interference) by 4–6 dB. These results are much more relevant to the observations of CA08 since they involve controllable phasing of independent ELF/VLF sources yet also intrinsically include the simpler non-controllable phasing resulting from a single oblique AM HF beam. While the discussion of *Barr et al.* [1988] may often be important for the interpretation of AM HF heating observations, they are significantly less important for interpreting experiments where multiple beam locations are utilized, such as the two-element array experiment presented by *Barr et al.* [1987].

[4] Oblique AM HF heating as discussed by MR09 does not fall into the category of "conventional AM method" as referred to by CA08. The 7–11 dB amplitude gains and 14 dB directionality was made in comparison to vertical AM heating, as is used in many ELF/VLF generation experiments. Additionally, vertical AM HF heating possesses the same azimuthal symmetry as the circle sweep, whereas the amplitude gains achieved with oblique AM HF heating occur only along one direction, so a comparison to vertical AM HF heating is more appropriate. Nonetheless, we consider here the contribution of oblique AM HF heating (since it has been brought to fore by MR09) and show that the phasing created by oblique AM HF heating can at best account for a small part of the amplitude gains and directionality associated with geometric modulation and reported by CA08.

[5] The observations of CA08 relate more closely to the mechanism of an ELF/VLF phased array as presented by *Barr et al.* [1987]. Geometric modulation intrinsically utilizes HAARP facility's new capability to steer the HF beam at 100-kHz rates over a 2D area, enabling dozens of beam locations in each ELF/VLF period. Since the relative phases of each element are determined by the controllable order in which the HF beam heats these locations within the ELF/VLF period (whereas the phasing effect of an oblique beam is dictated by geometry), geometric modulation does in fact represent an unprecedented technique for controlled ELF/VLF directionality, one that cannot be reproduced with single-location oblique AM HF heating as discussed by *Barr et al.* [1988].

2. ELF/VLF Wave Amplitudes

[6] Figure 1 shows schematically the concept of geometric modulation for both the circle-sweep and sawtooth-sweep, respectively. The red oval indicates the size of the HAARP

[1]STAR Laboratory, Electrical Engineering Department, Stanford University, Stanford, California, USA.

0094-8276/09/2008GL036519$05.00

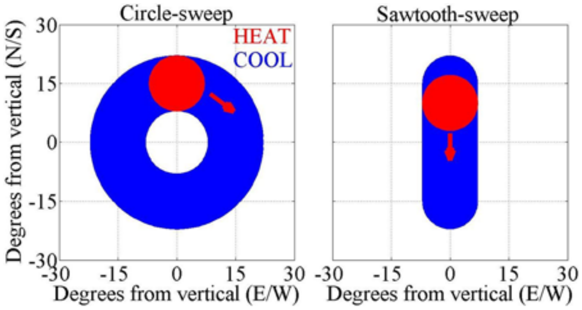

Figure 1. The area illuminated by the geometric modulation format (left) circle-sweep and (right) north-to-south sawtooth-sweep. The red spot shows the 3 dB beamwidth (where heating occurs), which moves in the direction of the arrow. The blue patch shows the shape of the rest of the illuminated region (where the cooling occurs).

HF heating beam at 3.25 MHz (and therefore the size of the heated region for AM). The blue portions indicate the rest of the ionospheric region heated.

[7] In their analysis of the circle-sweep (and also the sawtooth-sweep discussed later), MR09 implicitly assume that the signal at a distant receiver is dominated by the radiation from the component of the circle-sweep directed most closely toward the receiver, thereby ignoring the contributions from rest of the circle-sweep. This assumption is in direct disagreement with evidence presented by *Barr et al.* [1987] regarding a two-element array. When the distance between the two anti-phase sources increases beyond a half-wavelength (i.e., the optimal distance for constructive interference), the amplitude at the distant receiver decreases, indicating that the effect of destructive interference between two ELF/VLF sources dominates over the effect of phasing resulting from oblique AM HF heating [see *Barr et al.*, 1987, Figure 11]. This result implies that although the phasing effect described by *Barr et al.* [1988] may act as a small correction factor, for the purposes of multiple beam locations, treating each one effectively as a point source captures much of the physics. The circle-sweep experiment conducted by CA08 is considerably more complicated than the two-element array of *Barr et al.* [1987], since it contains many ELF/VLF sources with relative ELF/VLF phase shifts varying nearly continuously between 0 and 2π around the circle, so the contributions of constructive and destructive interference from point-source elements may be even more significant.

[8] The analysis presented by MR09 also does not account for the drastically differing duty cycle. *Cohen et al.* [2008] utilize 50% duty cycle square-wave for the AM generation in order to achieve the strongest ELF/VLF amplitudes with AM. However, for geometric modulation, the effective duty cycle is in fact quite different, being dictated by the ratio of the area of the HAARP HF beam to the total area illuminated by the HF beam in the geometric pattern. As shown in Figure 1, given the beam parameters of the HAARP array (3-dB beamwidth of ~13–16° at 3.25 MHz), the average duty cycle for the circle-sweep is ~12%, since the HF-heated spot represents ~12% of the total illuminated area. (It also varies between ~5% and ~20% as a function of radius from the center of the circle-sweep). Of the 20 beam steps around the circle, only ~2.5 are actually pointed even approximately toward a given receiver. In claiming that oblique AM HF heating achieves equivalent efficiency to that of the circle-sweep for a specific direction, MR09 overlook the fact that 6–7 dB less HF energy is placed at that location during the circle-sweep.

[9] Finally, even if one could simply subtract 3–5 dB from the reported 7–11 dB circle-sweep amplitude gain of CA08 as suggested by MR09 one is still left with 2–8 dB of amplitude enhancement which is not accounted for. The broader conclusion that geometric modulation yields enhanced ELF/VLF compared to vertical or oblique amplitude modulated HF heating thus appears to be valid.

[10] Based again on the observations of *Barr et al.* [1988], MR09 claim that 6–10 dB of directionality (out of the 14 dB demonstrated by CA08) arise from oblique AM HF heating. This claim is clearly incorrect by at least a factor of two. The comparison made by CA08 concerns the observations at a distant receiver of sawtooth-sweeps with azimuths oriented both toward, and perpendicular to, the HAARP-receiver path. MR09 implicitly assume that the signal received from geometric modulation is dominated by the radiation from the beam location at its closest point to the receiver. Under this assumption, the signal received from a sawtooth-sweep with azimuth toward a HAARP-receiver path would be dominated by the beam location at +15°, whereas the signal received from a sawtooth-sweep oriented orthogonal to the HAARP-receiver path would be dominated by a the vertically-directed beam location. As mentioned earlier, based on Figure 6 of *Barr et al.* [1988], this difference is only 3–5 dB, quite small compared to the 14 dB figure reported by CA08. Overall, the arguments made by MR09 do not in any way invalidate the conclusion of CA08 that "the directionality associated with the sawtooth-sweep arises at least in part from the effective creation of an ELF phased array."

3. Conclusion

[11] *Moore and Rietveld* [2009] discuss a comparison between geometric modulation and oblique AM HF heating, but utilize assumptions which do not take account important experimental differences between the two generation techniques. Even under these unjustified assumptions, the oblique AM HF heating results of *Barr et al.* [1988] are not sufficient to account for any more than a small portion of the amplitude gains and directionality observed by CA08. The *Barr et al.* [1987] results regarding an ELF/VLF phased array (as described by CA08) are more relevant to the physical mechanism of geometric modulation than the results of *Barr et al.* [1988].

[12] **Acknowledgments.** We thank T.F. Bell for helpful discussions. We acknowledge support from HAARP, Office of Naval Research (ONR), Air Force Research Laboratory, and Defense Advanced Research Programs Agency, via ONR grant N0001405C0308.

References

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

Barr, R., et al. (1988), Ionospheric heater beam scanning: A realistic model of this mobile source of ELF/VLF radiation, *Radio Sci.*, *23*, 379–388.

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.
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. Gołkowski, *Geophys. Res. Lett.*, *36*, L04101, doi:10.1029/2008GL036002.

M. B. Cohen, M. Gołkowski, and U. S. Inan, STAR Laboratory, Electrical Engineering Department, Stanford University, 350 Serra Mall Room 356, Stanford, CA 94305, USA. (mcohen@stanford.edu)