GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L15103, doi:10.1029/2009GL039669, 2009

Cross modulation of whistler mode and HF waves above the HAARP ionospheric heater

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

Received 18 June 2009; accepted 2 July 2009; published 5 August 2009.

[1] The HF facility of the High Frequency Active Auroral Research Program (HAARP) is employed to generate ELF/VLF radiation by modulation of overhead auroral electrojet currents for magnetospheric wave injection and propagation in the Earth-ionosphere waveguide. HAARP induced ducted magnetospherically amplified whistler mode signals are observed to return to the vicinity of the HF facility and experience cross modulation with simultaneous HF transmissions. The cross modulation effect results from modification of the attenuation properties of the ionospheric medium by HAARP HF waves in the daytime ionosphere. The cross modulation concept is subsequently investigated as a new method for ELF/VLF wave generation with the HAARP heating facility using two co-located HF beams. The new generation method is observed to generate radiation from 630 Hz–37 kHz. Observed amplitudes are an order of magnitude lower than fundamental frequencies generated using conventional AM, but of the same order as AM second harmonics. **Citation:** Gołkowski, M., U. S. Inan, and M. B. Cohen (2009), Cross modulation of whistler mode and HF waves above the HAARP ionospheric heater, *Geophys. Res. Lett.*, *36*, L15103, doi:10.1029/2009GL039669.

1. Introduction

[2] The ionospheric heating facility of the High Frequency Active Auroral Research Program (HAARP) in Gakona, Alaska (62.4°N and 145.2°W) has been actively used to generate ELF/VLF radiation by modulation of the overhead auroral electrojet currents for more than a decade [*Papadopoulos et al.*, 2003; *Moore et al.*, 2007; *Cohen et al.*, 2008a, 2008b]. Since 2007 the HAARP facility has been capable of radiating 3.6 MW of HF power in the 2.75–10 MHz band. A particular class of experiments involves using HAARP ELF/VLF waves for controlled studies of magnetospheric wave amplification. In such investigations HAARP ELF/VLF signals propagate in the Earth's magnetosphere in the whistler mode guided by field aligned density irregularities or 'ducts.' Ducted and amplified waves can return to the vicinity of the HF facility after reflection from the ionospheric boundary at the magnetic conjugate point and are termed '2-hop echoes' [*Inan et al.*, 2004; *Gołkowski et al.*, 2008]. In the course of wave injection experiments it was observed that 2-hop echoes experienced cross modulation with simultaneous HF transmissions of the HAARP array. We present observations and analysis of this new phenomena and experimentally investigate the concept as an alternative method of ELF/VLF generation.

2. Observation of Cross Modulation

[3] Observation of cross modulation between whistler mode 2-hop echoes and HF heating occurred on 23 August 2007 at 23:05–23:17 UT. At this time the HAARP 3.25 MHz HF beam was square wave amplitude modulated in X-mode with 3-second tones at 1110 Hz, 1590 Hz, and 930 Hz and a 500 Hz/sec frequency-time ramp. ELF/VLF observations were made with an AWESOME receiver [*Cohen et al.*, 2009] with two orthogonal air core loop antennas. Figure 1 shows a spectrogram from Chistochina (62.61°N, 144.62°W, 37 km from HAARP) in which HAARP transmissions and corresponding triggered 2-hop echoes (which arrive ~7 seconds later due to trans-hemispheric propagation through the magnetosphere in the whistler mode) are marked by the white dotted arrows. In addition to the 2-hop echoes excited by the ramps and pulses, 'replicas' of the 2-hop echoes shifted up in frequency are visible in the record as indicated by the black arrows. The frequency shift of the echo replicas corresponds exactly to the ELF frequency of the simultaneous HAARP transmission. The replicas thus appear to be a direct result of cross modulation between the down-coming 2-hop echoes and the concurrent up-going ELF modulated HF signals. The 2-hop echoes on their return to the northern hemisphere must therefore be propagating through the ionosphere in the heated region above the HAARP facility. This is in close agreement with the magnetospheric path determination results for these observations and others [*Inan et al.*, 2004; *Gołkowski et al.*, 2008] that were obtained by whistler mode dispersion analysis. The cross modulation observations and dispersion results are both consistent with the observed 2-hop echoes traveling along *L*-shells with footprints in the vicinity of the HF facility.

3. Cross Modulation Mechanism

[4] The cross modulation effect takes place in the heated region of the ionosphere where HF radiation modifies the electron temperature thus affecting the propagation characteristics of the medium for the down-going 2-hop signal. We utilize a numerical model similar to that used by *James* [1985], which tracks both HF absorption and energy loss by electrons as a result of temperature dependent collisions with neutral molecules. Acceleration and energy loss are calculated based on the assumption of Maxwellian-distributed electron energies. Ambient ionospheric parameters and input HF power are used as inputs to yield altitude distributions of the electron temperature, which evolve in time

[1]STAR Laboratory, Stanford University, Stanford, California, USA.

0094-8276/09/2009GL039669$05.00

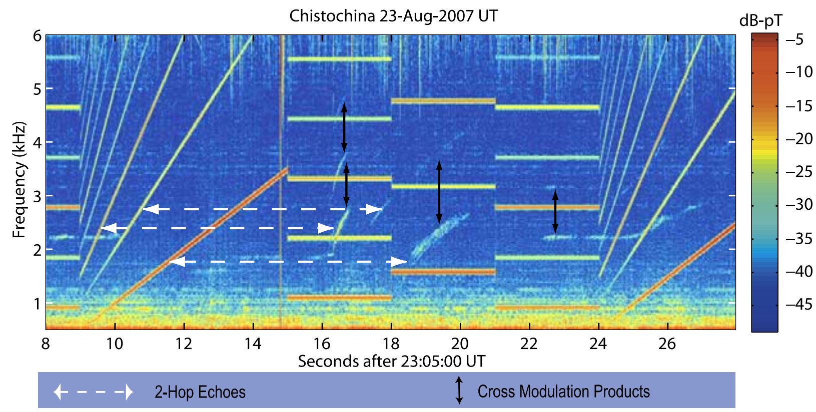

Figure 1. Echo heating cross modulation. HAARP transmitted ramps and pulses excite 2-hop echoes. Modulation products of 2-hop echoes with simultaneous HAARP transmissions are also seen in the record.

taking into account the modified ionospheric collision frequency (and therefore HF or ELF absorption) at each time step. Figure 2 shows the effect of a single 1110 Hz AM modulation cycle on typical daytime and nighttime ionospheres and the corresponding induced propagation characteristics for a 2 kHz wave. The assumed ionospheric profiles are shown in Figure 2a. The primary effect of the HF heating is to change the electron temperature as shown in Figure 2b. Figure 2c shows the attenuation coefficient for a 2 kHz wave obtained from the imaginary part of the refractive index that is calculated from the collisional Appleton-Hartree equation. The electron temperature change manifests itself exclusively as a change in wave attenuation, leaving the real part of the refractive index (not shown) virtually unchanged.

[5] The down-coming 2-hop signal passes through an attenuating ionosphere before reaching the ground. This attenuation coefficient is itself modulated (by HF heating) at a second ELF frequency, which thereby generates a cross-modulation product. Figures 2d and 2e shows 2 periods of the attenuation waveform that results from propagation through the HF modified daytime and nighttime ionospheres. Each attenuation waveform is a time series of vertical integrations of the HF induced attenuation in the ionosphere for a 2 kHz wave. This phenomenon is analogous to the Luxembourg effect [*Bailey and Martyn*, 1934] in that one signal modifies the ionosphere and so imposes its modulation on another signal that propagates through or in the vicinity of the same medium. Manifestation of this effect in the VLF band was reported by *Inan* [1990].

[6] A quantitative comparison of the observed cross modulation spectrum and that predicted from our modeling is shown in Figure 3. Figure 3a shows a spectrogram of a 2-hop echo and its cross modulation products from a simultaneous 1110 Hz HAARP transmission observed on a single antenna. Figure 3b shows the spectrum of data from both antennas during the time marked by the white dashed lines in Figure 3a after demodulation using a matched filter based on fitting a frequency-time curve to the observed 2-hop echo. The frequency-time signature of the matched filter is

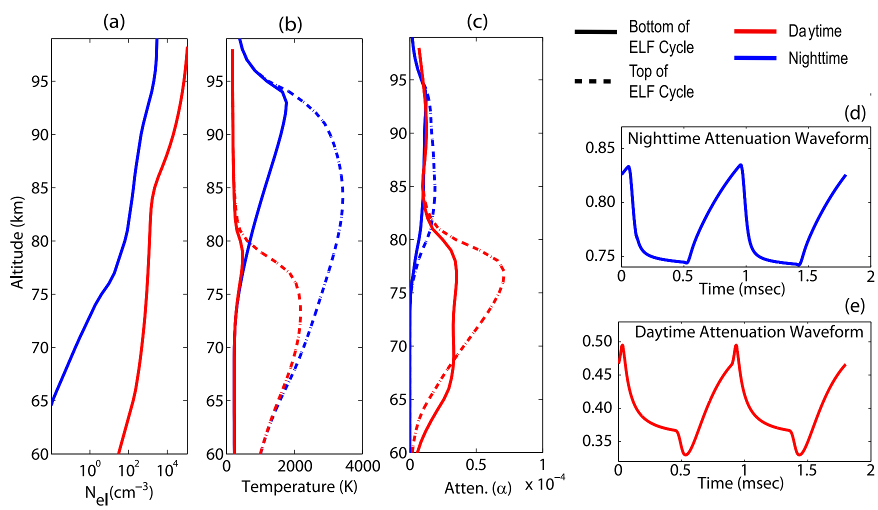

Figure 2. Effect of HF modulated heating on ionospheric medium. (a) Typical daytime and nighttime profiles. (b) The resulting electron temperature increase from modulated heating. (c) The attenuation coefficient for a 2 kHz wave. (d) Nighttime and (e) daytime attenuation waveforms obtained by vertically integrating the ionospheric attenuation as a function of time.

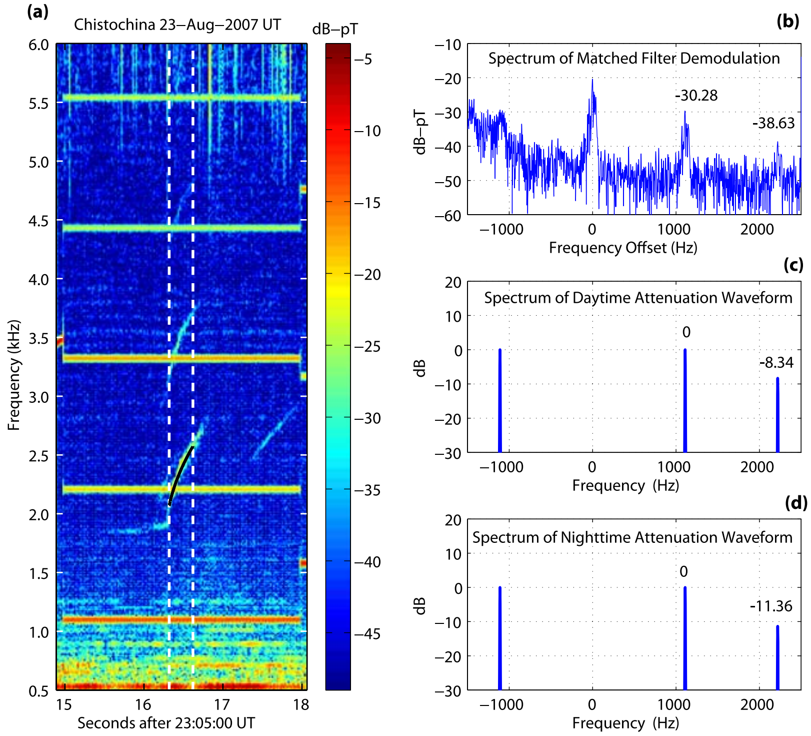

Figure 3. (a) Spectrogram with 2-hop echo and cross modulation products from a 1110 Hz transmission. (b) The spectrum denoted by white lines after demodulation with a matched filter (black trace in Figure 3a). (c) and (d) Spectra of the attenuation waveforms shown in Figures 2d and 2e.

also shown on the spectrogram in Figure 3a as a black line superposed on the 'fundamental' 2-hop echo. Since we seek to isolate the 2-hop echoes and its cross modulation products, prior to demodulation with the matched filter, the HAARP tone and harmonics at 1110 Hz, 2220 Hz, 3330 Hz, and 4440 Hz were removed from the data. Removal was accomplished using direct subtraction of signals synthesized from the observed amplitude and phase at these frequencies. Because of the high signal-to-noise ratio and phase stability of the HAARP transmissions, the direct subtraction method is effective in removing these monochromatic signals. Demodulation with a matched filter based on the 'fundamental' 2-hop echo, shifts the amplitude of this 2-hop echo to DC (0 Hz), while shifting its cross modulation products to frequencies equal to the offset from the 2-hop echo. The 2-hop echo modulation products shifted to higher frequency by 1110 Hz and 2220 Hz are clearly visible as spectral peaks in Figure 3b. The modulation product shifted to a lower frequency is also visible at −1110 Hz although power line harmonic noise makes this lower frequency peak more difficult to recognize. Figures 3c and 3d show the spectrum of the daytime and nighttime attenuation waveforms shown in Figure 2. Assuming that the received waves are dominated by a direct path from the ionosphere (which is reasonable since Chistochina is less than a wavelength from the HAARP facility), the harmonic content of the modulated 2-hop echo and the attenuation waveforms can be compared directly. The amplitudes of the observed modulation products at 1110 and 2220 Hz are identified in Figure 3b and yield a difference of 8.35 dB. The analogous harmonic ratios for the attenuation waveforms are 8.34 dB and 11.36 dB for the daytime and nighttime ionospheres, respectively. The observations, which occurred near 12:00 LT, thus seem to match the results for the assumed daytime ionosphere quite well.

4. Cross Modulation for Generation

[7] The observation of cross modulation of ELF/VLF signals in the HAARP heated region suggests the possibility of using the same concept as a new method for ELF/VLF generation with the HAARP HF facility. In this context we note that *Cohen et al.* [2008b] describe a ~10 dB enhancement of generated waves using a technique therein referred to as geometric modulation. In particular, it is desirable to extend generation beyond the hardware imposed 30 kHz upper limit of AM modulation and explore possibly more efficient methods of generating low-ELF and ULF frequencies. The cross modulation based generation concept is presented in Figure 4a. Here, we use two co-located HF heating beams operating at different modulation frequencies, so that the signal generated from one beam must pass through the absorbing ionosphere modulated by the other beam.

[8] The HF frequencies chosen for the experiment were 2.75 MHz and 4.8 MHz. Transmissions were performed over a range of output (sum and difference) frequencies from 630 Hz to 37 kHz using various combinations of driver frequencies. Frequencies below 630 Hz were not explored because of the limited frequency response of the receiver and higher noise power in this band. Three-second tones were generated with X-mode amplitude modulation in repetitive 15 or 30 second long formats run for 10–30 minute durations. The experiment was run for a total of 208 minutes during local daytimes spread over the days 15–16 January, 8 February, and 9 March 2008. The average

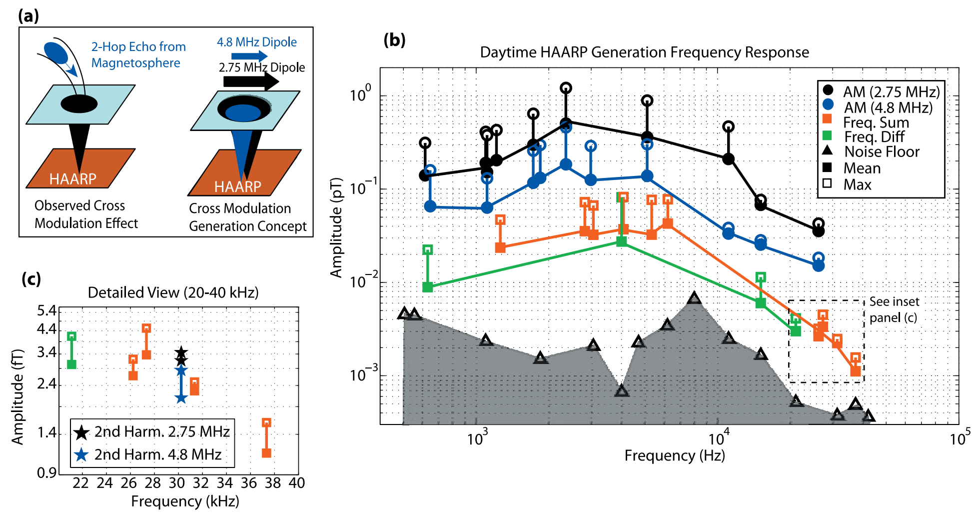

Figure 4. (a) Concept for cross modulation as a generation technique. (b) Results of HAARP generation using AM modulation (circles) and the cross modulation technique (squares). (c) An expanded view of the high frequency results and amplitudes of AM 2nd harmonics.

complex amplitude over each 3-second tone was calculated and all tones of the same frequency were averaged over each 10–30 minute transmission duration. Figure 4b shows the cumulative frequency response of the cross modulation method as well as conventional AM. The noise floor data shown was obtained by applying the same averaging technique but during times with no HAARP transmissions. The solid shapes in Figure 4b show the amplitude at a given frequency averaged over all transmissions, while the outlined shapes show the maximum average corresponding to a single 10–30 minute transmission period. The large spread between mean and maximum signal amplitudes shown is the result of natural variations of electrojet strength and ionospheric profile over the different days and times over which the experiment was run. Although data in Figure 4 illustrate that the cross modulation technique generates observable signals in a wide frequency range, the technique is seen to yield signal amplitudes about an order of magnitude lower than conventional AM generation.

[9] In interpreting the ELF/VLF signals generated by cross modulation it is important to note that their amplitude is directly proportional to the product of AM generated ELF/VLF and HF-induced ionospheric attenuation. The factor of ~10 lower amplitudes of the cross modulation technique likely result directly from the amplitudes of the modulating attenuation waveforms which are on the order of 10–15% as shown in Figures 2d and 2e. Likewise, the higher amplitudes achieved by frequency sums over frequency differences likely results from the need for higher VLF (AM generated) frequencies to yield difference products in the same band as the sum products. HAARP AM generation is known to be less efficient with increasing modulation frequency above 10 kHz, as is seen in Figure 4. Both AM generation and HF induced attenuation are degraded when the modulation period becomes short compared to the electron cooling scale. This dependence is corroborated by the similarity of the relative frequency response for cross modulation and AM techniques as shown by the best fit lines in Figure 4. Observations of cross modulation products above 30 kHz, where direct AM generation with HAARP is not possible, yielded signals with amplitudes of 1–3 fT. Another method of generating signals above 30 kHz with HAARP is via second harmonic radiation of AM signals below 30 kHz. Figure 4c shows a detailed view of the cross modulation results for 20–40 kHz and also the 2nd harmonics at 30.23 kHz of AM generation at 15.115 kHz that was part of the same experiment. The 2nd harmonic and cross modulation signals are observed to be on the same order. In general, second harmonics at all frequencies exhibit amplitudes about an order of magnitude lower than their AM generated fundamentals. Thus the amplitude ratios between AM generation and both cross modulation and second harmonic generation are similar although the cross modulation technique requires splitting the HF array to radiate at two different HF frequencies. It is worth mentioning an additional generation technique capable of generation above 30 kHz, which involves two CW HF beams separated in frequency by a desired ouptut VLF frequency. Such a technique was investigated at the Tromsø facility by *Barr and Stubbe* [1997] and found to yield amplitudes 11 dB lower than AM. Thus cross modulation, 2nd harmonic, and CW techniques all appear to yield amplitudes about an order of magnitude lower than AM generation.

5. Summary

[10] Periodic HF heating with the HAARP array significantly modifies the propagation characteristics of the overhead ionospheric medium causing cross modulation with whistler mode waves propagating therein. This effect needs to be taken into account in interpretation of observations of ELF/VLF radiation in the vicinity of HAARP during HF operation. Observations of cross modulation confirm the accuracy of whistler dispersion analysis in determining magnetospheric propagation paths of HAARP induced 2-hop echoes. The observed effect allows for verification of integrated *D*-region electron density profiles and in principle could serve as diagnostic tool.

[11] **Acknowledgments.** This work was supported by the High-frequency Active Auroral Research Program (HAARP), the Defense Advanced Research Programs Agency (DARPA), and by the Office of Naval Research (ONR) via ONR grant N0001405C0308 to Stanford University. The authors thank Mike McCarrick, Helio Zwi, and David Seafolk-Kopp for operation of the HAARP facility.

References

Bailey, V. A., and D. F. Martyn (1934), Interaction of radio waves, *Nature*, *133*, 218.

Barr, R., and P. Stubbe (1997), ELF and VLF generation by HF heating: A comparison of AM and CW techniques, *J. Atmos. Terr. Phys.*, *59*, 2265–2279.

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 E. Paschal (2009), Sensitive broadband ELF/VLF radio reception with the AWESOME instrument, *IEEE Trans. Geosci. Remote Sens.*, doi:10.1109/TGRS.2009.2028334, in press.

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

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.

Inan, U. S. (1990), VLF heating of the lower ionosphere, *Geophys. Res. Lett.*, *17*, 729–732.

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.

James, H. G. (1985), The ELF spectrum of artificially modulated D/E-region conductivity, *J. Atmos. Terr. Phys.*, *47*, 11, 1129–1142.

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.

Papadopoulos, K., T. Wallace, M. McCarrick, G. M. Milikh, and X. Yang (2003), On the efficiency of ELF/VLF generation using HF heating of the auroral electrojet, *Plasma Phys. Rep.*, *29*, 561–565.

M. B. Cohen, M. Gołkowski, and U. S. Inan, STAR Laboratory, Stanford University, Stanford, CA 94305, USA. (mag41@stanford.edu)