Frequency Dependence of VLF Wave Generation at Gakona, Alaska

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Objective

- Exploration of an efficient approach to generate VLF waves (3-30 kHz) by HF heater..
- This approach is particularly useful for generating radiations with freq. larger than 7 kHz, because the efficiency of the virtual ionospheric antenna in this frequency range becomes very low. As shown in Stubbe et al. [JATP **47**, 1151, 1985], the signal strength of experimentally detected VLF waves falls off as 1/f for f > 7 kHz up to 23 kHz.

How to improve it

- The mechanism is to use modulated HF heater to produce mode currents of whistler waves in the electrojet.
- It will be an active process by exciting a thermal instability:

  (1) HF wave heating results in the increase of plasma density.

  (2) Electron thermal diffusion then leads the electron temperature and density perturbations to evolve nonlinearly into periodic density irregularities varying along the magnetic field.

  (3) These periodic density irregularities couple with the temporal modulation of the electrojet to produce spatial-time dependent mode currents of whistler waves.
- In other words, the modulation current produced in electrojet is spatial-time dependences, rather than just time dependence.
- This modulation current generates whistler waves directly, rather than through antenna radiation process.

Experiments

1. Gakona Experiments in 2006

(a) X-mode HF heater of 4.9 MHz with a power of ~800 kW (ERP~ 80 MW).

(b) Rectangular wave modulation at modulation frequencies of 20 kHz, 23 kHz, 25 kHz, 28 kHz,and 2 kHz; 2 minutes each with a 50% duty cycle.

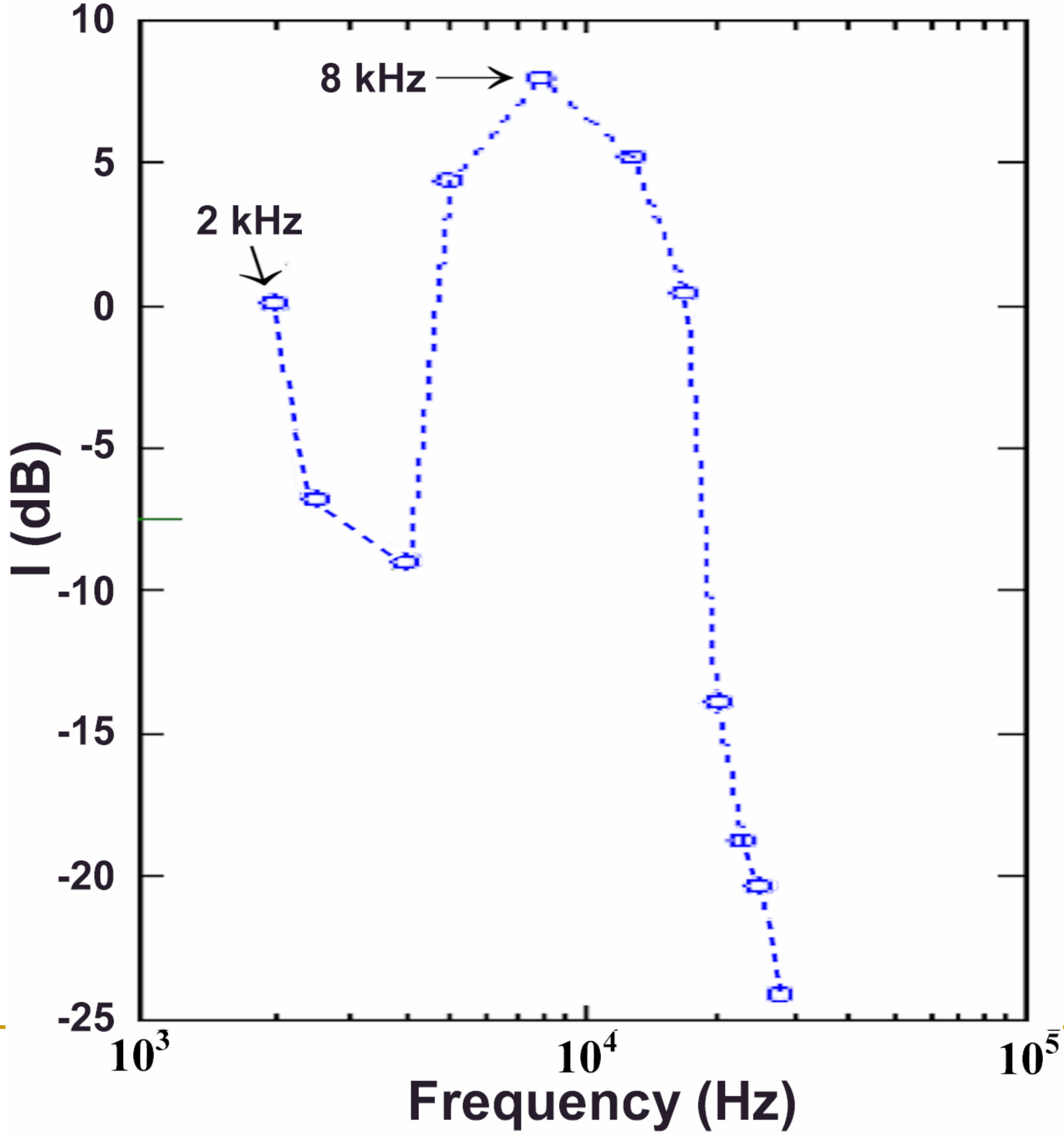
2. Gakona Experiments in 2007

(a) X-mode HF heater of of 2.75 MHz on July 30 and August 1 with a power of ~ 4 MW (i.e., ERP ~ 250 MW) and at 3.3 MHz on August 2 with an ERP ~ 400 MW.

(b) Rectangular wave modulation at modulation frequencies of 5, 8, 13 and 17 kHz each for 1 minute with a 50% duty cycle.

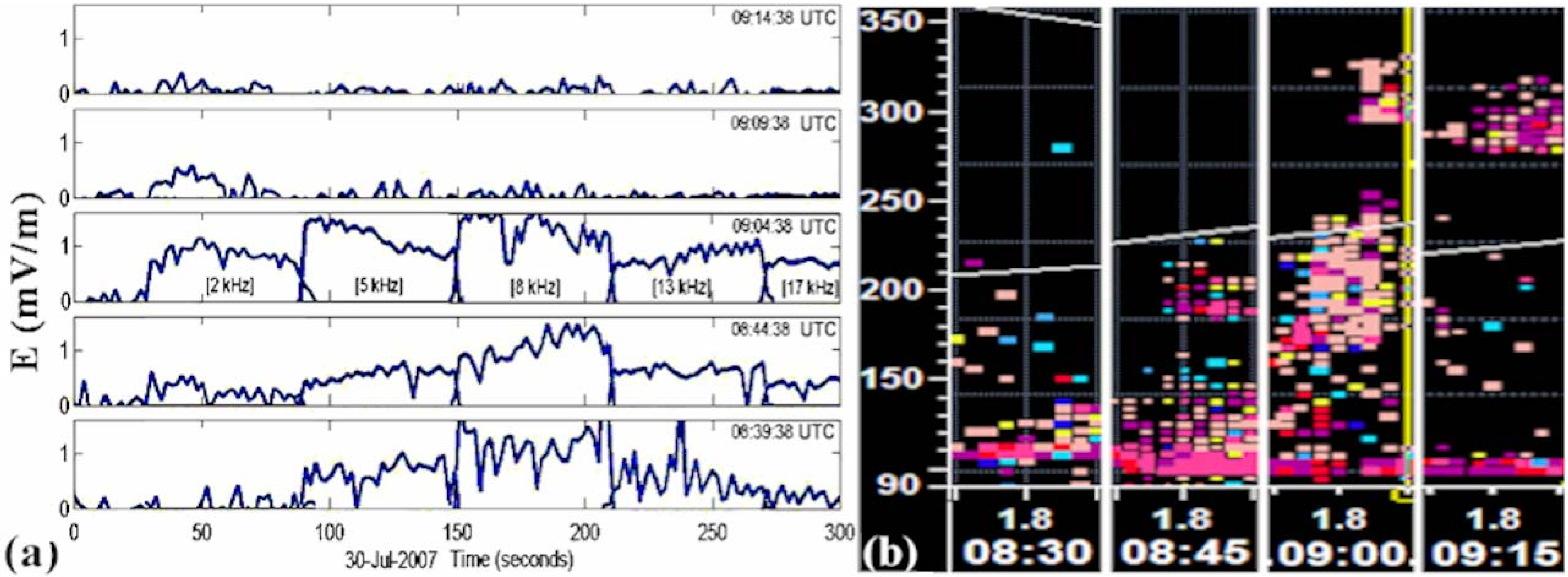
❖**a modulation wave at 2 kHz having the same rectangular waveform and duration was introduced, as a reference marker, after each sequential operation of four modulation frequencies in all experiments.**

Experimental Results



Frequency dependency of the radiation intensity. Rectangular wave modulation scheme was used in the experiments.

Experimental Results*



(a) Temporal variation of VLF emissions during the time interval of UTC 8:30 to 9:15 in experiment on July 30, 2007, and

(b) the corresponding temporal variation of the spread of the return echoes shown in the segment of the ionogram from 1.7 to 1.9 MHz.

*Spencer P. Kuo, Yen-Liang Wu, R. Pradipta, J. A. Cohen, and M. C. Lee, "VLF wave generation by amplitude-modulated HF heater waves at Gakona, Alaska", Geophys. Res. Lett., 35, L13101 (1-5), doi:10.1029/2008GL034414, June 2008.

Density Irregularity Generation Mechanism

The relation between the normalized electron density and temperature

$$n(T_e) / n(T_{e0}) \cong [0.6\,(T_e/T_{e0})^{0.7} + 0.4\,(T_e/T_{e0})^{1.2}]^{1/2}$$ (Gurevich [1978])

The dispersion relation of the whistler wave

$f_l = 13.32/\alpha^2\lambda_l^2$ KHz **where** $\alpha^2 = \langle n(T_e)/n(T_{e0}) \rangle$

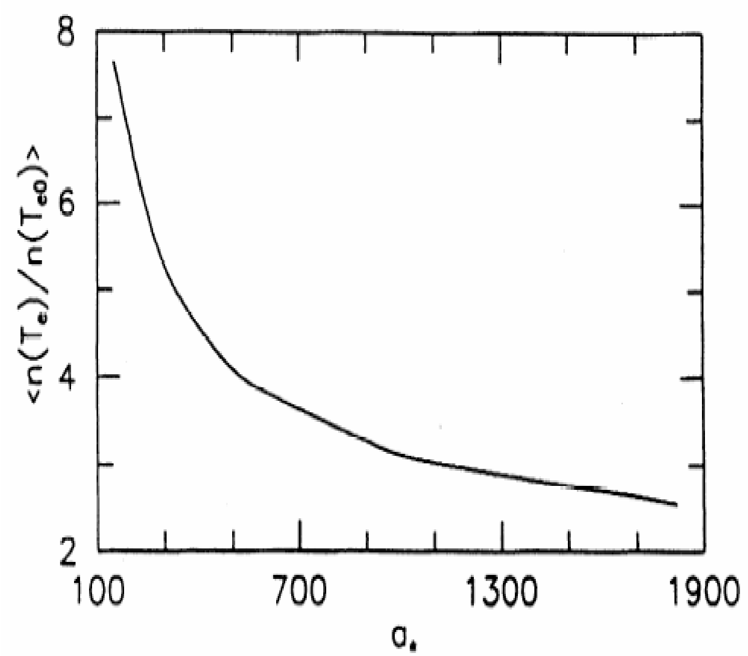


Figure 1. Normalized electron density as a function of $a_\pm$.

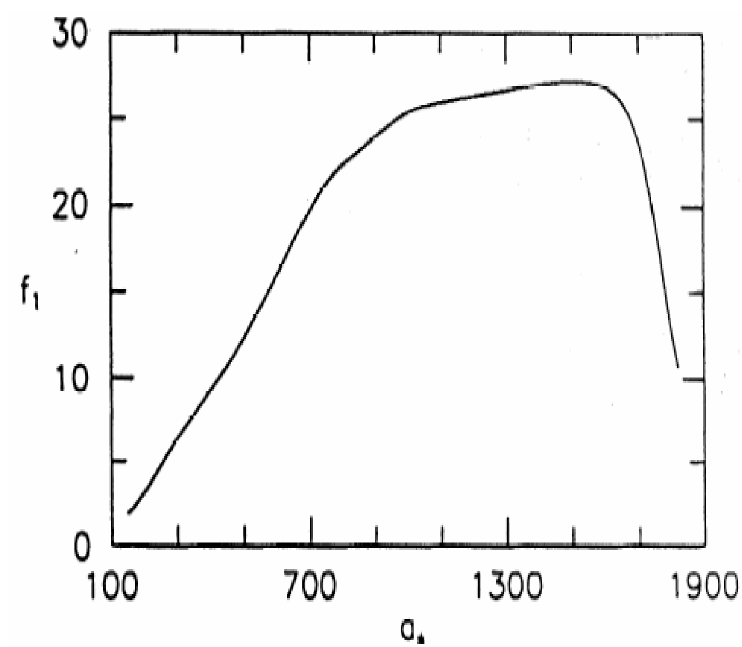


Figure 2. Modulation frequency f_1 (KHz) versus $a_\pm$.

1. **S. P. Kuo, E. Koretzky, and M.C. Lee, Plasma density enhancement and generation of spatially periodic irregularities in the ionospheric E-region by powerful HF waves, GRL, 26, 991, 1999.**
2. **S. P. Kuo, E. Koretzky, and M.C. Lee, A new mechanism of whistler wave generation byamplitude-modulated HF waves in the polar electrojet, GRL, 26, 1677, 1999.**

Relative Effectiveness of Two VLF Wave Generation Mechanisms

1) Antenna radiation

$$\mathbf{E}_a = k_1^{\,2}\,[(\hat{n}\times \mathbf{p})\times\hat{n}]\,\exp(ik_1 r)/4\pi\varepsilon_0 r$$

where the electric dipole moment of the antenna

$$\mathbf{p} = (i/\omega_1)\int \Delta\mathbf{J}_a\, dV \approx (i/\omega_1)\,\Delta\mathbf{J}_a\,\Delta z\,\Delta A$$

2) Whistler mode current

$$\mathbf{E}_w = (\hat{x} - i\hat{y})\,\mathcal{E}(k_1)\,\exp(-ik_1 z);$$

where $\mathcal{E}(k_1) = E(k_1)\Delta k$

$$\approx i(c^2\mu_0\Omega_e^{\,2}/4\omega_{pe}^{\,2}\nu_{en0})A\,\Delta z\,\Delta n\,(2\nu_{en0}k_1/\Omega_e);$$

$\Delta k \approx (2\nu_{en0}k_1/\Omega_e)$; and $A = (5e^2E_0/9m)(\nu_{en0}^{\,2}/\omega_1\Omega_e^{\,2})M_1(v_{q\pm}^{\,2}/v_{te}^{\,2})$.

Ratio

$$
\left|\mathbf{E}_w/\mathbf{E}_a\right| \approx \sqrt{2}\,|\mathcal{E}(k_1)|\; 4\pi\varepsilon_0 r\omega_1 / (k_1^2\,|\Delta J_a|\,V)
$$

$$
= (4\sqrt{2}\pi r\Omega_e^{3/2}\omega_1^{1/2} c/\omega_{pe}^3 \Delta A)[\Delta n/n_0]
$$

$$
\sim 9.1 \times (\underline{f}_1)^{1/2}[\Delta n/n_0].
$$

where $\Omega_e/2\pi \sim 1.4$ MHz; $\omega_{pe}/2\pi \sim 0.114$ MHz is calculated from the nighttime electron density at 95 km height; r = 95 km and $\Delta A \sim 100\pi$ km^2; $\underline{f}_1$ is the VLF wave frequency in kHz. Therefore, it can be seen from the ratio that the presence of 10% density irregularity (i.e., $\Delta n/n_0 \sim 0.1$) can enhance the intensity of the whistler wave at $\underline{f}_1 = 8$ by about 8 dB, consistent with the observation.

Summary and Conclusion

- The experimental results show that the VLF wave intensity does not decrease monotonically with the frequency;
- It peaks at 8 kHz, with about 7.5 dB stronger than that at 2 kHz.
- This spectral peak has a large width from 5 kHz to 17 kHz.
- The spectral intensity in this range is also larger than that of the marker.
- This discrepancy is explained in term of the whistler mode current mechanism.
- A whistler mode current radiates VLF whistler wave directly, which is more efficient than the antenna radiation mechanism.