Experimental Observations of ELF/VLF Wave Generation Using Optimized Beam-Painting

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Abstract

Observations performed during ELF/VLF wave generation experiments at the High-frequency Active Auroral Research Program (HAARP) observatory in Gakona, Alaska are used to validate a predictive optimization technique. The optimization technique employed is based on experimental observations and is used to identify the location of HF heating as well as the timing and duration of HF heating. As a result, the technique predicts an optimal heating pattern that maximizes the ELF/VLF signal amplitude received on the ground and simultaneously increases the HF-to-ELF/VLF conversion efficiency. Previous work suggested new modulation formats predicted to produce higher ELF/VLF amplitudes and efficiencies. This work presents the first experimental validation of these predictions and determines that an optimized HF beam-painting heating format can produce significantly larger ELF/VLF signal amplitudes with higher HF-to-ELF/VLF conversion efficiency than circle sweep geometric modulation.

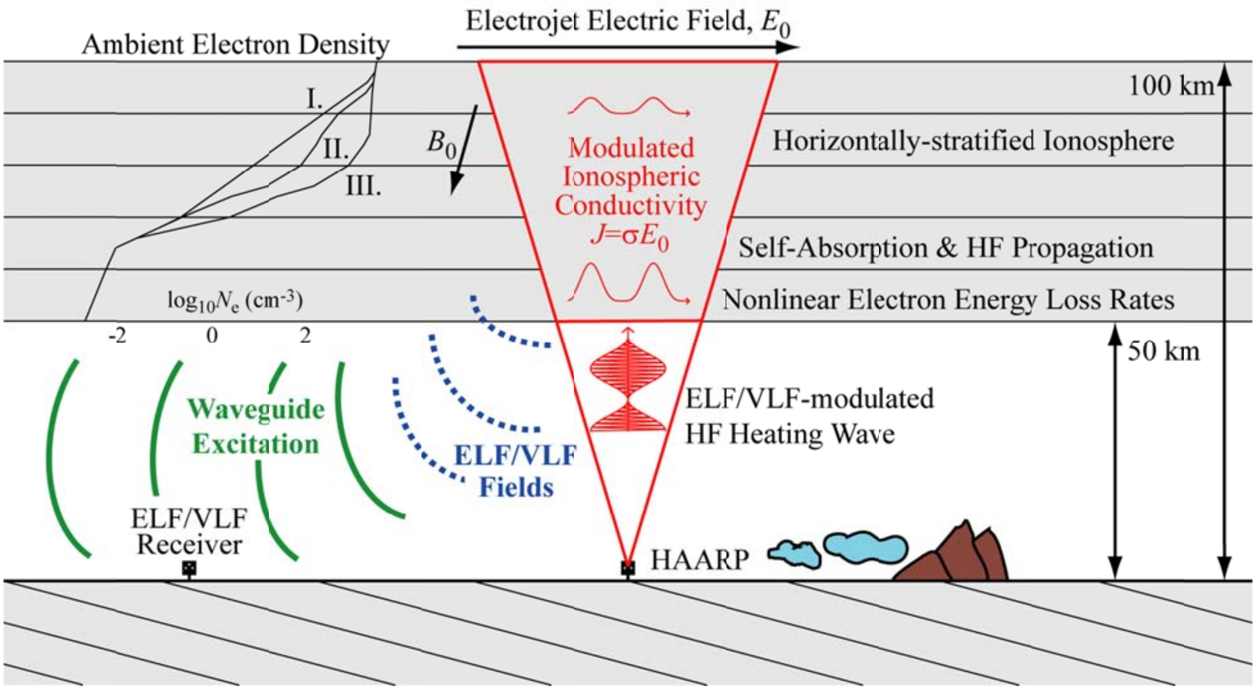

Figure 1. A cartoon diagram of ELF/VLF wave generation by modulated HF heating of the lower ionosphere.

Introduction

The generation of Extremely Low Frequency (ELF, 3-3000 Hz) and Very Low Frequency (VLF, 3-30 kHz) radio waves by High Frequency (HF, 3-30 MHz) heating of the lower ionosphere (~60-100 km altitude) has been performed since 1970's [1-4] and is depicted schematically in Figure 1. The conversion efficiency of HF-to-ELF/VLF power is very low (~0.001%), however [4]. To improve the efficiency, various HF heating techniques have been employed. In particular, a large change of the ELF/VLF amplitude is observed when the techniques produce a phased array with ELF/VLF source in ionosphere.

We investigate ELF/VLF phased arrays produced using two different techniques, depicted in Figure 2 together with standard amplitude modulated heating. The beam painting (BP) technique has been described in depth [5], and it effectively increases the area of the ionospheric ELF/VLF source region without significantly affecting the localized conductivity modulation.

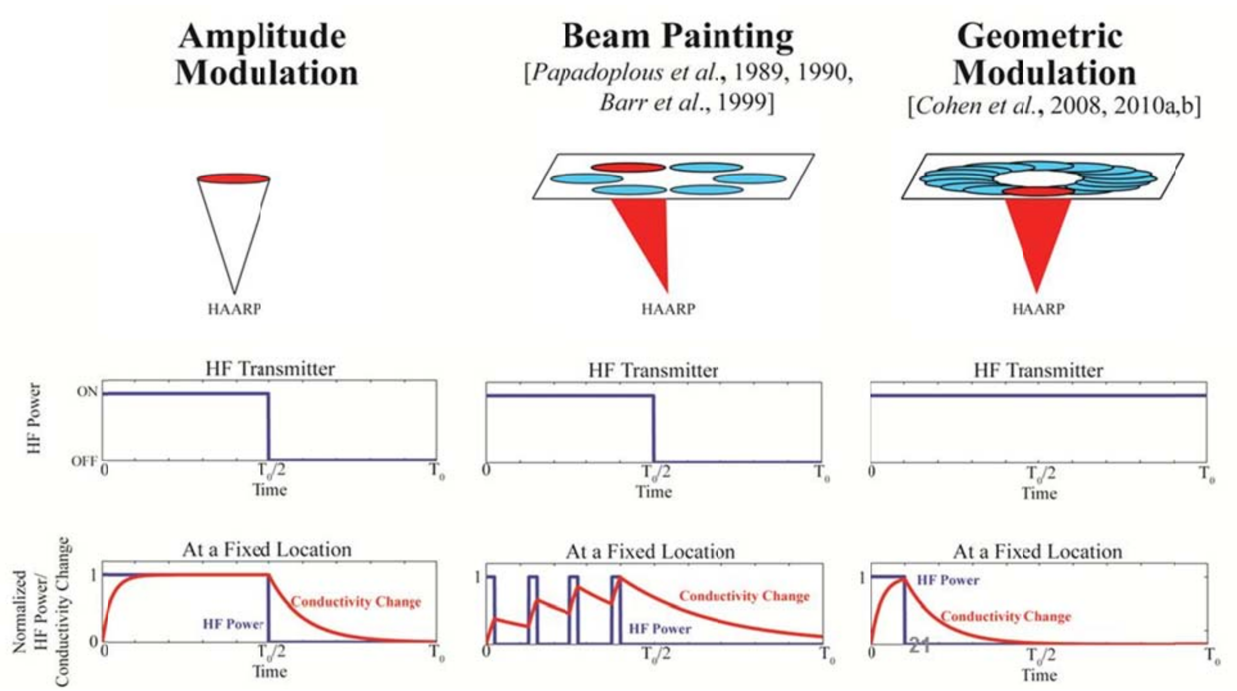

Figure 1. Schematic representation of Amplitude Modulation, Beam Painting, and Geometric Modulation transmission formats.

Geometric modulation (GM) [6] is a special case of beam painting: GM does not have any off time (the HF beam is always at full power) and GM cycles through the given spatial pattern only once per ELF/VLF period. The ~3-fold increase in generated ELF/VLF amplitude using GM drives a great deal of interest in the BP and GM techniques.

Recently, [7] demonstrated how experimental observations could be used to optimize the distribution of the source region (both spatially and temporally), predicting an additional large increase in radiated ELF/VLF power. For a given heating pattern, the technique optimizes the duration of heating at each point in the ionosphere, optimizes the off time between heating periods, and optimizes the order of heating among the selected locations, as shown in Figure 3. The transmission format, which is appropriately named "optimized beam-painting," was implemented at HAARP, and this paper presents the first experimental observations of ELF/VLF generated using the new format.

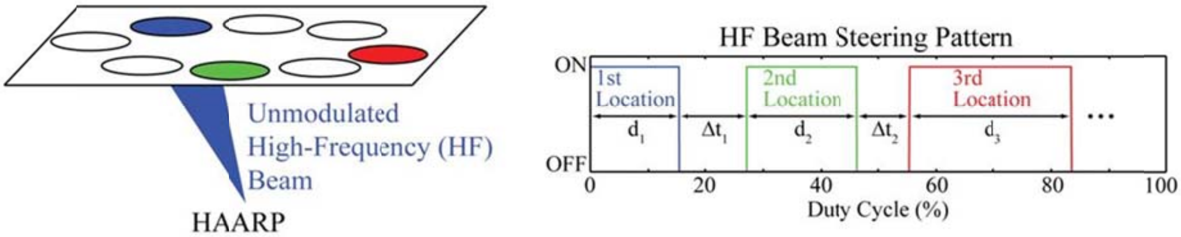

Figure 3. Amplitude, phase, and time-of-arrival (propagation delay) calculated as described in the paper.

Experimental Observations

HAARP implemented and transmitted the optimized format on 8 June 2014. The HF frequency was 3.25 MHz (X-mode), and the optimized format was transmitted alternately with AM format and GM format transmissions for reference. Observations were performed at Paradise (~100 km from HAARP, 81 deg azimuth) using two orthogonal magnetic loop antennas. Accurate timing is provided by GPS.

Spectrogram format results are shown in Figure 4. The optimized format produces a ~4 dB increase in amplitude over GM format modulation. This increase is ~3 dB smaller than predicted [7]. It should be noted that the optimized format was not developed in real time, but instead based on observations performed during a previous HAARP campaign. Thus, despite the lack of real-time information, the optimized format produces a ~4 dB increase in amplitude, and because the optimized format includes transmitter off-time, an ~8 dB increase in HF-to-ELF/VLF conversion efficiency.

Summary and Conclusions

The optimized beam painting format has been evaluated experimentally. ELF/VLF wave generation was improved by ~4 dB over the best technique currently available, and an efficiency

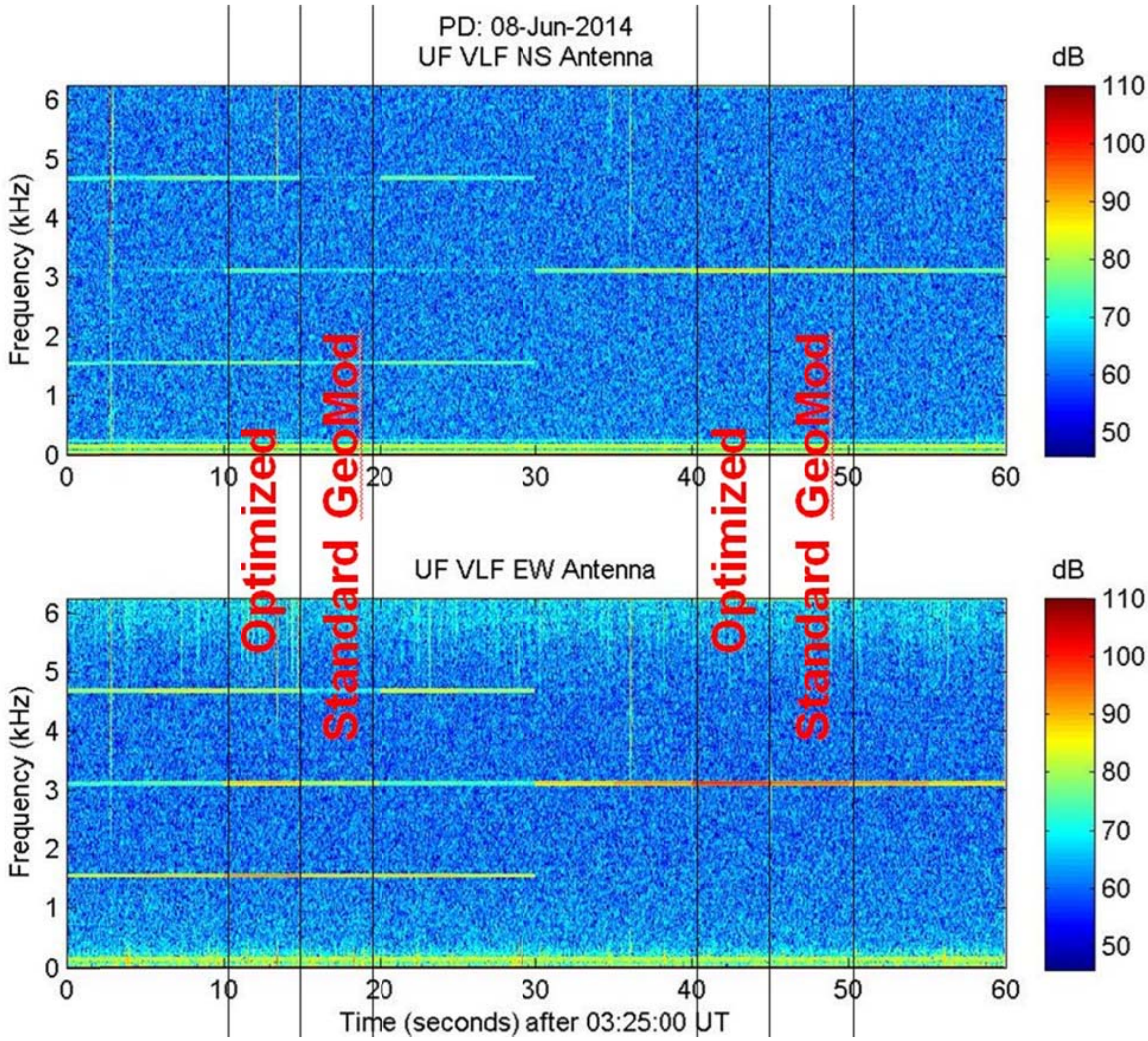

Figure 4. Spectrogram format observations at Paradise. Transmissions using standard GM format modulation and optimized beam painting are highlighted.

improvement of ~8 dB was realized. Improvements to the technique can be implemented by performing the optimization process based on more current observations.

References

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