Nonlinear Multi-Beam Interactions in the D-Region Ionosphere

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This paper presents experimental observations of ELF/VLF wave generation performed during multi-beam HF heating experiments at the High-frequency Active Auroral Research Program (HAARP) observatory. The primary objective of these experiments is to advance the scientific understanding of the nonlinear absorption processes occurring within the collisional D-region ionosphere. During the February, May, and August 2012 HAARP campaigns, a series of multi-beam HF transmissions were designed to produce inter-harmonic modulation products in the ELF/VLF range. Experiments were performed using a variety of simultaneous 2- to 6-frequency HF transmissions spaced at ELF/VLF frequencies. For instance, in order to generate the 3-frequency experiment using frequencies of 3,248,485 Hz, 3,251,515 Hz, and 3,250,200 Hz, one half of the array broadcast a synthesized-two-frequency (STF) modulation format centered on 3.25 MHz (X-mode) with a modulation frequency of 1515 Hz while the other half of the array broadcast CW at 3.250200 MHz (X-mode). In the presence of the auroral electrojet, this transmission format generated ELF/VLF tones at 1315 Hz, and 1715 Hz, and 3030 Hz, as expected. Additionally, in order to generate ELF waves by the cubic nonlinearity, one half of the array broadcast at 2,750,250 Hz while the other half broadcast at 5,499,500 Hz, generating ELF waves at 1000 Hz. These experiment were repeated using different HF frequencies, different modulation frequencies, and different HF power levels. During the May and August 2012 experiments, a frequency-time variation was imposed on the transmissions in order to enable time-of-arrival signal processing.

Experimental observations are compared with the initial results of a multi-beam HF heating model that accounts for inter-harmonic mixing among the various field components. We demonstrate that not all observations (particularly those for the cubic nonlinearity generation method) can be explained without accounting for the electron temperature oscillations that occur at the second harmonic of the HF waves.