Initial results of stimulated radiation measurements during the HAARP campaign of September 2017

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| Complete List of Authors:     | Yellu, Augustine; Virginia Polytechnic Institute and State University, Electrical Engineering  
                              | Scales, Wayne; Virginia Tech, Electrical/Computer Eng.  
                              | Mahmoudian, Alizera; InterAmerican University of Puerto Rico  
                              | Bernhardt, Paul; US Naval Research Laboratory, Plasma Physics Division  
                              | Siefring, Carl; US Naval Research Laboratory, Plasma Physics Division |
| Keywords:                     | stimulated electromagnetic emission, narrowband, wideband, parametric decay instability, stimulated Brillouin scatter, HAARP |

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Initial results of stimulated radiation measurements during the
HAARP campaign of September 2017

A.D. Yellu\textsuperscript{a*}, W.A. Scales\textsuperscript{a}, A. Mahmoudian\textsuperscript{b}, C. Siefring\textsuperscript{c}, and P. Bernhardt\textsuperscript{c}

\textsuperscript{a}Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA, USA; \textsuperscript{b}Department of Electrical and Computer Engineering, InterAmerican University, Puerto Rico; \textsuperscript{c}Plasma Physics Division, Naval Research Laboratory, Washington DC, USA

\textit{(v2.0 released January 2014)}

Initial results of stimulated electromagnetic radiation observed during an ionosphere heating experiment conducted at the High Frequency Active Auroral Program (HAARP) facility are reported. The frequency of the pump wave used in the heating is in the neighborhood of the third harmonic of the electron cyclotron frequency, and of interest are Simulated Electromagnetic Emissions (SEE) within $\pm 1$ kHz of the heating frequency known as narrowband SEE (NSEE) and the commonly known wideband SEE (WSEE) which occur within $\pm 10$ kHz of the pump wave frequency. With the transmit power maintained at maximum, and all other conditions of the experiment invariable, the characteristics of NSEE and WSEE as time progresses from the time the transmitter is switched on are detailed in the results. The dependence of the characteristics of the NSEE and WSEE with temporal evolution into the heating cycle are observed to be fundamentally different.

\textbf{Keywords:} stimulated electromagnetic emission; narrowband; wideband; parametric decay instability; stimulated Brillouin scatter; HAARP

1. Introduction

The first observations of stimulated electromagnetic radiation, more commonly known as stimulated electromagnetic emission (SEE), in an ionospheric heating experiment using the ionosphere heating facility now called the European Incoherent Scatter (EISCAT) radar near Tromso, Norway was reported in (1) and the first formal theoretical framework of SEE observed during ionospheric heating was postulated in (2). Since then, ionosphere scientists have leveraged on SEE as tool for ionospheric diagnostics. Useful diagnostics from SEE spectra include ionospheric plasma characteristics such electron temperature, ionospheric plasma dynamics and ionospheric plasma turbulence (3). Experimental observations of stimulated radiation and its theoretical foundation are well-established in the field of Laser Plasma Interactions (4) and thus intellectual transfer from this field has provided invaluable insight into SEE generated during ionosphere heating experiments.

To improve understanding of high power HF pump wave-ionosphere interaction, experiments were performed at the High Frequency Active Auroral Research Auroral Research Program (HAARP) facility near Gakona, Alaska in September 2017. Key goals of this measurement campaign include further development of SEE into a power diagnostic tool for aeronomy. Initial results from an experiment to investigate SEE conducted during this

\textsuperscript{*}Corresponding author. Email: ay113907@vt.edu
campaign are reported here. The rest of this paper is organized as follows; This intro- 
ductive section continues with a short exposition of what SEE is, an overview of past studies 
of SEE and concludes with an explicit statement of the goal of our experiment and how 
its outcome advances the state-of-art. In section 2 (‘Experiment Description and Signal 
Processing’), the experiment and experimental set-up are described, and techniques used 
to process the data are detailed. Results from our analyses are presented in section 3 and 
the paper concludes in section 4 with a discussion of the results and future work. 

SEE as used herein refers to secondary radiation that is produced when a high-power 
high frequency (HF) wave transmitted from a ground-based transmitter interacts with 
ionospheric plasma. A comprehensive review of SEE is given in (5). Scales (3) gives a 
more recent synoptic review of SEE observations at HAARP. The generation of SEE has 
been attributed to parametric decay instabilities (PDI) that develop in the ionospheric 
plasma when it interacts with a high-power HF pump wave (2). SEE can categorized into 
two (2) classes namely Wideband SEE (WSEE) which occurs within ±100 kHz of the 
pump wave frequency and narrowband SEE (NSEE) which occur within ±1 kHz of the 
pump wave frequency. Example (5) WSEE lines are as follows: 1) Downshifted peak (DP) 
which is a high intensity (relative to other WSEE spectral lines), narrow spectral line 
offset ∆f = 1-3 kHz below the reflected pump wave frequency f₀ and is generated when 
the pump wave frequency is close to a harmonic of the electron cyclotron frequency fₑₑₑ, 
2) Downshifted maximum (DM) which develops after heating has continued for some 
time. The DM is displaced ∆f = 2 × 10⁻³ f₀ below f₀, ∆f ≈ 8-10 kHz for typical 
DM observations in (1). Parametric decay instabilities PDI responsible for the DP and 
DM involve ion acoustic and lower hybrid waves as the low frequency decay products, 
respectively. DP and DM are both produced via an indirect process commencing with a 
PDI in which three waves interact (2, 5, 6) producing a downshifted electrostatic plasma 
wave. Subsequently, these scatter into electromagnetic waves resulting from beat currents 
due to growth of geomagnetic field-aligned striations in the plasma. On the other hand 
NSEE is produced by stimulated Brillouin scatter (SBS) processes which involves the 
the direct decay of the pump wave into two modes (3, 7). The WSEE feature of primary 
interest in this study is the DP.

After the first NSEE observations which showed remarkably strong SEE (as com- 
pared to previous SEE observations) located with 10s of Hz of the reflected pump wave 
frequency were reported in (7, 8), their predominant generating mechanism described, 
and the dependence of SBS on the geomagnetic field studied, several investigations 
(9, 10, 11, 12) to evaluate the effect of pump wave frequency, transmitter power and 
direction of beam of the transmitter antenna relative to the local geomagnetic field on 
NSEE generation have been conducted. An abbreviated review of NSEE research status 
is given by Scales (3). Consult (5) for a comprehensive review of WSEE. The goal of the 
experiment described in this paper is to investigate the temporal evolution of the charac- 
teristics of NSEE and WSEE. Specifically, we compare NSEE and WSEE characteristics 
immediately after after pump turn on with those at latter parts of the heating cycles for 
heating near 3 fₑₑₑ. As will be shown, these observations are quite unique compared to 
past results and provide further insight into the physical processes producing SEE.

2. Experiment description and signal processing

The HAARP facility located at latitude 62°23′24″N, longitude 145°9′0″W was the source 
of the pump wave used for the the heating. The ionosphere reflected pump wave was 
monitored at a receiving station located about 8 km from the HAARP facility. The 
receiving station set-up comprised two dipole antennas oriented orthogonal to each other.

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Each dipole was connected to a high sensitivity SDR-IP Wideband Digital Radio receiver from RFSPACE. These two receivers were synchronized using a GPS clock. Although there were other receivers monitoring harmonics of the pump frequency, the results in this paper are from only one of the receivers that monitored effects around the the pump wave frequency. The HAARP facility transmitted at a maximum power 2.78 MW. The transmitter was operated in continuous wave, ordinary wave mode. The zenith and azimuth angles of the transmitting antenna beam were 14° and 198° respectively.

The frequency of the transmitter was stepped from 4.35 MHz to 4.35 MHz in 20 kHz. These frequencies are near 3f_{ce} where f_{ce} ≈ 1.40 MHz. The duration of heating at each frequency was 60 seconds. There was an intermission of 30 seconds before heating starts at the next frequency to allow the ionospheric plasma an opportunity to relax to its quiescent state after heating. The duration of the experiment was 23:02:00 UTC-23:18:00 UTC on September 24, 2017. The results presented in this paper are for heating at 4.25 MHz. The time frame of the heating cycle for 4.25 MHz was 23:09:30 UTC-23:10:30 UTC. As a control real-time monitoring of the frequency spectrum within a few 100s of kHz around the pump wave frequency, logging of data from the receivers commenced several minutes before the start of the experiment. The presence, if any and the frequencies of interfering signals were noted. The receiver samples at 500 kHz. In computing the short-time Fourier transform (STFT) also known as the spectrogram and the power spectrum, the recorded data was divided into sections such that the frequency resolution ≈ 1 Hz. The power spectrum for a time window is the average of the power spectra for all the segments that fit within the time window. The duration of each time window was chosen so that an integer number of segments fits in the time window. A Blackman window was applied in computing the spectrograms and the power spectra. Matlab was used in the signal processing of the receiver data.

3. Results

The time evolution of the observed SEE features during a single heating cycle are depicted in Figure 1. Both spectrograms in Figure 1 cover the time period from 2 s before the start of the heating cycle to 20 s into the 60 s heating cycle. In the spectrograms, the start of the heating cycle corresponds to an absolute time offset of 0 s (on the ordinate axis). The spectrogram on the left panel shows NSEE features within ±100 Hz of the ionosphere reflected pump wave frequency. Sections of this spectrogram are annotated SBS where the NSEE is easily seen. As stated earlier, a primary source of NSEE is Stimulated Brillouin scatter (SBS). The spectrogram on the right panel shows WSEE spectral lines within ±10 kHz of the reflected pump wave frequency. A downshifted peak DP is seen approximately 2 kHz below the pump wave frequency.

From Figure 1, it can be seen that the NSEE appears immediately after the heating starts. The onset of the DP WSEE lags the NSEE by approximately 1 s. Moreover whereas the NSEE is bursty (occurring between 1 s - 2 s, 2 s - 3 s, 10.5 s - 11.5 s etc.), the WSEE DP is continuously present after its onset (at least for 20 s into the heating cycle in Figure 1). This fact provides further confirmation that the generation mechanism for NSEE is indeed different from that of WSEE.

The power spectra ±100 Hz within ionosphere reflected pump wave frequency for two sections of the heating cycle are shown in Figure 2. The upper panel is the power spectrum for the first 2.1 s of the heating cycle. The lower panel is the power spectrum for 40 s - 59.9 s into the heating cycle. Although a monochromatic, continuous wave was was transmitted from the HAARP facility, a prominent feature in the reflected pump wave during the first 2.1 s of the heating cycle is the spectral broadening of approximately 25
Figure 1. Evolution of SEE spectral lines with time. Both spectrograms cover the time period from 2 s before pump turn on to 20 s after pump turn on. Figure on the left show narrowband SEE (NSEE) within 20 Hz or so of the ionosphere reflected pump wave. Sections of this spectrogram where the NSEE is obvious have been labeled SBS. The spectrogram on the right shows a wideband SEE feature namely the downshifted peak (DP). Intensity scale of the spectrogram on the right has been compressed to highlight WSEE DP. Time frame of the heating cycle for 4.25 MHz was 23:09:30 UTC-23:10:30 UTC, September 24, 2017.

Hz around the pump wave frequency. This NSEE is believed to be primarily due to SBS. Another notable feature is that this broad NSEE is very strong and only 15 dB below the peak of the ionosphere reflected pump wave. During the latter part of the heating cycle as shown in the lower panel of Figure 2, there is a downshifted NSEE 7 Hz below the pump wave frequency. This downshifted NSEE is 30 dB below the peak of the ionosphere reflected pump wave. It is in line with past investigations of SBS generated during heating experiments (9, 10, 11, 12).

Figure 2. Narrowband SEE features for different time periods of the heating cycle. Upper panel is for the first 0 s - 2.1 s after turn on. The lower panel is for the 40 s - 59.9 s into the heating cycle.
The power spectra of WSEE \( \pm10 \) kHz within the ionosphere reflected pump wave frequency corresponding to the same sections of the heating cycle as the narrowband spectra in Figure 2 are shown in figure 3 below. Early in the heating cycle (within 2 seconds) there is little evidence of the DP. However after this period there is evidence of the DP and a very weak DM.

![Wideband SEE features for different sections of heating cycle. Upper panel is for the first 2.1 s after turn on. The lower panel is for the 40 s - 59.9 s into the heating cycle.](image)

4. Conclusions

Initial results of an ionospheric modification campaign at the HAARP facility have been presented. These results underscore that WSEE and NSEE have a fundamentally different physical nature. NSEE tends to be much stronger with a faster growth time than WSEE. As shown in these results NSEE develops very rapidly, within 1 second of the heater turn-on, assuming sufficient power to be above the PDI threshold. Due to the strong build up of the PDI, NSEE may exhibit a relatively broad spectral characteristic for sufficiently high pump power. Later in the heating cycle the spectrum appeared as a much narrower well defined spectral line. Early (within a few seconds) in the heating cycle the prominent WSEE spectral lines (e.g. DP) were absent. However when WSEE is well developed and nearly continuous in strength, the NSEE exhibits a very intermittent character. There are number of possibilities for this. One important reason could be the development of geomagnetic field-aligned striations that are necessary for the WSEE process and not NSEE. The observation of the WSEE relies on the growth of these striations which takes a period of several seconds. The development of these striations may in some sense inhibit the development of NSEE and lead to its bursty, intermittent nature. This may be likely due to the fact that the WSEE and NSEE are generated at different altitude layers in the ionosphere with the NSEE being generated at a slightly higher altitude nearer the plasma resonance layer. Further analysis is ongoing to consider striation development using High Frequency HF radar observations during the experiment. It is also clear that NSEE observations are much more in line with the past research observations during
laser plasma interactions and this body of work over the past several decades may be used to make progress in both understanding physical processes associated with NSEE and also further developing it as a powerful diagnostic during ionospheric modification experiments.
References


