The Largest Ionospheric Disturbances Produced by the HAARP HF Facility

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ABSTRACT

The enormous transmitter power, fully programmable antenna array, and agile frequency generation of the High Frequency Active Auroral Research Program (HAARP) facility in Alaska has allowed the production of unprecedented disturbances in the ionosphere. Using both pencil beams and conical (or twisted) beam transmissions, artificial ionization clouds have been generated near the 2nd, 3rd, 4th, and 6th harmonics of the electron gyro frequency. The conical beam has been used to sustain these clouds for up to 5 hours as opposed to less than 30 minute durations produced using pencil beams. The largest density plasma clouds have been produced at the highest harmonic transmissions. Satellite radio transmissions at 253 MHz from the NRL TACSat4 COMMX experiment have been severely disturbed by propagating through artificially plasma region showing greater than 16 dB scintillations and an S4 index of unity. Similar propagation experiments with the ePOP CERTO beacon with signals aligned with the geomagnetic field show 25 dB scintillations at 150 MHz and 20 dB Scintillations at 400 MHz. Previous attempts to produce scintillations with ionospheric heating have been limited to 3 dB or less. The CERTO beacon transmissions have measured artificial enhancements in field-line integrated electron densities that were over 2 TECU. The goals of future HAARP experiments should be to build on these discoveries to sustain plasma densities larger than that of the background ionosphere for use as ionospheric reflectors of radio signals.

1. INTRODUCTION

High power radio waves in the 2.6 to 10 MHz frequency range can produce a wide range of modifications to the F-region ionosphere. Figure 1 documents the basic physical phenomena responsible for the artificial changes in the ionosphere. As pointed out by Carlson and Jenson [2014], thresholds in HF power are needed to initiate different levels of disturbances in the ionosphere. The lowest powers for the pump electromagnetic (EM) wave are used to increase the electron temperature and produce localized regions of enhance pressure that are communicated along magnetic field lines by thermal conduction and plasma diffusion. Field-aligned plasma irregularities are produced with increases in HF power where a thermal parametric instability channels high frequency electrostatic wave (Langmuir and Upper Hybrid) inside field aligned cavities that are intensified by the pressure of the waves. The generation of electrostatic waves is either by (1) direct mode conversion where the frequency of the wave from electromagnetic to electrostatic does not change or by (2) parametric decay where a low frequency electrostatic (ES) wave and a high frequency electrostatic wave is simultaneously excited with the sum of their frequencies equal to the frequency of the driving wave. The driving wave can be either electromagnetic or electrostatic. Mode conversion of the high frequency electrostatic waves back to an EM waves yields stimulated electromagnetic emissions that can propagate to the ground for reception as a downshifted sideband of the original EM pump wave. If the phase velocity of the high frequency waves matches the velocity of electrons, then these electrons can be accelerated to large enough energies to produce artificial aurora or breakdown ionization of the background neutral species.

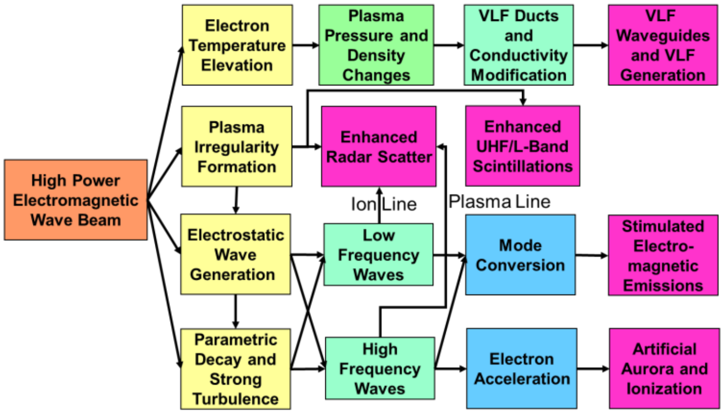

Figure 1. Four basic processes that describe the physics of high power interactions with the plasma in the ionosphere. The thresholds for each process increases from top to bottom. Enhancement of self-action effects involve feedback and coupling between two or more processes.

The upper-atmospheric science community has access to a large number of high power HF transmitters used to modify the F-region ionosphere. These include SURA in Russia [Belikovich et al., 2007], EISCAT Heating in Norway [Kosch et al 2014], and the soon to be operational Arecibo HF facility in Puerto Rico. Each facility has unique capabilities because of their location with ambient electron densities that tend to be larger at lower latitudes and the inclination of the magnetic field which ranges from horizontal at the equator to nearly vertical at high latitudes. In terms of pure power, the HAARP facility in Gakona Alaska ranks the highest and has produced a number of disturbances in the ionosphere not seen at other facilities. The next sections illustrate some of the most prominent ionospheric disturbances in terms of plasma density enhancements, irregularity formation, plasma wave generation, and optical emissions.

2. ENHANCED DENSITIES

Generation of artificial enhancements of the electron plasma density by high power radio waves is currently a unique capability of the HAARP facility in Alaska [Pedersen et al., 2009; 2019]. This is primarily due to (1) the continuous power capability of the transmitter (3.6 MW total), (2) the highest gain of the 12 x 15 element array (30 dB at 10 MHz), and (3) the full range frequency agility of the HAARP system (2.6 to 10 MHz). As will be shown later, the beam-pointing and beam-forming ability of the HAARP array is also very important for producing artificial plasma clouds with HAARP.

Observations of artificial ionization at HAARP are usually based on HF reflection at the critical density regions recorded with the digital ionosonde at Gakona. The ionosonde records show an initial electron density growth at the point the pump frequency matches the existing plasma frequency profile. This indicates that formation of artificial plasma clouds requires an ambient ionosphere with a density greater than the critical density for reflection of the HF pump wave. At the early phase in the plasma cloud formation, a diffuse ionosonde signature is observed and usually unstable optical emission structures are seen with a wide range of dynamics.

After about a minute, the ionization enhancements transition into excitation of a single mode at a gyro harmonic resonance that may potentially be maintained after the decay of ambient ionosphere. This is seen as an isolated signature in the ionograms. For a single, pencil beam using the HAARP antenna with uniformly distributed phase across the array, the plasma clouds drop in altitude. The top of the cloud is screened from the HF by enhanced plasma that is formed on the bottom of the cloud and recombination/diffusion eliminates the topside plasma. This process is illustrated in Figure 2 for transmissions near the 3rd gyro harmonic of the electron gyro frequency over HAARP.

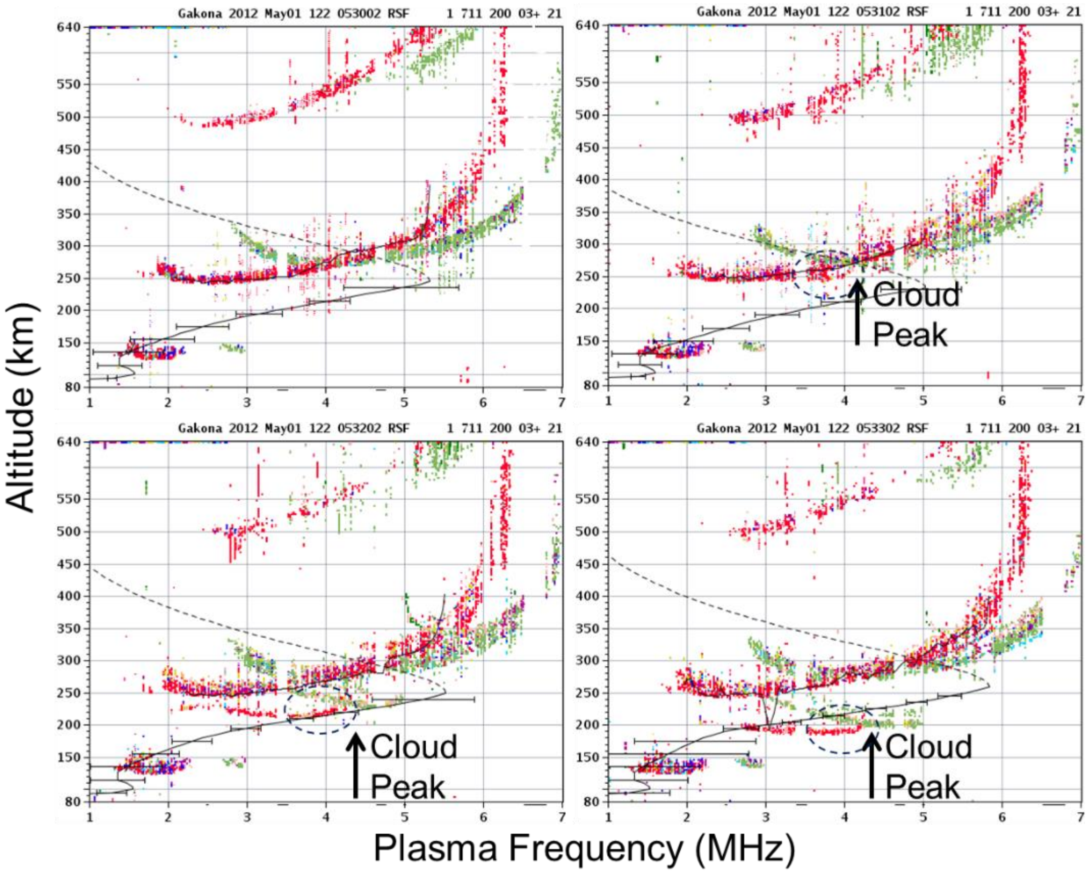

Figure 2. Artificial ionization cloud formed with peak plasma frequency at the 3rd electron gyro harmonic around 4.325 MHz. The altitude of the cloud descends with time.

To search for and maintain a gyro resonance with the plasma cloud as it drops in altitude, the transmitted HF wave is swept with a slow rise in frequency. As the frequency increases, it excites plasma waves which re-radiate as stimulated electromagnetic emissions (SEE). The SEE spectra for the plasma shown in Figure 2 are illustrated in Figure 3. Short gaps in the HF transmissions from HAARP are used to form the ionograms shown by the insets on the figure. The SEE comes from excitation of the plasma both in the ambient ionosphere and in the artificial plasma region below the background layer.

With this process, enhanced plasma regions can only be formed with densities lower than the density of the background plasma. Figure 4 shows artificial ionization clouds produced at the 2nd, 3rd, 4th, and 6th harmonic of the electron cyclotron frequency near 1.44 MHz. Plasma clouds with gyro harmonic transmissions near the 5th harmonic at 7.2 MHz because this frequency is in the middle of the amateur radio band. The last ionogram in Figure 4 uses a transmitter frequency of 8.58 MHz to produce the densest plasma cloud ever sustained by HF transmissions with HAARP.

One objective of the artificial ionization experiments at HAARP is to form plasma clouds with densities larger than the background ionosphere. In the laboratory, it has been shown that lower powers are needed to sustain a plasma cloud than to initiate the breakdown process [Bernhardt et al., 2015]. Some experiments at HAARP have attempted to initiate plasma clouds at a lower gyro harmonic and then hop to the next harmonic frequency (say step from the 3rd to the 4th harmonic) to use the existing plasma cloud as a seed for the denser plasma cloud. Thus far, this technique has not been successful a producing clouds with higher densities than the background.

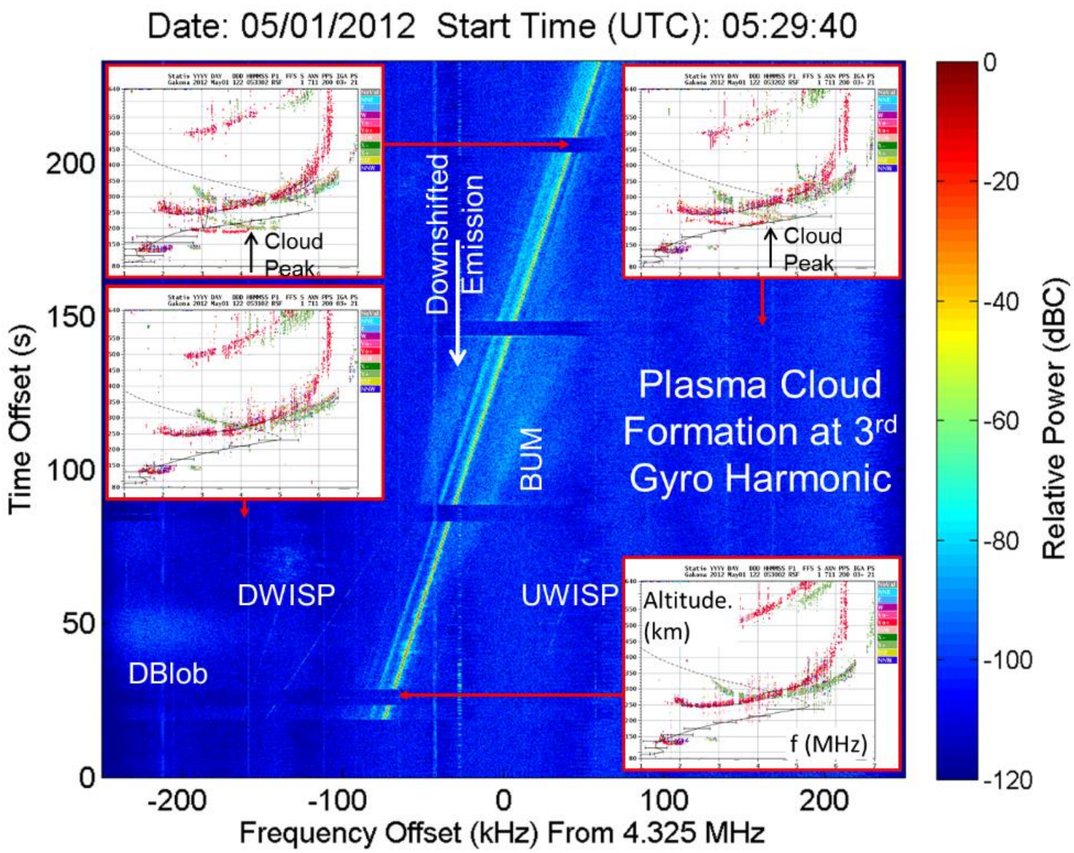

Figure 3. Stimulated electromagnetic emissions (SEE) observed during a 3rd f_{ce} frequency sweep that produced artificial plasma clouds.

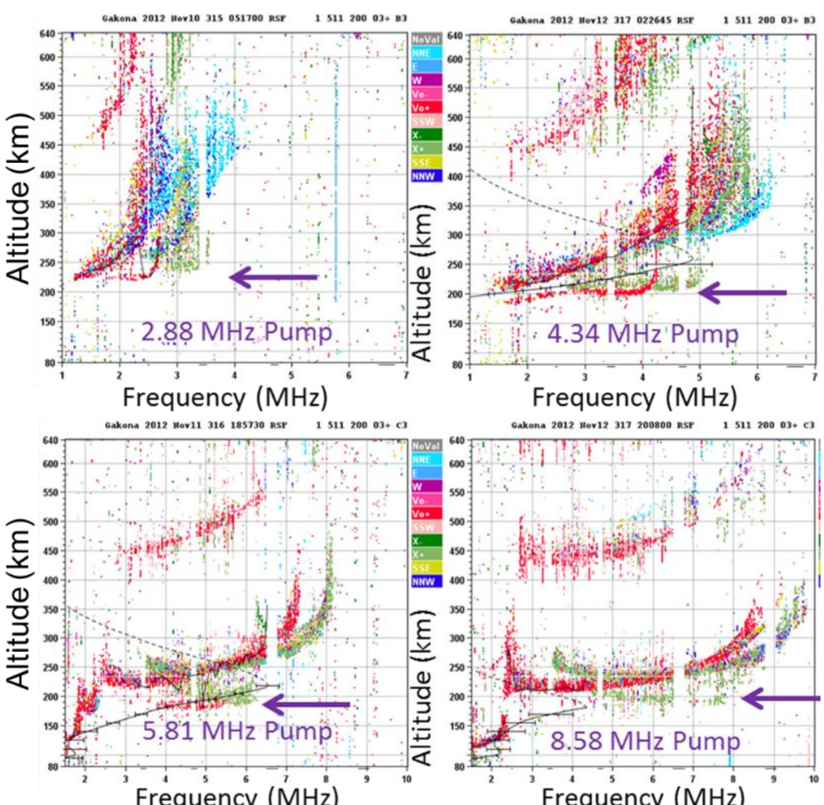

Figure 4. Tuning HAARP to the 2nd, 3rd, 4th, 6th gyro harmonics to form plasma clouds near multiples of 1.44 MHz electron cyclotron frequency.

Another approach to forming artificial ionization with densities above ambient is to sustain a plasma cloud while the background ionosphere decays after sunset. The formation of a stable plasma cloud using a pencil beam is not possible because of the altitude reductions associated with plasma formation on the bottomside as described above. The only way to form a long duration patch of artificial ionization is to use a structured beam. With proper phasing of the HAARP array transmissions, a "twisted beam" can be formed that an annulus pattern with minimum power at the center. Briczinski et al. [2015] has shown than this beam can form regions of artificial ionization even though the peak electric field in this wider angle beam is about 5 dB less than the power of a pencil beam at the same frequency. Simulations of the pencil and twisted beams for HAARP are given as antenna gain patterns in Figure 5. The zero order L=0 mode forms a single maximum with a gain of 24 dB. The first order L=1 mode forms a ring with a maximum gain of 19 dB.

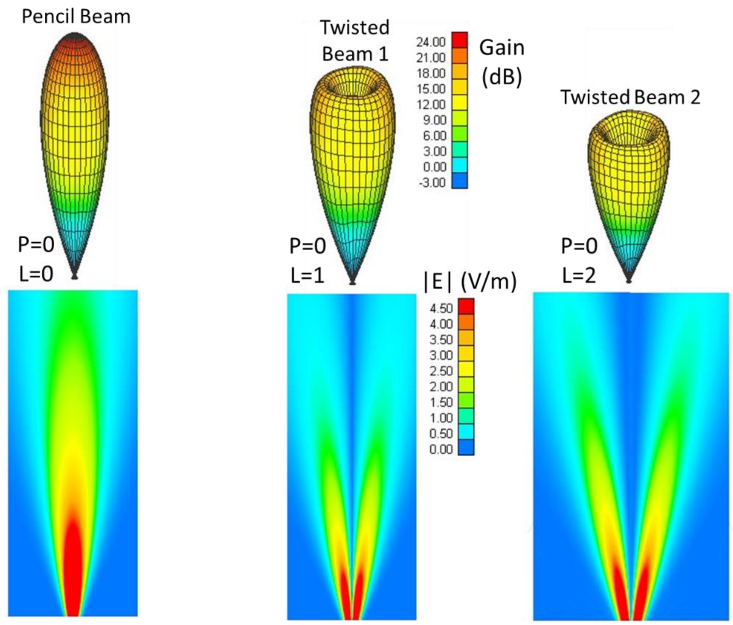

Figure 5. HF array beam twisted-beam modes formed by exciting the HAARP array with the phase equal to integer multiples of the azimuth angle from the central point of the array.

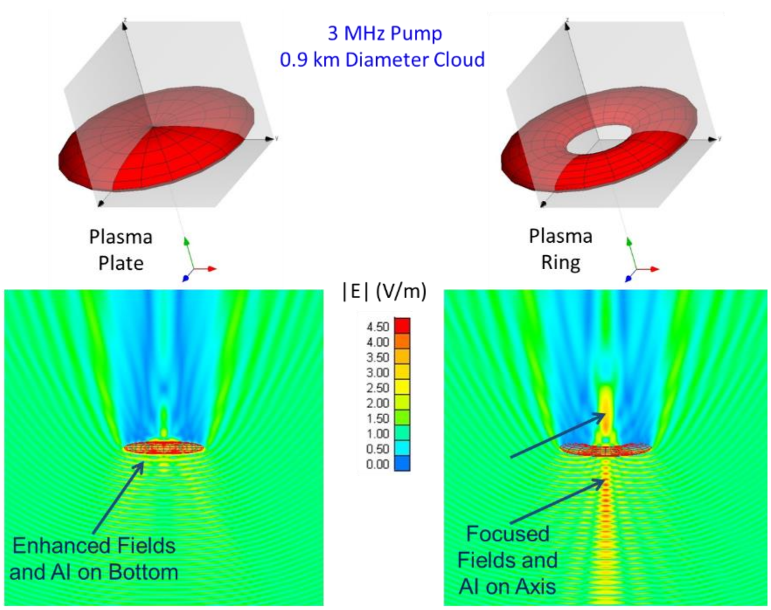

Figure 6. Numerical electromagnetic simulations of plate and ring distributions illuminated by a 3 MHz electromagnetic wave. The plasma plate intensifies the incident electric field on the bottom. The ring structure produces plasma breakdown above and below the cloud height.

One factor that makes the L = 1 twisted beam successful at sustaining a long duration plasma cloud is the electromagnetic field interactions with horizontal ring-structure in the cloud. Figure 6 shows a simulation of a plane wave impinging on a pancake-plasma cloud and a toroidal plasma cloud. The plasma pancake from a pencil beam will concentrate all the large amplitude fields on the bottom of the plasma where enhanced plasma production will occur. The plasma ring will focus some electric fields on the axis, bottom and sides of the cloud to form horizontal gradients that do not drop in altitude.

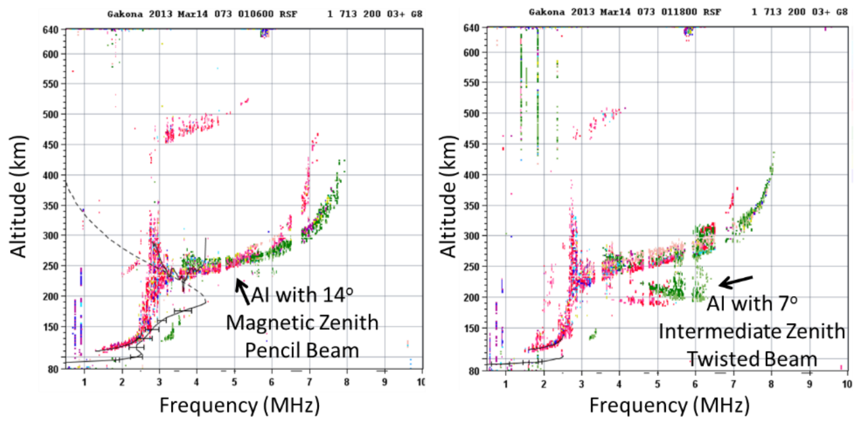

Figure 7. Ionosonde signatures of artificial ionization (AI) with a 5.8 MHz pencil beam points at the magnetic zenith (MZ) and a 5.8 MHz twisted beam pointed between MZ and vertical. The transmissions started at 01:06 GMT with the pencil beam and 01:10 GMT with the twisted beam in virtually the same background ionosphere.

Using both pencil and twisted beams, HAARP transmissions were made at 5.8 MHz near the 4th gyro harmonic. The L=0 pencil beam produced very little enhanced ionization but the L=1 twisted produced much stronger artificial ionization even though the peak electric field was 5 dB lower (Figure 7). At 5.8 MHz, the twisted beam has peak power at a 7 degree offset from the beam axis. The beam was tilted at 7 degrees over the vertical along the magnetic meridian to align a portion of the ring-beam with the magnetic field and another portion of the beam with the vertical. This produced the strongest artificial ionization at a fixed altitude. Once the plasma cloud was formed with the twisted beam, the 5.8 MHz transmissions were continued for 5 hours to follow the evolution of the plasma clouds. The ionograms from the Gakona Digisonde were analyzed to give a true-height profile of the plasma cloud. Samples of these profiles for the first 3 hours of excitation are shown in Figure 8. The characteristics of the artificial plasma region are (1) the peak density is clamped to the critical density corresponding to the 5.8 MHz pump, multiple ionization patches form in the 1.5 to 2.0 hour segment since initiation of the cloud, and the height of the artificial ionization region slowly moves 170 to 200 km altitude range. The 4th gyro harmonic experiments at 5.8 MHz with an L=1 twisted beam produced the longest sustained plasma cloud observed with HAARP. Residual plasma structures during the continuous pumping period were seen optically at 05:30 GMT, 4½ hours after the start of the experiment.

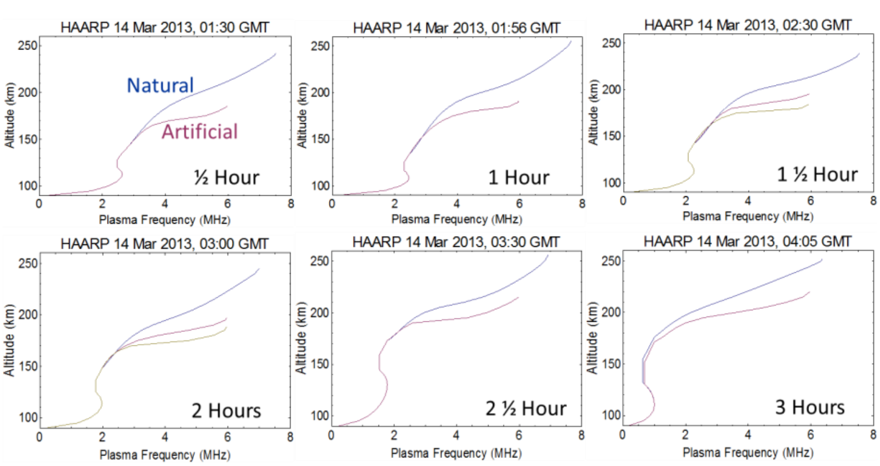

Figure 8. Natural and artificial ionization profiles of the ionosphere provided by the HAARP ionosonde. The altitude of the plasma cloud remains offset from the background layer by about 40 km for the period of extended high power HF pumping at 5.8 MHz.

3. ARTIFICIAL IRREGULARITIES

Satellite beacon signals passing through the modified ionosphere provide a power technique for measuring artificially created plasma irregularities. The generation of artificial irregularities that can produce radio scintillations is important for testing of navigation, communications and radar system susceptibility to natural ionospheric disturbances. Up to now, high power radio waves have not been able to duplicate the strong scintillation environment of the natural ionosphere associated with auroral arcs, intense substorms and polar cap patches. On measure of amplitude scintillations is the S4 index which is the radio of the standard deviation of signal intensity to the average signal intensity. Natural irregularities during solar maximum at high latitudes that produce S4 indices above 0.6 are considered strong and they can have serious impacts on UHF satellite communications and the operation of other UHF systems [Basu et al. 1982]. Strong phase scintillations at high latitudes have been recorded even during solar min [Prikryl et al., 2010].

Previous attempts to generate UHF radio scintillations with ionospheric heaters have produced detectable but weak fluctuations in satellite and radio star signals passing though the modified plasma. Frey et al. [1983] detected radio star scintillations at 933 MHz with an S4 = 0.05 or less. Basu et al. [1987] measured amplitude scintillations at 250 MHz the largest reported S4 of 0.2 using EISCAT 5.423 MHz transmissions at effective radiated power (ERP) of 218 MW. Subsequent experiments at EISCAT using frequencies between 3.85 and 5.56 MHz with 240 MW ERP were reported by Basu et al [1997] and Costa et al [1997]. These experiments yielded 4 dB fluctuations in 250 MHz signals and S4 indices between 0.1 and 0.35. An S4 index of 0.3 or less is considered weak scintillations and most UHF systems will not be adversely affected. Current research at HAARP is designed to increase the intensity of artificial irregularities and to produce UHF radio scintillations with S4 indices approaching unity.

The moderate level of radio scintillations produced by high power radio waves have been attributed to self-focusing instabilities which redistribute the plasma into field aligned irregularities (FAI). UHF waves passing through the region of enhanced FAI develop random and distorted phase fronts. As the disturbed wavefront propagates past the irregularity region to the ground, diffraction and phase front mixing produces an amplitude pattern. The motion of this pattern past a receiver antenna causes amplitude and fluctuations called scintillations. Recently, the HAARP facility in Alaska has been able to create artificial ionization clouds with potentially stronger fluctuation in electron densities. Several recent experimental campaigns were conducted to measure the UHF scintillations associated with these artificial ionization regions.

To monitor the scintillations from artificial ionization regions, the NRL TACSat4 was tasked to transmit 253 MHz through the ionosphere over HAARP. TACSat4 which is in orbit with a 63 degree inclination contains the COMMX experiment to demonstrate the capabilities of VHF/UHF SATCOM. TACSat4 is in a repeating orbit that flies directly over the HAARP transmitter. For the HAARP experiments, the 401.25 MHz beacon transmissions for DORIS stations at Cold Bay Alaska and Yellow Knife Canada were received by the TACSat4 COMMX receiver. COMMX then translates these signals to 253 MHz for re-broadcast with using the high gain parabolic antenna on the satellite. This antenna was continuously pointed to the ground receiver located directly underneath the HAARP modified ionosphere. The NRL ground receiver system for TACSat4 translated the VHF/UHF signals to 10.7 MHz for digitization by a software based receiver for further processing. A schematic of TACSat4/HAARP scintillation experiment is illustrated in Figure 9.

The VHF/UHF SATCOM scintillations from the HAARP/TACSat4 experiments are up to 20 dB larger than any previously observed during ionospheric modification experiments using high power HF waves. A sample of the scintillation results are shown in Figure 10. Up to 20 dB enhancements of scintillations and S4 indices of over 1.0 have were detected during these experiments over the period of 3 March 2013 and 16 March 2016. The strongest effects of one VHF/UFH SATCOM were produced with a continuously pumped HF wave near the 3rd and 4th gyro harmonics with both pencil and twisted beam. The scintillation index for 253 MHz was typically between 0.6 and 1.0 whereas all previous attempts are affecting the 250 MHz band with high power HF in the ionosphere only yielded scintillation indices of 0.2 or less. This is a significant change in the level from weak to strong scintillations when artificial ionization clouds are formed.

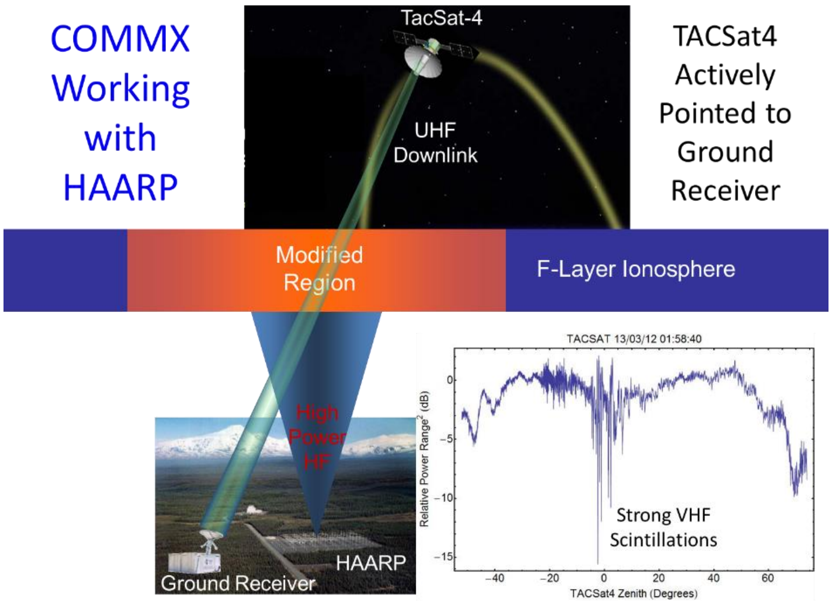

Figure 9. Satellite transmissions from TACSat4 along a propagation path in the ionosphere illuminated by the high power HAARP beam. The strong 253 MHz occur with the satellite orbit carries the COMMX/TACSat4 transmissions through the region of artificial ionization by HAARP.

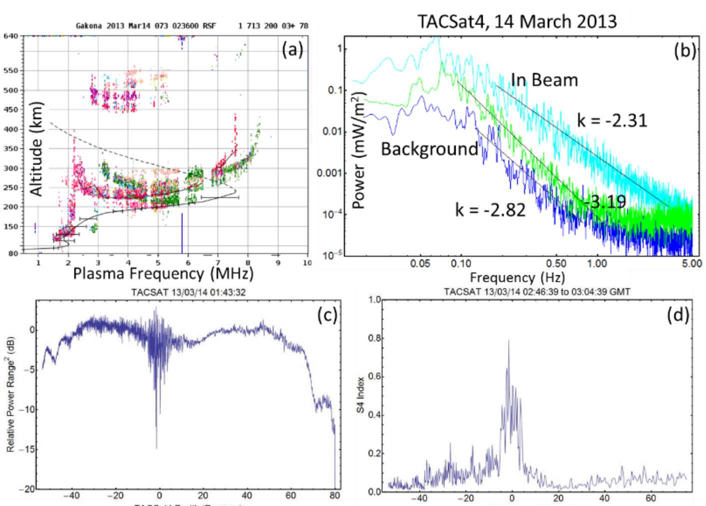

Figure 10. 14 March 2012 TACSat4 253 MHz scintillations produced by 4th (5.8 MHz) Gyro harmonic HF transmissions from HAARP with a continuous twisted beam. The artificial ionization profile (a) with a peak plasma frequency of 5.8 MHz causes a 10 dB increase in scintillation power (b) over a wide disturbance spectrum extending from 0.l to 3 Hz. The 15 dB enhancement in power (c) is equivalent to a scintillation S4 index of 0.8 (d). The spectral fall off for the irregularities has a power law index near k = -2.3 to -3.0 for both artificial and natural irregularities.

ACKNOWLEDGMENTS

This work was supported by the 6.1 Base Program at the Naval Research Laboratory and the DARPA BRIOCHE Program.

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