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On the occurrence of ground observations of ELF/VLF magnetospheric amplification induced by the HAARP facility

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[1] The ionospheric heating facility of the High Frequency Active Auroral Research Program (HAARP) has been used extensively in the last 3 years for injection of ELF/VLF waves into the magnetosphere via modulated heating of the overhead auroral electrojet currents. Of particular interest are waves that are observed to be nonlinearly amplified after interaction with hot plasma electrons in the Earth's radiation belts. Past results have shown HAARP to be an effective platform for controlled studies of wave particle interactions in the Earth's magnetosphere. A summary of the experimental results is provided in the context of dependencies on geomagnetic conditions and transmitter parameters. It is deduced that the primary variable that is associated with successful ground observations of HAARP-induced magnetospheric amplification is availability of magnetospheric wave guiding structures. Such structures are found to be most prevalent under quiet geomagnetic conditions following a disturbance when the plasmapause extends to the latitude of the HAARP facility or higher. Strong electrojet currents and high amplitudes of generated ELF/VLF signals observed on the ground are poor indicators of observation probability on a day to day basis although variation of these variables can be important on minute and second timescales. Frequency-time formats with continuously increasing ELF/VLF frequency show preferential amplification as predicted by nonlinear theory of electron trapping. Amplification of signals is also found to be possible for signals with noncoherent bandwidths of up to 30 Hz.

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1. Introduction

[2] Amplification of whistler mode waves in the Earth's magnetosphere plays a central role in the high-energy particle dynamics since such gyroresonance interactions are responsible for both particle acceleration and particle loss through pitch angle scattering [*Bortnik and Thorne*, 2007]. Naturally occurring nonlinear amplification of whistler mode waves in the form of chorus emissions has received considerable attention in recent years as satellite observations [*Santolík*, 2008], ground observations [*Gołkowski and Inan*, 2008] and targeted ray tracing studies [*Bortnik et al.*, 2008] have brought many interesting features to light. Specifically, there is now a general consensus that chorus waves are generated within a few degrees of the equator and initially have wave normal angles that are close to parallel to the geomagnetic field. On the other hand, investigating the nonlinear amplification mechanism using man made transmitters offers the unique opportunity of performing controlled studies. When transmitter signals excite the nonlinear instability the phenomena is often referred to as "triggered emissions" even though the underlying wave-particle interaction is believed to not be different from that of natural chorus waves [*Nunn et al.*, 2009].

[3] The primary challenge of controlled wave injection experiments is the difficulty in generating signals in the required 500–5 kHz (ELF/VLF) band since waves at these frequencies have free space wavelengths on the order of many kilometers. Two notable research facilities which have successfully performed controlled magnetospheric amplification studies are the Siple Station Transmitter in Antarctica (1973–1988) [*Helliwell*, 1988] and the currently operating ionospheric heater of the High Frequency Active Auroral Research Program (HAARP) in Gakona, Alaska [*Gołkowski et al.*, 2008, 2010]. The HAARP facility generates ELF/VLF waves by modulating overhead auroral electrojet currents using high power HF (2–9 MHz) waves to change the local D-region ionospheric conductivity. The HAARP facility has been operational at a total radiated power of ~3.6 MW since 2007.

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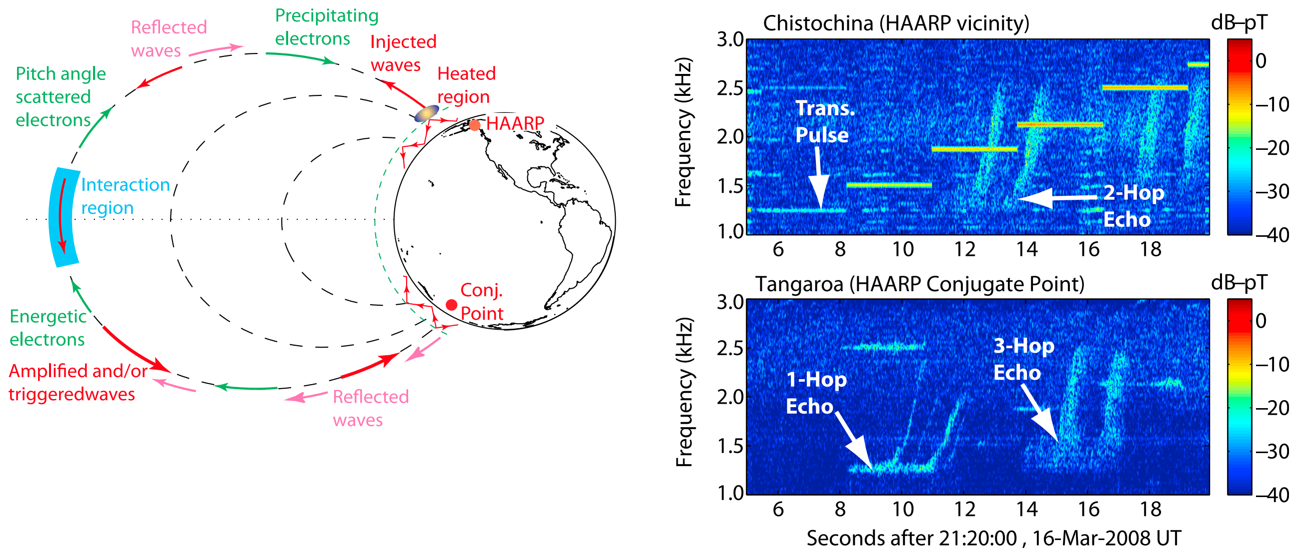

Figure 1. (left) Schematic of HAARP wave injection experiment and (right) spectrogram showing multihop whistler mode echoes. Data from the conjugate point was recorded aboard the ship *Tangaroa*, while data in the HAARP vicinity were recorded at Chistochina 36 km northeast of the HAARP facility.

[4] The basic experimental setup for using HAARP to study nonlinear magnetospheric amplification can be described as follows. The HAARP heater modulates the electrojet at a frequency in the ELF/VLF band. Observations are made at ground based receivers (described by *Cohen et al.* [2010a]) in the vicinity of the HAARP facility and its conjugate point in the southern Pacific Ocean. Observations at the conjugate point are difficult to obtain because of the logistic challenge of making measurements in the remote ocean. HAARP-induced magnetospheric amplification is observable when HAARP-generated signals are observed at the conjugate point (so called one-hop echoes) or near the HAARP facility (two-hop echoes) after making one or two crossings, respectively, of the magnetospheric equator. One-hop or two-hop echoes are identified by the correspondence of their periodicity and general frequency content to the HAARP transmission format offset by the time of magnetospheric propagation. The typical two-hop propagation time is ~8 s. Figure 1 shows a spectrogram with example one-hop and two-hop signals along with a schematic of their propagation path.

[5] The observation of HAARP-induced magnetospheric echoes requires some kind of cold plasma guiding structure either in the form of a "duct" or the plasmapause boundary [*Inan and Bell*, 1977] since in a "smooth" magnetosphere (without any sharp density gradients), whistler mode waves will generally not propagate along the geomagnetic field lines and hence will not be observed on the ground. Likewise, signals not experiencing any amplification in the magnetosphere will not have sufficient amplitudes to be observable on the ground. In fact, all observations of HAARP-induced echoes exhibit characteristics of nonlinear amplification, including phase advance and temporal growth as observed at a stationary receiver. Observations of HAARP-induced magnetospheric amplification are found to typically occur on one out of every 7 to 10 days of continuous operation. In this report we discuss the factors that control the occurrence of observations of wave amplification to elucidate the physics of the waves particle interaction and the practical aspects of running the experiment. We consider the role of generated ELF/VLF amplitude, magnetospheric propagation path, geomagnetic conditions, and transmitted frequency-time format and establish the degree to which the above factors impact the likelihood of inducing observable magnetospheric amplification with HAARP. We find that the primary limiting factor is proper magnetospheric conditions (which dictate on which days amplification will likely be observed) followed by the availability of ducts (which dictate which hours and minutes will yield observable amplification). However, when those conditions are favorable, higher generated ELF/VLF amplitudes and choice of frequency-time format significantly impact the amplification process.

2. HAARP-Generated ELF/VLF Amplitude

[6] The nature of ELF/VLF generation by way of HF ionospheric heating involves considerable variation in generated ELF/VLF amplitude because the electrojet currents and ambient ionospheric profile are key parameters in the efficiency of the process [*Rietveld et al.*, 1987; *Cohen et al.*, 2008a]. Since the nonlinear processes in magnetospheric amplification involve a documented threshold amplitude [*Helliwell et al.*, 1980], one might expect that the times of observed induced amplification coincide with the times of strongest HAARP-generated ELF/VLF amplitude. However, this is not the case. Although the amplitudes of HAARP-generated ELF/VLF signals that are injected into the magnetosphere (before amplification) are not easily observed, it is not unreasonable to expect that amplitudes radiated above the ionosphere will be at least correlated with amplitudes radiated below the ionosphere and observed on the ground. Figure 2 shows the HAARP-generated signal amplitude, as observed on the ground at Chistochina (37 km

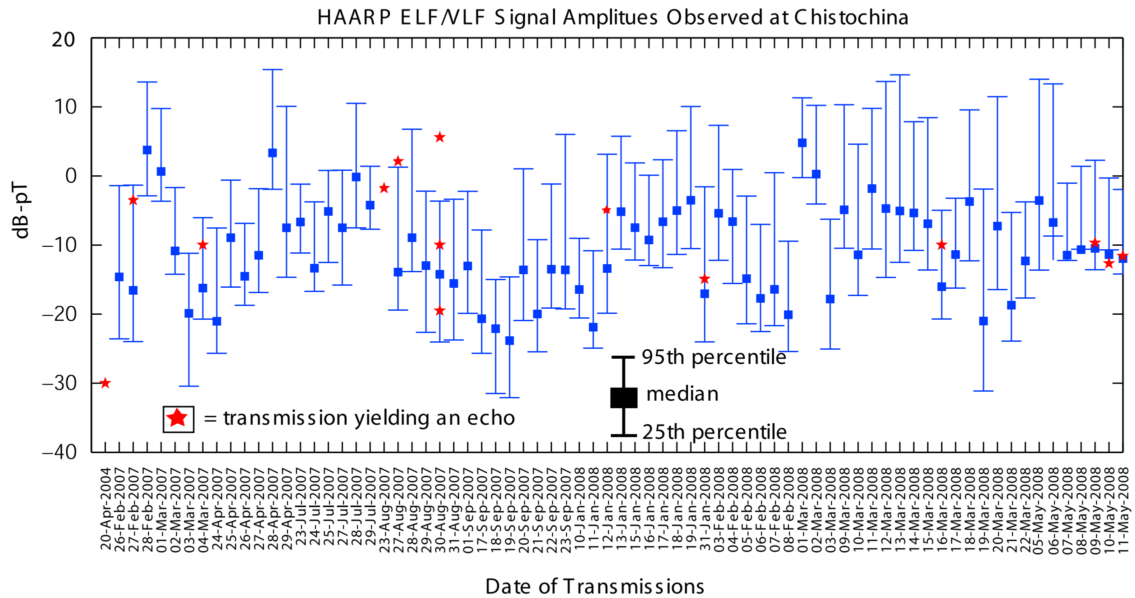

Figure 2. Amplitude variation of HAARP-generated ELF/VLF signals for all days of wave injection experiments from HAARP facility upgrade through May 2008. Red stars indicate amplitudes of signals that yielded one-hop or two-hop echo observations.

away from the HAARP facility), for days of wave injection experiments since the facility upgrade in 2007. The amplitude variation is expressed using range bars showing the 20th percentile, median and 95th percentile of the observed signals. The stars in Figure 2 show the HAARP signal amplitudes for cases in which one-hop or two-hop echoes are observed. The two-hop echoes are also observed at the Chistochina site. It is apparent that, in general, echo observations do not correspond to the strongest generated signals as observed on the ground. In fact there are times, such as those on 20 April 2004, when very weak signals are observed to trigger magnetospheric echoes.

[7] The role of HAARP-generated ELF/VLF amplitude becomes more nuanced when one looks at shorter timescales during which echoes are being actively observed, however. Figure 3 is a reproduction of Figure 5 from an earlier report by *Gołkowski et al.* [2008] and shows a representative case of the variation of HAARP generated ELF/VLF amplitudes and one-hop echo amplitudes. Figure 3 (top) shows the amplitude of the ELF/VLF magnetic field components recorded at Chistochina on 27 February 2007 during the observation of one-hop echoes in the conjugate region. Figure 3 (middle) shows the deviations from an hourly mean of three components of the Earth's magnetic field recorded with a magnetometer at the HAARP site. The magnetometer readings provide a measure of the electrojet strength and direction. Figure 3 (bottom) shows the amplitude of one-hop echoes observed on board *Tangaroa* that was in the conjugate region at the time of the observation. The two maxima in the echo amplitude at 0625 and 0632 UT show good correspondence with amplitudes of HAARP signals observed locally at Chistochina, which themselves exhibit strong correlation with the north-south horizontal (H) component of the geomagnetic field. The correspondence between echo observations and HAARP signal amplitude ends at 0645 UT, however, when the HAARP ELF/VLF intensity and the electrojet intensity (north-south horizontal component) exhibit a third maximum of equal amplitude during which no further echoes are observed on the ship. It seems that although the strength of HAARP ELF/VLF radiation clearly plays a role in echo observations on minute to minute timescales, other processes are also at work. As explained in sections 3–5, the presence and dynamics of cold plasma guiding structures in the magnetosphere play a key role.

[8] The key implications on the role of signal amplitude can be summarized as follows. During any individual experiment, observation of high-amplitude HAARP ELF/VLF signals in itself is a poor indication of the probability of HAARP-induced magnetospheric amplification. However, if HAARP-induced one-hop or two-hop echoes are being observed, generated signal amplitude is very important and efforts should be made to maximize it in order to continue echo observations. The latter point is particularly relevant in the context of new techniques being developed to increase HAARP-generated signal amplitudes [*Cohen et al.*, 2008b, 2010b].

3. Magnetospheric Path Determination

[9] Since whistler mode propagation in the magnetosphere is highly dispersive, it is possible to use the frequency-dependent propagation delay of one-hop and two-hop echoes to infer the characteristics of their magnetospheric propagation path using well developed whistler dispersion techniques [*Sazhin et al.*, 1992]. Specifically we assume propagation parallel to the geomagnetic field, a dipole geomagnetic field model and a diffusive equilibrium model

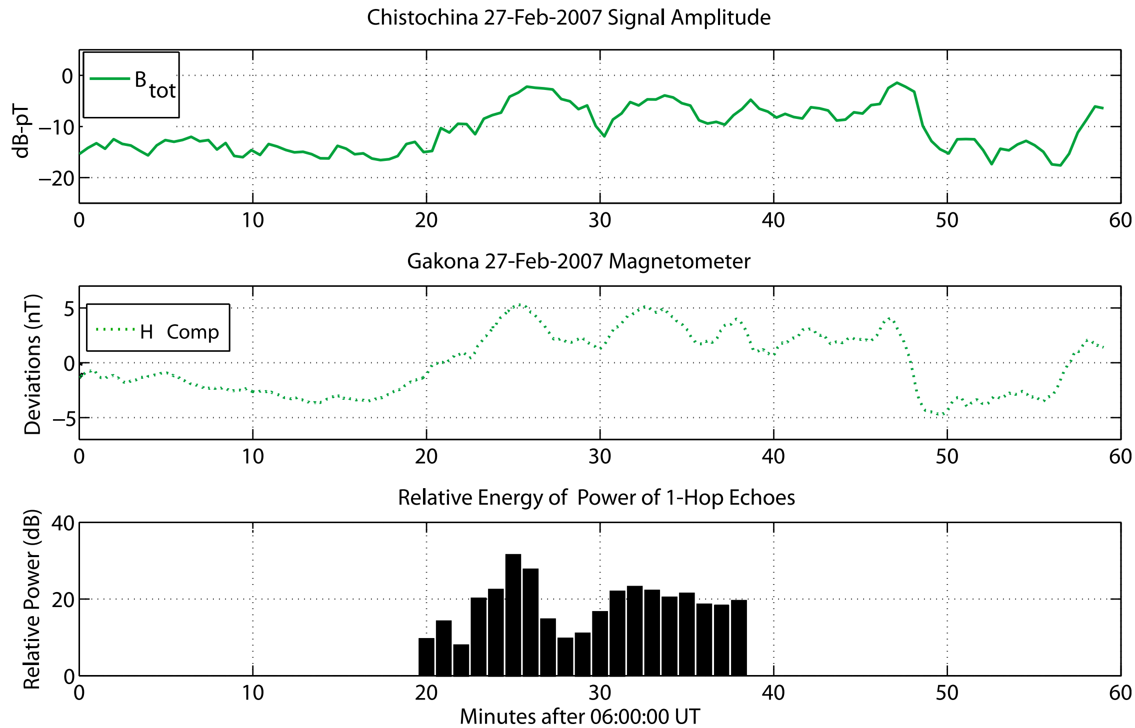

Figure 3. (top) Local HAARP ELF/VLF signal strength at Chistochina as observed in the amplitude of the total magnetic field (B_{tot}). (middle) Variations of the geomagnetic field from a magnetometer at the HAARP site with positive northward component (*H*). (bottom) Relative integrated power of one-hop echoes observed on *Tangaroa*. Maxima occur at 0626 and 0635 UT for all plots, although no echoes are observed during the third maximum in signal power and electrojet strength at 0646 UT.

[*Angerami and Carpenter*, 1966] of the field aligned cold plasma density to estimate the L shell and associated equatorial cold plasma density of an observed echo. If the observed echoes are induced by signals transmitted over a bandwidth of at least 1 kHz then a unique L shell and equatorial electron density can be determined. In practice, the best results are achieved when echoes are observed to be induced by components of 500 Hz/s frequency-time ramps spanning 500 Hz to 3 kHz that are often transmitted in the experiment.

[10] Figure 4 shows the magnetospheric L shell and cold plasma density for all observations for which such a determination was possible. The path results are clustered around the L shells corresponding to the dimensions of the HAARP HF heated region projected vertically upward to an altitude of 300 km. In other words, HAARP-generated signals that are subsequently observed as amplified echoes are coupled into the magnetosphere directly over the heated region. Additional evidence that the magnetospheric propagation paths do in fact correspond to magnetic field lines with foot prints close to the HF facility is reported by *Gołkowski et al.* [2009].

[11] The fact that HAARP is able to excite observable whistler mode echoes only on magnetic field lines crossing the heated region is likely related to the fact that this region is also where HAARP-generated ELF/VLF signals are known to have maximum amplitudes. In particular, the HAARP-generated ELF/VLF radiation pattern has been shown experimentally [*Piddyachiy et al.*, 2008] and theoretically [*Lehtinen and Inan*, 2008] to produce a narrow vertical "column" with horizontal diameter on the order of the heated region. If we now consider the equatorial cold plasma density data from Figure 4, we see that the derived results also correspond to magnetospheric paths inside the plasmapause. To emphasize this point we have also included equatorial density profiles corresponding to "quiet" and "disturbed" geomagnetic conditions based on the empirically derived formulations of *Carpenter and Anderson* [1992]. The quiet profile corresponds to a $Kp_{\max}$ of 0+ while the disturbed profile shown in red corresponds to $Kp_{\max}$ of 6. $Kp_{\max}$ is defined by *Carpenter and Anderson* [1992] as the highest Kp value recorded in the preceding 24 h. (A more detailed analysis of geomagnetic conditions is provided in section 4.) As can be seen, the equatorial cold plasma density values derived from the echo observations are in close agreement with the quiet profile corresponding to locations clearly inside the plasmapause.

[12] The propagation L shell of the echo observations can thus be attributed to the HAARP radiation pattern, as discussed above. However, the restriction of observations to within the plasmapause can potentially be explained in two distinct ways. Observation of whistler mode echoes on the ground (in either hemisphere) requires both magnetospheric amplification and a guiding structure that confines wave energy to the geomagnetic field line. Hence, the high cold plasma densities inside the plasmasphere must provide

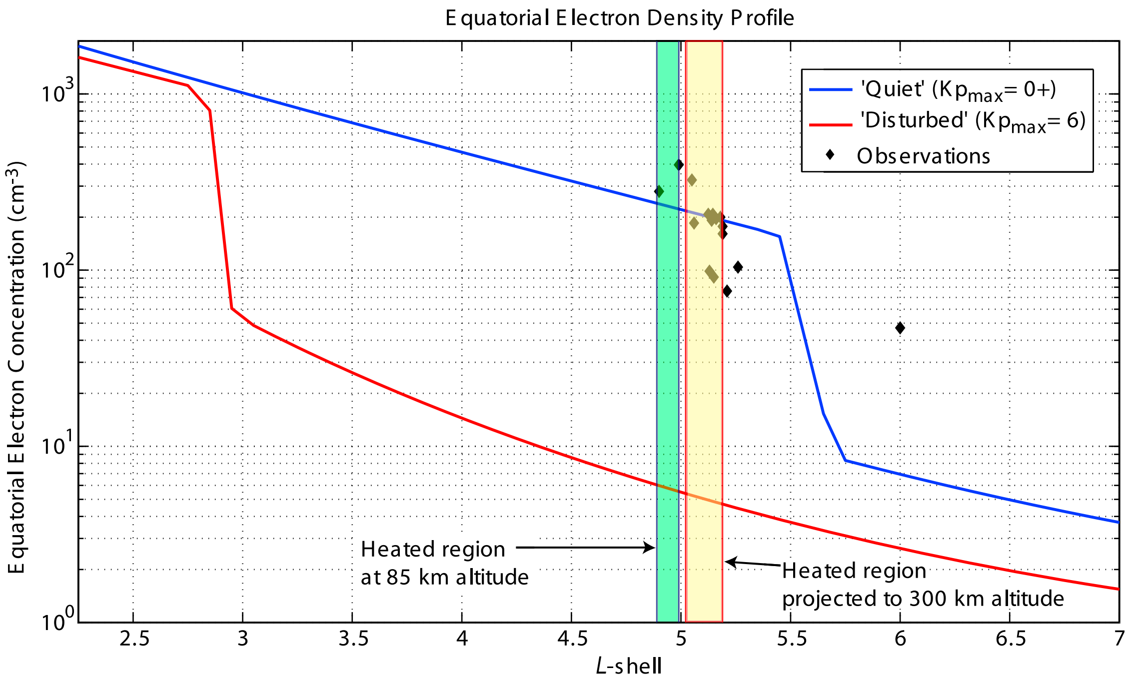

Figure 4. Magnetospheric path and equatorial cold plasma density determinations from observed echoes plotted with equatorial density profiles typical for quiet and disturbed magnetospheric conditions. The *L* shells corresponding to the HAARP heated region at 85 km and projected to 300 km above the HAARP HF array are also shown.

favorable conditions either for hot plasma wave-particle interactions or for the existence of cold plasma magnetospheric ducts. It is hard to accept that magnetospheric amplification is more prevalent inside the plasmasphere given that chorus waves are well documented to be observed predominantly outside the plasmapause boundary [*Santolík*, 2008]. On the other hand, magnetospheric ducts and related cold plasma density irregularities capable of guiding whistler mode waves are known to be more likely to occur inside the plasmapause [*Carpenter*, 1981].

[13] Further evidence for the key role of magnetospheric ducts was obtained from a special experiment involving changing the position of the HAARP HF beam. In a special format the same ELF/VLF frequencies are generated using AM modulation but by aiming the beam to 4 different positions in the sky. The dwell time in each position is only 15 s, shorter than the typical timescales of changing echo response. Figure 5 shows the arrangement of the four different beam positions and also a spectrogram showing the triggering of two-hop echoes by 1.525 kHz pulses from the A and C beam positions observed at Chistochina on 10 May 2008. The format was transmitted from 1727 to 1817 UT and two-hop echoes were observed to be excited by transmissions from at least one of the beam positions from 1727 to 1800 UT. There was considerable variation in the beam position that was most favorable to triggering echoes, with the greatest number of echoes (21) induced from the southeast C position. The preferential excitation of echoes as a function of beam position points to a sensitivity to coupling energy into available ducts. Unfortunately, the results in Figure 5 cannot be reduced to an oversimplified scenario of a duct being located directly over a given beam position and drifting between positions accordingly. It must be remembered that HAARP ELF/VLF signals most likely couple into ducts several hundred kilometers above the heated area. Propagation through the ionosphere to the duct entry point is strongly affected by the ionospheric medium. The upper ionosphere is known to host many irregularities [*Gross and Muldrew*, 1984; *Sonwalkar and Harikumar*, 2000], and the HAARP heater itself is known to generate irregularities during its operation [*Djuth et al.*, 2006], so the mapping of beam positions that excite echoes to fixed duct entry points is not straightforward. Nonetheless, both the results from various beam orientations and the magnetospheric path determination results discussed above suggest that availability and coupling into ducts are the primary factors controlling the occurrence of whistler mode echo observations.

[14] At this time, the ability of the HAARP facility to induce observable magnetospheric echoes can be described as follows. HAARP radiates ELF/VLF waves with a radiation pattern characterized by a thin vertical column. If ELF/VLF wave energy in this column can be coupled into an existing magnetospheric duct, then it is possible for HAARP to excite magnetospheric echoes. If echoes are observed then the stability of the guiding duct remains a major factor in the duration of the repeated echo observations. It is believed that the typical 20–40 min durations of echo observations (like the example shown in Figure 3) are of such temporal length and not longer because of the dynamics of the guiding duct and ability of HAARP ELF/VLF waves to be coupled into it. There exists the possibility that the guiding duct for most echo observations is in fact the

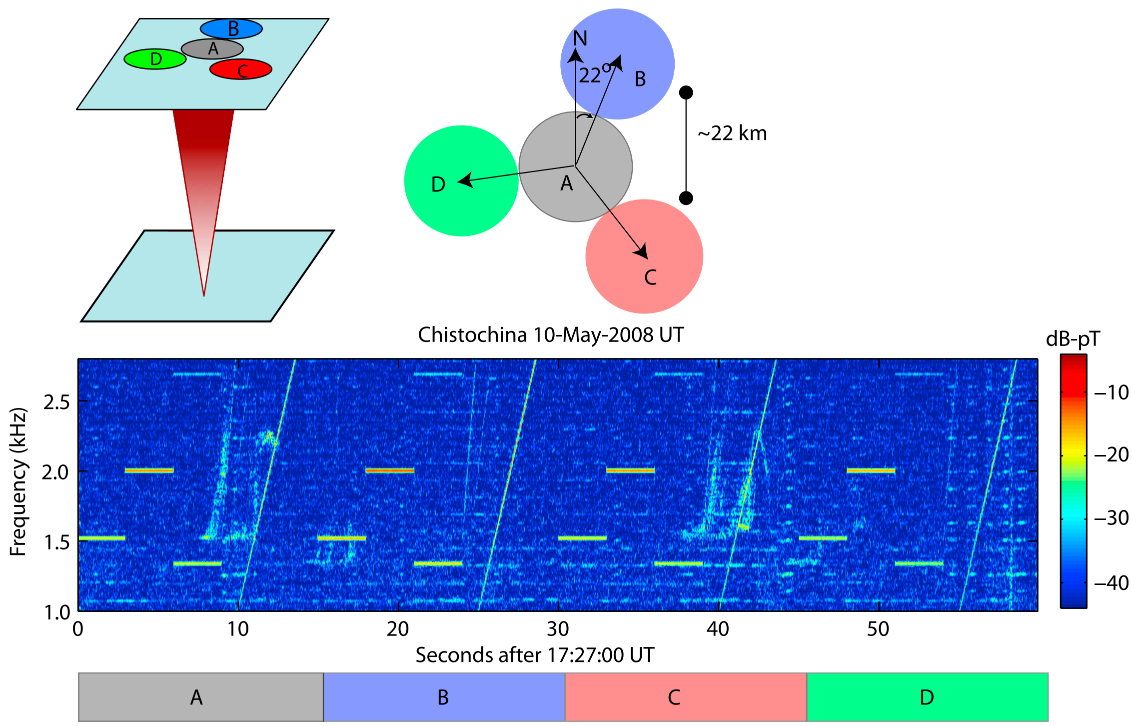

Figure 5. (top) Schematics of the experiment setup for investigating the effect of HF beam position on triggering of echoes. The HF beam is directed to four adjacent overhead positions marked as A, B, C, and D. The dwell time in each position is 15 s, and signals are generated using AM modulation. (bottom) The spectrogram of a sample result showing two-hop echoes observed at Chistochina triggered by the A and C positions.

plasmapause boundary itself, which is known to be an effective guiding structure for whistler mode waves [*Inan and Bell*, 1977].

4. Geomagnetic Conditions

[15] Since we have identified the availability of field aligned magnetospheric guiding structures to be a factor of key importance in ground observations of HAARP-induced echoes, it is expected that this dependence should also be exhibited in the geomagnetic conditions. In this section we provide a statistical analysis of the geomagnetic conditions before and during echo observations using geomagnetic indices.

[16] Figure 6 (top) shows the averaged *Kp* conditions preceding all cases of two-hop echo observations (dark blue stems). The time axis of the plot is measured in days relative to the observation of two-hop echoes. The trend exhibited is that of a quiet period (low *Kp*) 12–36 h before two-hop echo observations and a disturbed period (high *Kp*) 4 days before observations. The light red stems show the *Kp* values for all transmission days since the HAARP upgrade in 2007 regardless of whether two-hop echoes were observed or not. Because of the large number of transmission days, the red stems are seen to closely approximate the average of *Kp* indices for all days in 2007–2008 (with and without HAARP transmissions) that are denoted by the dashed line. All averages of the *Kp* index were done by first linearizing the *Kp* indices to the *Ap* equivalent.

[17] The conditions associated with two-hop echo observations (dark blue stems in Figure 6) are seen to clearly be distinct from the all transmission days (light red stems) and the difference can be statistically quantified. Figure 6 (bottom) shows the results of a Kolmogorov-Smirnov two-sample statistical test in which the distribution of *Kp* indices associated with two-hop echo observations was tested against the distribution of *Kp* indices for all transmissions. The *p* values from the test are plotted on an inverse scale in Figure 6 (bottom). The *p* values can be interpreted as the probability that the two distributions (all transmissions and transmissions yielding echoes) are identical. The low *p* values ($p < 0.03$) during the quiet period just before two-hop echo observation and during the disturbed period 4 days before observation provide quantitative evidence that two-hop echo observations occur in the presence of a specific geomagnetic signature.

[18] In addition to the *Kp* index, we also examined the associated *DST* and *AE* indices. The results were largely similar to the *Kp* study presented in Figure 6 with an average quiet period 12–36 h before echo observations and a disturbed period 3–4 days before observations. One nuance worth mentioning is that for the *AE* index the disturbed period 3–4 days prior to observations was found to have a weaker statistical significance ($p > 0.04$) while the quiet period 12–36 h before had a greater statistical significance than for the other indices with $p < 0.001$. We also note that at this time no diurnal dependence has been observed for

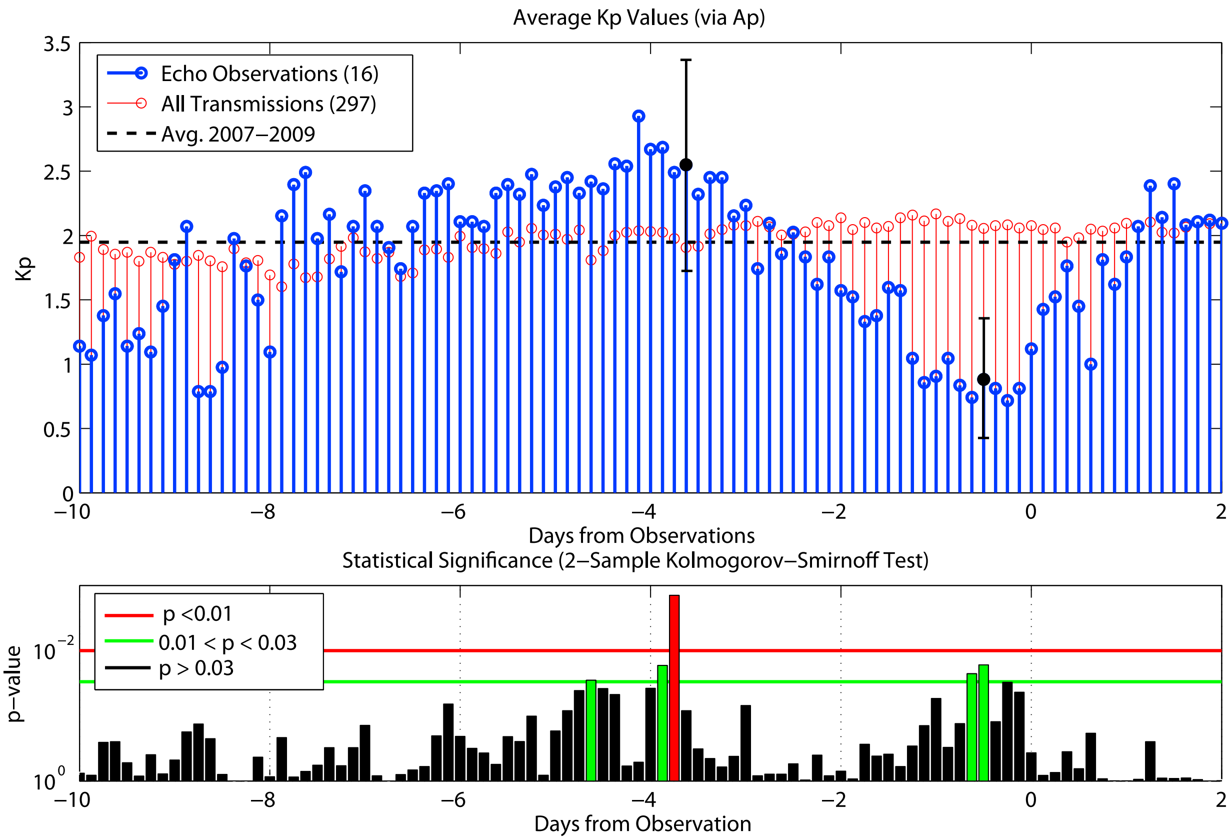

Figure 6. (top) The average *Kp* conditions for all cases of two-hop echo observations and preceding days (dark blue stems). The red stems show the same average but for all days of HAARP wave injection transmissions. The dashed line is an average of all *Kp* values in the years 2007–2009 including days without HAARP transmissions. (bottom) Results from a statistical test comparing the *Kp* distributions corresponding to the (dark) blue and (light) red stem plots. The blue stems are shown to be a unique signature for favorable two-hop echo observations. The two range bars in Figure 6 (top) at −3.75 and −0.5 days show standard deviations from the mean for these key data points.

echo observations with echoes having been observed at all times, including local noon.

5. Frequency-Time Format

[19] One of the goals of the HAARP wave injection program is to determine how to maximize the magnetospheric amplification of man-made waves as such knowledge can be of operational value for both ground and space based ELF/VLF transmitters. In this context, the sensitivity of magnetospheric amplification to certain frequency-time signatures is of key importance. It is worth mentioning that in the Siple Station experiments a wide range of frequency-time formats (including formats with negative *df*/*dt*) were observed to be amplified under diverse conditions [*Carlson et al.*, 1985; *Helliwell et al.*, 1990]. However, the Siple Station experiment involved ELF/VLF amplitudes at least 100 times greater than in the HAARP experiment and hence the Siple ELF/VLF signals were almost always above the nonlinear amplification threshold [*Helliwell et al.*, 1980]. The lower amplitude HAARP ELF/VLF signals are close to the nonlinear threshold and better represent the case of a space based transmitter where finite payload and antenna coupling issues limit the amplitude of radiated VLF waves.

[20] In the HAARP experiment, signals with *df*/*dt* near 500 Hz/s are found to preferentially induce magnetospheric echoes. This is especially the case when amplification is weak and magnetospheric echoes exhibit a weak signal-to-noise ratio. Figure 7 shows typical cases from three different days when 500 Hz/s frequency-time ramps are observed to trigger echoes while single frequency pulses are not. Figure 7 (bottom) shows that only a positive slope of the frequency-time ramps induces echoes, since the ramps with negative slope ($df/dt < 0$) do not induce observable echoes. (Note that the case shown in Figure 5 is a rare exception where pulses trigger echoes but ramps do not.)

[21] Another important issue in the investigation of magnetospheric amplification is whether or not waves need to be coherent in order to be amplified. This issue is important not only in the context of understanding the generation mechanism of natural chorus but also evaluating unconventional schemes of generating broadband wave energy such as the so-called chemical release methods

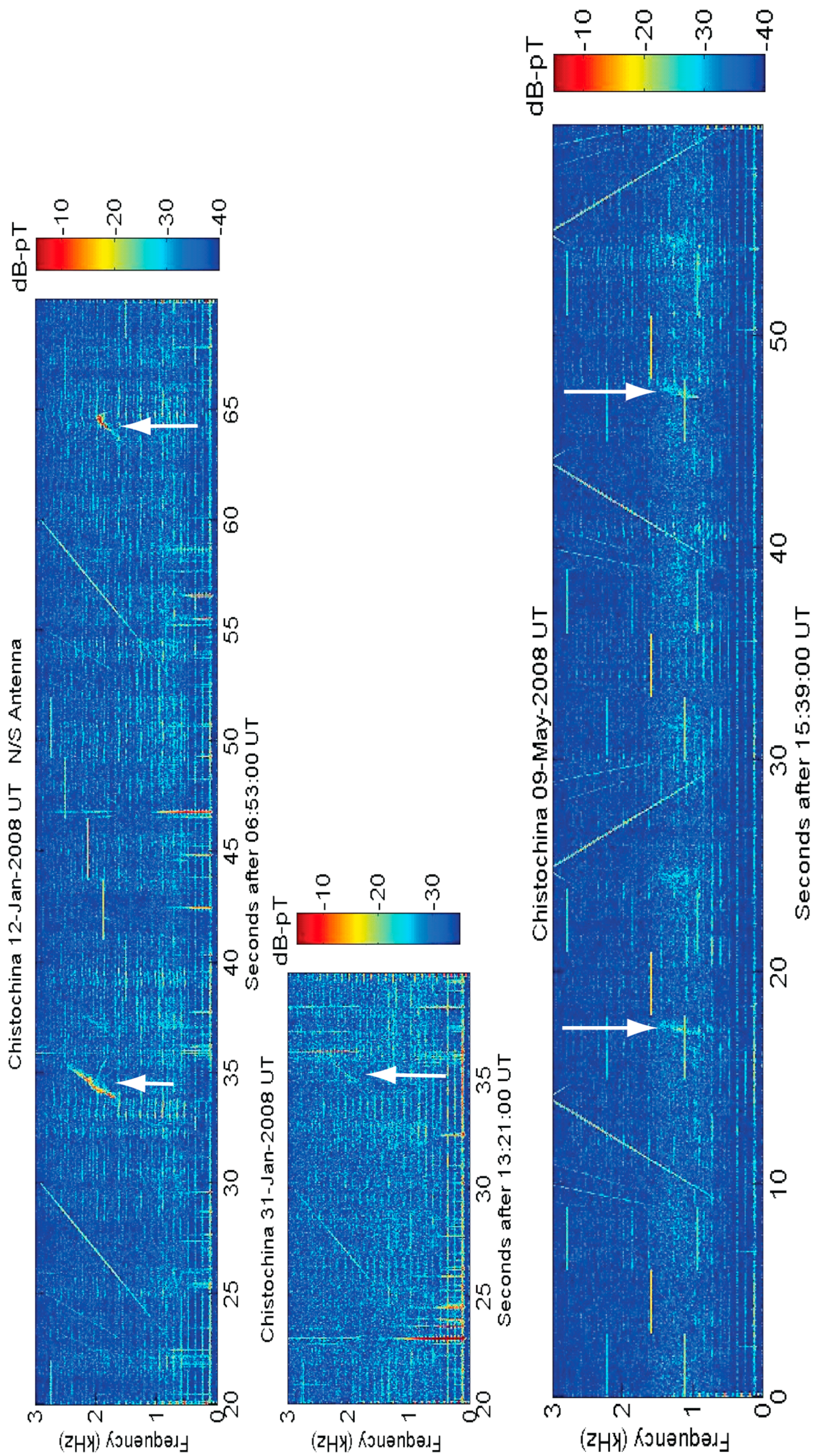

Figure 7. Spectrograms from Chistochina showing two-hop echoes induced by frequency-time ramps and not by other signals transmitted at the same time. Two-hop echoes are identified by white arrows.

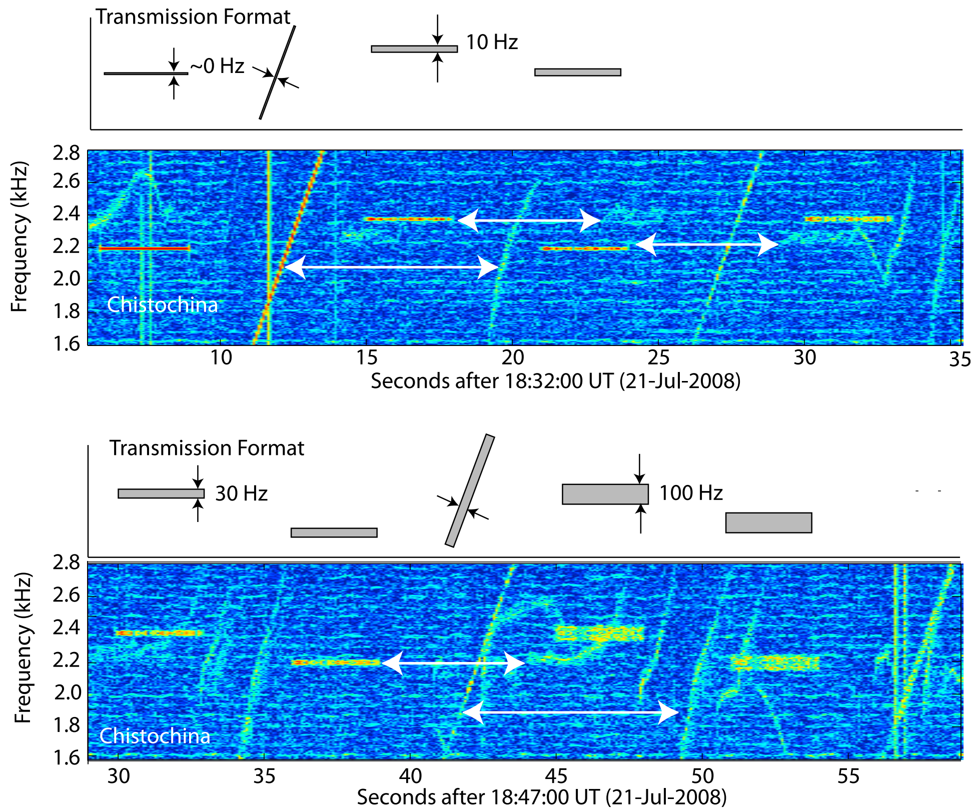

Figure 8. Transmission format and observations from Chistochina from experiment involving signals of varying bandwidth. White arrows indicate observation of induced two-hop echoes.

discussed by *Ganguli et al.* [2007]. A special transmission format was designed to test the coherence limits of the magnetospheric amplification of HAARP-induced signals. As shown in Figure 8, the standard 1 min repetitive format involving four sets of three 3 s pulses and a 6 s 500 Hz/s frequency-time ramp was modified so that the bandwidth of the signals was increased for each subsequent set within the minute. The bandwidth was increased by modulating the signals with filtered Gaussian noise of either 10, 30, or 100 Hz bandwidth. In each minute the first four signals (3 pulses and a ramp) were standard monochromatic signals, the next set had the same signals modulated with 10 Hz noise, the third and fourth sets were modulated with 30 and 100 Hz, respectively. Figures 8 and 9 show two distinct cases in July and December of 2008 when parts of this format yielded observable magnetospheric echoes. On both days, the HAARP HF frequency was 2.75 MHz X mode. In both cases the monochromatic and the 10 and 30 Hz bandwidth signals triggered two-hop echoes while the 100 Hz bandwidth signals did not. We thus have direct evidence that signals with up to a 30 Hz bandwidth can experience nonlinear magnetospheric amplification. The lack of observable amplification for the 100 Hz signals could result from the bandwidth being too broad or also from the drop in spectral density that resulted from the modulation. All the signals generated in the format involved operating HAARP at full power. The experiment will be repeated with a new format that includes power steps so that the effects of bandwidth broadening and simultaneous amplitude drop can be distinguished.

6. Discussion

[22] At the present time, the best prediction metric for HAARP-induced echo observations is quiet magnetospheric conditions (*Kp* 0–1) 12–24 h before transmissions following a geomagnetic disturbance (*Kp* 3–4) 3–4 days prior. In other words, one would not expect to be able to trigger magnetospheric echoes with HAARP during a prolonged quiet period lasting many days nor during a strongly disturbed period. It is believed that both the immediately preceding quiet period and earlier disturbed period have to do with the formation and subsequent stability of field aligned cold plasma irregularities that guide the HAARP ELF/VLF waves to the magnetic equator and back to Earth. Studies have shown that the magnetosphere exhibits more density irregularities after periods of high geomagnetic activity [*Darrouzet et al.*, 2009], which would explain the need for a geomagnetic disturbance. At the same time, the quiet conditions just before transmission yield extension of the plasmasphere, where such ducts are known to be most stable, to HAARP latitudes. In this context, we note that studies of plasmasphere refilling rates by *Tu et al.* [2003] suggest a ~3 day timescale for recovery of cold electron density from a 70% depletion, which would agree with our identification of 3–4 days as a significant time duration.

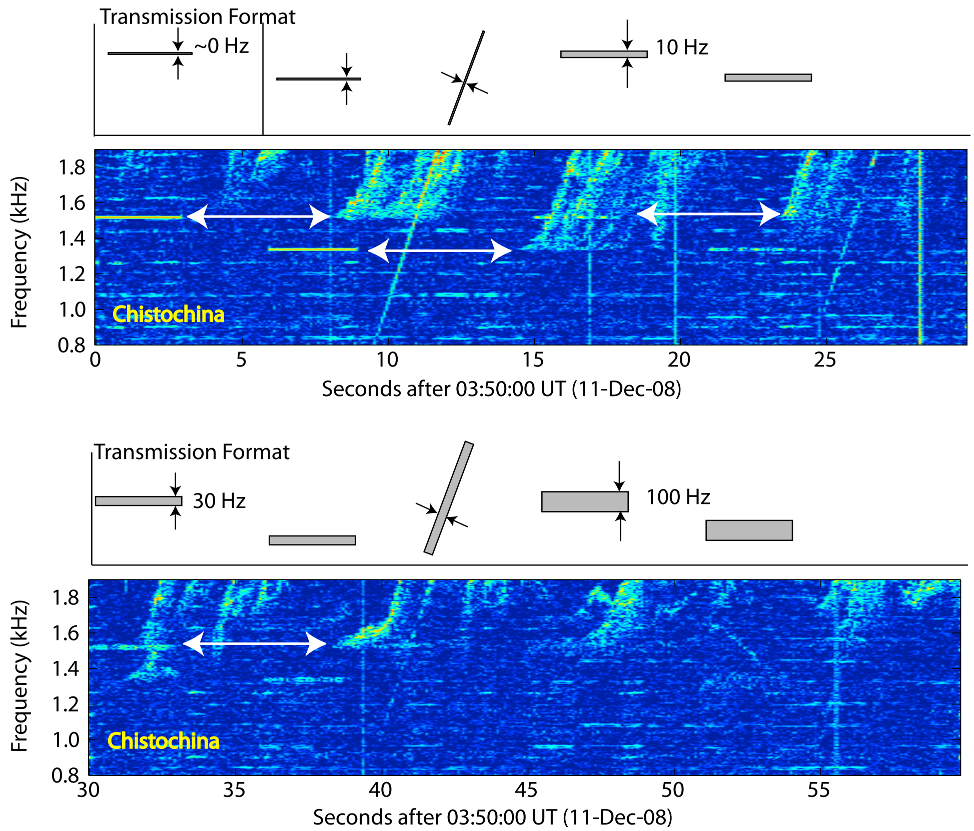

Figure 9. Second case of transmission format and observations from Chistochina from experiment involving signals of varying bandwidth. White arrows indicate observation of induced two-hop echoes.

Observations by *Reinisch et al.* [2004], however, suggest that the refilling rate may be significantly faster (~30 h).

[23] It is also possible that the geomagnetically disturbed period 3–4 days before echo observations has to do with injection of energetic hot plasma electrons that subsequently drive the observed magnetospheric amplification. At this time, there does not seem to be a rigorous way to test this hypothesis with ground measurements and it is hoped that upcoming experiments with space based VLF transmitters will shed light on this issue since such experiments will be less reliant on the presence of ducts.

[24] The prominent role played by ducts in the experiment also explains why observed HAARP-induced echoes are often associated with weak HAARP ELF/VLF amplitudes. Maximizing HAARP-generated ELF/VLF is important but unfortunately the strong electrojet conditions associated with strong signals usually occur during disturbed geomagnetic conditions which are not favorable for ducting. This situation makes the investigation of new techniques for ELF/VLF enhancements all the more important. Geometric modulation as described by *Cohen et al.* [2008b, 2010a] has shown the greatest promise as evidenced by observations of higher amplitudes being coupled into the Earth-ionosphere waveguide using this technique. A distinct preheating technique has been described by *Milikh and Papadopoulos* [2007] but has not been successfully verified by experiment.

[25] The identification of duct availability as a key factor begs the question whether the HAARP facility could be actively employed to change this variable. Although the possibility of using the HAARP facility to create artificial magnetospheric ducts has received serious attention [*Milikh et al.*, 2008], at this point it is not known if such structures can be reliably created and if they would be able to extend to the magnetic equator to provide the necessary guiding. We note that in the majority of the wave injection experiments the heater was operated for up to 12 h (sometimes 24 h) in a variety of modes (including CW and O mode heating) so if the HAARP facility can in fact create ducts, then this ability would have been intrinsically taken advantage of in our experiments. At this time there is no evidence to believe that prolonged HAARP operation has increased the probability of observing whistler mode echoes.

[26] The preferential magnetospheric amplification of HAARP signals with positive slope ($\frac{df}{dt} > 0$) frequency-time formats is in agreement with theoretical formulations of nonlinear whistler mode wave amplification. Wave-particle calculations show that a counter streaming electron can remain in phase with a wave over an extended region if the increasing frequency of the wave offsets the inhomogeneity of the geomagnetic field that determines the adiabatic trajectory of the particle [*Omura et al.*, 1991]. In particular, recent particle in cell codes suggest that a positive $\frac{df}{dt}$ that satisfies the resonant condition within a few degrees of the magnetic equator is the origin of natural chorus waves [*Omura et al.*, 2008]. Input waves with higher amplitudes, however, are less sensitive to the $\frac{df}{dt} > 0$ requirement which is

in agreement with those HAARP observations where echoes are not limited to ramps and also the database of Siple Station observations.

7. Summary

[27] It is found that HAARP-induced triggered emissions are most likely to occur during quiet magnetospheric conditions following a geomagnetic disturbance. Observations of whistler mode echoes do not coincide with the strongest ELF/VLF-generated amplitudes, and the input amplitude as observed on the ground is found to be significant parameter only when magnetospheric and ducting conditions are favorable for amplification. Dispersion analysis indicates that the signals yielding amplified echoes are injected into the magnetosphere directly above the HF heater, in agreement with satellite observations and numerical models that show the highest amplitudes of the HAARP-induced ELF/VLF dipole to be confined to a narrow vertical column with a diameter on the scale of the heated region. The narrow column radiation geometry is most likely responsible for the sensitivity of echo observations to available magnetospheric ducts, as is suggested by experimental evidence involving spatially varying the position of the HAARP-induced ELF/VLF dipole. Magnetospheric echoes have been observed to be induced by signals modulated with Gaussian noise of bandwidth up to 30 Hz. Further experiments investigating the coherence limits of the wave-particle interaction are planned.

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