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An Artificial Particle Precipitation Technique Using HAARP-Generated VLF Waves

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14. ABSTRACT, A new ground-based experimental technique is described, which is designed to optimize artificial precipitation of magnetospheric electrons at high latitudes, due to man-made VLF waves. High-latitude ionospheric modification facilities may be used to modulate the Hall conductance, which modulates the electrojet current, and in turn radiates VLF whistler waves. Assuming the VLF waves are ducted along the magnetic field lines, the frequency of the VLF wave is modulated in time such that Doppler-shifted cyclotron resonance between the wave and gyrating electrons is maintained along a large fraction of the magnetic field line for a selected particle energy. The electron travel time is a function of particle energy, which is selected to be at the loss cone, and magnetic field strength. The VLF wave travel time is a function of frequency, which we calculate, the electron gyro-frequency, which is a function of magnetic field strength, and the plasma frequency, which we model. The frequency-time modulated VLF wave patterns have been successfully implemented at the HAARP ionospheric modification facility in Alaska, USA. Two initial attempts have failed to produce an unambiguous signature of particle precipitation to date.

15. SUBJECT TERMS

Wave-particle interactions, VLF propagation, Particle precipitation, Optical emissions, Ionospheric heating

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1. Introduction

A large number of spacecraft now orbiting the planet provide services such as communications, navigation, weather monitoring and images, all now considered essential for modern living. The operational lifetime of spacecraft is partly determined by the radiation dose it receives in space, which affects the lifetime and performance of the electronics. On occasion, relativistic "killer" electrons, whether geomagnetic or manmade in origin, may cause premature spacecraft failure [e.g., Baker et al., 1998]. Given the enormous and ever-increasing investment in satellite assets, it is reasonable to investigate methods of reducing the radiation associated with degradation and failure of spacecraft. The problem is particularly acute in the belts of trapped radiation where spacecraft can spend much of their time. This radiation consists of energetic protons and electrons. The proton radiation belt contains significant fluxes in excess of 10 MeV [Walt, 1994, p.77], and occupies the region between ~1.5 and 7 R_E. The trapped, energetic electrons (>1 MeV) exhibit a two-zone structure [Walt, 1994, p.82]: an inner radiation belt (<2 R_E) which is relatively stable, and an outer belt (>3 R_E) which can vary by a factor of >1000 on timescales ranging from minutes to hours [Blake et al., 1992; Li et al., 1993; Baker et al., 1994; Selesnick and Blake, 1997; Onsager et al., 2002], and respond in an apparently unpredictable way to geomagnetic activity [Reeves et al., 2003].. Work done by Abel and Thorne [1998] and Inan et al. [2003] show that ground-based Very Low Frequency (VLF) transmissions significantly shorten the lifetime of energetic particles, especially in the inner radiation belt.

It is well known that lightning strikes radiate VLF electromagnetic waves in the kilo-Hertz range, which propagate in the Earth-ionosphere waveguide, and partially leak through the ionosphere. This wave energy may become ducted in enhanced electron density structures and propagate along magnetic field lines through the magnetosphere to the opposite hemisphere. Artificially generated VLF waves may do the same [Carlson et al., 1985; Inan et al., 2004]. The frequency dependent propagation of so-called whistlers has been extensively used as a natural ground-based diagnostic of magnetospheric plasma [e.g. Carpenter, 1963; Sazhin et al., 1992]. Artificially injected VLF waves have also been used to study wave-particle interactions in the near-Earth magnetosphere [Carlson et al., 1985; Helliwell, 1988].

Naturally occurring whistler-mode waves, e.g. hiss or chorus, which originate in the plasma itself, have been associated with the optical aurora, i.e. particle precipitation, at L = 4 from ground-based observations [Hansen and Scourfield, 1990; Hansen et al., 1988, 1986; Scourfield et al., 1984; Helliwell et al., 1980]. Artificially injected VLF waves from the ground have been observed to amplify or trigger stronger secondary VLF emissions, which were correlated to fluxes of energetic particles (<20 keV) from satellite data [Bell et al., 2000; Kimura et al., 1983]. Similarly, artificially injected VLF waves from the ground have been correlated with energetic particle precipitation (predominantly at E ~ 10-100 keV) from satellite data [Imhof et al., 1983, 1985]. Goldberg et al. [1983] found evidence of artificial VLF-induced precipitation using rocket borne X-ray observations. It generally assumed the VLF wave particle interaction is due to cyclotron resonance. The propagating VLF waves can interact with counter-streaming electrons by Doppler-shifted cyclotron resonance, causing the pitch angle of the electrons to change [Inan et al., 1978]. From satellite measurements at L ≈ 2.3, Imhof et al. [1983] found particle pitch angle changes of $>1^{\circ}$ for single encounters with the VLF wave. If this process brings the electrons' pitch angles into the bounce loss cone, they will precipitate in the hemisphere where the VLF wave originated.

Imhof et al. [1983, 1985] estimated the VLF-induced precipitating energy flux to be $\sim10^{-4}$ $erg.cm^{-3}.s^{-1}$. Assuming 100% conversion efficiency, this translates to a photon flux of 2.2 Rayleigh (R) at 557.7 nm, which is within the detectable range of modern optical imagers (threshold ~0.5 R). If we assume a more realistic 4% conversion efficiency [Rees et al., 1963] then the photon flux becomes 0.09 R at 557.7 nm, which is still detectable by suitable background subtraction and/or integration. The primary reason that past ground-based VLF transmission experiments have not resulted in detectable optical emissions is that the imaging technology was not sensitive enough, having a typical threshold of 100-1000 R at the time of the Siple experiments. Sensitive photometers have existed for a long time, but the location of the VLF ducts is not known in advance, which severely limits the usefulness narrow field-of-view optics, and using wide field-of-view optics admits a large background signal which swamps the desired signal. The typical diameter of VLF ducts is ~30 km [Helliwell et al., 1980], which is a small area compared to the ~500 km visible radius. Given the optical technological advancements, the possibility now presents itself to repeat the early ground-based VLF experiments at Siple and elsewhere using all-sky imagers and attempt to detect the precipitation optically near the VLF source, something that has not been reported before.

It is well known that high power radio waves transmitted from the ground cause large electron temperature enhancements (~2500 K) in the D-layer [Kero et al., 2000], thereby modulating the Hall conductance. If the ionospheric polar electrojet flows through this heated region, as is the case for high latitude ionospheric modification facilities (e.g. EISCAT, L = 6.2, and HAARP, L= 4.8), it can be similarly modulated to radiate observable coherent whistler-mode VLF waves of up to 1-3 pT in strength and up to ~7 kHz [Stubbe et al., 1982]. The VLF signal strength falls off rapidly for <2 kHz and >6 kHz [Rietveld et al., 1989] and is a function of the electron temperature and density time constants to reach a new equilibrium as well as reflected pump-wave self-interference. Pumping with X-mode polarisation produces a much stronger signal strength than does O-mode [Stubbe et. al., 1982]. VLF signals produced by electrojet modulation at HAARP have been detected by satellite [Platino et al., 2004] and are known to propagate, on occasion, to the opposite hemisphere and back, presumably by ducting [Inan et al., 2004]. Although whistler waves will propagate in the magnetosphere without ducting [Carpenter and Sulic, 1988], the experiment described below relies on VLF ducting to reach the equatorial plane. Only here is cyclotron resonance possible because of the relatively low maximum VLF frequency which can be achieved by modulating the electrojet (<8 kHz).

Past ground-based VLF transmission experiments have relied on constant frequency, or ramped frequency transmissions. It is not clear whether these transmissions had any sound theoretical basis. Inan [1978] found that particles had to be within ~3% of ideal local resonance for the VLF wave to be effective. Brinca [1981] introduced the idea of modulating the VLF wave frequency in time such that, for a given location and particle energy, cyclotron resonance would be maintained for a large fraction of the electron's flight path along the magnetic field line, thereby maximizing the change in pitch angle or minimizing the VLF wave strength needed. Brinca [1981] performed the theoretical calculation for the EISCAT ionospheric modification facility (L = 6.2), but this was never implemented. We follow this method and implement it for the HAARP ionospheric modification facility (L = 4.8), where the chances of finding VLF ducts is significantly greater [Cerisier, 1974]. Since (linear) cyclotron resonant scattering is symmetric in pitch angle, some particles will be driven away from (and some into) the loss cone by a change in momentum. On average, the VLF wave will exchange very little energy with the particles but approximately half the interacting particles near the loss-cone will precipitate into the dense atmosphere. This feature is advantageous because of the limited VLF signal strength that can be generated by modulating the electrojet [Stubbe et al., 1982].

Since cyclotron resonance is likely to be most effective at the equatorial plane where the magnetic field strength minimizes, spacecraft-borne VLF transmitters would seem the best way to induce particle precipitation. Until this becomes a reality, the optimized ground-based VLF transmission approach seems the most viable method of inducing radiation belt particle precipitation. An obvious limitation is the need for VLF ducting, which is unpredictable. Also, the available L-shells are limited to where ionospheric heaters are available. HAARP addresses the lower L-shells of the outer radiation belt. We treat the experiment described below as a proof-of-principle concept.

2. Experiment Description

Cyclotron resonance between a ducted whistler-mode VLF wave and gyrating electron may only occur when the wave and particle are propagating in opposite directions, taking the Doppler shift into account [Rash et al., 1984b]. The particle will be guided by the magnetic field line, and the VLF wave should be guided by a plasma duct centered on the same magnetic field line. For a given particle energy and (parallel propagating) wave frequency component, cyclotron resonance is a function of magnetic field strength and electron density along the VLF duct [Rash and Scourfield, 1984a; Rash et al., 1984b]. In order to maximize the wave-particle resonance path length, which will in turn maximize pitch angle scattering, the artificial VLF wave frequency must vary along the magnetic field line [Brinca, 1981]. The targeted bunch of particles will vary their parallel velocity as they propagate along the magnetic field line [Rash et al., 1984b]. This is a function of particle energy, which we select to optimize the optical detection of precipitation, particle pitch angle, which we select to be at the loss cone, and magnetic field strength, which we can model (e.g. Tsyganenko or Dipole). Likewise, the frequency-dependent VLF propagation velocity will vary [Rash and Scourfield, 1984a]. This is a function of the wave frequency, which we calculate, electron gyro-frequency, which we model from the magnetic field strength, and plasma frequency, which we also model (e.g. Diffusive equilibrium or R_E^{-4})

In order to calculate the VLF frequency-time transmission pattern for HAARP's location (L = 4.8), we choose a dipole magnetic field model and electrons at the loss cone angle. We select the particle energy to be targeted for optimum optical detection. The N_2^+ 427.8 nm prompt emission is attractive but its wavelength is too short for efficient detection by the available camera systems. The O(1D) 630 nm emission is forbidden and has a 110 s delay, at least in vacuum, which makes it unsuitable. The most suitable optical compromise is the O(1S) 557.7 nm emission, which is also forbidden but with a delay of only 0.7 s, and is efficiently detected by available camera systems. For natural precipitation, the O(1S) intensity maximum comes from an altitude around 105-110 km, which is the deposition altitude of precipitating electrons with energies of 5-10 keV [del Pozo et al., 1997]. In addition, since HAARP's location is sub-auroral, we choose to run this experiment for quiet geomagnetic conditions, i.e. Kp < 3, which generally ensures that the natural aurora is poleward of the facility and wave propagation is within the plasmasphere.

The plasma density along the magnetic field lines is the least well defined parameter, and is a function of geomagnetic history and the plasmapause position. Statistical satellite-based models exist describing the plasma density along the magnetic field lines [e.g. Denton et al., 2002a,b]. We choose to use a diffusive equilibrium model, suitable for quiet geomagnetic conditions, but this still requires the equatorial plane plasma density to be known. Again, statistical satellite-based models exist [e.g. Carpenter and Anderson, 1992]. The equatorial plasma density is also a function of geomagnetic history and the plasmapause position [Moldwin et al., 2002; O'Brien and Moldwin, 2003]. Statistically, HAARP remains within the plasmasphere for Kp < 3 [Sheeley et al., 2001]. For HAARP's location (L = 4.8), and assuming Kp < 3, the equatorial plasma density is typically in the range 65-225 el/cm^3 if the plasmapause is greater than L = 4.8 [Sheeley et al., 2001]. However, following a period of heightened activity, the plasmapause may be less than L = 4.8, in which case HAARP will be located in the plasmatrough with plasma densities typically <20 el/cm^3 [Sheeley et al., 2001]. The actual equatorial plasma density can be inferred from satellite data, e.g. the EUV imager on the IMAGE satellite [Craven et al., 1997; Sandel et al., 2000; Goldstein et al., 2003], but this is difficult in real time.

Figure 1 shows the theoretical frequency-time curves computed using the parameters described above. The top and bottom panel is for 5 keV and 10 keV electrons, respectively.

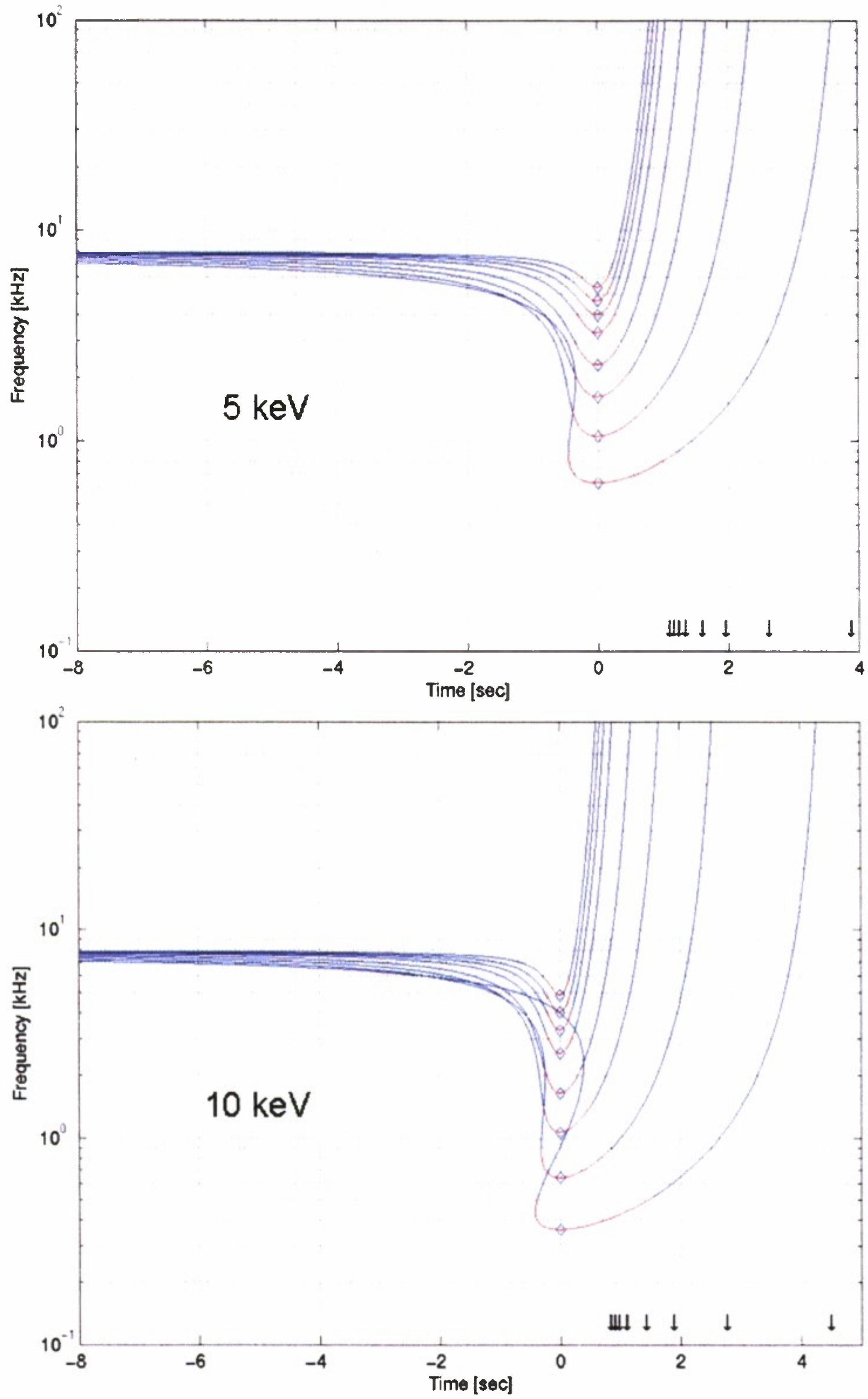

Figure 1: Theoretical frequency-time curves to optimize the VLF cyclotron resonance.

The time origin corresponds to the electron crossing the equatorial plane. The arrows indicate the time when the particle will precipitate. The different curves in each panel correspond to 2, 5, 10, 20, 50, 100, 200, 400 el/cm^3 plasma density in the equatorial plane, stacking top to bottom at t = 0. These plasma densities cover all possibilities from the plasma trough outside the plasmapause to the expected density range inside the plasmapause. Since whistler wave ducting outside the plasmapause is relatively rare [Carpenter and Sulic, 1988], we have not attempted the proposed experiment for low plasma densities, i.e. less than 100 el/cm^3.

The electron gyro-frequency at L = 4.8 is ~8 kHz in the equatorial plane. A VLF wave of higher frequency can not propagate beyond the equatorial plane because the propagation speed goes to zero and reflection occurs. This explains the maximum wave frequency of ~8 kHz for t < 0 in Figure 1. Since the ionosphere can not efficiently generate VLF waves above ~8 kHz, the higher frequencies for t > 0 can not be realized, corresponding to region of space near the VLF wave source. Hence, only that part of the magnetic field line close to the equatorial plane, corresponding to frequencies less than ~8 kHz can be used for artificial cyclotron resonance. Hence, it is imperative for VLF ducting to occur in order for the proposed ground-based technique to function. Obviously, this condition falls away for an in-situ satellite capable of VLF transmissions.

A first attempt at artificial VLF-induced particle precipitation was made during the HAARP optical campaigns of January/February 2005 and again in March 2006. In the first campaign, data from the IMAGE satellite was available, which showed that the equatorial plasma densities targeted were in the correct range (not shown), but the satellite had failed prior to the second campaign. Figure 2 shows ground-based recordings of the artificial VLF signal produced by modulating the electrojet with a 3.25 MHz X-mode carrier wave. White labels indicate the electron energy and equatorial plasma density targeted. The modulation sub-harmonic is seen in all traces. Manmade interference is seen at ~2 kHz in the E/W channel. The transmitter-off periods are deliberate in order to obtain background images of the sky (discussed below). Only 5 and 10 KeV electron energies were targeted to best suit optical detection of any precipitation. The equatorial plasma densities targeted correspond to the most likely being present for low to moderate geomagnetic activity at HAARP's location. For the January/February 2005 operations Kp < 4+ and for March 2006, Kp < 3+. Both campaigns had intervals of Kp = 0. No experiment within the plasma trough has been

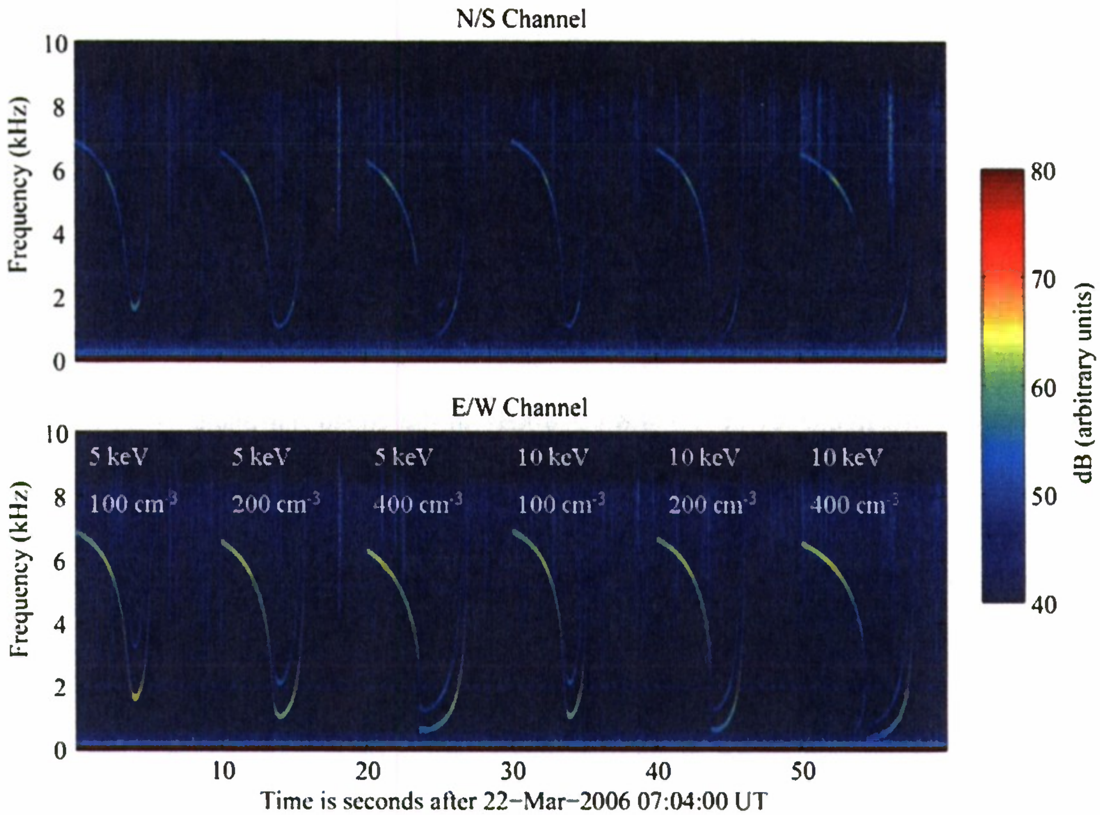

Figure 2: Ground-based VLF recordings produced by HAARP modulation of the electrojet.

attempted as this requires a Kp > 3, which is usually associated with auroral activity over HAARP.

To optimize the chances of detecting the expected weak optical emissions from the induced precipitation, we operated an all-sky imager in an extreme binning mode specifically formulated to improve sensitivity. This sacrifices spatial resolution but preserves significant imaging capability, which is essential to locating the actual precipitation and the ducts that may have fostered VLF propagation to the equatorial plane. The 3.5" HAARP bare-CCD all-sky imager was operated with 20 x 20 binning reducing the 1340x1300 pixel chip down to an effective detector consisting of 67x65 pixels each 0.4 mm on a side. This corresponds to a ~10x10 km spatial resolution in the E-layer, sufficient to resolve any VLF ducts. Exposures 2 s long were taken centered on the expected arrival time of any precipitated particles and during transmitter-off periods bracketing the VLF transmissions (see Figure 2). A calibrated image taken during the experimental run of 2005 is shown in Figure 3. A natural auroral arc

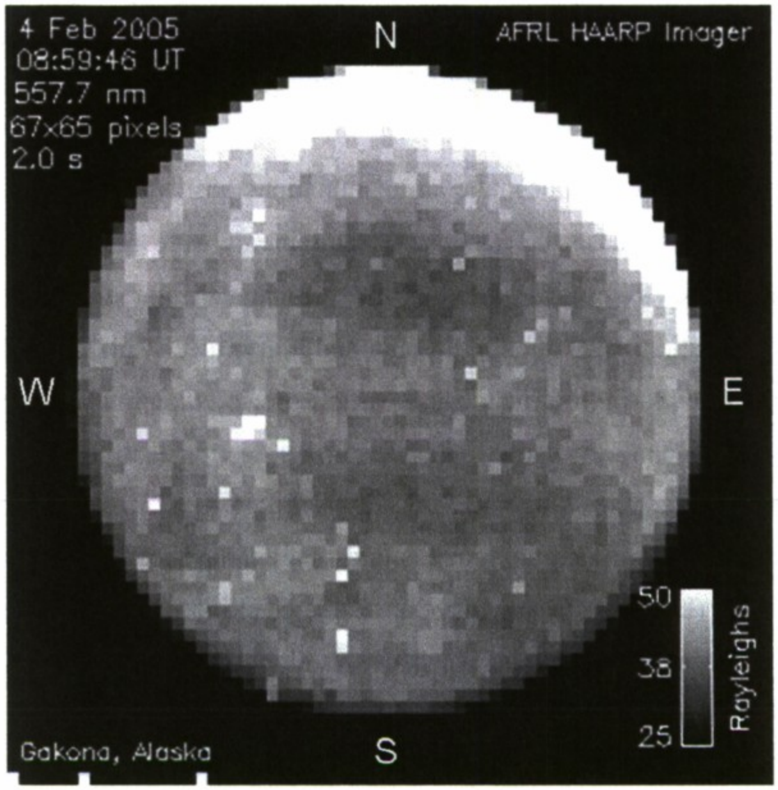

Figure 3: Example image of the night sky taken during the VLF cyclotron resonance experiment.

is present on the far north-east horizon. The average sky intensity seen through the 557.7 nm filter, which admits light over a 2 nm passband, was approximately 40 R. Statistics for a 7 x 7 pixel region near the center of the image give an average of 40.12 R and a standard deviation of 0.974 R. It is clear from the image, however, that most of the features represent actual structure in the sky, including stars, distant aurora, and airglow waves, and thus the detection limit from instrument noise can be expected to be significantly smaller than the ~1 R fluctuations seen in the background. Sky background therefore appears to pose a more significant limitation to detectability than instrument sensitivity does, at least at this wavelength. Hence, during the analysis the paired background images are subtracted from the data images. One method for reducing the sky background intensity in the data images is by utilizing shorter exposure times more closely synchronized to the arrival time of the particles, assuming the mono-energetic particle precipitation produces a very short burst of photons. Uncertainty in the arrival time of VLF-induced precipitation, due to magnetic field and plasma density modelling constraints, limit the minimum exposure time unless the camera read-out dead time can be reduced to zero. A night vision TV camera would, in principle, be adequate were it not for their very poor self-induced noise performance.

3. Results

These initial experiments did not make an unambiguous positive optical detection of VLF-induced precipitation because the necessary requirements were never met simultaneously, namely, cloud-free sky for optical detection, low geomagnetic and auroral activity, electrojet overhead for modulation, VLF ducting present, and transmitter availability. We do not claim that the experiment will ever routinely cause particle precipitation but aim to provide proof of principle. Of the currently available ionospheric modification facilities, HAARP's location remains the best choice (L = 4.8). The EISCAT facility (L = 6.2) is within the auroral oval, making contamination from natural auroras almost inevitable and VLF ducting less frequent. The SURA facility (L = 2.5) does not have a reliable electrojet which it can modulate, except under active geomagnetic conditions, which are unsuitable.

4. Conclusion

An experiment has been designed to optimize manmade precipitation of magnetospheric electrons by VLF cyclotron resonance. The frequency of the VLF wave is modulated in time such that Doppler-shifted cyclotron resonance between the wave and gyrating electrons is maintained along a large fraction of the magnetic field line for a selected particle energy. The VLF signal is generated in the ionosphere by modulating the electrojet current. This modulation is achieved by affecting the Hall conductance of the ionosphere using powerful high-frequency radio waves transmitted upwards from the ground. Such modulation has been successfully implemented at the HAARP facility in Alaska, USA. Whilst artificial VLF signals have been produced, the optical signal of cyclotron resonance induced precipitation has not been detected yet in the first two attempts. This has been due to either no electrojet available overhead as detected by magnetometers, cloudy skies, natural auroras dominating, or presumably no suitable VLF ducts being present. The latter point is the least well known parameter in this experiment.

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