POLAR AERONOMY AND RADIO SCIENCE (PARS) ULF/ELF/VLF PROJECT

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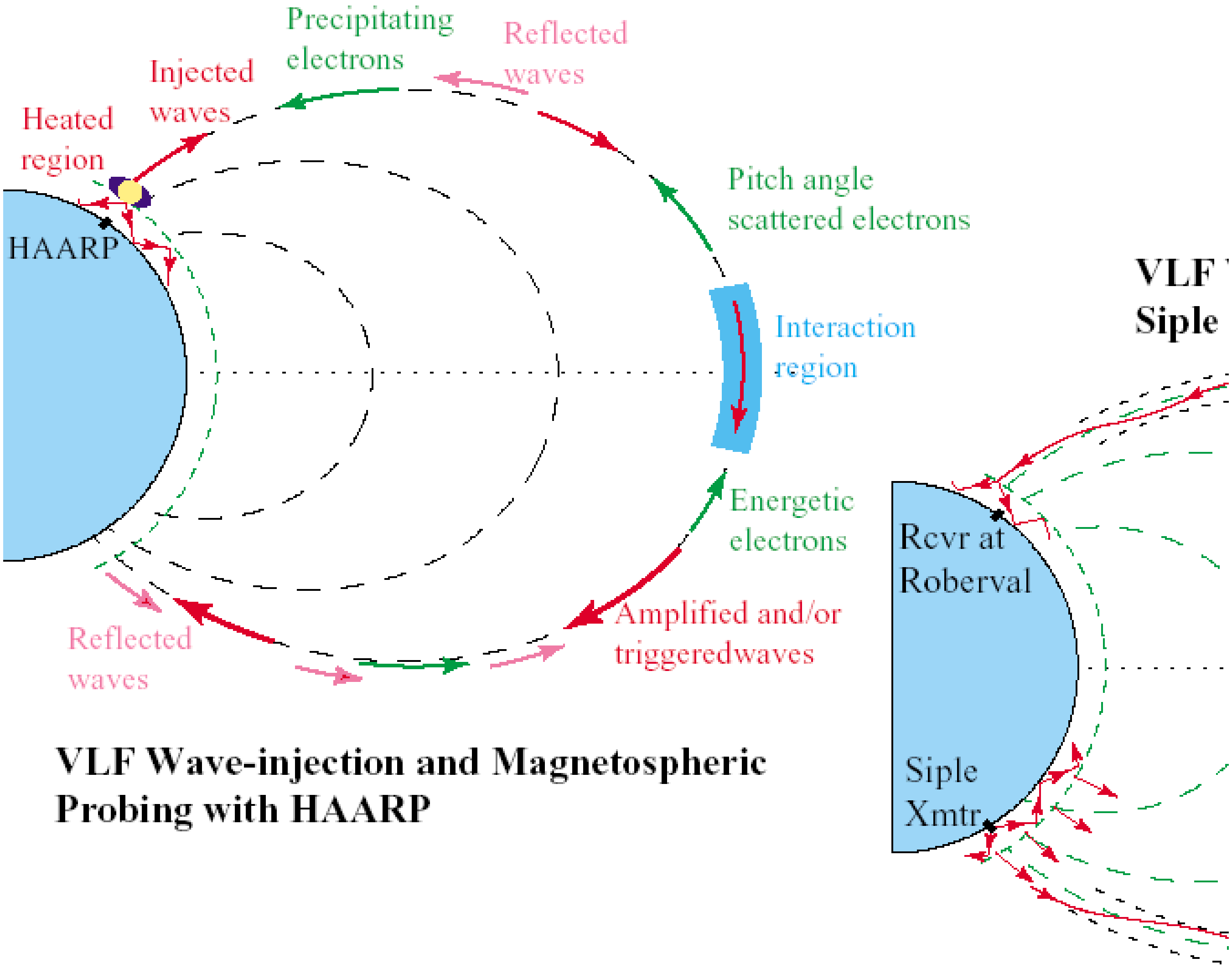
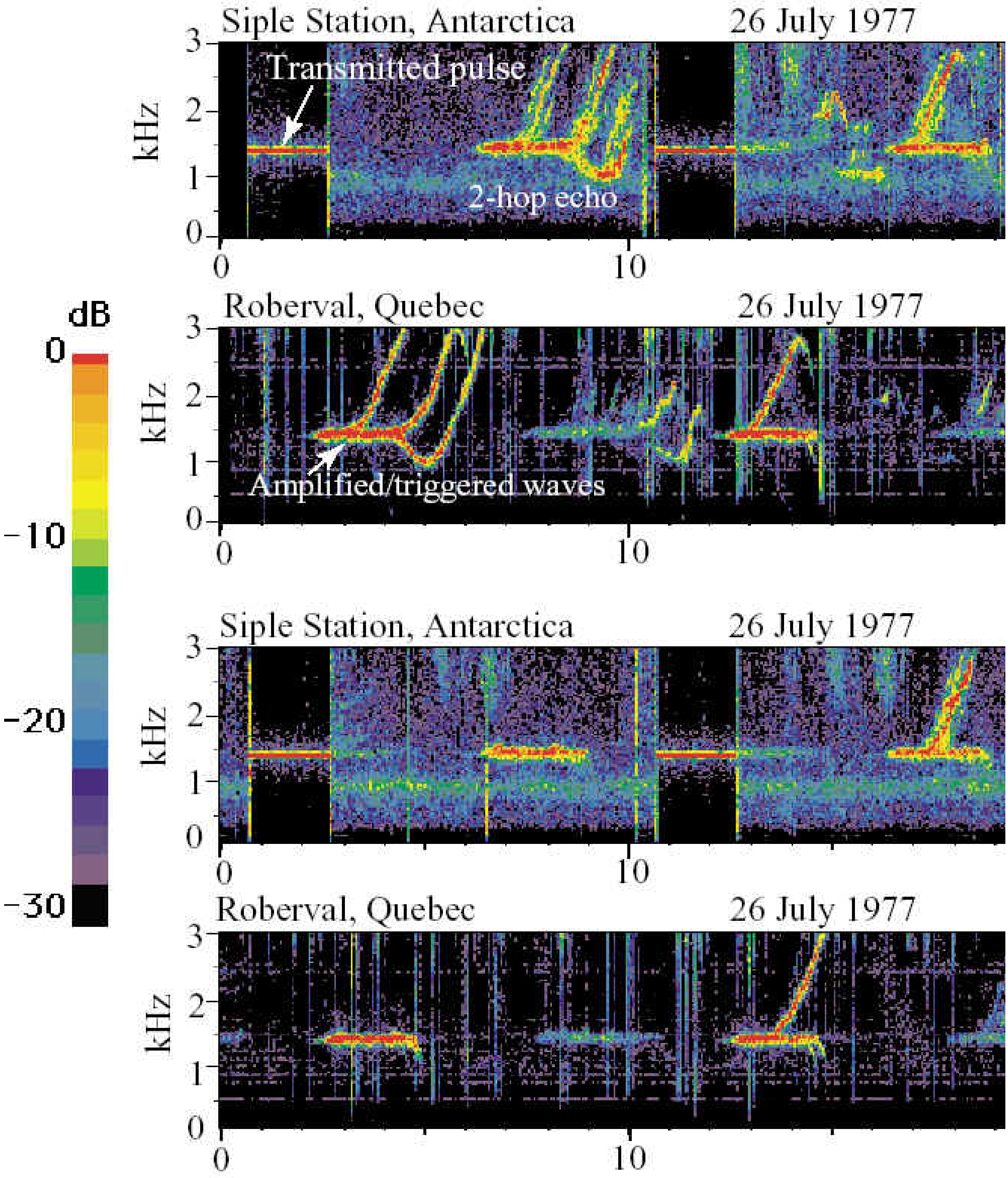


VLF Wave-injection and Magnetospheric Probing with HAARP

Outline



1. INTRODUCTION

The collection of state-of-the-art (and in some cases unique) geophysical instruments at or near the HAARP Gakona site, as well as the capability for active ionospheric modification and ULF/ELF/VLF wave-injection with the HAARP heater, provide an outstanding opportunity for experiments aimed at studying the mechanisms and effects (both ionospheric and magnetospheric) of wave-particle interaction processes, in subauroral regions near and immediately outside the plasmapause. The L-value of Gakona (L=4.89) is within the range of L-shells explored in an extensive set of coordinated ionospheric and magnetospheric experiments conducted from Siple Station, Antarctica (L = 4.2). These experiments included a wide range of ELF/VLF (1.5 to 7 kHz) wave-injection experiments accompanied by a host of passive ionospheric diagnostics, including optical imaging, photometers, riometers, ULF micropulsations, ionosondes, and magnetometers, and were conducted during 1970s and 1980s. Active wave-injection and passive geophysical observations from Siple Station were often coordinated with high and low altitudes satellites, such as ISIS-1,2, IMP-6, ISEE-1, and DE-1 and DE-2. No such experiments have been carried out since the closure of Siple Station in 1988 due to logistical difficulties in maintaining this dedicated Antarctic facility. At present, some coordinated geophysical observations of the plasmapause/subauroral regions are carried out from the Halley Bay (UK) and to a more limited degree from the Sanae (South Africa) Stations in the Antarctic.

Resonant interactions between ELF/VLF waves and energetic particles are pervasive throughout the Earth’s magnetosphere and are believed to play a controlling role in the dynamics of the inner and outer radiation belts. A primary natural example of waves is the so-called ELF/VLF chorus, which is well known as the most intense electromagnetic emission in near-earth space, and which is a driver of electron precipitation, believed to be responsible for pulsating aurora and the morning side diffuse aurora. The generation mechanism of this intense coherent laser-like emission is not yet understood, in spite of many years of observations and theoretical analyses.

Chorus occurs primarily on closed field lines, typically outside the plasmasphere, and can thus be optimally observed from Gakona. It is often associated with burst particle precipitation, leading to secondary ionization (as may be viewed with riometers and ionosondes), optical emissions (as may be viewed by photometers and all-sky cameras), x-rays (as may be observed on high altitude balllons), and micropulsations (ULF receivers), thus requiring coordinated sets of observations.

A primary example of particle phenomena at subauroral latitudes are the relativistic electron enhancements, which are observed at geosynchronous orbit as well as on low altitude satellites (e.g., SAMPEX), and which are one of the important aspects of Space Weather. Although it is well known that these enhancements are associated with the solar wind, and in fact exhibit strong 27-day periodicity, how they are accelerated to relativistic energies is not yet known and is under debate. Wave-particle interactions are definitely involved, in ways not yet understood. Most of the present observations of this phenomena is being carried out on lowand high-altitude satellites. Ground-based observations of ionospheric effects of the associated precipitation enhancements can complement spacecraft data by providing continuity in time and by also documenting the associated wave activity. ELF/VLF chorus and relativistic electron enhancements are just two examples of subauroral phenomena which lend themselves to coordinated observation from the ground. Other waves that are prominently observed in subauroral regions include ion-cyclotron waves in the ULF range.

An exciting component of the PARS ULF/ELF/VLF Project involves active generation of ULF/ELF/VLF waves by modulated HAARP HF heating. Such waves may well get amplified and lead to triggering of additional waves (i.e., at frequencies other than that is transmitted) as a result of interactions with energetic particles. Preliminary estimates indicate that once HAARP goes to full power it will be able to generate in-situ ELF/VLF wave power densities comparable to those injected from Siple Station, thus leading to initiation of well documented nonlinear effects, triggered VLF emissions, and even controlled precipitation of energetic electrons. Other HF heater facilities around the world (e.g., EISCAT) are located at latitudes generally too high to launch ULF/ELF/VLF waves on closed field lines. With HAARP, on the other hand, it may well be possible to observe the so-called whistler-mode two-hop echo, i.e., the ELF/VLF signal which is generated by modulating the electrojet overhead HAARP, which travels to the geomagnetically conjugate hemisphere, being amplified along the way and reflecting (specularly) from the sharp lower boundary of the ionosphere thereof, and travelling back to the hemisphere of origin, thus being observable there within a few seconds of its generation. At a later stage, it may also be possible to conduct ship-based observations of amplified and triggered waves in the geomagnetically conjugate region. At a minimum, a coordinated ULF/ELF/VLF campaign will involve an excellent set of passive observations of natural waves (e.g., chorus, ULF micropulsations) and associated ionospheric effects (precipitation, optical signatures etc, while at the same time quantifying the overhead ionosphere with the collection of outstanding instruments at HAARP.

Better understanding of wave-particle interactions under controlled conditions will allow us to in turn understand high latitude phenomena which occur under less controlled circumstances, as well as contributing to the general knowledge base of ELF generation and propagation for communication purposes.

2. SCIENTIFIC BACKGROUND

A two-prong review of scientific literature and other background which was recently conducted provides scientific background that will guide the specific experiments to be conducted as part of the PARS ULF/ELF/VLF Project.

2.1. ELF/VLF Wave-injection experiments

The first goal of the study was to develop of a plan of ELF/VLF wave-injection experiments to launch ELF/VLF waves on closed field lines. The two main bases for this study are (i) the results of the ELF/VLF wave-injection experiments carried out with the Siple Station, Antarctica facility during 1974-1989, and (ii) the results of previousHFheater-induced ELF/VLF generation experiments, notably the Tromsø/EISCAT experiments. The study was focused on the two scientific issues of how to maximize the possibility of ducting of ELF/VLF signals between the two hemispheres by specifying geomagnetic conditions during which the highest L-shell ranges can be excited, and how to specify the transmitter frequency, modulation scheme (amplitude, phase, or frequency modulation), and patterns to maximize both excitation and detection of the waves. More specifically, this study aimed at producing a detailed account of the primary results of the relevant Siple Station experiments, and a plan of HAARP operations and associated observations to maximize the chances of detecting ducted two-hop echoes of HAARP-generated ELF/VLF signals and possible accompanying ionospheric effects, for example due to induced precipitation of energetic electrons.

Appendix A.1–A.5 Sections provide a summary of primary results of ELF/VLF generation experiments and the results of ELF/VLFwave injection experiments which have been carried out either by HF heaters or ground based ELF/VLF transmitters. Also summadrized are spacecraft observations of ELF/VLF waves injected into the magnetosphere by HF heaters and spacecraft observations of energetic electrons, amplified electromagnetic VLF waves and triggered VLF emissions. The primary theme unifying most of these observations is the fact that the phenomena become more pronouced both during and immediately following periods of moderate to strong geomagnetic activity, where Kp>3. Under these conditions, the auroral electrojet currents are generally increased, leading to larger HF-heating-induced conductivity changes and thus ELF/VLF currents and radiation. At the same time, large fluxes of energetic electrons are injected into the plasmasphere from the magnetotail, and these fluxes generally amplify the ELF/VLF waves which propagate through them. Furthermore during the magnetic disturbance and in the recovery phase immediately after the disturbance the contraction and expansion of the plasmasphere tends to produce plasma irregularities, some of which can duct ELF/VLF waves between conjugate hemispheres.

Although ELF/VLF waves may be more pronounced during periods of magnetic disturbance, the plasmaspheric ducts necessary to guide the HAARP-generated ELF/VLF waves will generally be located at magnetic latitudes which are much lower than the magnetic latitude of HAARP. Thus the HAARP generated ELF/VLF waves must travel further in the Earth - ionosphere waveguide before they enter the ducts, and their amplitude will be reduced because of additional attenuation and spreading in the waveguide. Thus if we wish to take advantage of the possible amplification of HAARP generated ELF/VLF waves, then a reasonable compromise for these conflicting requirements is needed. One compromise is to conduct the ELF/VLF wave injection experiments during the first few days following moderate to strong magnetic activity. In this quieting period the plasmasphere will expand towards the HAARP location, while at the same time the injected energetic electron fluxes within the plasmasphere will remain high, and significant amplification will remain a possibility. We also propose to establish a baseline for ELF/VLFwave injection experiments by performing them during magnetically quite times when the plasmasphere expands over the HAARP site. These experiments will involve ducted propagation of HAARP generated ELF/VLF waves to the conjugate hemisphere and back . Based on the above considerations, as well as the material provided in the Appendix, the following recommendations were formulated for the ELF/VLF wave-injection experiments to be conducted with the HAARP heater:

1) Carry out nighttime ELF/VLF wave injection experiments using the HAARP HF heater during magnetically quiet periods, as well as the first few days following moderate to strong magnetic disturbances.

2) Use a modulation pattern similar to that used at the Tromsø facility during successful ELF/VLF wave injection experiments. This pattern consists of a repeated series of five or more one second CW pulses at frequencies between 500 Hz and approximately 6 kHz. The upper frequency will be set to half of the equatorial electron gyrofrequency on the magnetic field line tangent to the plasmapause position, as estimated according to the degree of

magnetic disturbance.

3) Point the HF beam toward the electrojet position in order to enhance the production of ELF/VLF waves.

2.2. ULF/ELF Wave-injection experiments

The second goal of the background study was to review the literature and develop a plan for ULF/ELFwave generation experiments. The main basis for the study are the results of ULF/ELF experiments at Arecibo, Tromsø, and HAARP.

Appendix A.6 provides a summary of relevant results of previous experiments. Concerning ULF/ELF wave-injection experiments, it is important to note that the wavelength of electromagnetic waves in the lower ELF (<100 Hz) and ULF frequency range is too large for these waves to become trapped in typical whistler mode ducts. However the plasmapause suface can form a guiding boundary for these waves, as well as for waves of higher frequencies [*Inan and Bell*, 1977]. ULF/ELF waves guided along the plasmapause boundary can echo back from the conjugate hemisphere with time delays of as much as a few minutes. Thus the duty cycle of the HAARP HF signal needs to be adjusted so that the echoing ULF signal can be detected without interference from HAARP. One straightforward strategy is to pulse and listen. When the echo is detected, its time delay is noted and the period of the pulse mode is adjusted to equal the wave time delay. In this manner the wave amplitude can be increased.

Willis and Davis [1976] appeared to have success in producing ULF/ELF waves in the frequency range 0.2 to 5Hz by squarewave modulating at ULF/ELF frequencies the power output of the 1.3MW, 14.7 kHz VLF transmitter at Cutler, Maine. The experiments were most successful when carried out during the quieting period following magnetic disturbances. The *L*-shell along which the ULF/ELF waves appeared to propagate lay in the range 3.9 to 4.8. This upper limit is close to the *L*-shell of HAARP. We propose to repeat the *Willis and Davis* [1976] experiments, as well as those successfully carried out by McCarrick et al. [1990] using the HIPAS HF heating facility.

3. SCIENTIFIC QUESTIONS

A preliminary list of scientific questions have been formulated as a result of the review of relevant background. It is expected that these questions will be expanded in the course of further discussion among individual participants to the PARS ELF/ELF/VLF campaigns. The current list of important scientific questions include those which can be addressed during ULF/ELF/VLF wave injection experiments at HAARP. Some of these are directly related to the injected waves, while others are related to natural phenomena. The same instruments will be used to address both classes of experiments. We list the HAARP related questions first:

1) What are the magnitudes of fluxes of energetic particles precipitated from the radiation belts by ULF/ELF/VLF waves injected into the magnetosphere by HAARP ?

2) What is the mechanism by which the energetic particles are precipitated ? How efficient is this mechanism ?

3) How does the precipitated flux vary as a function of magnetic activity ?

4) What is the magnitude of the energetic particle flux precipitated by ELF/VLF chorus ?

5) How is ELF/VLF chorus related to pulsating aurora and the morning side diffuse aurora ?

6) What are the ionospheric effects of relativistic electron precipitation ?

To answer the questions listed above a constellation of ground-based instruments. In addition, data from the POLAR and CLUSTER-2 spacecraft will be important in determining the radiation belt fluxes during the wave injection experiments. Funding for analyzing the relevant spacecraft data will be provided through sources other than HAARP. The PARS ULF/ELF/VLF Project will involve targeted periods during which observational campaigns will be conducted, with all relevant instruments putting out a maximum effort for coordinated observations, of either the waves or their associated ionospheric and magnetospheric effects. The ULF/ELF/VLF team conducting these active experiments and passive observations will consist of selected scientists and engineers from the polar aeronomy and radio science community who will be encouraged to use the HAARP facility in a coordinated and focused manner in order to obtain the maximum scientific benefit from each usage.

All aspects of the HAARP ULF/ELF/VLF campaigns will be approved and organized by a

Steering Committee. Required instruments will include appropriately placed ULF/ELF/VLF receiver(s) and other ionospheric sensors, such as riometers, photometers and all-sky cameras, ionosondes, coherent HF radars, and others yet to be determined. An important goal of the experiments will be to launch ULF/ELF/VLF waves on closed field lines under geomagnetically quiet conditions and to detect two-hop reflected echoes of these waves (and any amplified or triggered components thereof) at appropriately placed sites near and around HAARP. Detection of HAARP-generated ULF/ELF/VLFwaves in this mannerwould set the stage for an entirely new set of magnetospheric excitation and probing experiments that can uniquely be conducted with the HAARP facility. A much broader set of phenomena can be investigated with HAARP compared to the >1.2 kHz excitation which was practical in Siple Station, Antarctica experiments, since with HAARP it is possible to excite waves at frequencies below 1 kHz, including waves in the low-ELF (<300 Hz) range and ULF ion-cyclotron waves at a few Hz.

We propose to address the scientific questions by means of coordinated observations carried out in three separate campaigns. The campaigns would take place in Fall 2001 and 2002, and in Spring 2002. Seed research funding to cover incremental costs, such transportation, travel, food/lodging for each campaign will be provided to participating team members as required.

Team members will be encouraged to obtain funding for data analysis and interpretation from other agencies, such as NSF. The precise time and duration of each ULF/ELF/VLFwave injection

campaign will be established in consultation with the management team of the HAARP project,

although a preliminary basic campaign strategy is discussed in the next Section.

The specific goal of each campaign will be to answer one or more of the science questions

listed above. Deliverables will consist of the science data sets acquired during the campaigns.

Analysed data sets will be available to the public through the HAARP web page.

4. PARS ULF/ELF/VLF CAMPAIGN STRATEGY

A preliminary observational strategy for the ULF/ELF/VLF campaigns is provided below, with

special emphasis on the timing and duration of modulated HAARP transmissions.

4.1. Basic program of wave injection experiments

The scientific questions listed above will be addressed in the context of three separate campaigns,

taking place in Fall 2001, Spring 2002, and Fall 2002. To conserve the limited resources of

the HAARP program, the ULF/ELF/VLF campaigns would take place during the same time

as the HAARP campaigns already planned for Fall 2001, Spring 2002. and Fall 2002.The

ULF/ELF/VLF wave injection experiments will primarily be conducted during the first few

days following moderate to strong magnetic activity. In this quieting period the plasmasphere

expands towards the HAARP location, while at the same time energetic electron fluxes injected into the plasmasphere from the tail of the magnetosphere remain high, enhancing the chances

of significant amplification of the injected waves.

On average there are approximately three quiet days following the typical disturbed day.

During the campaign the wave injection experiments will not in general be undertaken on

disturbed days. Use will be made of the data from the NOAA Space Environment Center

in order to predict at least one day in advance the days expected to be disturbed. HAARP

ULF/ELF/VLF wave injection transmissions will begin on the day following the disturbed day

or days.

Energetic electron data from the POLAR spacecraft show that injected energetic electron

fluxes are most intense within the plasmasphere in the midnight to dawn local time sector.

Consequently it is expected that wave amplification would be more prevalent in this region. In

view of this situation the wave injection experiments will intially be confined to the 0000-0600

local time period.

According to this plan the wave injection experiments would be carried out on approximately

15 days out of the ~21 days of each campaign. The number of hours of dedicated HAARP

operations during each of the 15 days will be determined via negotations with the HAARP

Program management.

4.2. Extended program of wave injection experiments

The program described above represents the minimum effort that can adequately address the

scientific questions outlined in the report to the PARS team. However if sufficient resources can be found, each HAARP campaign can be lengthened by one additional week with HAARP

transmissions during this week being dedicated to ULF/ELF/VLF wave injection experiments.

Transmissions would occur each night during the 2000-0600 local time period without regard to

the degree of magnetic disturbance. The extra week of transmissions would provide a baseline

for characterizing the success of the experiments as a function of magnetic disturbance.

A. APPENDIX: REVIEW OF EXISTING SCIENTIFIC DATA

Below we discuss the salient points of our review of the relevant data concerning ULF/ELF/VLF

generation by HF heaters, ULF/ELF/VLF wave injection into the magnetosphere, and spacecraft

observations of ULF/ELF/VLF waves and energetic electrons.

A.1 Siple Station Experiments

Stanford University has had many years of experience with ELF/VLF wave-injection experiments

carried out with the Siple Station, Antarctica facility during 1974-1989. In these

experiments, 1.2 to 7 kHz waves were launched on field lines ranging from $L = 5$ to $L = 3$,

with ducting, amplification, and emission triggering occurring in many cases. In 1973 and 1974

ducted signals were observed on approximately 20% of the total number of days, and on these

days ducting occurred over intervals of 4 to 8 hours [*Carpenter and Miller,* 1976, 1983; *Carpenter*,

1981; Carpenter and Bao, 1983]. Ducted signal propagation occurred most frequently during the quieting periods following magnetic disturbances. The experiments were conducted for a wide range of transmitter radiated power levels, and geomagnetic conditions. The minimum radiated power for wave growth and emission triggering was approximately 1 W [*Helliwell et al.*, 1980]. Experience with Siple indicates that the selection of geomagnetic conditions and transmitter frequency and modulation are critically important to the success of ELF/VLF wave injection experiments.

Although the Siple transmitter signals were not observed to be ducted for $L > 5$, this is thought to be due to a poor signal to noise ratio for these signals, since they lose power as a result of wave spreading loss and attenuation in the Earth- ionosphere waveguide as they propagate from the transmitter location at $L = 4.2$ to ducts at $L > 5$. In fact lightning generated whistlers, which in general have much higher amplitudes than the typical signals from Siple, have been observed to propagate in the ducted mode on L shells as high as $L = 8$ [*Carpenter*, 1981]. Thus there is good reason to expect that whistler mode ducts will be present in the vicinity of HAARP.

A.2 Tromsø Experiments

Electromagnetic waves in the 200 Hz to 6.5 kHz frequency range have been generated by the Max Planck Institute’s HF heating facility near Tromsø, Norway, through modulation of the overhead auroral electrojet currents. The Tromsø experimental data, as well as theoretical models interpreting the data, have been published in a long series of papers spanning more than a decade [e.g., *Stubbe and Kopka*, 1977; *Stubbe et al.*, 1981, 1982; *Barr and Stubbe*, 1984a, 1984b; 1991a, 1991b; *Rietveld et al.*, 1987, 1989; *James*, 1985]. Below we list the most important features of these experiments.

1) The Tromsø HF ionospheric heating facility successfully produced electromagnetic waves in the 200 Hz to 6.5 kHz frequency range with an amplitude of approximately 1 pT as measured on the ground. The ELF/VLF wave amplitude was roughly constant between 2–6 kHz, but dropped by 3 dB at the lower end of the frequency range.

2) The HF heater frequency generally lay within the three frequency bands: 2.75 - 4 MHz, 3.85 - 5.6 MHz, and 5.5 - 8 MHz, and the HF signal was generally 100% amplitude modulated with a square wave.

3) The HF radiated power was approximately 1 MW, and the effective radiated power (ERP) generally lay in the range of 200 to 300 MW.

4) It was generally found that X-mode polarization of the HF signal resulted in a more intense radiated ELF/VLF signal than O-mode polarization.

5) The ELF/VLF signal strengthwas highly correlated with magnetic activity, and significantly more intense ELF/VLF waves were produced during periods of moderate geomagnetic disturbance with Kp~ 3.

6) The amplitude of the ELF waves was essentially independent of the ERP of the HF signal,

but depended only on the total HF power delivered to the ionosphere.

7) The ratio of heating to cooling time constants ranged from 1 at 510 Hz to 0.3 at 6 kHz.

The Tromsø facility was also used to excite ULF waves in the 1.67 - 700 mHz frequency range

[*Stubbe and Kopka*, 1981; *Stubbe et al.*, 1985; *Maul et al.*, 1990]. A variety of HF modulation

schemes were attempted. The amplitude of the excited ULF waves were of the order of 100 -

10,000 pT.

A.3 Arecibo, HIPAS, and HAARP ELF/VLF Experiments

The high power HF ionospheric heating facilities at the Arecibo, HIPAS, and HAARP Observatories

have been used in a number of campaigns to modulate ionospheric current systemsw at

ELF/VLF frequencies in order to produce ELF/VLF waves. At Arecibo, the equatorial dynamo

current was modulated and ELF/VLF waves were produced over the frequency range of 500 Hz

to 5 kHz using a heater frequency of approximately 3 MHz and a total HF input power of 800

kW, with an ERP of 160 - 320 MW [*Ferraro et al.*, 1982]. There was also evidence that the

HF heater sometimes created ducts along which VLF signals could propagate into the conjugate

ionosphere [it M. Starks, 2000].

At HIPAS, the HF heater was used to create ELF/VLF waves through three different modulation

techniques, amplitude modulation, phase modulation, and beat-frequency modulation

[*Wong et al.*,1995]. Amplitude modulation appeared to be generally the most efficient. The generation of ELF/VLF waves at HIPAS was most successful when the electrojet was overhead, when there was low D region absorption, and when energetic particle precipitation and visible aurora were not overhead [*Wong et al.*,1996]. Enhancement of the ELF/VLF wave amplitude could sometimes be achieved by pointing the HF beam in a direction other than vertical, leading to the conclusion that ELF/VLF wave production is optimized when the HF beam has is pointed toward the electrojet position [*Garnier et al.*, 1998].

ELF wave generation at HAARP has been carried out using varying frequency and polarization [*Milikh et al.*, 1998]. Results implied that the polarization of the generated ELF wave can be controlled by changing the frequency or polarization of the heating HF waves. The efficiency of ELF wave generation at HAARP has also been studied as a function of HF frequency and polarization and ELF frequency and waveform [*Rowland and McCarrick*, 2000]. Results indicated that the largest ELF signal was produced when the HF frequency was 3.3 MHz in x-mode with 100% square wave modulation and the ELF frequency was approximately 1 kHz.

A.4 Spacecraft Observations

The efficacy of the use of a modulated HF heater to inject ELF/VLF waves into the magetosphere has been demonstrated using four spacecraft: DE-1, ISIS-1, Aureol-3, and EXOS-D [*James et al.*, 1984,1990; *Berthelier et al.*,1983; *Wong et al.*,1995]. Waves in the frequency range 525 Hz - 5.85 kHz produced by the Tromsø heating facility were observed during passes of these spacecraft near the heater. The HF frequencies used during these observations were 2.759 and 4.04 MHz. The HF carrier waves were square wave modulated, either at a series of four frequencies (0.525,1.725, 2.925, and 4. kHz) or five frequencies (0.525, 1.525, 2.225, 2.925, 4.425, and 5.925). In all cases the pulse length at each frequency was one second. The total HF power was 1.08 MW, and the polarization was periodically switched between x-mode and o-mode. In general the x-mode polarization produced the most intense ELF/VLF signals at the spacecraft location. Harmonics of the ELF/VLF modulating signals were also observed, as would be expected for square wave modulation.

During the ISIS observations it was found that amplitude of the ELF/VLF signals at the spacecraft were approximately 10 dB stronger than the amplitude of the ELF/VLF signals measured on the ground near the HF facility. The highest amplitude ELF/VLF signals observed by the spacecraft were those at 525 Hz and 1.75 kHz. From the DE-1 data the power output from the modulated electrojet was estimated to be approximately 30 W.

A.5 Amplification of ELF/VLF Waves

Within the plasmasphere, discrete VLF emissions are commonly triggered by externally injected discrete whistler mode waves such as lightning generated whistlers and fixed frequency signals from ground based VLF transmitters, with peak emission intensities reaching values as large as

16 pT [*Bell, 1985*]. During this process the input waves can be amplified by 30 dB or more. It is commonly believed that the amplification of the input waves and the triggering of emissions takes place near the magnetic equator through a gyroresonance interaction between ~ 1-20 keV energetic electrons and the triggering wave in which the particle pitch angles are altered and free energy is transferred from the particles to the waves [*Helliwell, 1967; Matsumoto and Kimura, 1971; Omura, et al., 1991; Nunn and Smith 1996*]. Understanding the physical mechanism of the emission process is important since these interactions can directly affect the lifetimes of the resonant electrons.

Recently, simultaneous ELF/VLF plasma wave data and 0.1 - 20 keV energetic electron data have been acquired with the PWI and HYDRA instruments on the POLAR spacecraft during periods when VLF emissions were triggered by VLF transmitter signals [*Bell et al.*, 2000]. Itwas found that in all cases the pitch angle distribution of the resonant electrons is highly anisotropic, with the average electron energy transverse to Earth's magnetic field exceeding that parallel by a large factor. According to theory, this type of electron distribution can greatly amplify ELF/VLF waves which propagate through it, and this undoubtedly is the cause of the observed amplification and emission triggering [*Bell* et al., 2000]. It was also found that amplification of 20 dB or more appeared to require a minimum perpendicular energy flux at 20 keV at the magnetic equator of $\sim 6\ ?10_{6}(cm_{2} - s - sr)_{-1}$. This flux level was observed to occur under conditions of moderate to strong magnetic activity when Kp > 3 , and it was equaled on only 3 equatorial dawn passes in January, 1997, and emissions were observed on 2 of these 3. However, amplification without emission triggering appeared to commonly occur at lower flux levels.

A.6 Excitation of ULF and Lower-ELF Waves

No wave-injection experiments were carried out in the lower ELF and ULF range using the Siple Station, Antarctica, transmitter, since the Siple transmitter was not usable at frequencies below about 1.2 kHz. However, there have been other attempts at generating ULF waves. For example, the U. S. Navy VLF transmitter at Cutler, Maine, was square wave modulated at frequencies of 0.2, 1, and 5 Hz over the course of one month [*Willis and Davis*, 1976]. Micropulsations occurred on a number of occasions at harmonics of the transmitter modulation frequency. These events all occurred in the quieting period following geomagnetically active days. In addition, as mentioned above, The Tromsø facility has been used to excite ULF waves in the Pc 5 frequency range [*Stubbe and Kopka*, 1981.

There is some evidence that ULF waves can be excited more efficiently by heating the E or F regions rather than the D region. For example, according to the model of *C. L. Chang* [1996], the plasma density changes in the E or F regions produced by the heater can engender larger conductivity changes than can be produced in the D region through collision frequency

variations. At higher frequencies, 6 - 76 Hz, the HIPAS HF heater has been used to generate ELF

waves through modulation of the polar electrojet [*McCarrick et al.*, 1990;*Wong et al.*, 1996].

ELF wave magnetic fields at the ground were approximately 1 pT. At HAARP ELF waves have

also been produced at frequencies as low as 10 Hz at amplitudes of order 1 pT [*Rowland and*

McCarrick, 2000].

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