

# **ELF/VLF Wave-injection and Magnetospheric Probing with HAARP**

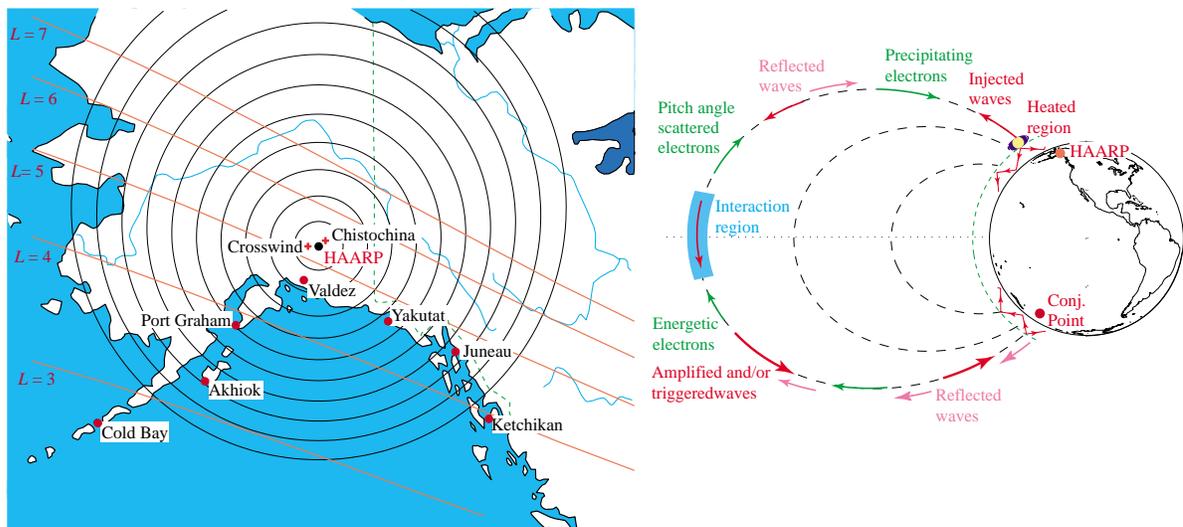
Stanford University  
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## 1. INTRODUCTION

A three year research program is proposed to establish an array of wideband ELF/VLF receivers and to conduct continuous measurements of the magnetospheric response to the injection of ELF/VLF waves using the HAARP HF heater. The primary objective of the proposed program is to detect the so-called ‘one-hop’ direct and the ‘two-hop’ whistler-mode echo of a HAARP-injected ELF/VLF signal, and to study the characteristics of these signals to determine the degree to which injected ELF/VLF signals are amplified by the magnetospheric plasma, leading to the triggering of new emissions and enhanced precipitation of energetic electrons from the radiation belts. The scientific opportunities, background and justification for ELF/VLF wave-injection and magnetospheric probing experiments with HAARP are provided in **Attachment A**, which is a copy of a detailed report prepared earlier (April 2001) by Stanford for preliminary ELF/VLF wave-injection campaigns conducted under the auspices of the Polar Aeronomy and Radio Science (PARS) program.



**Fig. 1. Proposed Program of ELF/VLF Observations in the northern hemisphere.** At each of the sites shown, broadband ELF/VLF measurements will be conducted with identical equipment and with two orthogonal magnetic loop antennas. The purpose of the measurements is to detect the two-hop whistler-mode echo of ELF/VLF signals injected into the magnetosphere by modulated HF heating of the auroral electrojet by HAARP. The solid line circles are incremented in radii by 100-km, with the outermost one having a radius of 1000-km. The loci of the  $L$ -shells shown correspond to 100-km altitude, so that the  $L$ -value at the ground levels are somewhat lower. For example, the HAARP facility at ground level is located at  $L \simeq 4.89$ , while the  $L$ -value at 100-km altitude immediately above HAARP is  $L \simeq 5.25$ .

The measurements of the two-hop signals in the northern hemisphere would be complemented with ELF/VLF observations in the geomagnetically conjugate region (in the Southern Pacific Ocean) on buoy (see Figure 3), aimed at observing amplified one-hop whistler-mode signals and associated triggered emissions. Based on results from 15-years of experimentation with the VLF wave-injection facility at Siple Station, Antarctica ( $L \simeq 4.2$ ), observation of the amplified one-hop signal with triggered emissions is  $\sim 5$  times more likely than the detection of the two-hop echo [Carpenter and Bao, 1983]. Accordingly, the ocean-based measurement is considered a

crucial component of the proposed program, both for the initial detection of an amplified whistler-mode HAARP-injected VLF signal during the next two years when HAARP will operate at less than its full capacity (in terms of power level and antenna array and thus ultimately the intensity of the induced ELF/VLF signal), and also for the conduct of repeatable and routine ELF/VLF wave-injection experiments when HAARP is developed to its full capacity.

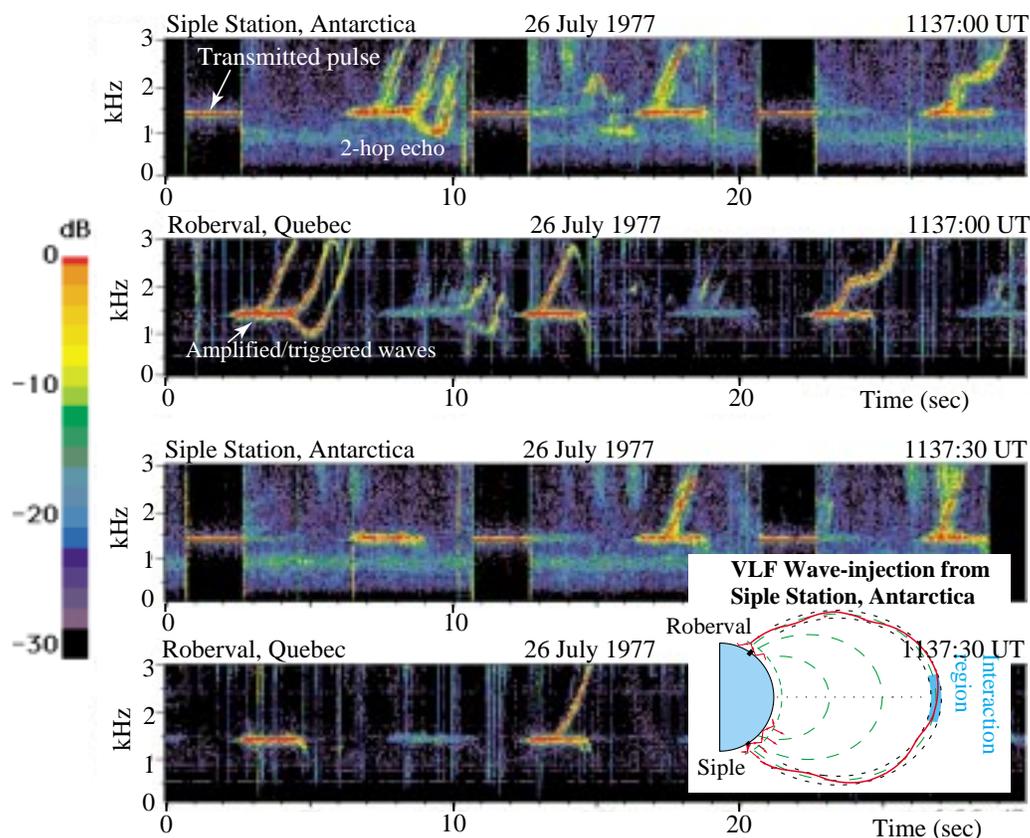
A second objective of the proposed program is to detect ionospheric effects of HAARP-VLF-induced electron precipitation via the subionospheric VLF remote sensing method, which is particularly sensitive for measurements of effects in the nighttime *D*-region of  $>50$  keV electrons. This objective is described in Section 2-C.

In the course of pursuing these two objectives, the proposed ELF/VLF measurements will also serve to determine the amplitude and phase of HAARP-induced ELF/VLF signals as a function of distance on the ground, over a range of up to  $\sim 1500$  km. This determination will in turn allow an indirect assessment of the extent of the magnetospheric regions illuminated by HAARP-induced ELF/VLF waves, even when the two-hop whistler-mode echo might not be observable. The phase-coherent (facilitated by GPS-timing) nature of the measurements will allow the delineation of the individual Earth-ionosphere waveguide modes which carry the HAARP-induced to distant points in the waveguide.

Furthermore, the continuous ELF/VLF measurements at the distributed sites will in addition provide a unique data base for investigations of natural magnetospheric ELF/VLF wave activity (and associated particle precipitation effects) in the important subauroral region in the vicinity of the plasmapause. In the latter context, the proposed array of observing sites represents the most comprehensive set of measurements ever conducted of the subauroral near-plasmapause region.

The scientific motivation for the proposed work arose in the context of discussions (during March – August 2001) of a panel of experts assessing the means by which artificial enhancements (e.g., as a result of atmospheric nuclear explosions) of radiation belt fluxes can be mitigated by controlled transmissions of ELF/VLF waves. The results of the deliberations of the panel indicated that it would be feasible to mitigate such artificial enhancements by injecting ELF/VLF waves *in-situ* from satellite-based transmitters. However, implementation of a practical system required that we take advantage of the natural magnetospheric amplification and growth of whistler-mode signals as a result of cyclotron-resonant interactions. Such interactions are highly coherent and wave amplification is strongly dependent on the frequency-time format of the injected signals as well as factors. Thus, it was found necessary that we *learn to amplify* signals prior to designing a space-based mitigation system. The HAARP facility provides the only source available for this purpose, and the proposed set of wave-injection experiments are thus aimed at investigating the wave amplification and growth processes so that we can determine the conditions (and the modulation formats) under which injected signals are most likely to be amplified. A recent report prepared on the topic of radiation belt mitigation drawing from the conclusions arrived at the HAARP panel deliberations is attached as *Attachment B*. A detailed technical/scientific evaluation of the considerations of the HAARP panel undertaken by radiation belts experts Dr. M. Schulz and Dr. H. Petschek is enclosed as **Attachment C**.

As described in **Attachment B**, the radiated power level and the HF antenna array size of



**Fig. 2. Observations of amplified two-hop signals and triggered emissions.** The transmitted pulses are 2-s long, during which time the VLF receiver at Siple Station is muted (hence the black background). The transmitter is then turned OFF for 8-seconds, during which time the two-hop echo, which is amplified and is accompanied by new emissions which are triggered, is observed. Note that the one-hop signal is observed at Roberval, Quebec, as well as the three-hop signal. There is also clear evidence of the four-hop signal in the Siple records. The procedure is repeated, with the character of the two-hop echo changing somewhat as a function of time.

the present HAARP facility allows for average ELF/VLF signal intensities which are a factor of  $\sim 5$  below the threshold of nonlinear magnetospheric amplification. Observation of two-hop whistler-mode echoes are thus expected to occur under highly specialized conditions. Such relatively rare observations can nevertheless allow us to probe the magnetosphere and determine the means by which HAARP-induced ELF/VLF signals couple to high altitudes. In view of the recognition that observations of two-hop echoes would be relatively rare, we propose a continuous program of observations involving HAARP transmissions on at least  $\sim 100$  days each year for 8 to 10 hours/night. If the HAARP facility were to be upgraded to its full power and full array capacity over the next few years, we can expect to regularly trigger amplification and wave growth, allowing in depth experimentation with transmission formats and full exploration of the conditions under which amplification can be achieved.

Figure 2 shows the type of data that we ideally seek to acquire in the context of the proposed program. It has been found that such well defined two-hop echoes and triggered emissions only

occur if the amplitude of the injected ELF/VLF signals is above the threshold of nonlinear amplification. These types of highly defined interactions may occur quite rarely with the presently available HAARP power levels ( $\sim 1$  MW and existing array) so that an in depth study may only be possible with the use of full-up HAARP (3.6 MW and complete array). Nevertheless, we expect to use the type of methodology shown in Figure 2 to identify two-hop echoes in ELF/VLF data, and design ELF/VLF transmission formats that would maximize likelihood of growth and identification of two-hop echoes.

The proposed set of ELF/VLF observations at distributed sites in the northern hemisphere are aimed at the measurement of the two-hop whistler-mode echo of HAARP-injected ELF/VLF signals. The scientific investigations proposed to be undertaken here could be very usefully complemented via associated measurements in the geomagnetic conjugate region in the southern hemisphere, as shown in Figure 3. However, the particular location of the conjugate region in the southern Pacific ocean makes such measurements quite difficult, requiring a semi-permanent platform, such as a buoy. Accordingly, an important component of the proposed program is to carry out ELF/VLF measurements on such a buoy deployed in the conjugate region shown. While some of the program objectives can be addressed with measurements in Alaska of the two-hop signals, the likelihood of observing the one-hop signal is much higher (by about a factor of ten) based on Siple experiments, so that the buoy-based measurements are required for realization of all of the program objectives.

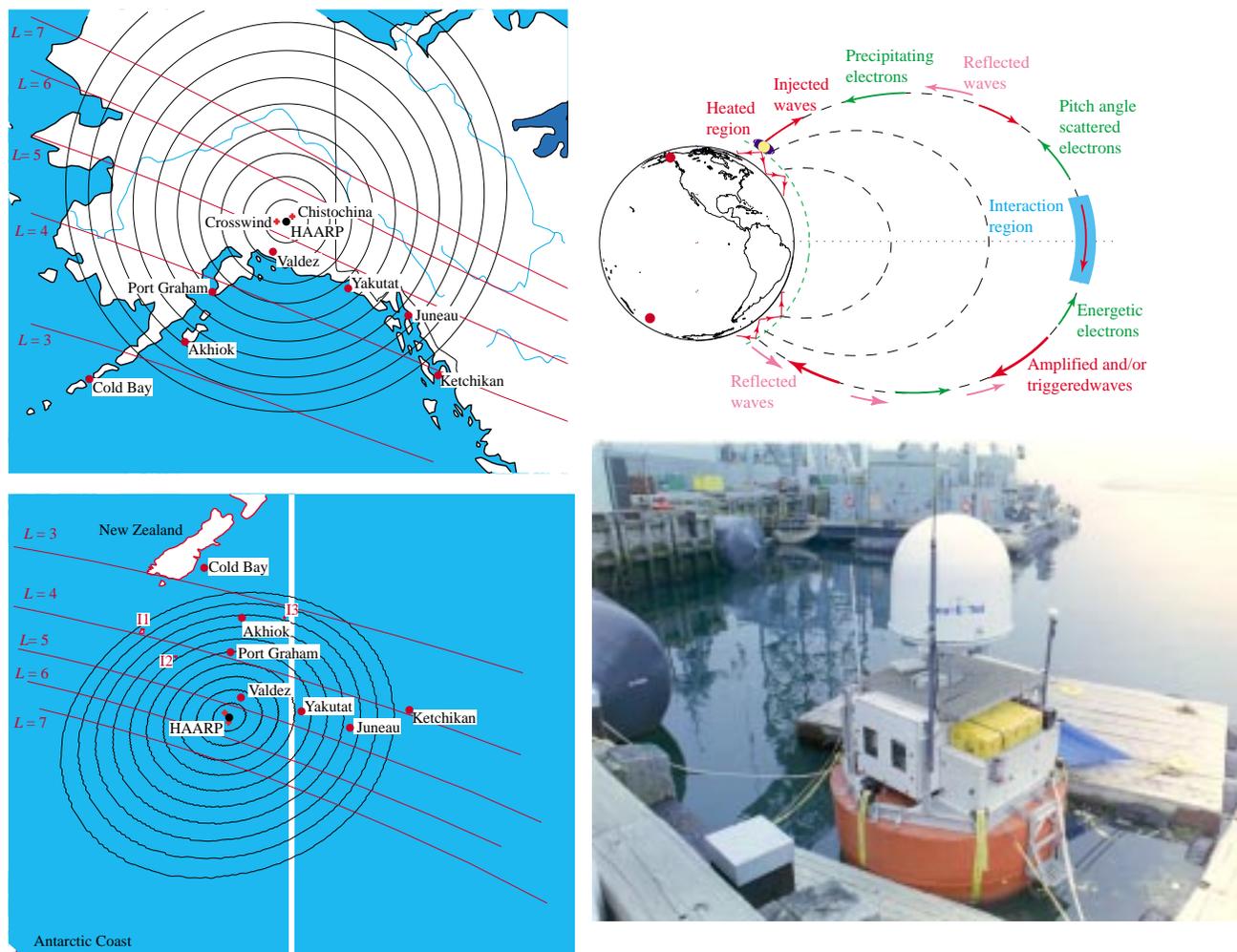
A description of the proposed research program is provided in Section 2, followed by a Statement of Work describing specific Tasks to be performed which is given in Section 3.

## 2. PROPOSED RESEARCH

The proposed program is an outgrowth of an initial set of observations that were conducted during 2001 and 2002 in the context of the Polar Aeronomy and Radio Science (PARS) ULF/ELF/VLF Project, involving ELF/VLF measurements at two sites within  $<50$  km of HAARP and another site (Valdez, see Figure 3) at a distance of  $\sim 150$  km from HAARP. The scientific justification and background for the proposed program ELF/VLF Wave-injection and Magnetospheric Probing with HAARP is detailed in a report prepared by Stanford for the PARS project, which is provided as **Attachment A**.

The PARS ELF/VLF wave-injection project involved the conduct of three campaigns, during Fall 2001, Spring 2002 and Fall 2002. The first two of these campaigns only involved ELF/VLF measurements at one or two sites within  $<50$  km of HAARP, while the third one conducted in October/November 2002 and involved ELF/VLF measurements at three additional (unmanned) sites at distances of  $\sim 70$  km from HAARP and yet another site (Valdez) at a distance of  $\sim 150$  km.

Preliminary results of observations from the first two PARS ELF/VLF campaigns are briefly discussed in the next subsection (Section 2-A) and provide the context upon which we expect to build the proposed program. A detailed description of these results were given in a paper presented at the recent URSI General Assembly; a copy of the talk presented at this meeting



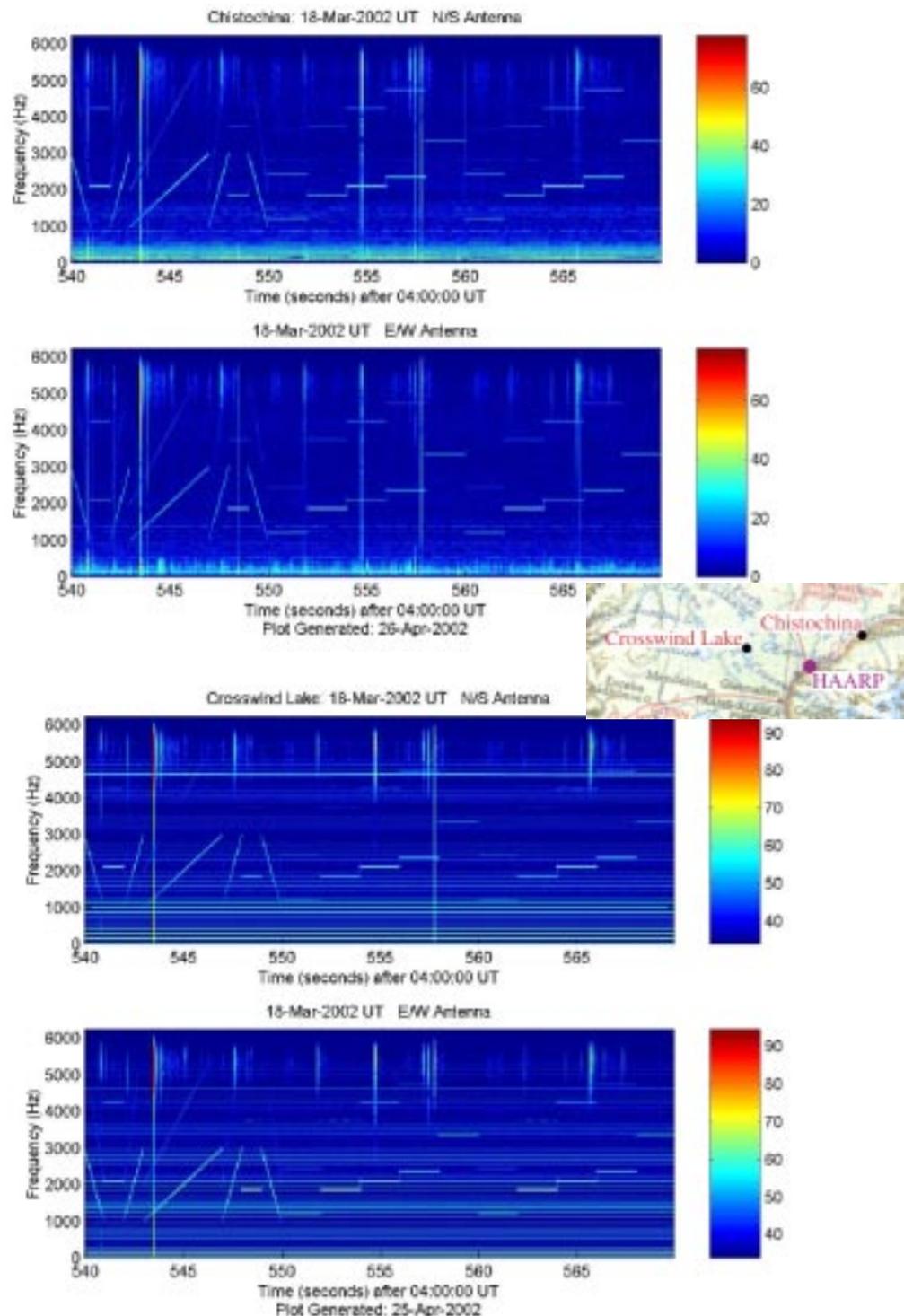
**Fig. 3. Geomagnetic conjugate region of HAARP.** The proposed program of HAARP ELF/VLF wave-injection experiments with measurements in the northern hemisphere should ideally be complemented with similar measurements (at at or two sites) in the geomagnetic conjugate region. However, conducting such measurements over meaningful periods of time (many days to weeks) requires the use of a semi-permanent platform such a buoy. Each point in the northern hemisphere is mapped along the Earth's magnetic field lines (using an accurate IGRF model of the field) to the conjugate hemisphere. The circles centered around HAARP with radii incremented by 100-km are also mapped in the same way. Although New Zealand lies at a distance of >1000 km from the HAARP conjugate region, there are several (uninhabited) islands (marked I1, I2, and I3) that are closer.

by Professor Inan is provided as **Attachment D**. Analysis of the data from the third campaign (November 2002) is currently in progress. The rationale for the two-hop component of the proposed program, involving observations at a spatially distributed set of sites in Alaska extending to lower  $L$ -shells (up to  $L \simeq 3.5$ ) is described in Section 2-B, together with a description of proposed measurements of electron precipitation effects that may be produced by HAARP-induced ELF/VLF signals and opportunities for phase coherent measurements of natural ELF/VLF signals and triggered emissions.

### **A. Preliminary Results from Initial HAARP ELF/VLF Wave-injection Campaigns**

Figure 4 shows examples of ELF/VLF data collected at Chistochina and Crosswind Lake during HAARP ELF/VLF wave-injection experiments conducted in Spring 2002. For this purpose, electromagnetically quiet sites were identified at locations many miles away from power lines (which produce ‘hum’ in the ELF/VLF frequency range) and two large ( $\sim 5$ -m square) orthogonal loop antennas were erected, aligned in the geomagnetic North-South and East-West directions. The output of matched preamplifiers were fed to a line receiver located at a distance of  $\sim 2000$ -ft, the outputs from which were then digitized with 100-kHz sampling and 16-bit resolution and recorded continuously for many hours per night. The HAARP HF heater was modulated with specially designed formats, including stair-cases in frequency, descending and ascending frequency-time ramps, and chirped signals that are known (based on Siple experiments) to often maximize wave growth. The continuous wideband recording of the data allows maximum spectral and temporal resolution, as is evident from the spectrograms shown. HAARP-induced ELF/VLF was observed nearly 40% of the time at both sites, often quite similar between the two sites (due to their proximity) but sometimes exhibiting interesting differences between sites and also often between N-S and E-W recordings at the same site. No evidence for magnetospheric transmission or a two-hop echo was observed during  $\sim 12$  days of nightly (10 hours per night) transmissions in March 2002.

The primary conclusions derived from these preliminary measurements at Chistochina and Crosswind Lake is that HAARP routinely and robustly produces well defined ELF/VLF signals. It was also evident that the two sites are too close to one another, and basically see the same activity most of the time. For the upcoming campaign in Fall 2002, we plan to conduct measurements at Chistochina and at Valdez, the latter being at a distance of 150 km from HAARP. These two sites provides a larger baseline, which may improve the chances of observing the two-hop echo. Nevertheless, the Valdez site is still at a relatively high  $L$ -shell, most likely outside the plasmapause, the sharp gradients of which may help guide the whistler-mode signal (and thus the two-hop echo) between hemispheres. The proposed program of observations at a distributed set of sites extending to  $L$ -shells which straddle the plasmapause boundary and extend to within the plasmasphere will truly maximize the chances of observation of magnetospheric signatures of HAARP-induced ELF/VLF signals.



**Fig. 4. HAARP-induced ELF/VLF signals observed at Chistochina and Crosswind Lake.** The transmissions were designed so as to allow the detection of the two-hop whistler-mode echo, expected to arrive with a time delay of a few seconds. The descending and ascending frequency-time ramps were used to explore the possibility of frequency selective magnetospheric transmission or amplification. At both sites, data was collected with two orthogonal loop antennas, oriented in the geomagnetic East-West (EW) and North-South (NS) directions. The vertical lines are radio atmospheric from distant lightning discharges, whereas the continuous horizontal lines (especially evident in Crosswind Lake data) are local interference.

## B. Two-hop whistler-mode echoes and triggered emissions

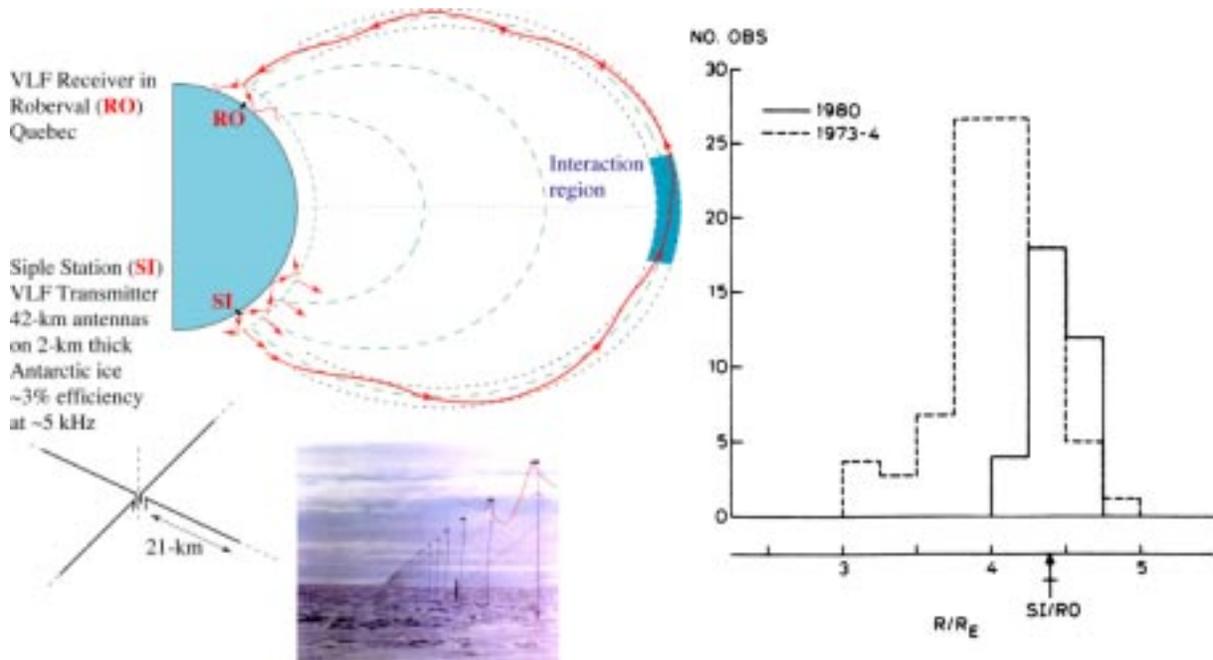
### a. Rationale for the Proposed Distribution of ELF/VLF Measurement Sites

The most extensive set of controlled ELF/VLF wave-injection experiments were carried out with the Siple Station VLF transmitter facility operated by Stanford University during 1973-88. The experience gained in these experiments provides much of the basis for the design of the proposed program of wave-injection experiments using the HAARP facility. Figure 5 shows a depiction of these experiments and a summary of results of observations reported in a comprehensive paper [Carpenter and Bao, Journal of Geophysical Research, p. 7051, 1983].

During VLF wave injection experiments at Siple Station, it was found that two-hop signals were observed at Siple station approximately 70% of the times that one-hop signals were observed at the magnetically conjugate station at Roberval, Quebec. Thus the two-hop signals were a common feature of the wave injection experiments. By analyzing the properties of whistlers which were also propagating along the same ducts that guided the Siple signals through the magnetosphere, it was possible to quite accurately determine the  $L$ -shell along which propagation occurred. Figure 5 shows the distribution of the  $L$ -shells of these paths for two different periods in 1980 and 1973-4. The majority of the ducts excited during the 1980 period were located on  $L$ -shells whose ionospheric foot print was within  $\sim 100$  km of the station. However, the 1980 data set only included data from 12 days of strongest activity, so that this distribution is not representative of what we can expect for the case of wave-injection with HAARP. The data from the 1973-74 period on the other hand, represents an all inclusive analysis of data from a four month period, regardless of how well defined the Siple transmitter signals were in Roberval. It is clear from the 1973-74 distribution that ducts were often excited over the  $L$ -shell range  $3.8 < L < 4.2$ , substantially below the  $L$ -shell of the Siple-Roberval path ( $L \simeq 4.3$ ), and that sometimes propagation paths at  $L$ -shells as low as  $L \simeq 3$  were excited. The distribution of propagation paths may well have been strongly influenced by the average location of the plasmopause at  $L \simeq 4$ ; it is well known that the sharp density gradients of the plasmopause may effectively guide whistler-mode signals between hemispheres. The distribution of our proposed observation paths as shown in Figure 1 is designed to capture the two-hop echoes of HAARP-induced ELF/VLF signals over the entire range of distances explored in the Siple experiments.

### b. Subionospheric VLF Measurements of Energetic Electron Precipitation

In recent years, the subionospheric VLF remote sensing method (Figure 5), involving high-resolution measurements of the amplitude and phase of VLF signals propagating in the Earth-ionosphere waveguide, has emerged as a powerful new tool for measurements of both transient and steady perturbations of the nighttime  $D$ -region, in the altitude range of  $\sim 70$  to 90 km. In recent years, the VLF remote sensing method has been extensively utilized to study a variety of lower ionospheric disturbances, including those associated with lightning discharges, ionospheric heating by HF and VLF waves, the auroral electrojet, and relativistic electron precipitation enhancements. Computer-based models of VLF propagation and scattering are now

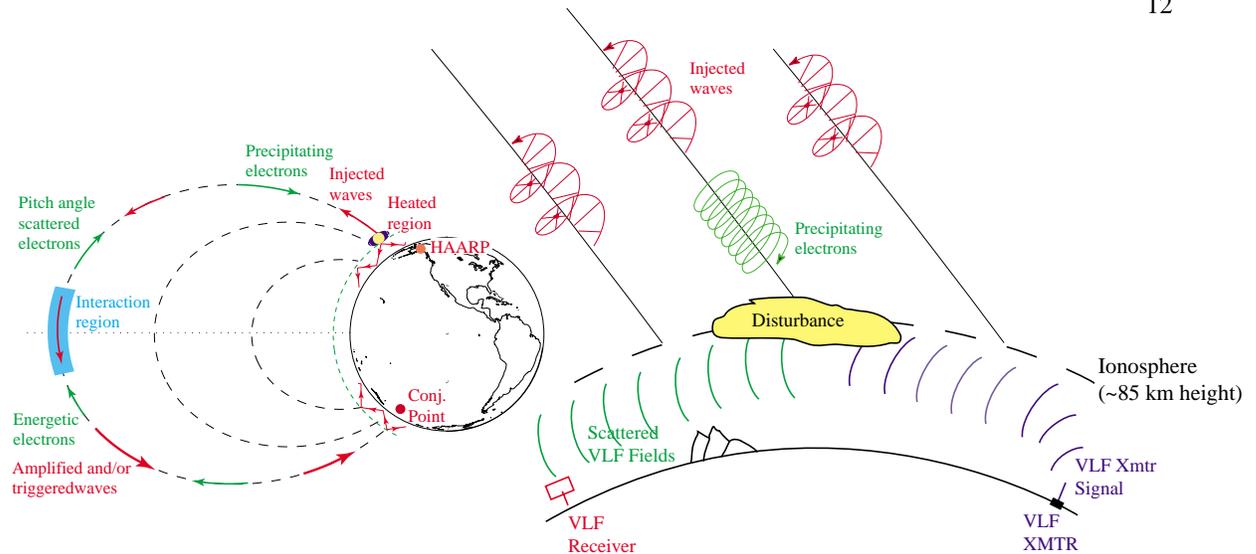


**Fig. 5.** *L*-shell distribution of Siple transmitter signal paths observed at Roberval during two different periods. The data from the first period, 1973-74, were extensively and all-inclusively analyzed, regardless of how weak the signal might be at Roberval. For the second period, data from only 12 days of strongest activity were considered. It is clear that magnetospheric paths well equatorward of the Siple transmitter were commonly excited.

available so that the VLF method can now be quantitatively used to interpret ionospheric signatures of electron precipitation in terms of their spatial extent and the altitude profiles of ionization. Stanford University extensively uses VLF remote sensing for detecting electron precipitation bursts induced by lightning discharges, using a holographic array of stations extending from Wyoming to New Mexico.

In this connection, the proposed ELF/VLF observation program will provide outstanding opportunities to continuously monitor energetic electron precipitation over the  $L$ -shell range of  $3 < L < 5$  as shown in Figure 5. The availability of many criss-crossing paths will allow the delineation of the spatial distribution of ionospheric disturbances (and hence the precipitation regions). Energetic electron precipitation monitored in this manner may be caused by natural signals, such as lightning-generated whistlers, or ELF/VLF chorus emissions, or may be induced by ELF/VLF signals injected by HAARP. The latter are expected to be at very low levels, but may still be detectable by means of superposed epoch analysis under conditions of imposed periodicities.

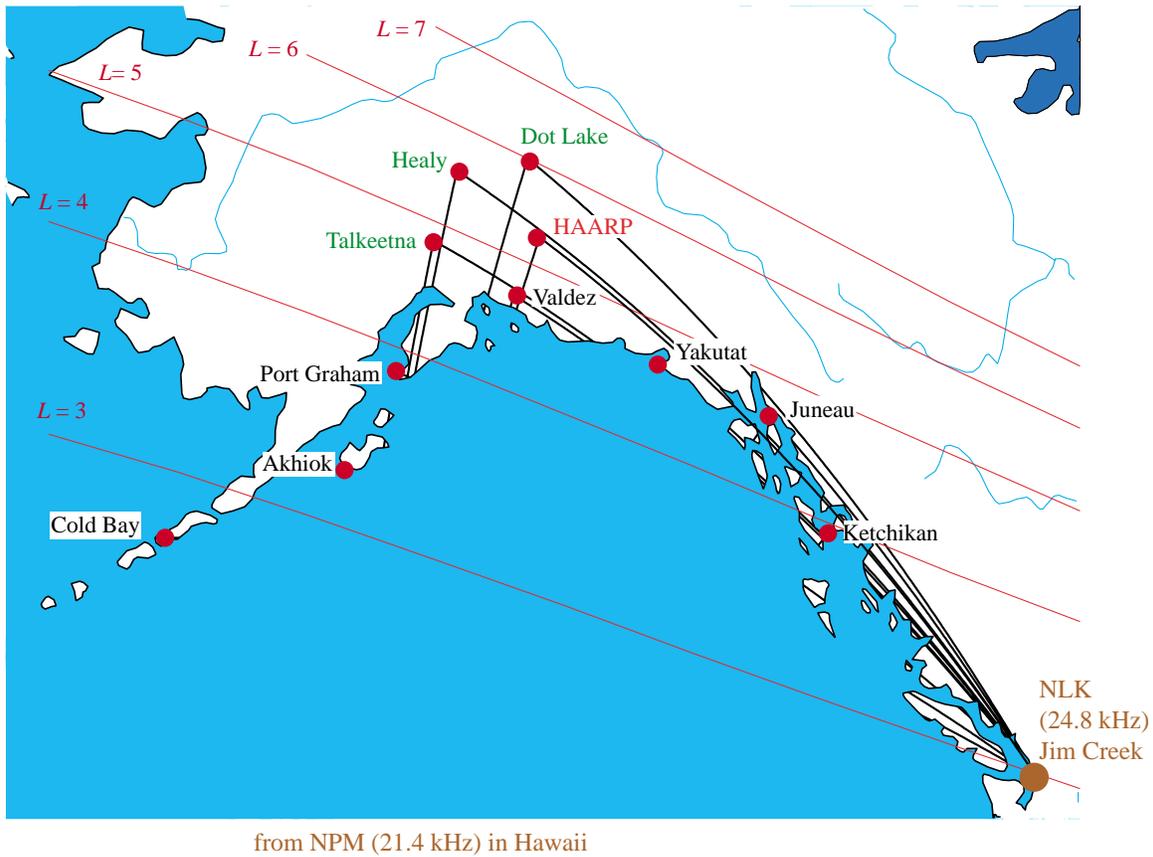
Based on Figure 5 we note that the parallel energies of electrons resonant with 3 kHz waves are  $>50$  keV during disturbed times, indicating that any wave-induced precipitation of these particles would produce ionospheric disturbances at altitudes below 90 km, readily observable with the VLF sounding technique.



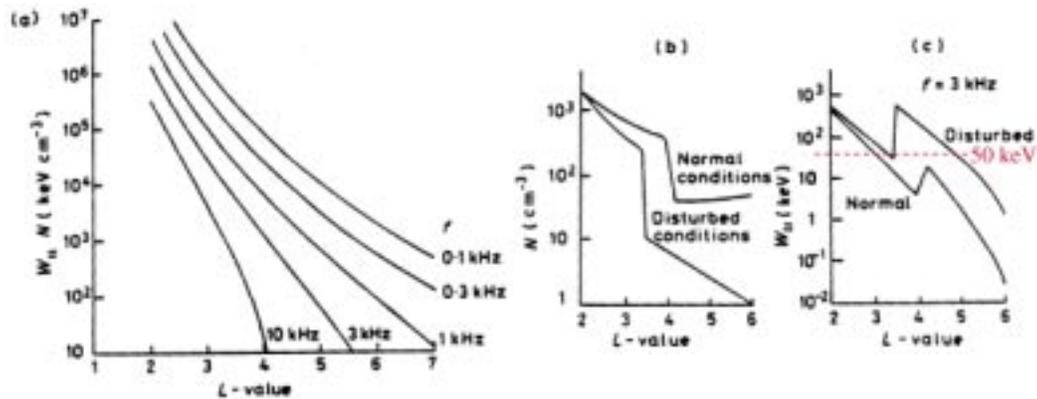
**Fig. 6. Subionospheric VLF remote sensing of energetic electron precipitation.** Detection and measurement of energetic electron precipitation via the associated phase and amplitude perturbations of subionospheric VLF signals is now a well established technique. The precipitating energetic ( $>$ )50 keV electrons penetrate to altitudes below the nighttime reflection height ( $\sim$ 85 km) of the VLF signals, creating secondary ionization, which in turn affects the waveguide mode structure of the VLF signals propagating in the Earth-ionosphere waveguide. In the case of transient bursts of precipitation, the excess secondary ionization created lasts for 30 to 100 s, until the ionosphere recovers back to its ambient levels.

### *c. Interferometric Measurement of Natural ELF/VLF Signals*

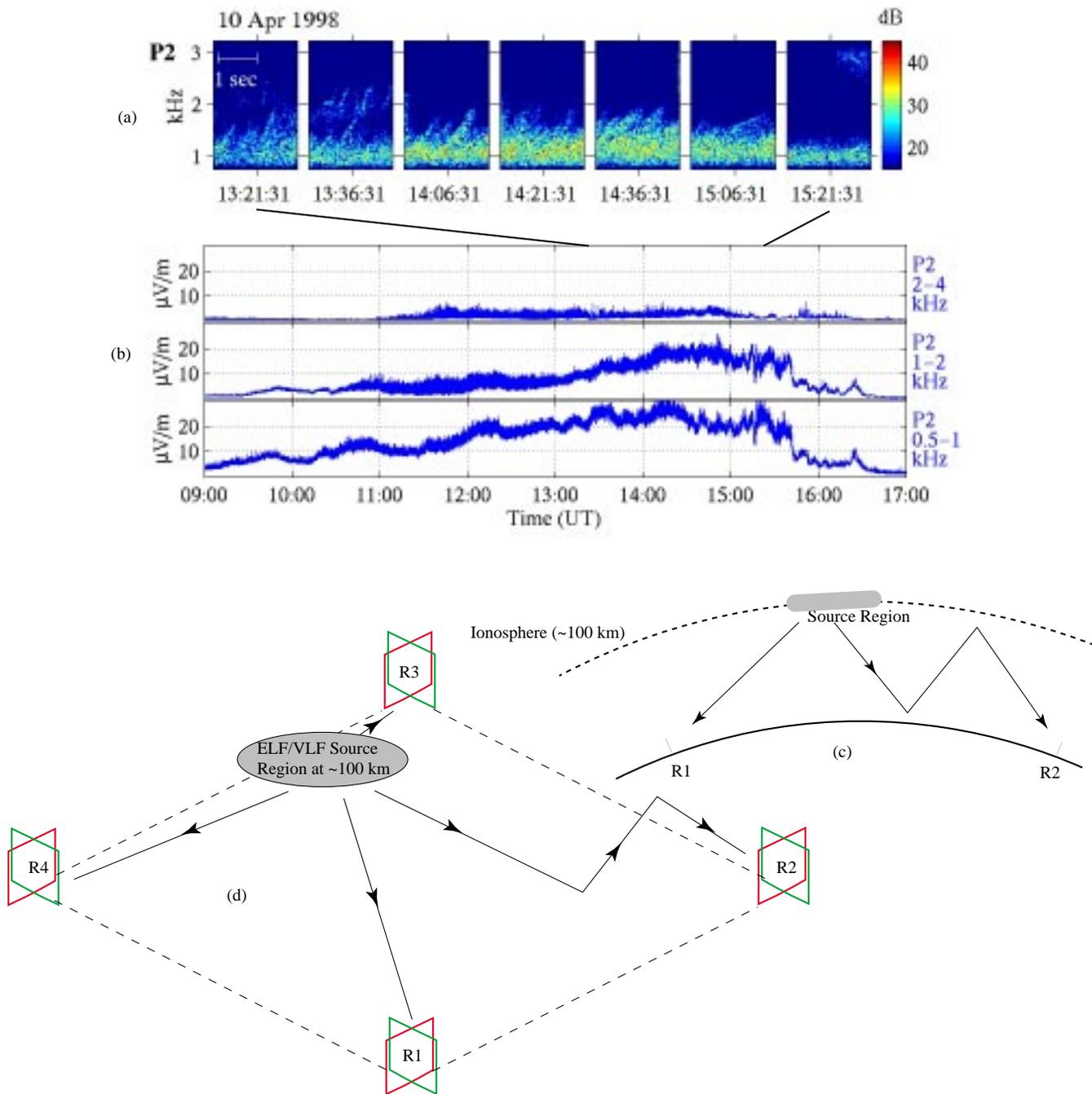
The proposed set of extensive multi-site ELF/VLF observations will additionally provide a data base with unprecedented resolution and coverage, with which investigations of ionospheric exit points of natural waves of magnetospheric origin (e.g., whistlers, chorus, or hiss) can be determined. Such determination is not possible with single site observations, which constitute the majority of ground-based observations of ELF/VLF phenomena conducted so far. Although some multi-site measurements have been conducted, the data recordings were typically not done in wideband fashion, and GPS-timing was not available, so that phase coherence between distant sites could not be achieved.



**Fig. 7. Distribution of VLF signal paths which will be monitored with the proposed array of ELF/VLF observing sites.** To avoid clutter, signal paths are shown for only two VLF transmitters, namely the NPM transmitter in Hawaii and the NLK transmitter in Jim Creek, Washington. The observing sites labeled in green (Talkeetna, Healy, and Dot Lake) are already in-place and operating as part of a D-region diagnostic system for HAARP.



**Fig. 8. Parallel energy of cyclotron resonant electrons.** (a) The product of parallel resonant energy ( $W_{\parallel}$ ) and electron density  $N$  versus  $L$ -shell for selected frequencies. (b) Equatorial cold plasma density in the magnetosphere during normal and disturbed conditions. (c) The corresponding parallel resonant energy versus  $L$ -shell for 3-kHz signals, during disturbed and normal times.



**Fig. 9. Interferometric Measurements of Discrete Chorus Emissions.** (a) Two second snapshots illustrating the characteristic frequency-time signatures of rising chorus emissions. (b) Continuous records of signal amplitude in selected narrow bands, illustrating the characteristic morning local time (magnetic noon is approximately 1500 UT) peak in chorus activity. (c) Since chorus is believed to exit the magnetosphere in relatively compact ionospheric exit points, the determination of the location and aperture distribution of such exit regions requires coherent measurements at spaced sites, as will be facilitated by the proposed array (Figure 1) of ELF/VLF observing sites.

### C. One-hop whistler-mode signals and triggered emissions

The scientific rationale for this component of the proposed work is the same as that discussed above for the measurement of amplified two-hop whistler-mode signals and triggered emissions. It is clear from the right hand panel of Figure 5 that the optimum location for observation of amplified signals is at the the point which is geomagnetically conjugate to the source of the injected ELF/VLF waves. For the case of ELF/VLF waves injected by the HAARP HF heater, this location lies in the Southern Pacific ocean as shown in Figure 3. The conduct of repeatable ELF/VLF wave-injection experiments with the HAARP facility thus requires the use of an ocean-based platform, for which we propose to use a buoy. The feasibility of such measurements have been thoroughly investigated during the past three months under the auspices of a separate ONR grant at Stanford, considering all important aspects of the experiment, including design, construction, transportation, and deployment, as well as cost. The results of this feasibility study provides guidance for the manner in which we propose to conduct this component of the proposed program, and is described in **Attachment E**, which is a report prepared by ENS Noah Reddell, who conducted the feasibility study. Mr. Reddell will also be one of the key personnel on this project in the implementation phase, as is described separately in Section 4.

## 5. ATTACHMENTS

### **Attachment A:**

**Scientific Opportunities, Background and Justification of ELF/VLF Wave-injection and Magnetospheric Probing Experiments with HAARP.** This report was prepared by Stanford University in April 2001 to provide the background for the preliminary HAARP ELF/VLF wave-injection experiments carried out under the auspices of the Polar Aeronomy and Radio Science (PARS) program.

### **Attachment B:**

**Mitigation of Enhanced Radiation.** This report was recently (July 12, 2002) presented by Professor Umran Inan to distinguished visitors of the HAARP facility. It is an expanded summary of the results of the deliberations of the HAARP Panel chaired by Dr. T. Tether.

### **Attachment C:**

**Evaluation of a Proposed Program to Use Orbiting VLF Transmitters for Radiation Belt Mitigation.** This report was prepared in October 2001 by Dr. M. Schulz and Dr. H. Petschek, both experts on radiation belts and wave-induced diffusion and scattering of energetic particles.

### **Attachment D:**

**Paper presented at the URSI General Assembly.** This paper, presented by Professor Umran Inan at Maastricht in August 2002, described results from the first two HAARP ELF/VLF wave-injection campaigns.

### **Attachment E:**

**ELF/VLF Measurements at the HAARP Conjugate Point: Buoy Feasibility Study.** This document was prepared by ENS Noah Reddell, based on his work during the Fall Quarter, under the auspices of a separate feasibility study grant from ONR.

**Attachment A: Scientific Opportunities, Background and Justification of ELF/VLF Wave-injection and Magnetospheric Probing Experiments with HAARP.** This report was prepared by Stanford University in April 2001 to provide the background for the preliminary HAARP ELF/VLF wave-injection experiments carried out under the auspices of the Polar Aeronomy and Radio Science (PARS) program.

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

U. S. Inan and T. F. Bell

STAR Laboratory, Stanford University

### **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 balloons), 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 low- and 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 previous HF heater-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/VLF wave injection experiments which have been carried out either by HF heaters or ground based ELF/VLF transmitters. Also summarized 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 pronounced both during and immediately following periods of moderate to strong geomagnetic activity, where  $K_p > 3$ . 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/VLF wave injection experiments by performing them during magnetically quiet 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 plasmopause 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/ELF wave 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 plasmopause surface 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 plasmopause 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 5 Hz by square wave modulating at ULF/ELF frequencies the power output of

the 1.3 MW, 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 ULF/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/VLF waves in this manner would 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 four week 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/VLF wave injection campaign will be established in consultation with the management team of the HAARP project.

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.

## 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 strength was highly correlated with magnetic activity, and significantly more intense ELF/VLF waves were produced during periods of moderate geomagnetic disturbance with  $K_p \sim 3$ .
- 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  $\simeq 1$  at 510 Hz to  $\simeq 0.3$  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 systems 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 [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 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 magnetosphere 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  $\sim 1$ -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]. It was 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  $\sim 6 \times 10^6(\text{cm}^2 - s - sr)^{-1}$ . This flux level was observed to occur under conditions of moderate to strong magnetic activity when  $K_p > 3$ , 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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# Attachment D



## ELF/VLF Wave-Injection via Modulated HF Heating of the Ionosphere

Umran S. Inan

Space, Telecommunications and Radioscience Laboratory  
Stanford University, Stanford, California 94305

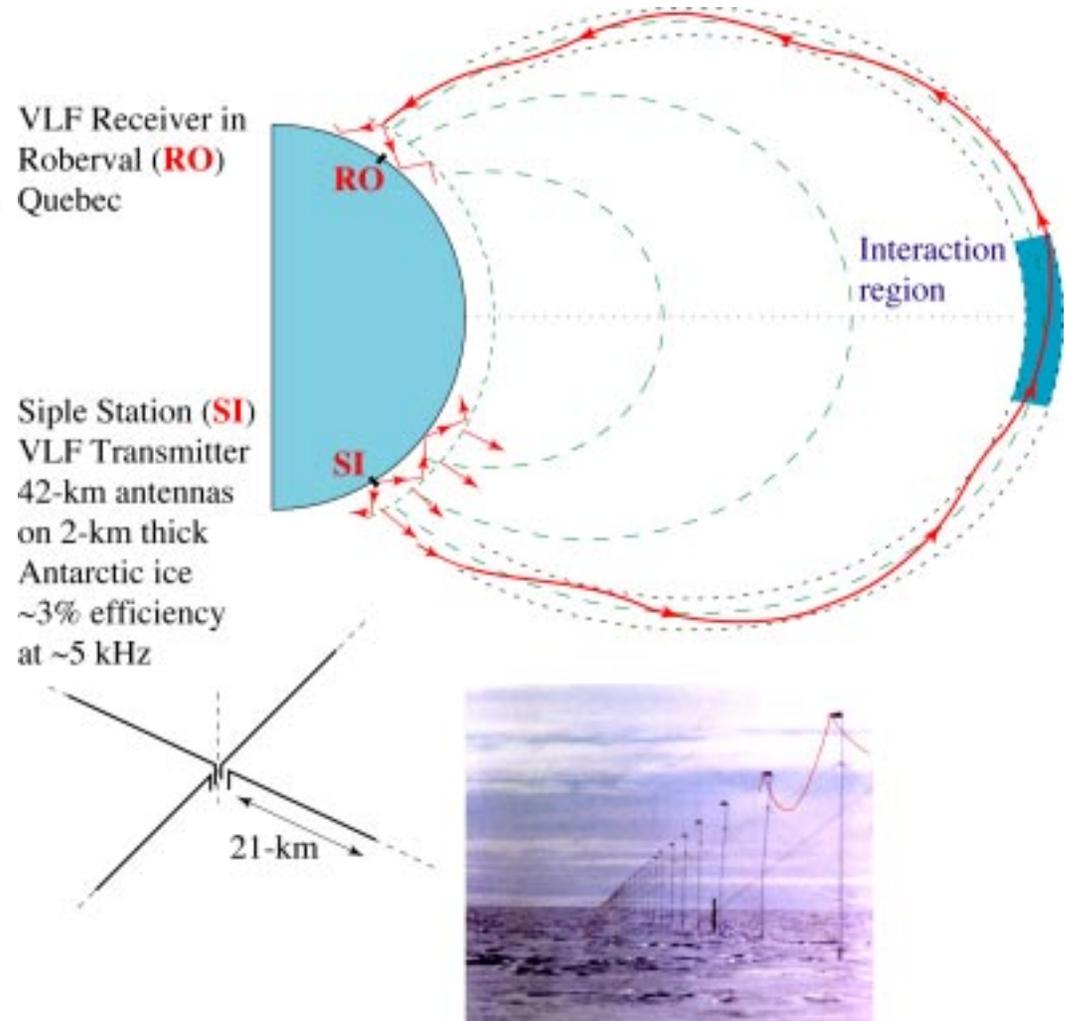
<http://www-star.stanford.edu/~vlf/>



# VLF Wave-injection Experiments

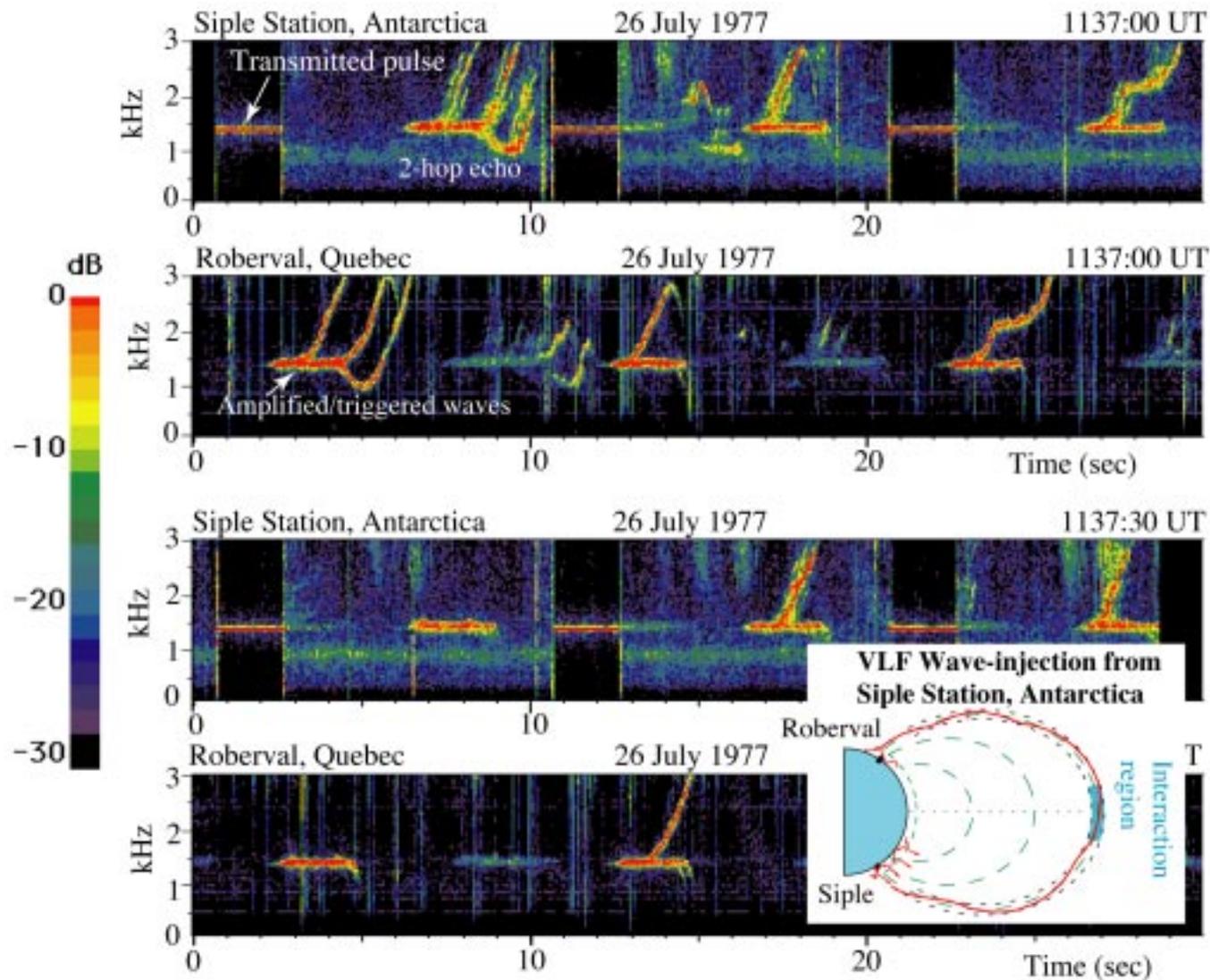


- NSF-funded Stanford experiment (1973-88)
- VLF waves (~2-6 kHz) injected from Siple Station, Antarctica
- 150 kW transmitter
- Tuned with large capacitors and coils
- VLF receiver at Roberval, Quebec
- Controlled studies of cyclotron resonant wave-particle interactions
- Uncovered many aspects of wave growth and emission triggering





# Injected VLF Signals are Amplified and Trigger Intense Emissions

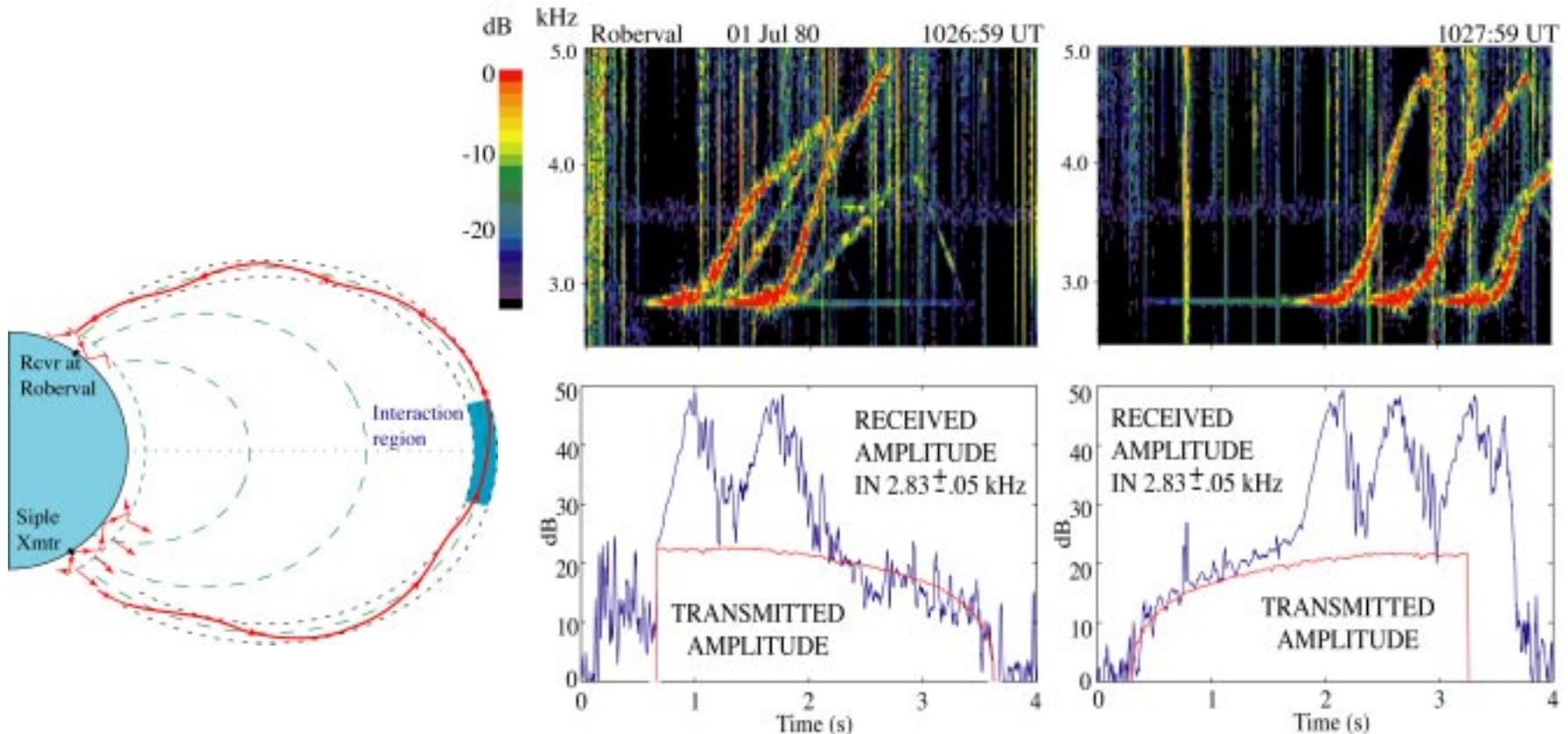




# Threshold for Growth/Triggering



- Simple transmitter signals often amplified by 10 to 30 dB and new emissions are triggered for input  $B_w > B_{th}$
- Minimum radiated power for growth and triggering was measured to be ~1 Watt [Helliwell et al., 1980]

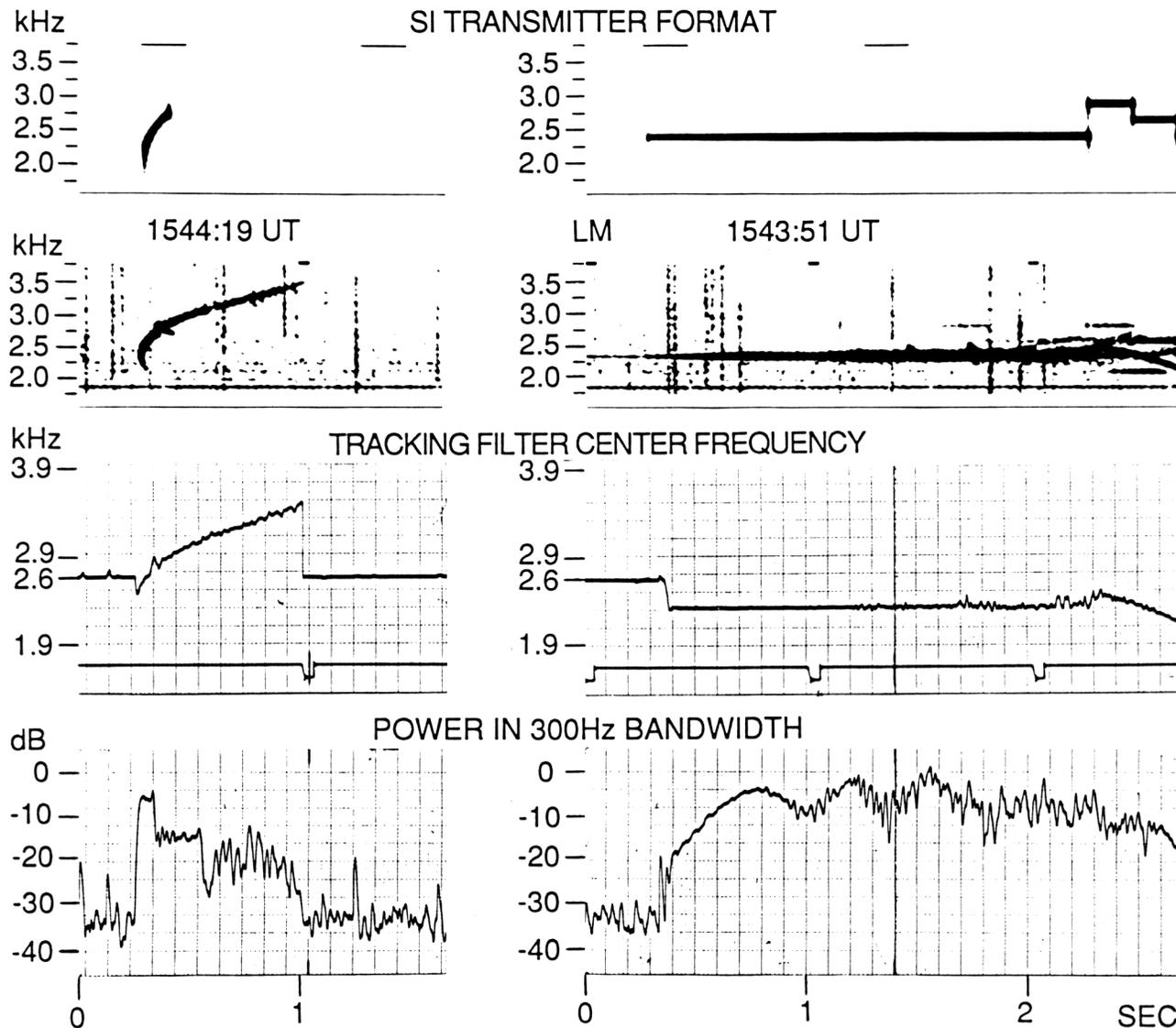




# Chirped Modulation Leads to More Rapid Growth

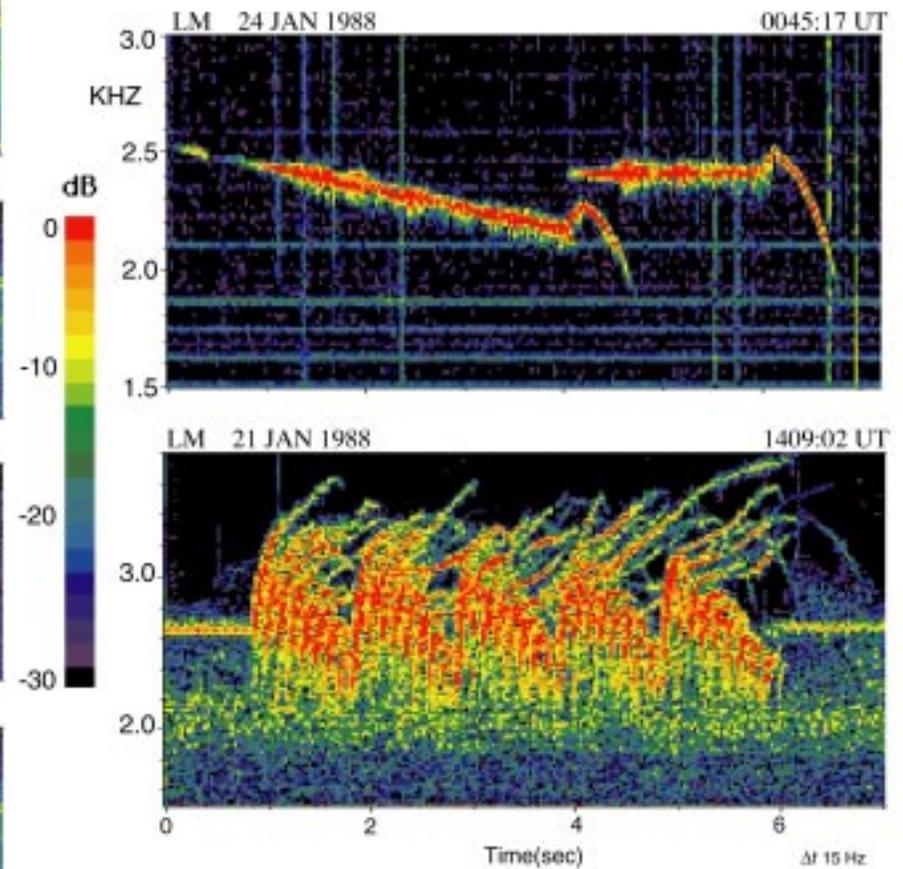
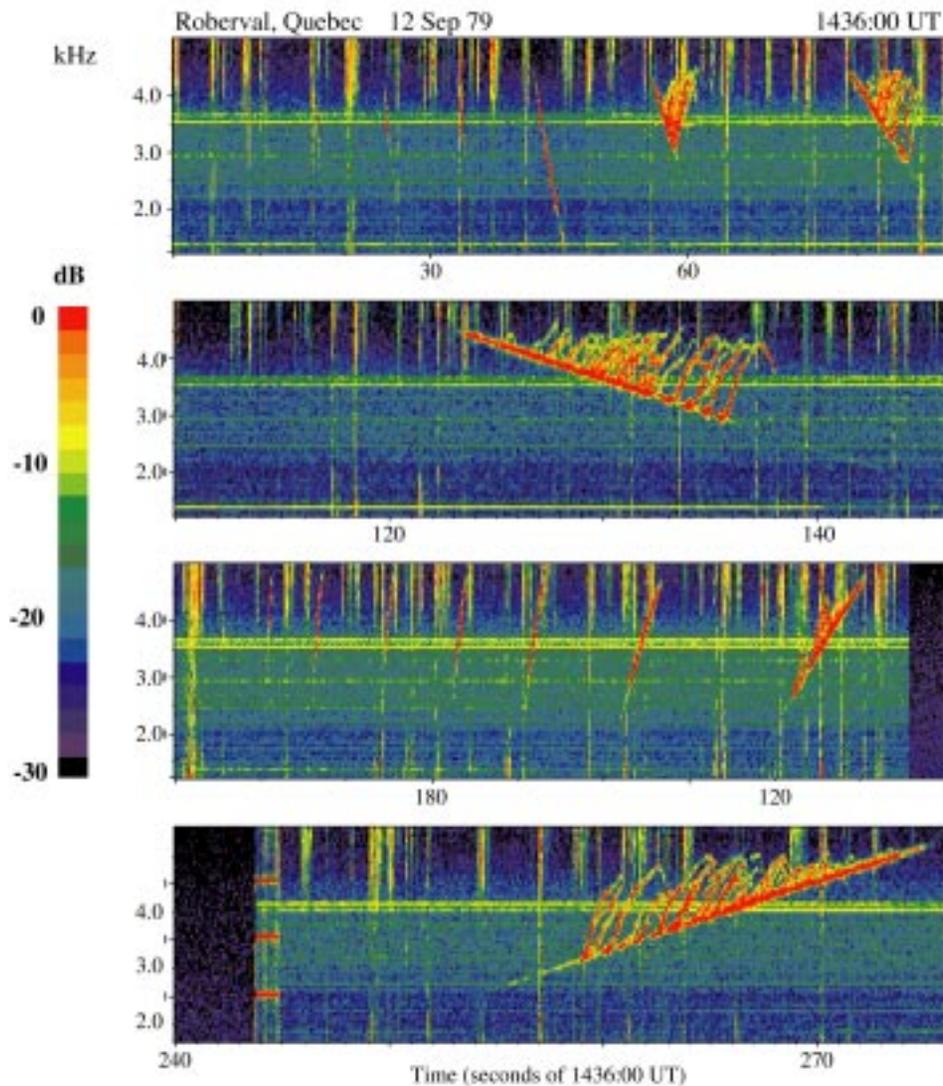


9 DEC 87



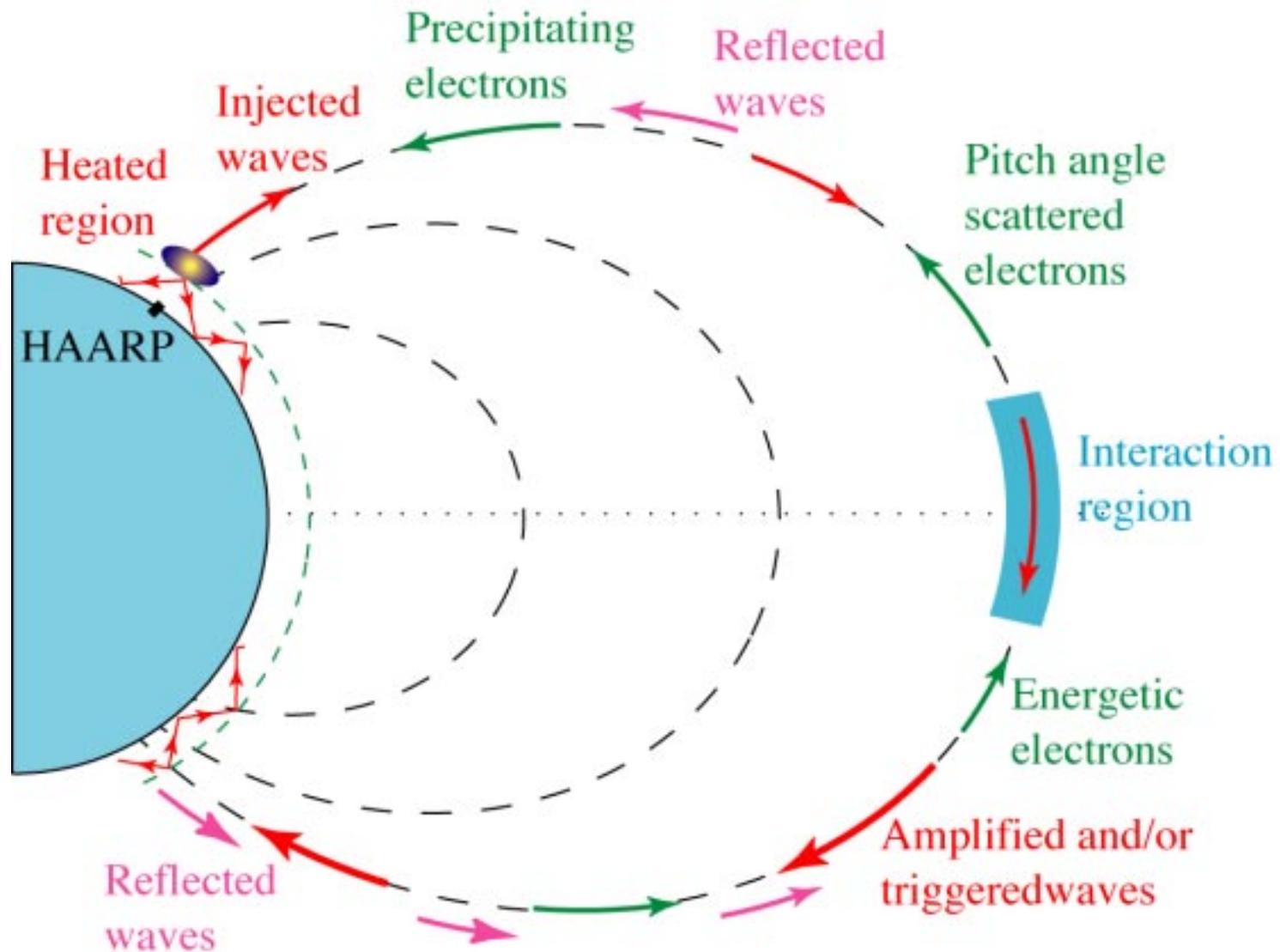


# Coherent Growth & Triggering





# ELF/VLF Wave-Injection Experiments with HAARP

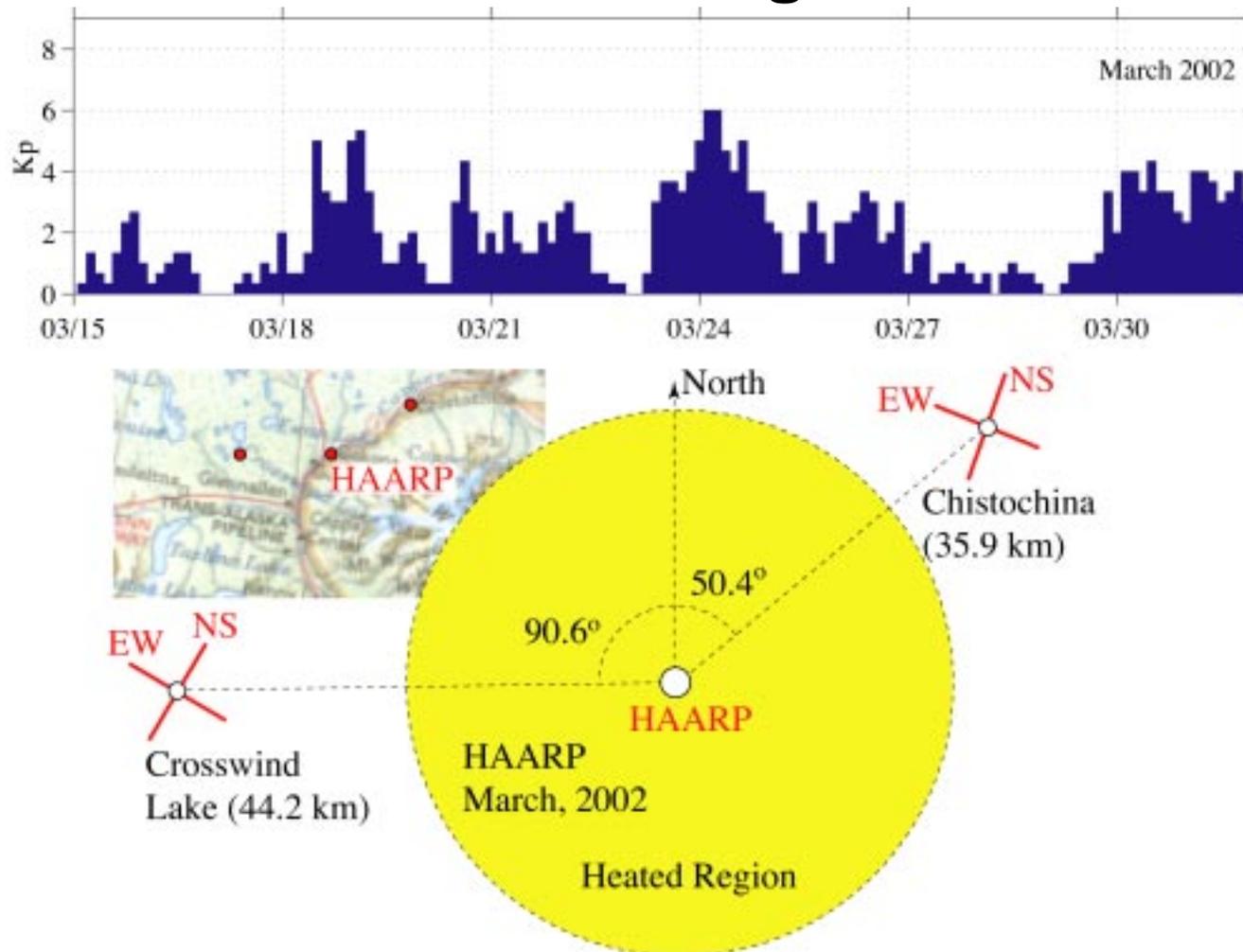




# HAARP March 2022 Campaign



- Specially designed ELF/VLF formats were transmitted for 10 hrs/night for ~2 weeks

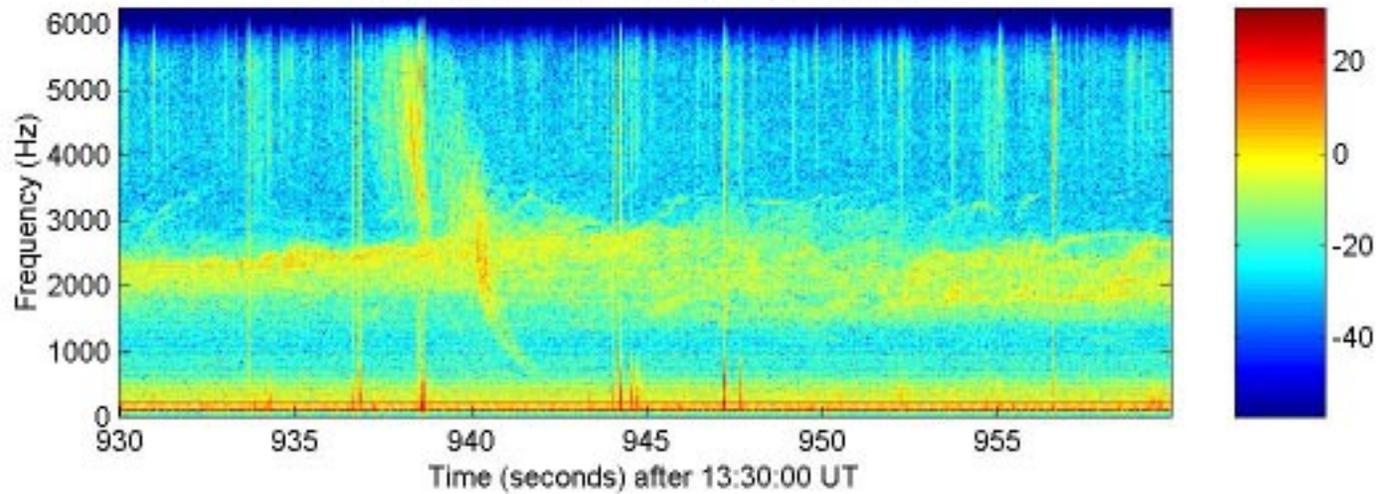




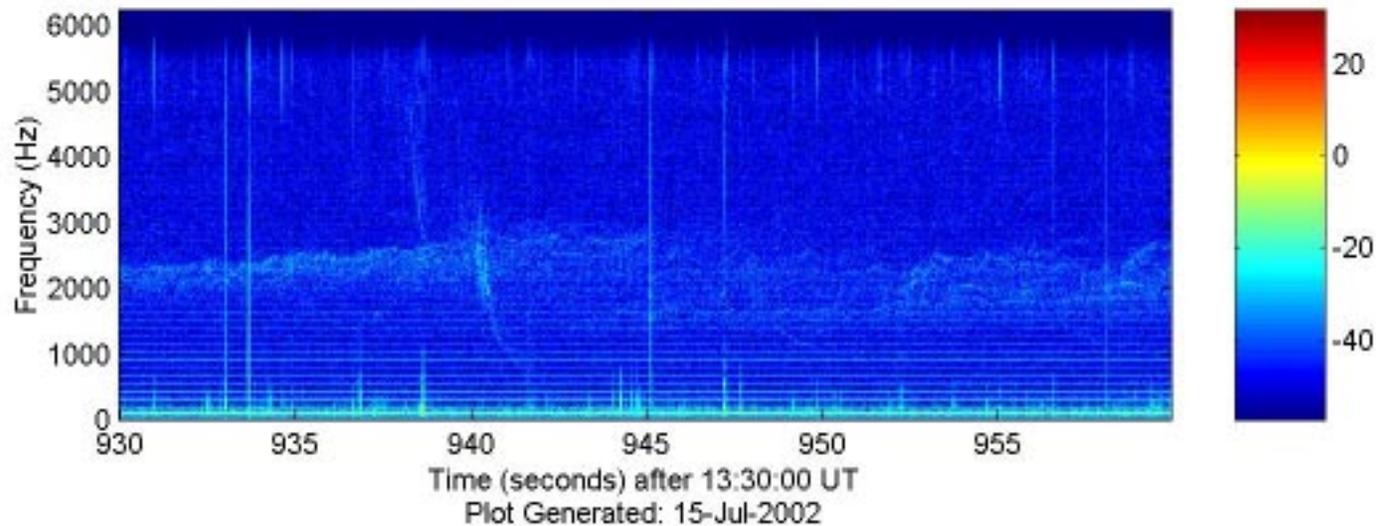
# Whistlers and Triggered Emissions at Chistochina



Chistochina B&B: 16-Mar-2002 UT N/S Antenna  
HAARP Transmission: HAARP Not Transmitting



16-Mar-2002 UT EW Antenna

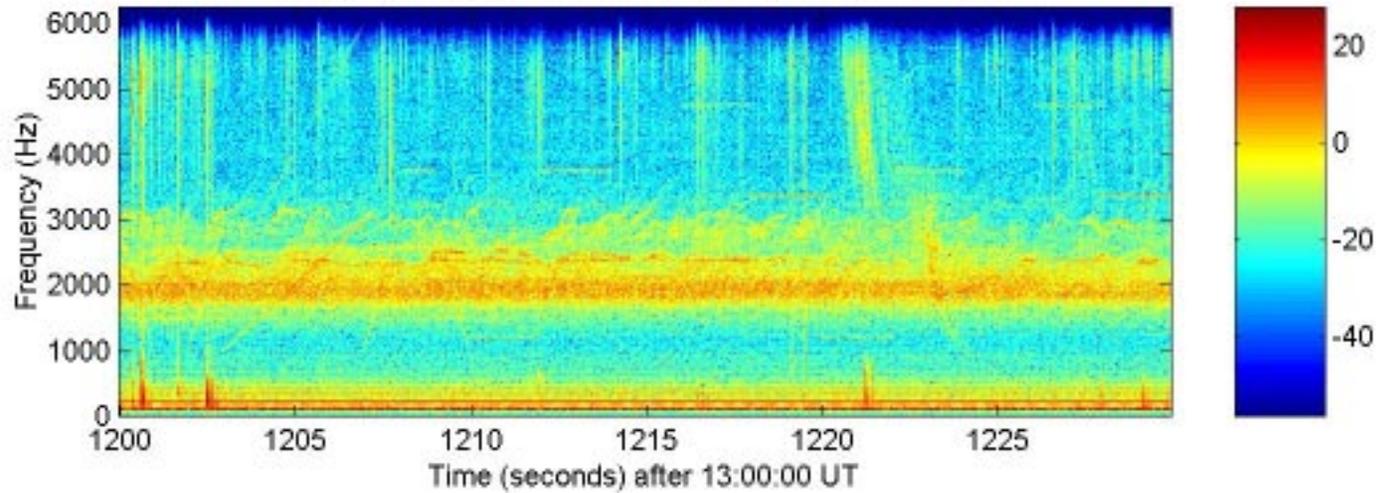




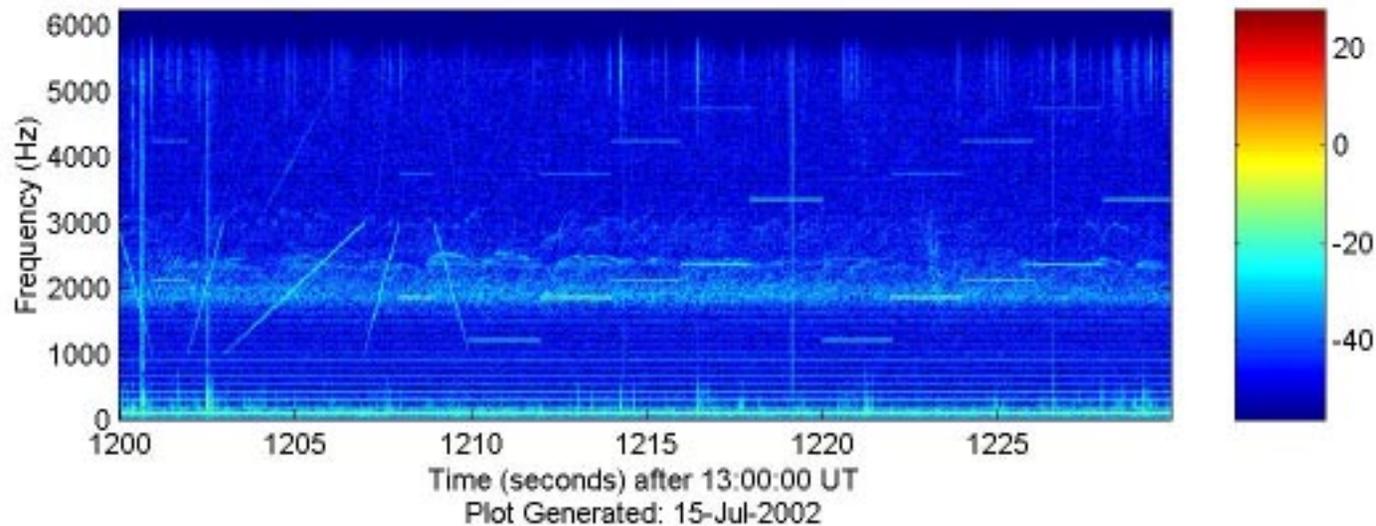
# HAARP ELF/VLF Signals



Chistochina B&B: 16-Mar-2002 UT N/S Antenna  
HAARP Transmission: 3.2 MHz Carrier, Vertical Orientation



16-Mar-2002 UT EW Antenna

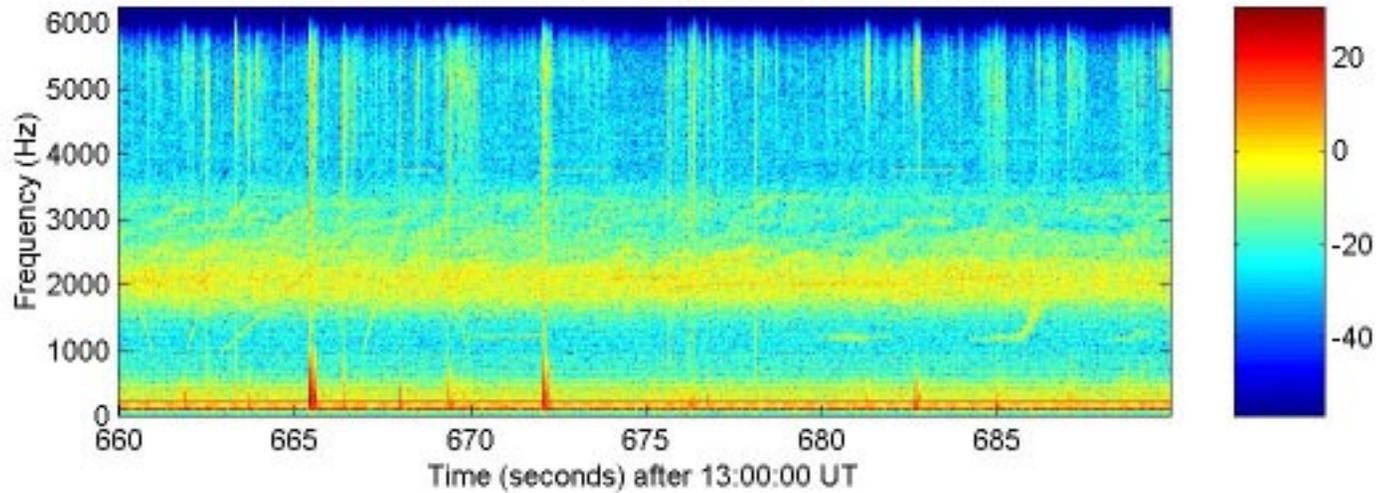




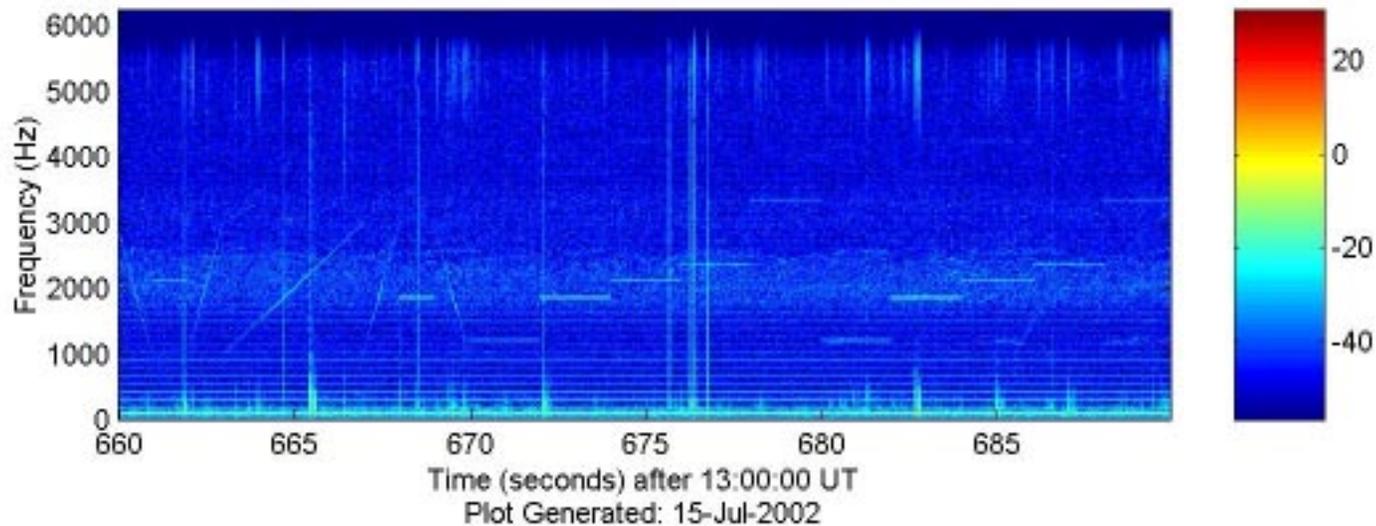
# HAARP Signals at Chistochina



Chistochina B&B: 16-Mar-2002 UT N/S Antenna  
HAARP Transmission: 3.2 MHz Carrier, 30 Deg South



16-Mar-2002 UT EW Antenna

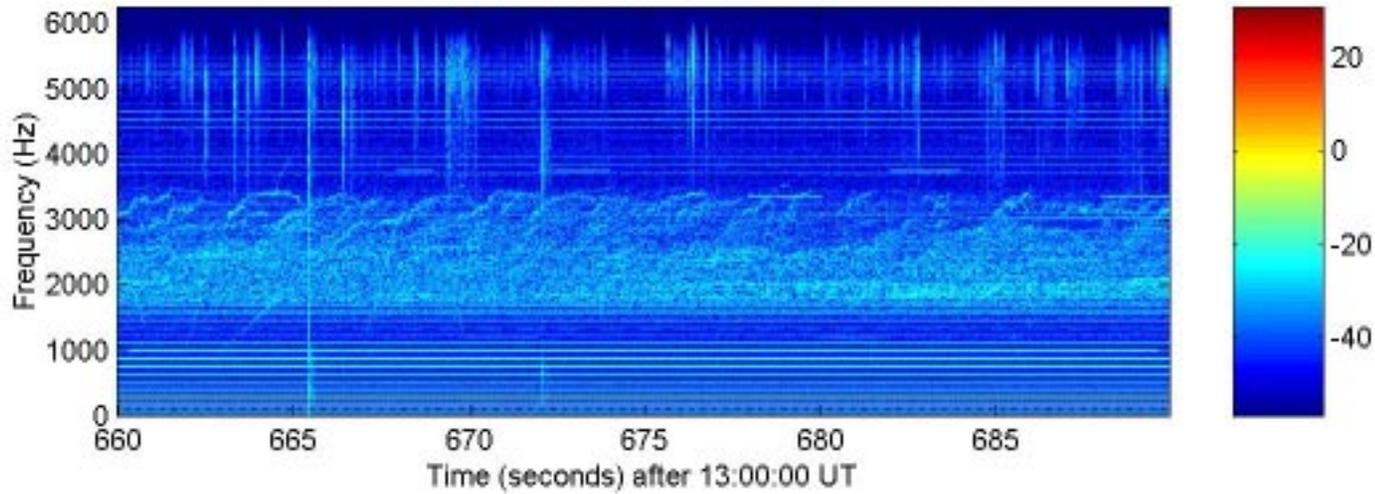




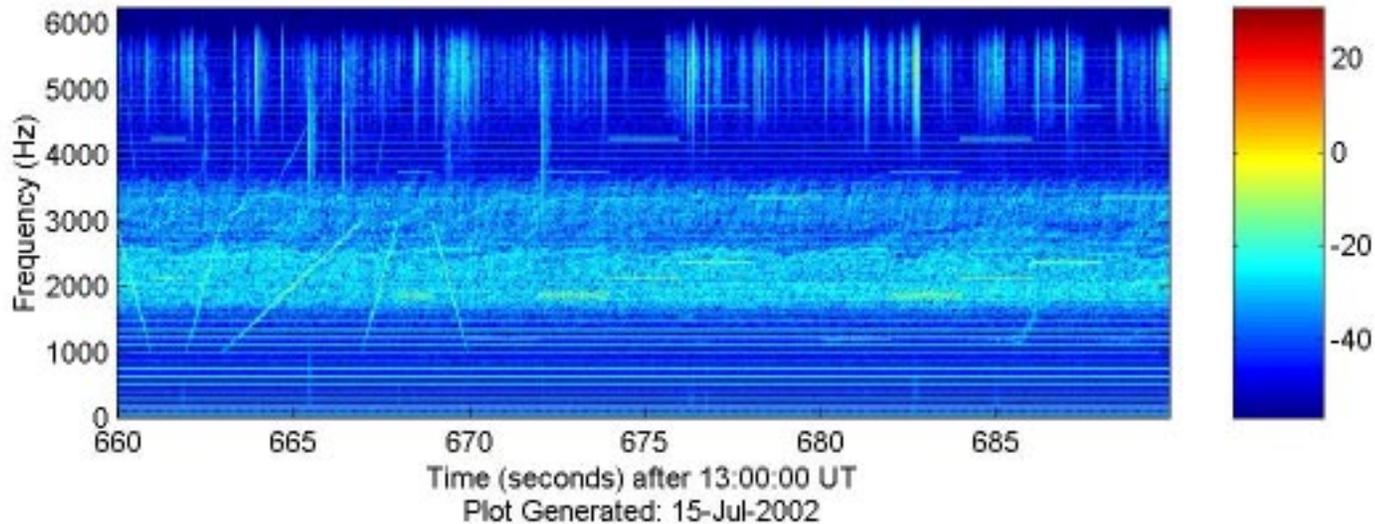
# and at Crosswind Lake



Crosswind Lake: 16-Mar-2002 UT N/S Antenna  
HAARP Transmission: 3.2 MHz Carrier, 30 Deg South



16-Mar-2002 UT EW Antenna

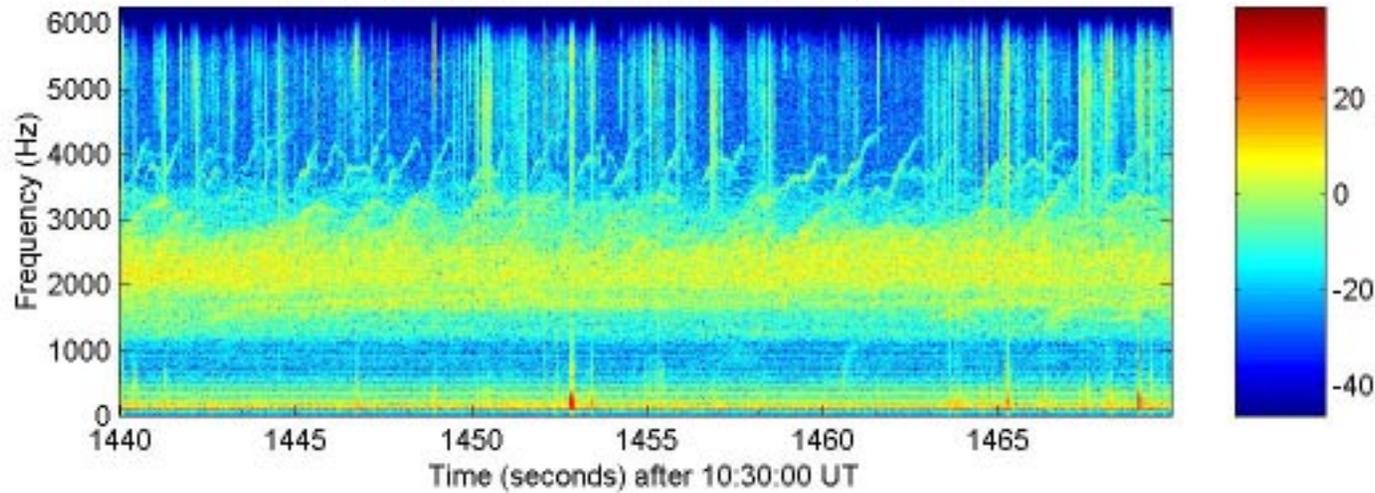




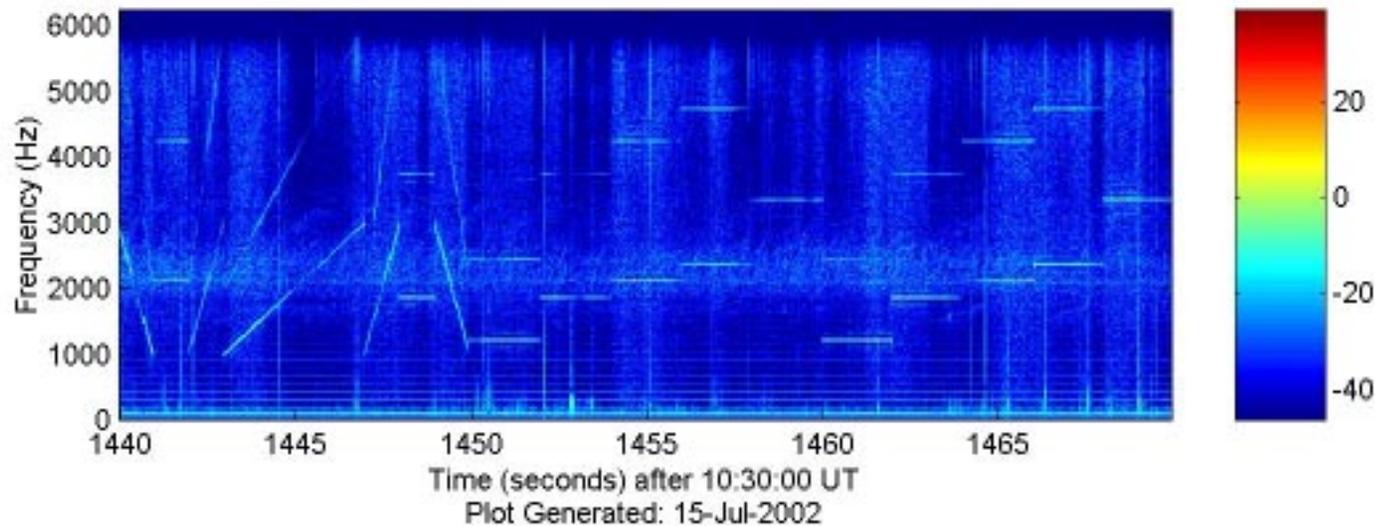
# HAARP VLF & Natural Signals



Chistochina B&B: 16-Mar-2002 UT N/S Antenna  
HAARP Transmission: 5.8 MHz Carrier, Vertical Orientation



16-Mar-2002 UT EW Antenna

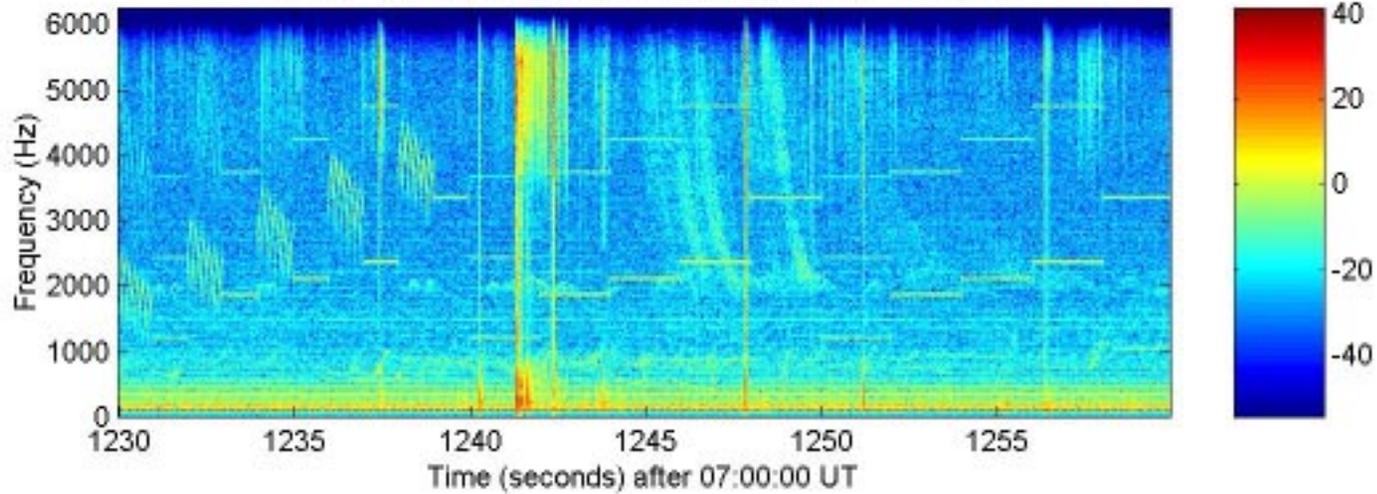




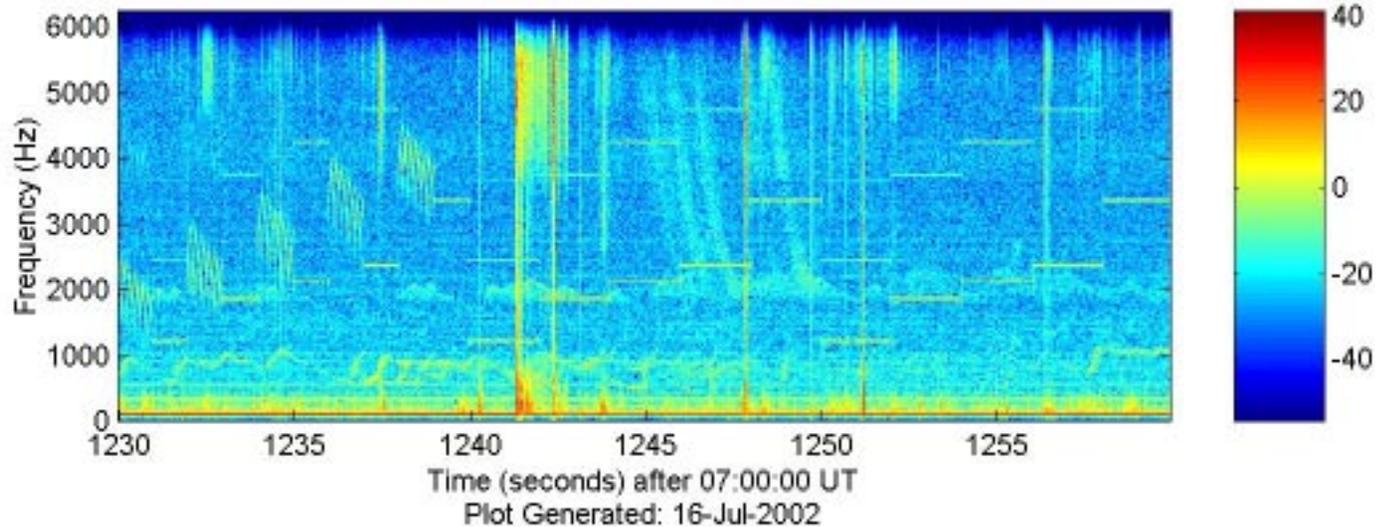
# Whistlers and HAARP Signals



Chistochina B&B: 21-Mar-2002 UT N/S Antenna  
HAARP Transmission: 3.2 MHz Carrier, Vertical Orientation



21-Mar-2002 UT EW Antenna

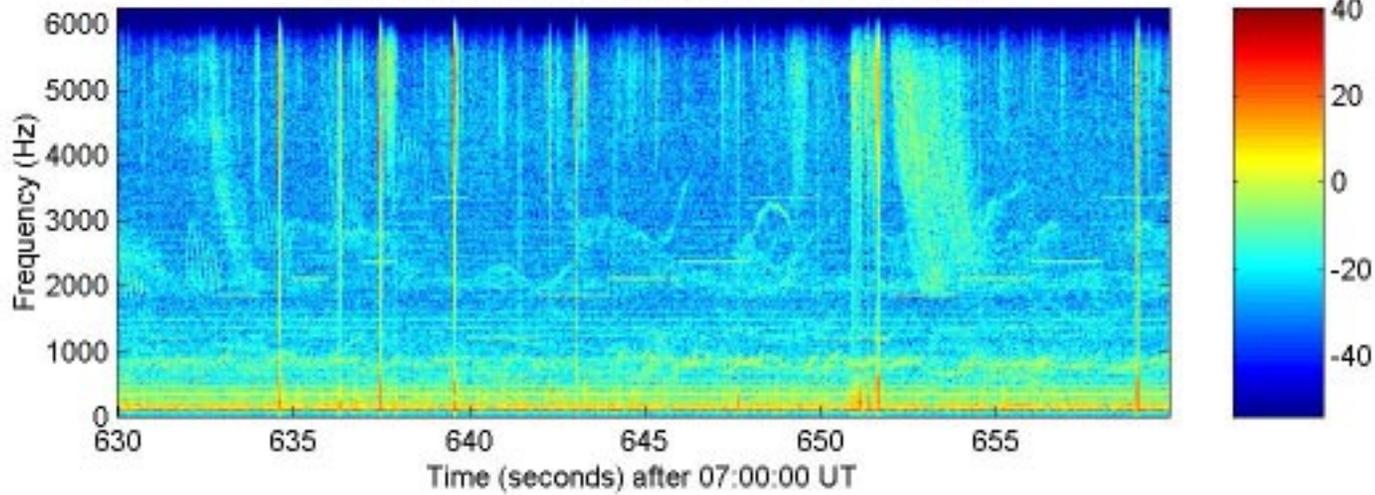




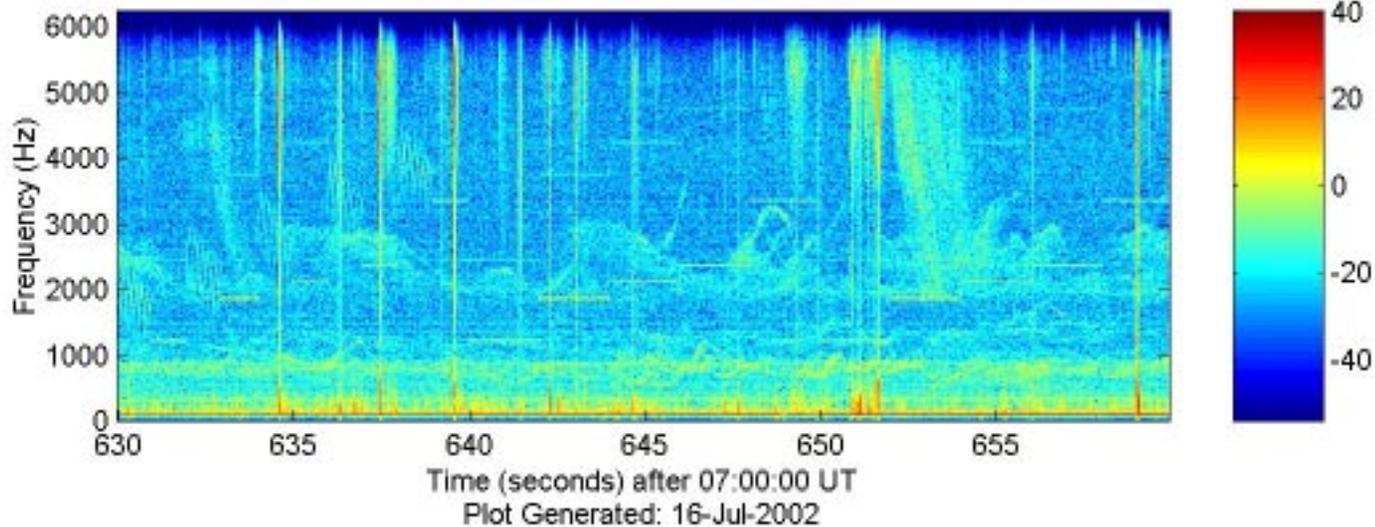
# Beam at 30° South



Christochina B&B: 21-Mar-2002 UT N/S Antenna  
HAARP Transmission: 3.2 MHz Carrier, 30 Deg South



21-Mar-2002 UT EW Antenna

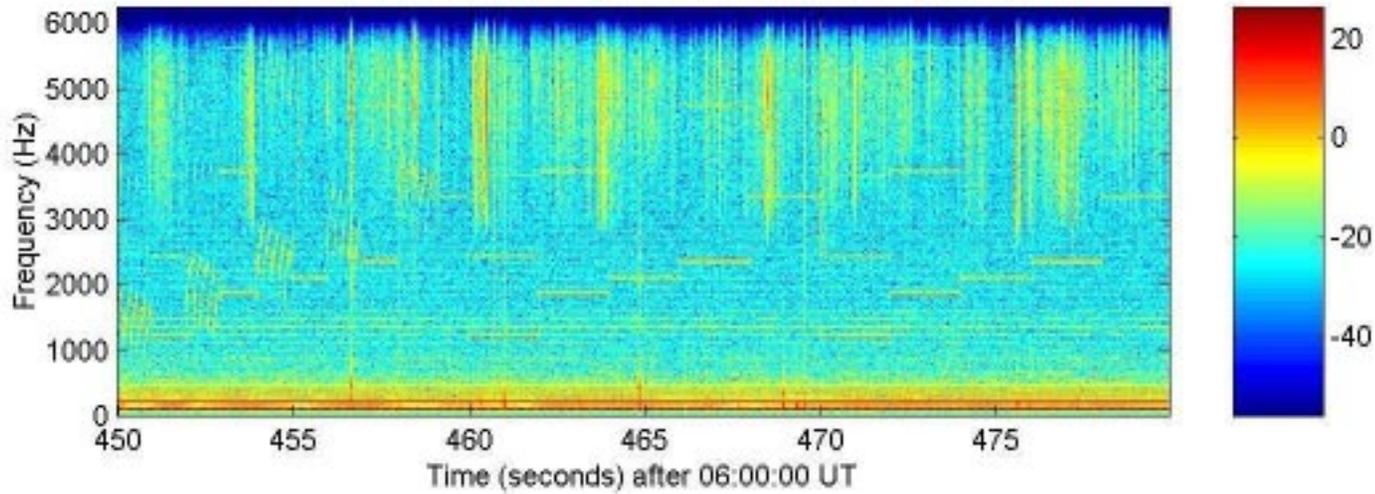




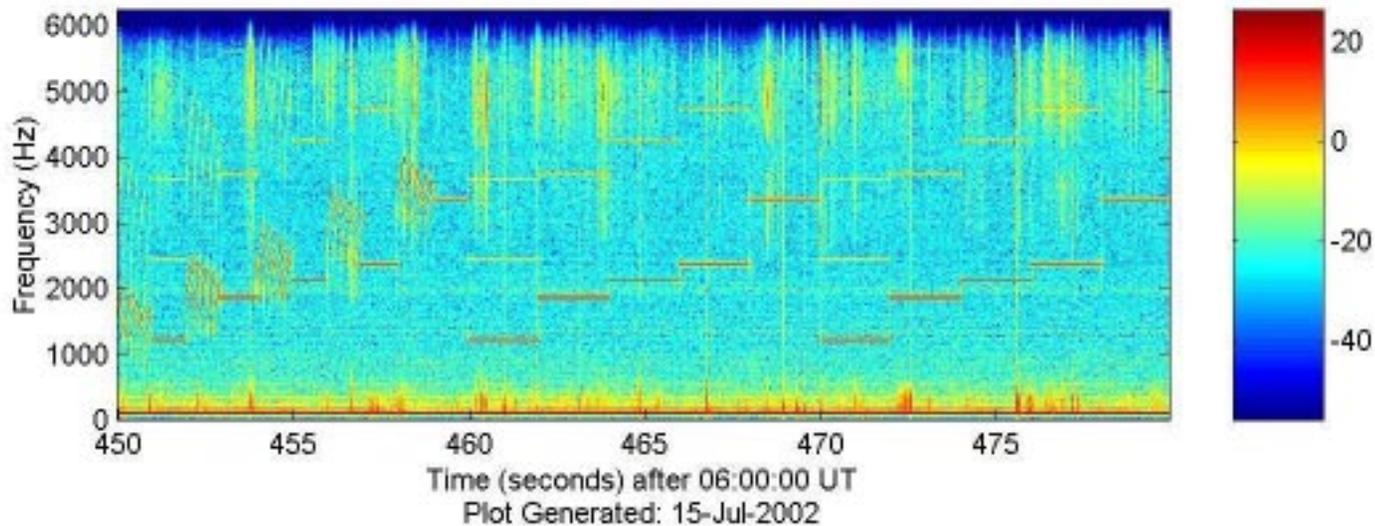
# HAARP at Chistochina



Chistochina B&B: 18-Mar-2002 UT N/S Antenna  
HAARP Transmission: 3.2 MHz Carrier, Vertical Orientation



18-Mar-2002 UT EW Antenna

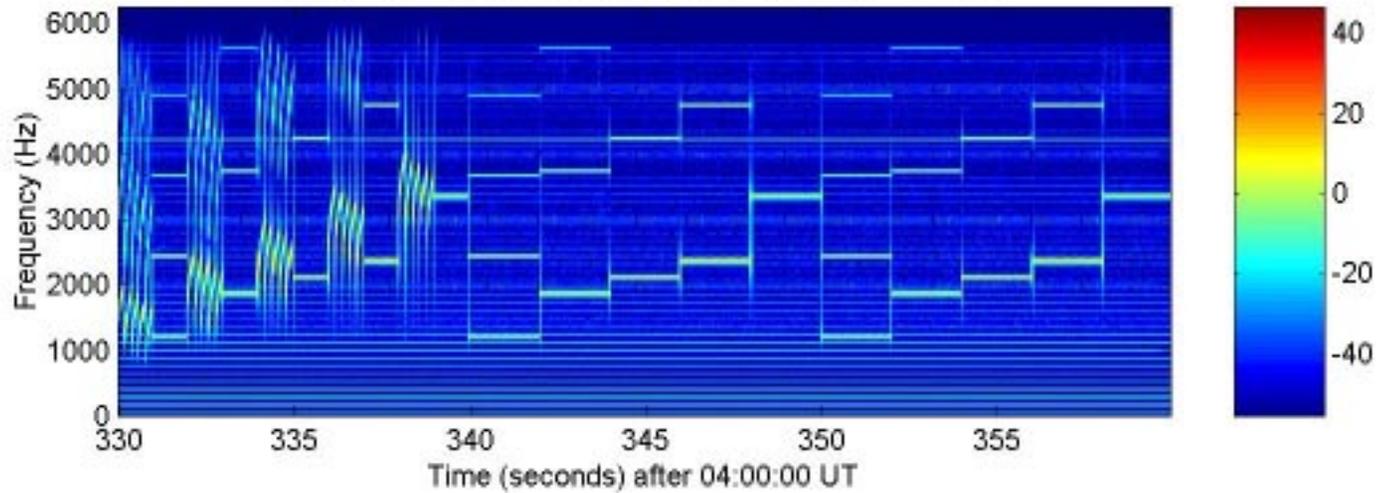




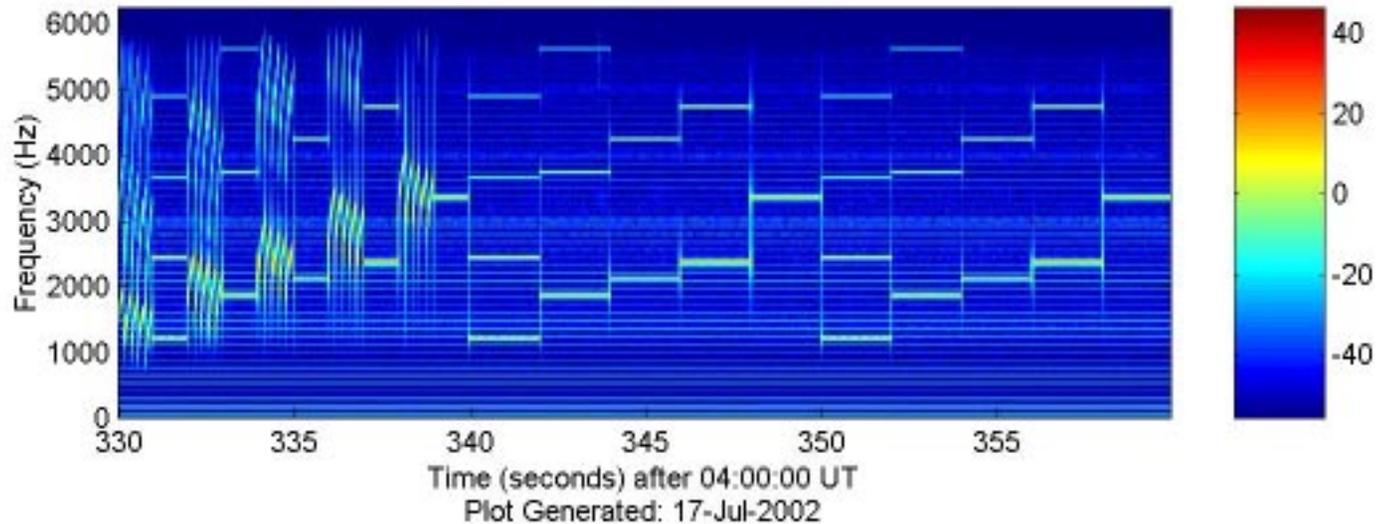
# Very Strong HAARP VLF Signals



Crosswind Lake: 24-Mar-2002 UT N/S Antenna  
HAARP Transmission: 3.2 MHz Carrier, Vertical Orientation

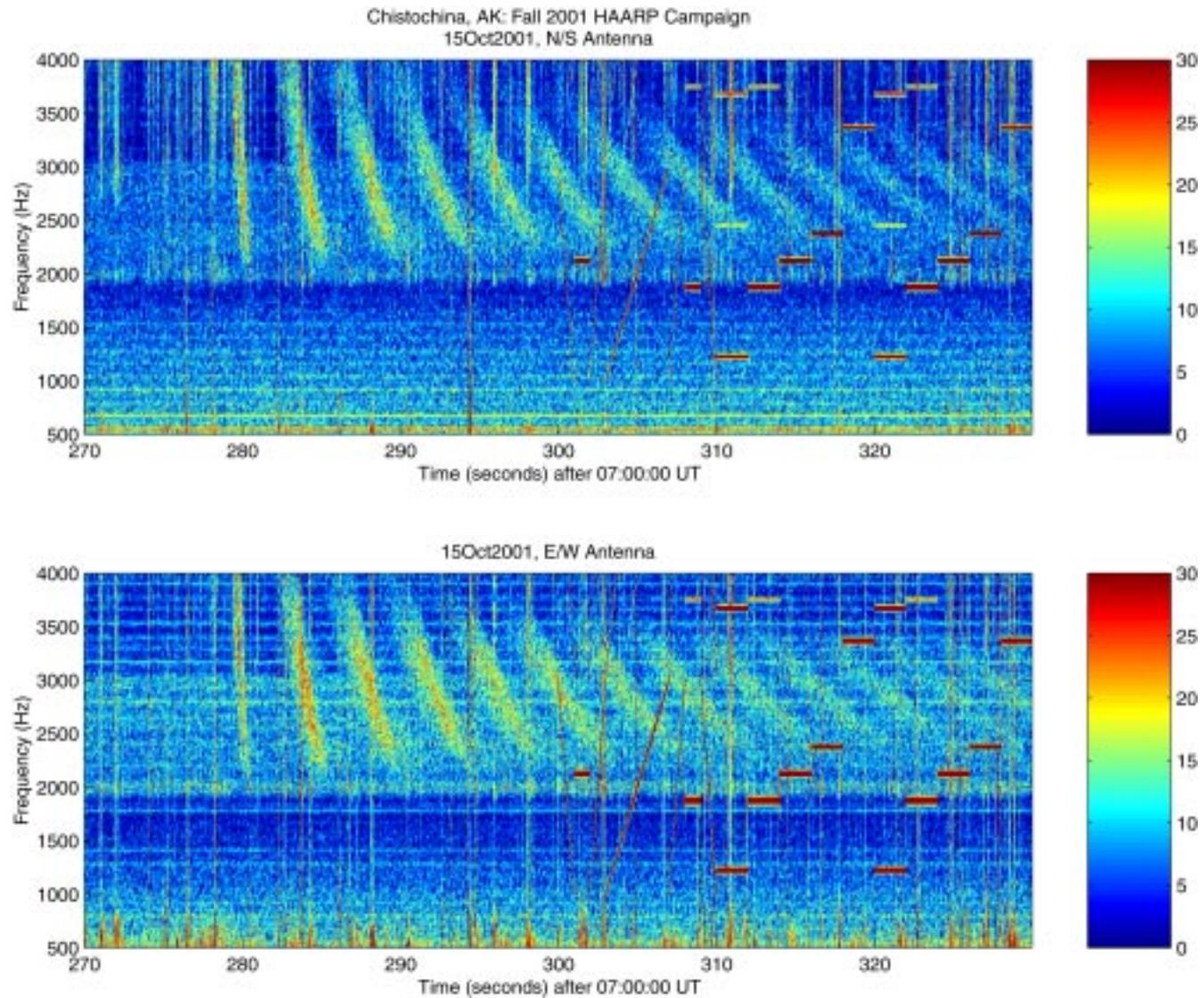


24-Mar-2002 UT EW Antenna





# Whistler Echo Train

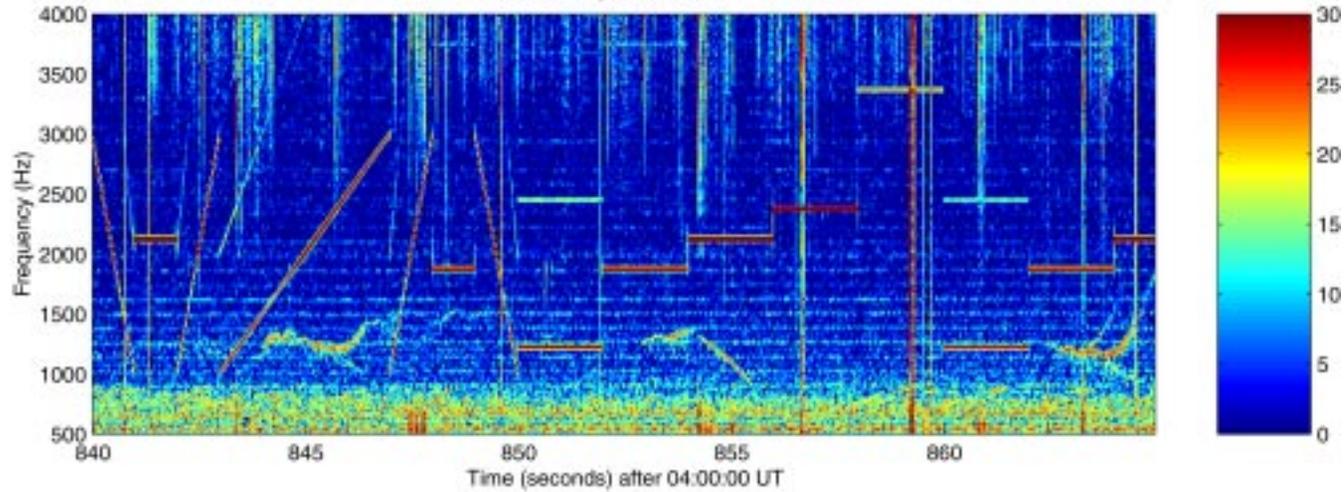




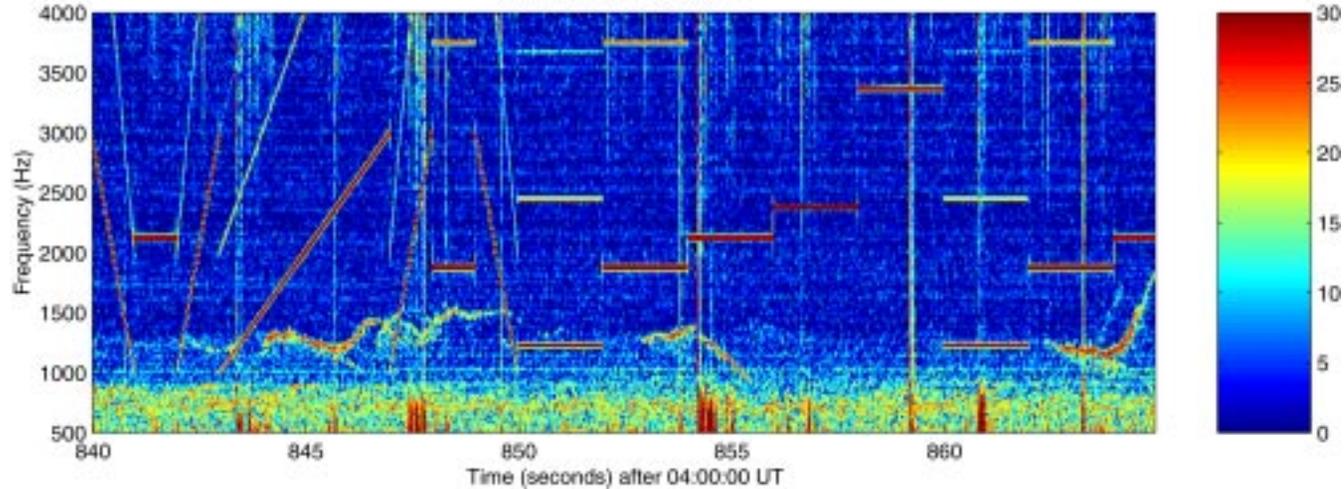
# HAARP VLF & Natural Emissions



Chistochina, AK: Fall 2001 HAARP Campaign  
19Oct2001, N/S Antenna

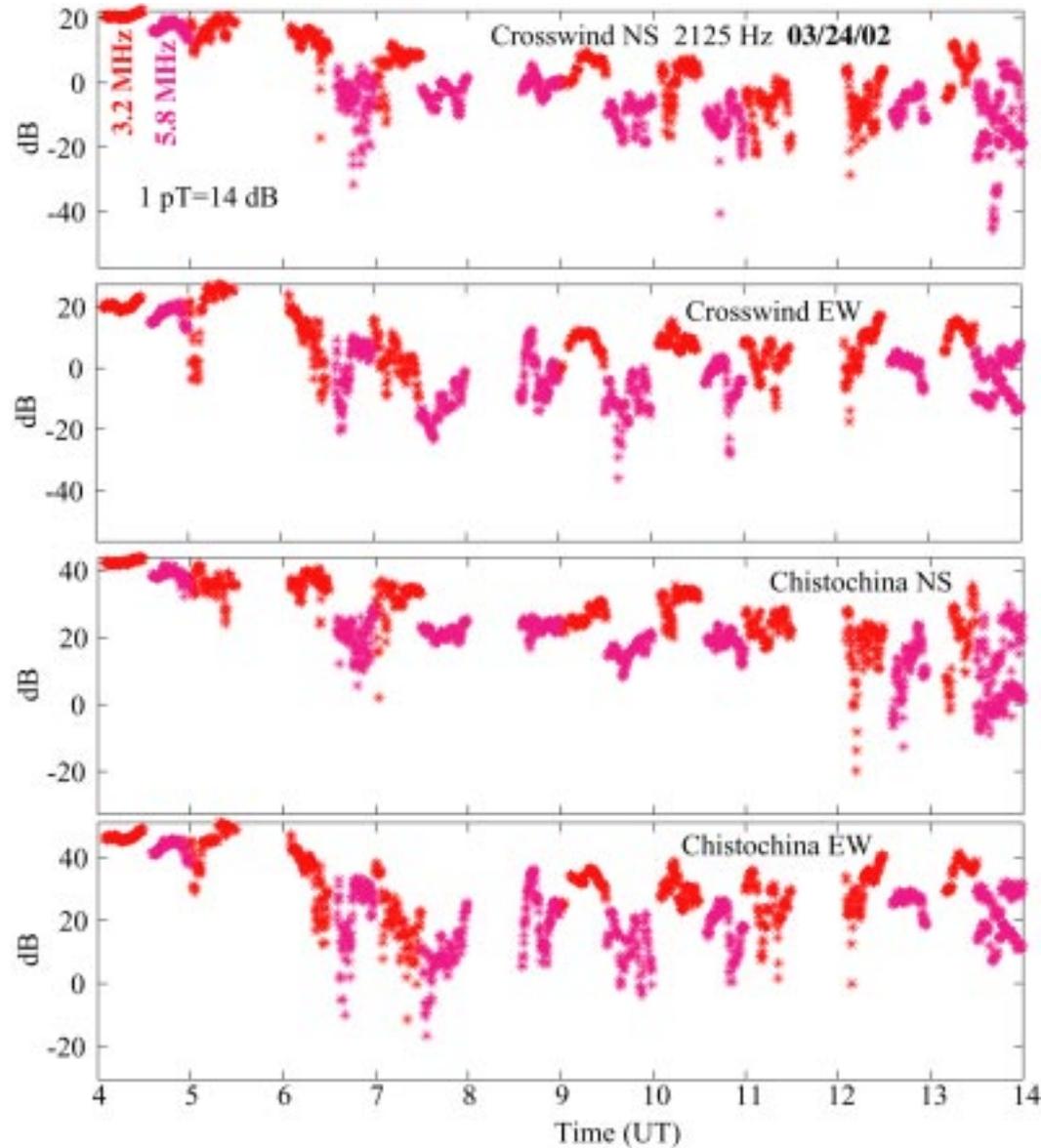


19Oct2001, E/W Antenna



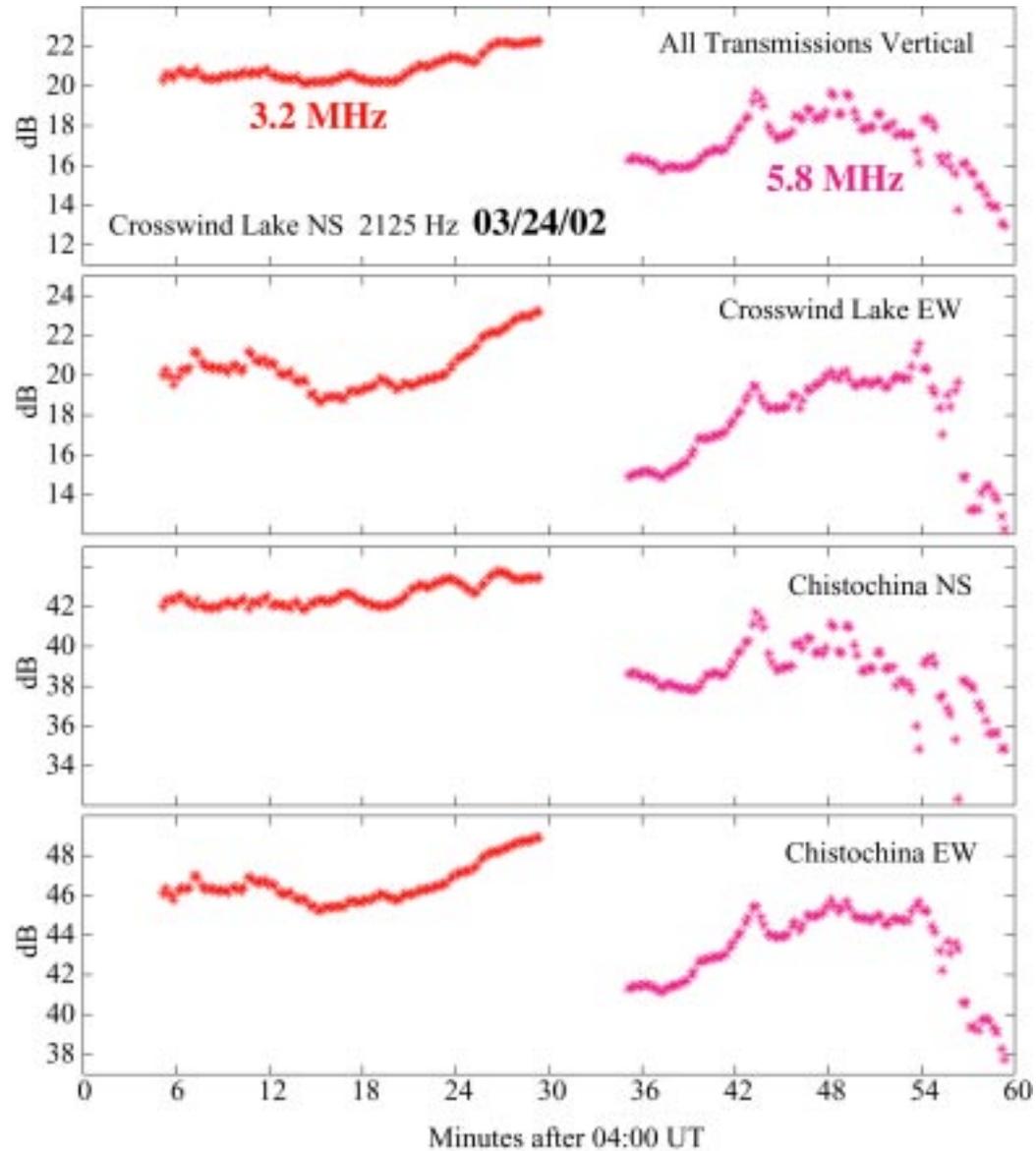


# Daily Variation of HAARP VLF



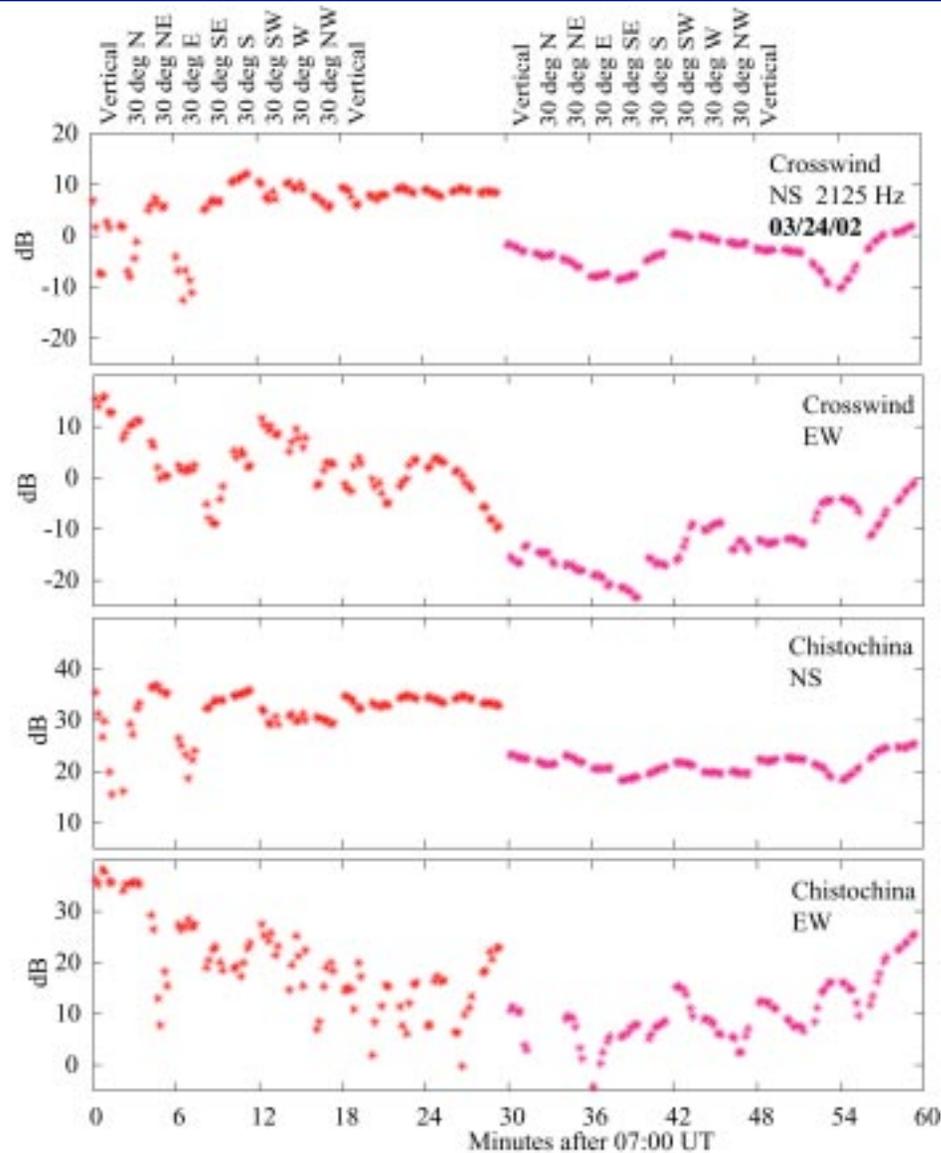


# Vertical Orientation 04: to 05: UT



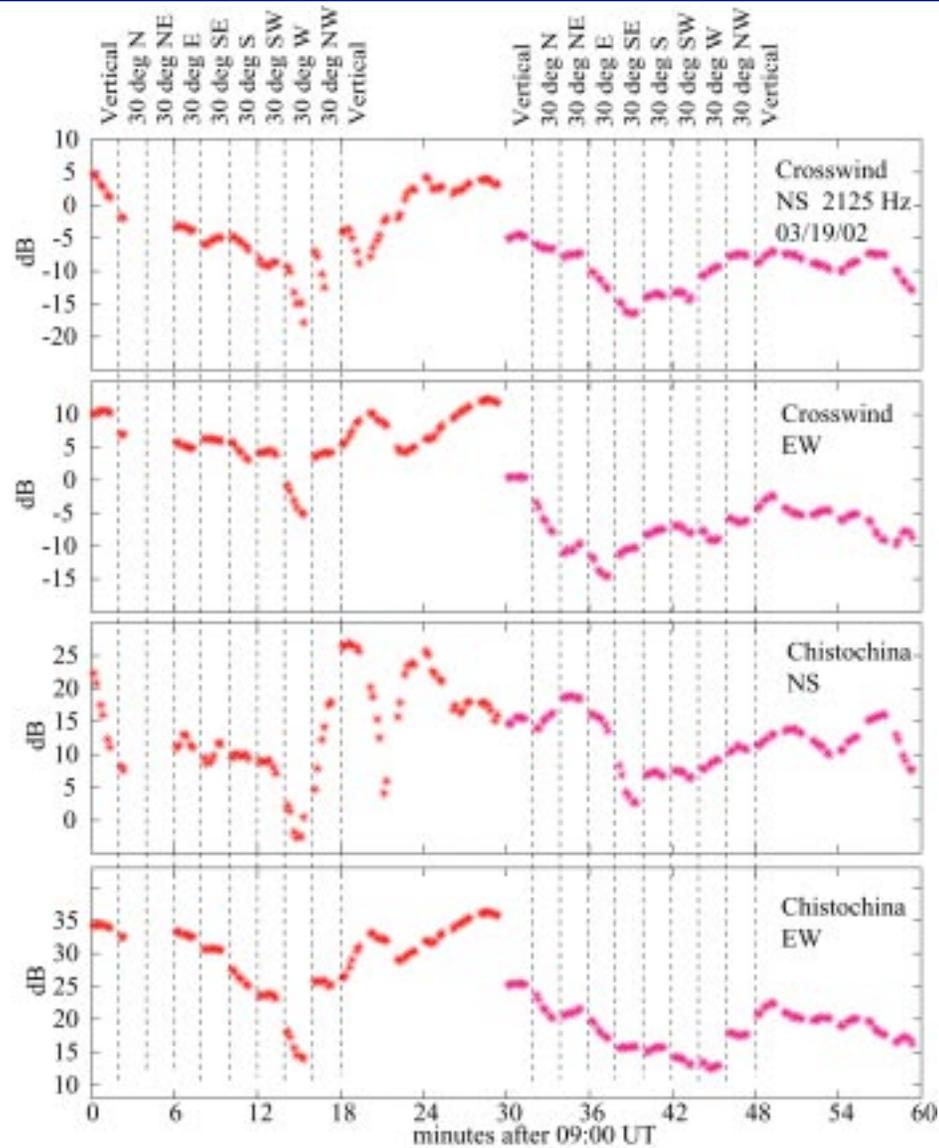


# Beam Swinging 07: to 08: UT



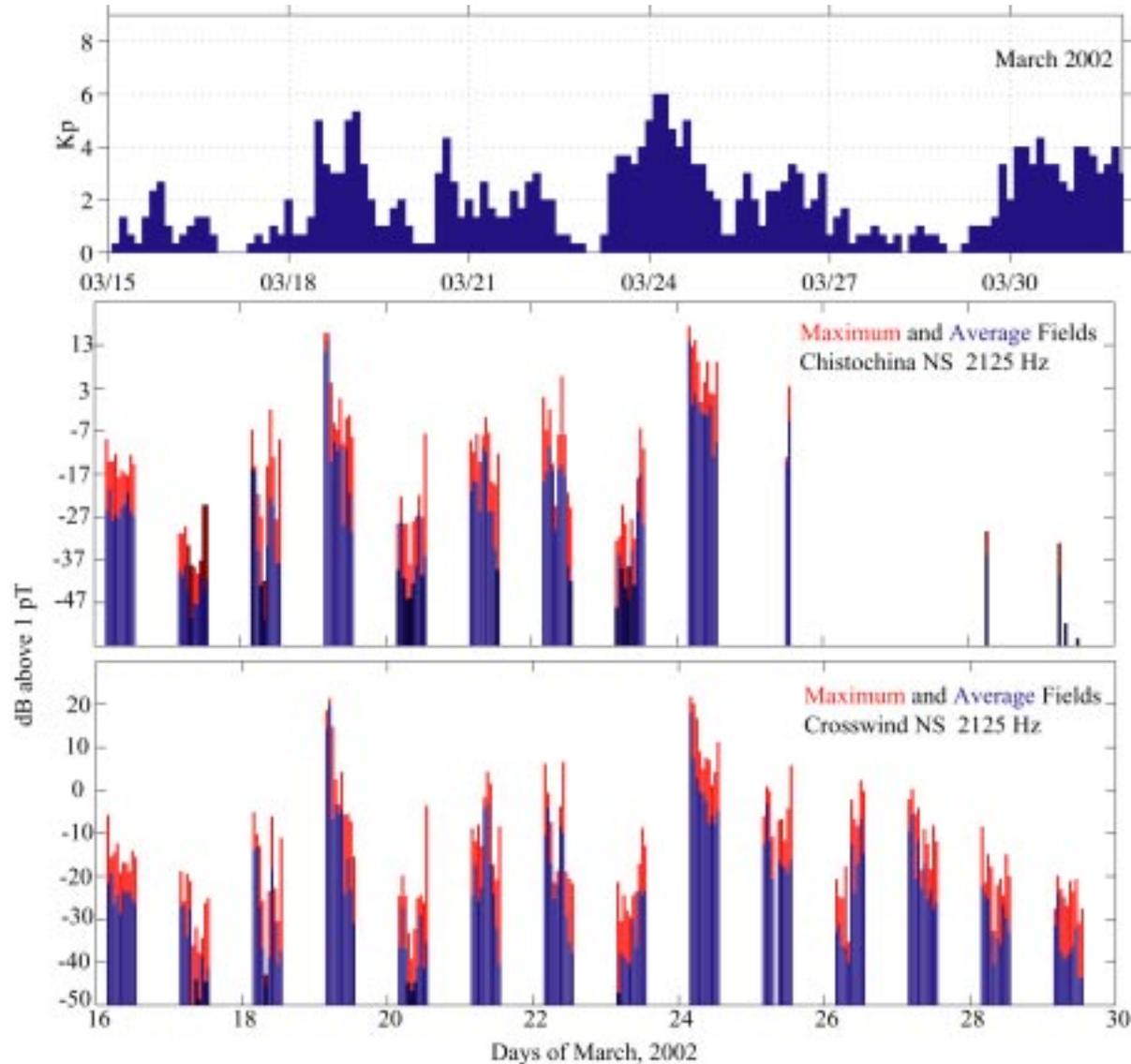


# More Beam Swinging



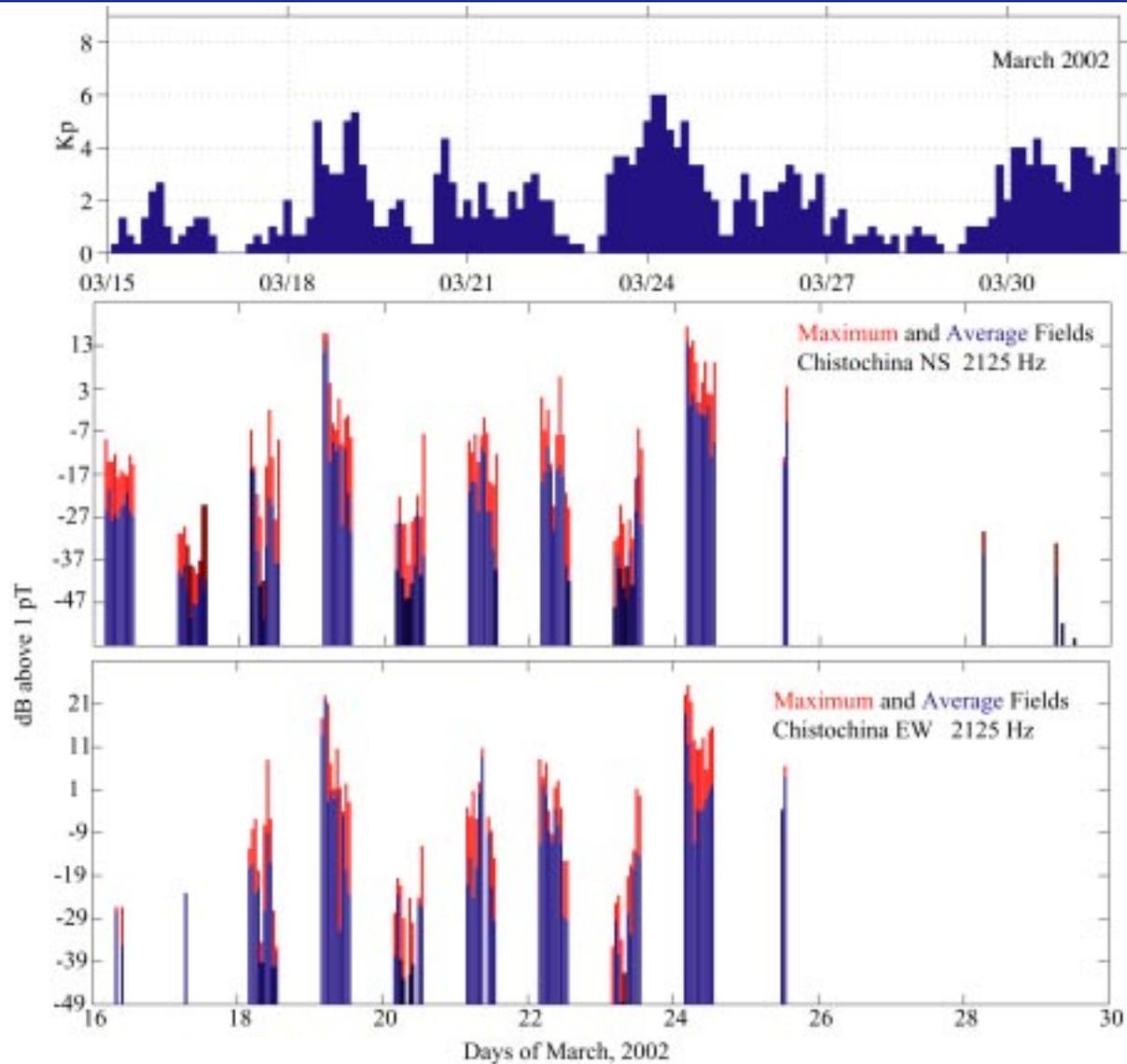


# HAARP 2125 Hz Signal at Chistochina & Crosswind Lake



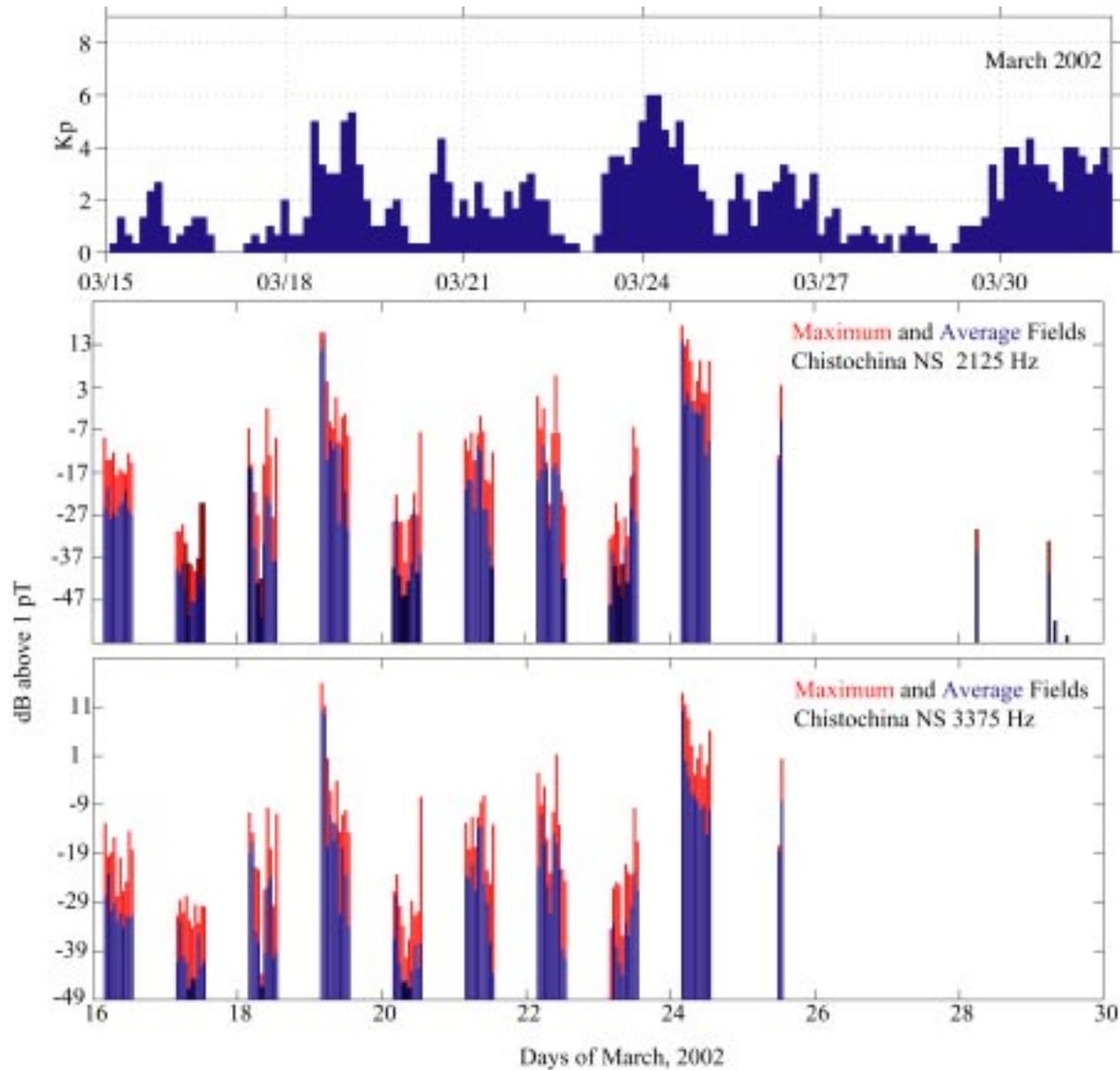


# 2125 Hz at Chistochina





# N-S at Chistochina





# Summary

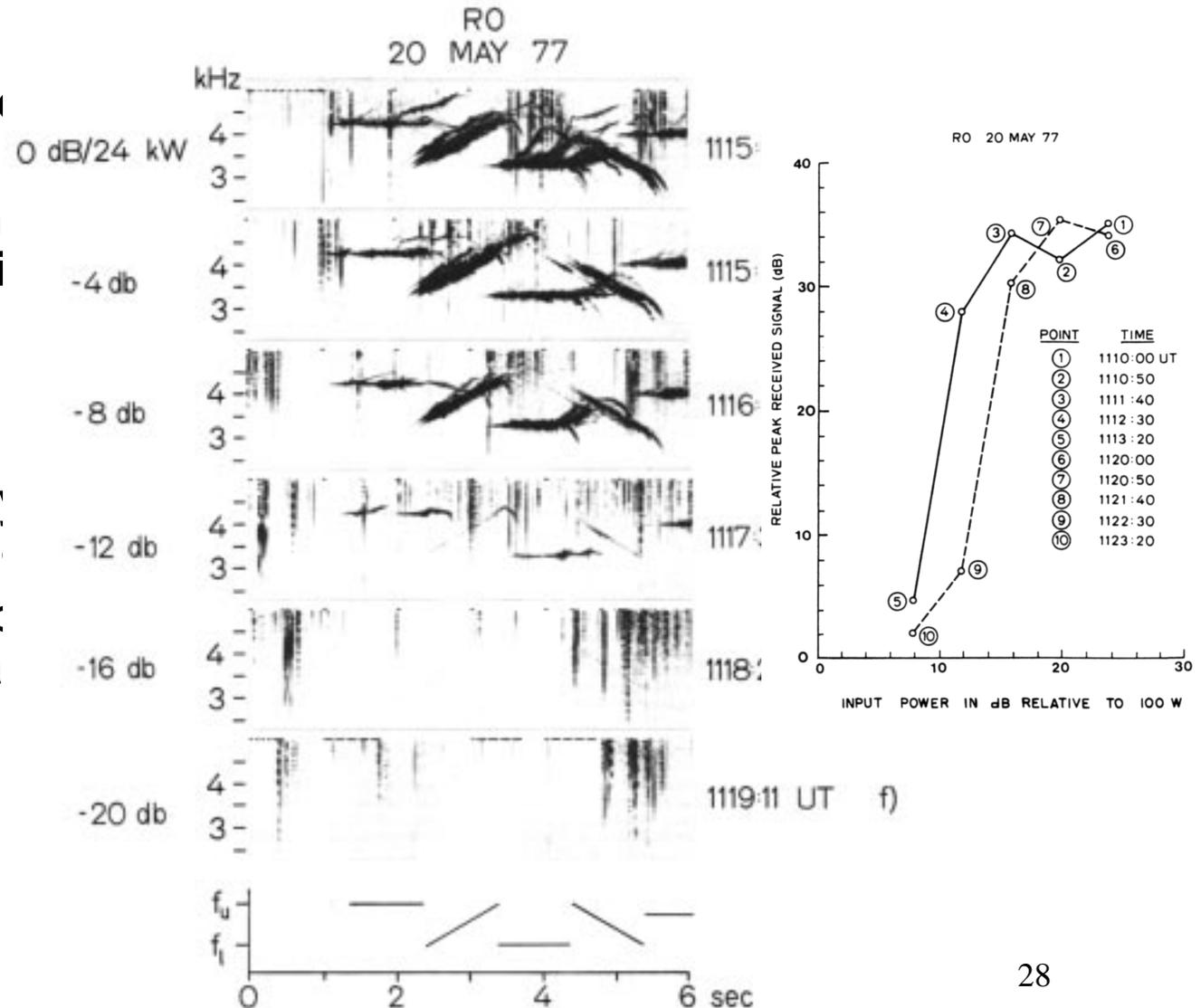
- **ELF/VLF signal intensities at similar distances on the ground were found to be typically fractions to a few pT (rarely up to 10 pT) in Tromso/EISCAT experiments [e.g., Barr et al., 1985]**
- **Intensities ~2 kHz HAARP signals range from a typical value of ~0.3 pT to 20 pT for 2 to 4 kHz frequencies Simple analysis (assuming a line current at ~80 km, and lateral diameter of ~40 km) indicates that:**
  - **Radiated power =  $0.2 (B_w f)^2$  for <3 kHz (near-field)**
  - **Radiated power =  $6 B_w^2$  for >3 kHz (far-field)**
- **It thus appears that VLF power radiated via modulated HF transmissions with the present HAARP facility may typically be <1 Watts but may sometimes be as high as a few hundred Watts**
- **Proposed completion of HAARP to full capability can provide for 10-20 dB higher signal levels**
  - **Threshold for growth & triggering may be regularly exceeded**



# Power Threshold for Growth



- Multiple ducts excite full power
- Ducts drop out with reduced power, until there is only one
- Minimum radiated power is ~1 Watt
- HAARP occasionally exceeds this threshold
- Two-hop echo can be observed, if ducts are available





# Siple Experiments



- Amplified signals and triggered emissions were observed for many hours per day
- Two-hop echoes were observed 20 to 30% of the time when one-hop was observed
- Wide range of L-shells were excited

