VLF Interferometry

ELF/vlf Near field Imaging of modulated
Auroral electrojet Currents (ENIAC)

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Outline

A. ABSTRACT

The nine-element ELF/VLF interferometer system is used as a source current imaging array in support of the High-frequency Active Auroral Research Program (HAARP) in Alaska. HAARP is a congressionally initiated program jointly managed by the U.S. Air Force and U.S. Navy. The goal of the program is to provide a state-of-the-art U.S. owned ionospheric research facility readily accessible to U.S. scientists from universities, the private sector and government.

One of the research topics of present interest is the generation of ELF/VLF waves through HF heating of the auroral electrojet, the intense current system that flows in the auroral regions between 70 and 120 km altitude. Potential DoD applications of this research are to provide communications to submerged submarines at ELF frequencies and to use the generated waves to locate and probe underground structures.

The purpose of the ELF/VLF current imaging array is to provide an experimental tool that can be used to determine the HF heater-induced time varying electrojet currents that actually radiate the ELF/VLF waves. Without this knowledge there is presently little hope of understanding and optimizing the process by which the waves are produced.

To resolve the important unknowns concerning the spatial distribution of the modulated currents, we propose to construct and deploy an ELF/VLF current imaging system near the HAARP facility in Alaska. The ELF/VLF interferometer system would consist of nine ELF/VLF receivers, each with triaxial crossed loop antennas and one vertical electric antenna, arranged in the form of a cross with the central receiver located within ~10 km of the HAARP facility. Each leg of the cross consists of five receivers, each spaced by a distance of 70 km, with the central receiver being common to both legs of the cross.

The array would be used to map out the modulated currents using the near field of these currents. The known relationship between the near fields and the modulated currents provides the link which makes this possible.

B. INTRODUCTION

A low-power (battery operated) nine-element interferometric array is to be constructed and assembled for ELF/VLF measurements in remote regions. An important application of this new array include (imaging the three dimensional structure of the HF heater modulated auroral electrojet currents that radiate ELF/VLF waves, with specific application to the High-frequency Active Auroral Research Program (HAARP) in Alaska.

The new method is based on measurements of wideband ELF/VLF waveforms at nine suitably distributed (Figure 1) remote sites, with a GPS-based absolute timing accuracy between distant sites of <1 us. The GPS timing allows the waveform data from the different sites to be phase comparable in the same sense as a traditional *interferometer*, except for the fact that the object being ?imaged? is in the near-field (rather than far-field as in most other interferometric applications) of the sensors.

The ELF/VLF interferometer system consists of nine low power radio receivers as shown in Figure 1, allowing the specification of the three dimensional distribution of the source current region with ~5 km resolution in both the vertical and lateral dimensions. One of the important applications of the new interferometer will involve its use in connection with the powerful HAARP HF heater, for which the array design will be specifically tailored. HAARP is a congressionally initiated program jointly managed by the U.S. Air Force and U.S. Navy with the overall goal of providing a state-of-the-art ionospheric research facility readily accessible to U.S. scientists from universities, the private sector and government.

This facility is currently operational at a total radiated power level of 960 kW, and has been successfully used controlled heating of the ionosphere, for production of artificial ionospheric irregularities, and for generation of ELF/VLF signals. When the full array of transmitting antennas are completed within the next few years, the HAARP facility will be the most advanced and powerful ionospheric heater in the world, capable of producing the most intense ELF/VLF signals that can be used for remote sensing of underground structures, for probing the earth?s outer radiation belts, and for communication with submerged vehicles.

The interferometer is a unique experimental tool that can be used to determine the HF heater-induced time varying electrojet currents that actually radiate the ELF/VLF waves. This knowledge will not only enhance our understanding of the fundamental processes of ELF/VLF generation but will also allow the optimization of the process by which the waves are produced.

The data to be obtained from the proposed program will be used to analyze basic properties of ionospheric ELF/VLF radiating systems and to assess the potential for developing ionospheric enhancement technology for communications and surveillance purposes.

C. SCIENTIFIC BACKGROUND

ELF/VLF waves are important not only as communication tools, but also as remote diagnostic probes to determine the characteristics of the Earth, the ionosphere, and the magnetosphere. Since the controlled production of these waves on the ground generally requires large, elaborate and expensive antennas and associated facilities [*C. H. Richard, Sub vs. Sub*, Orion Books, New York, 1988], it is important to explore alternate means of generating these waves.

One promising alternate method for producing ELF/VLF waves is to use a powerful ground based HF radar to modulate the intense auroral electrojet currents that flow in the auroral D and E regions, causing these natural currents to radiate ELF/VLF waves from an altitude range of 70-110 km, depending upon the HF frequency. This technique works in the following way.

The HF waves heat the ambient electrons in the D and E-regions where the electrojet current flows, causing the electrons to collide more frequently with the ambient neutral particles. The increased electron collision rate changes the local conductivity of the medium, and this in turn changes the electrojet current flow. If the HF heater is modulated at a frequency in the ELF/VLF range, the electrojet current will vary at this same frequency and will then radiate waves at this frequency.
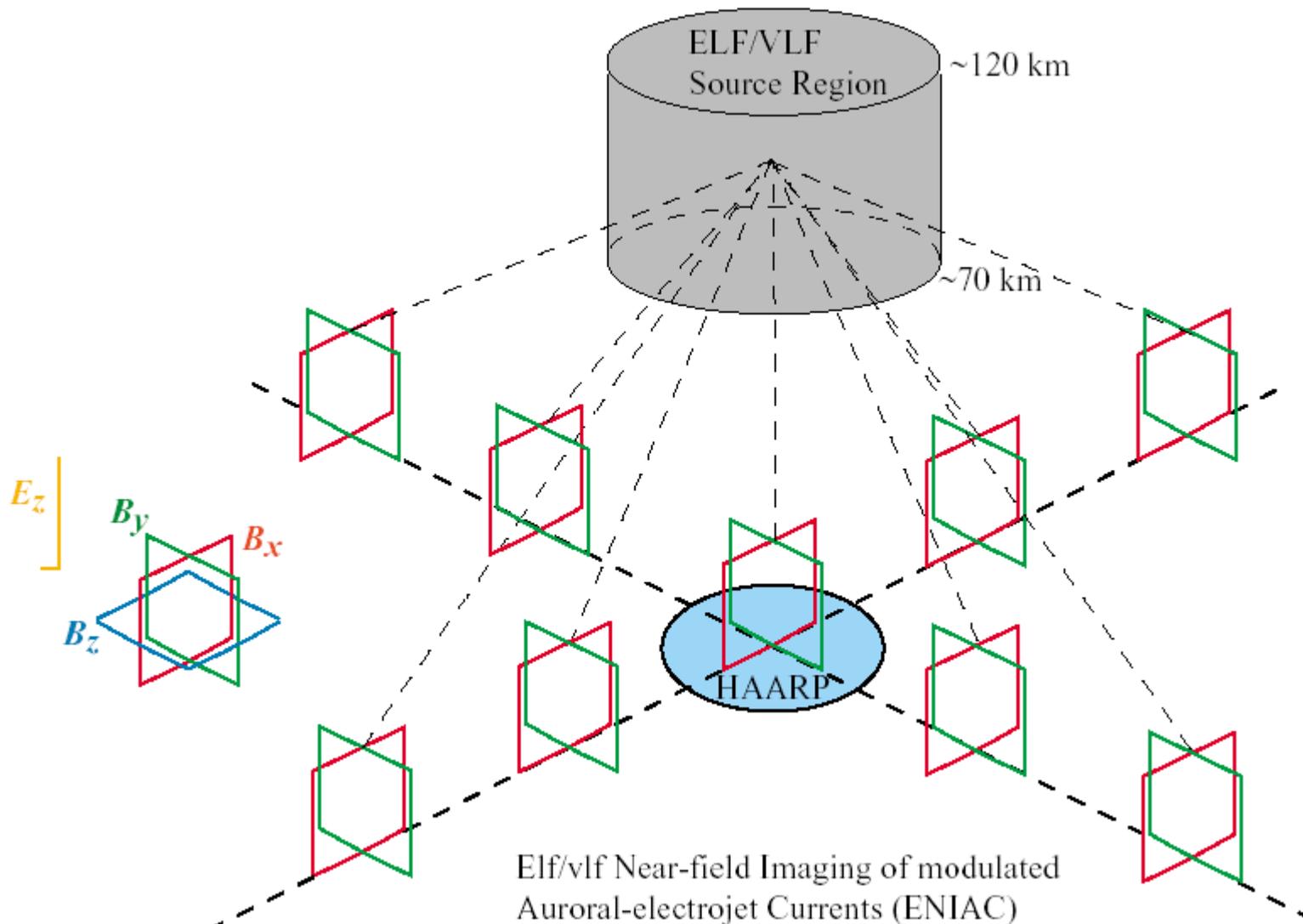
Controlled experiments using this technique have been successfully conducted in Norway

[*Stubbe et al.*, 1982; *Barr and Stubbe*, 1984; *Reitveld et al.*, 1986; *Barr and Stubbe*, 1991], Russia [*Kapustin et al.*,1972], and Alaska [*Ferraro et al.*,1982; *McCarrick et al.*, 1990; *Villasenor et al.*, 1996]. Furthermore, VLF waves generated in the D-region by ground based HF heaters have been detected by a number of spacecraft, including ISIS 1 [*James et al.*, 1984], Aureol 3 [*Lefeuvre et al.*, 1985], DE 1 [*Inan and Helliwell*, 1985], and Akebono [*Kimura et al.*, 1991, 1994].

Although it has been amply demonstrated that HF heaters can modulate the auroral electrojet currents to produce ELF/VLF waves in the D-region, there is very little known about the actual details of the mechanism through which the waves are generated. For example, the horizontal spatial distribution of the currents that radiate the waves is not known. Thus the waves could be produced through quadrupole radiation rather than through dipole radiation. Furthermore the altitude of the modulated currents is not known, other than the fact that they must be located above 70 km where the conductivity is high enough to support intense electrojet currents [*Rowland et al.*, 1996].

Since very little is known about the spatial distribution of the modulated currents that produce the ELF/VLF waves, there is no experimentally verified model which could be used to optimize the wave generation process. Instead, trial and error methods have been employed which are very difficult to interpret because of the well known variability of the auroral ionosphere.

To resolve the important unknowns concerning the spatial distribution of the modulated currents, we propose to construct and deploy the ELF/VLF inteferometer array near the HAARP facility in Alaska. As shown in Figure 1, the system would consist of nine ELF/VLF receivers, each with triaxial crossed loop antennas and a vertical electric antenna, arranged in the form of a cross with the central receiver located within ~10 km of the HAARP facility. Each leg of the cross consists of five receivers, each spaced by a distance of ~70 km.

ELF/VLF Source Region

~120 km

~70 km

HAARP

Elf/vlf Near-field Imaging of modulated
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The interferometer array would be used to map out the modulated currents using the near field of these currents. The known relationship between the near fields and the modulated currents provides the link which makes this possible. The spatial resolution of the imaging will depend upon the signal-to-noise ratio of the near field measurements. However since this ratio can generally be improved by averaging, we believe a 20 dB ratio is achievable.

In this case the imaging should be able to achieve a spatial resolution of ~5 km or better in both the horizontal and vertical directions. Achieving this goal will require operations in which the HF beam is directed away from the vertical, but always well within normal operating configurations. A resolution of ~5 km appears sufficient for most applications, since simulations suggest thatELF/VLF radiation is enhanced for a fixed HF power level when the heated region is made as large as possible [*Taranenko et al.*, 1992]. The modulated auroral electrojet currents produce a magnetic field at ground level which is described by Maxwell?s equation

$$\nabla \times \vec{B} = \frac{1}{c^2}\frac{\partial E}{\partial t} + \mu_o \vec{J}$$

where *B* is the magnetic field, *E* is the electric field, *c* is the velocity of light, *t* is the time, .is the divergence operator, and *J* is the sum of the modulated source current density and eddy currents in the ground induced by the time varying magnetic field. The *E* field in (1) is predominantly produced by space charge . in the source region which is associated with the current flow. The quantities *J* and . are related through the equation of continuity.

$$\nabla \cdot J + \frac{\partial \rho}{\partial t} = 0$$

Within the source region the local charge density . is significant only in regions where there are significant gradients in the local conductivity, such as near the boundaries of the heated volume. Since it is the time derivative of . which enters into (2), it is clear that the effects of . on *J* decrease as the driving frequency is decreased. In the limit of decreasing driving frequency, (1) and (2) can be approximated by the relations:

$$\nabla \times \vec{B} = \mu_o \vec{J}$$

$$\nabla \cdot \vec{J} = 0$$

In cases when ground eddy currents are negligible the relationship between the *B* field at the ground and the source currents can be described through the generalized Biot-Savart Law [*Inan & Inan*, 1999]:

$$\vec{B}(\vec{r}) = \frac{\mu_o}{4\pi} \int \frac{\vec{J} \times \hat{R}}{R^2} dV'$$

where *B* is the field produced by the currents, *J* is the current density in the source region, *R* is a unit vector along the line connecting the source and observation points, *R* is the distance between the source and observation points, and the integral includes the volume of space containing the modulated currents, and *dV* is a volume element in the source region.

To solve (1) for *J*, given *B* at the ground, we divide the source regions into identical small volume elements .*V* and approximate the integral by the finite sum:

$$\vec{B}(r) = \frac{\mu_o}{4\pi} \sum_i \frac{\vec{J}_i \times \hat{R}_i}{R_i^2} \Delta V$$

Assuming that the summation has *i* elements and that we have measured *B(r)* at *i* separate locations, we can then write (5) as the matrix relationship

$$\overline{B} = \overline{\overline{M}}\,\overline{J}$$

where *B* is a column vector containing the *B* measurements and *J* is a column vector containing the 3*i* unknown values of *J* in the discretized source region. Given that *M* is not singular, we can invert (3) to obtain the current density from the measured values of *B*:

$$\overline{J} = \left[\overline{\overline{M}}\right]^{-1}\overline{B}$$

In cases where ground eddy currents are significant, (4) must be modified through the inclusion of the image currents. However, the solution proceeds in a similar manner.

In general the horizontal scale of the modulated currents is just the full width of the HF beam at ~80 km altitude, which is generally less than 50 km. The vertical scale is unknown, but probably of the order of 25 km. For a spatial resolution of 5 km we would then have *i* 500 in the summation of (5). To obtain 500 separate measurements of *B* at our 9 sites, it is necessary to use the HF beam pointing capability to move the heated region with respect to the fixed sites. This can be done quite simply for example, by tilting the HF beam a few degrees from the vertical and then sampling *B* at the 9 sites as the azimuth is changed in steps. Then tilting the beam a few degrees more from the vertical and repeating the azimuth sean.

Given that the maximum inclination angle from the vertical is 30. for the HAARP HF beam and that the source currents are located somewhere between 70 to 120 km altitude, the mimimum effective area that can be sampled with the current imaging array is shown in Figure 2. In this figure the center circle includes all the points with respect to the center of the heated region that can be sampled by the central site of the array as the HF beam moves from 0 to 30. with respect to the vertical, and at each zenith angle moves through 360. of azimuth.

The other circular regions represent the effective area sampled at each of the remaining 8 sites. The dashed circle in the center of the central circular area represents the projection on the ground of the area illuminated by the HF beam at 80 km altitude when the HF frequency is 2.8 MHz and the beam is vertical. It is clear that the central site of the array can effectively sample all points on the ground directly beneath the heated region and that measurements can be made at any point up to 175 km from the center of the heated region along each leg of the cross. In the central region the sample points can be arranged in a rectangular grid with axes parallel to the cross axes and with 5 km separation between sample points.

This scheme produces ~150 measurements of B. At the 4 sites closest to the central site the sample points can be more widely separated because of the increased distance from the source region. With a rectangular sampling grid with a separation of 8.5 km between sampling points we get ~220 measurements of B in these 4 sites. Finally in the outermost sites with a separation of 11 km between sampling points we get ~130 measurement of B for a grand total of 500 measurements of B, as required.

Fig. 2. Effective area sampled by the proposed ELF/VLF interferometer array. The center solid circle includes all points with respect to the center of the heated region that can be sampled by the central site of the array as the HF beam moves from 0 to 30 degrees from the vertical and at each zenith angle moves through 360 degrees of azimuth. The other circular regions represent the effective area sampled at the other 8 sites as the beam swings through the same angular range. The dashed circle at the center of the central solid circle is the projection of the source region onto the ground when the HF beam is vertical and the frequency is 2.8 MHz.
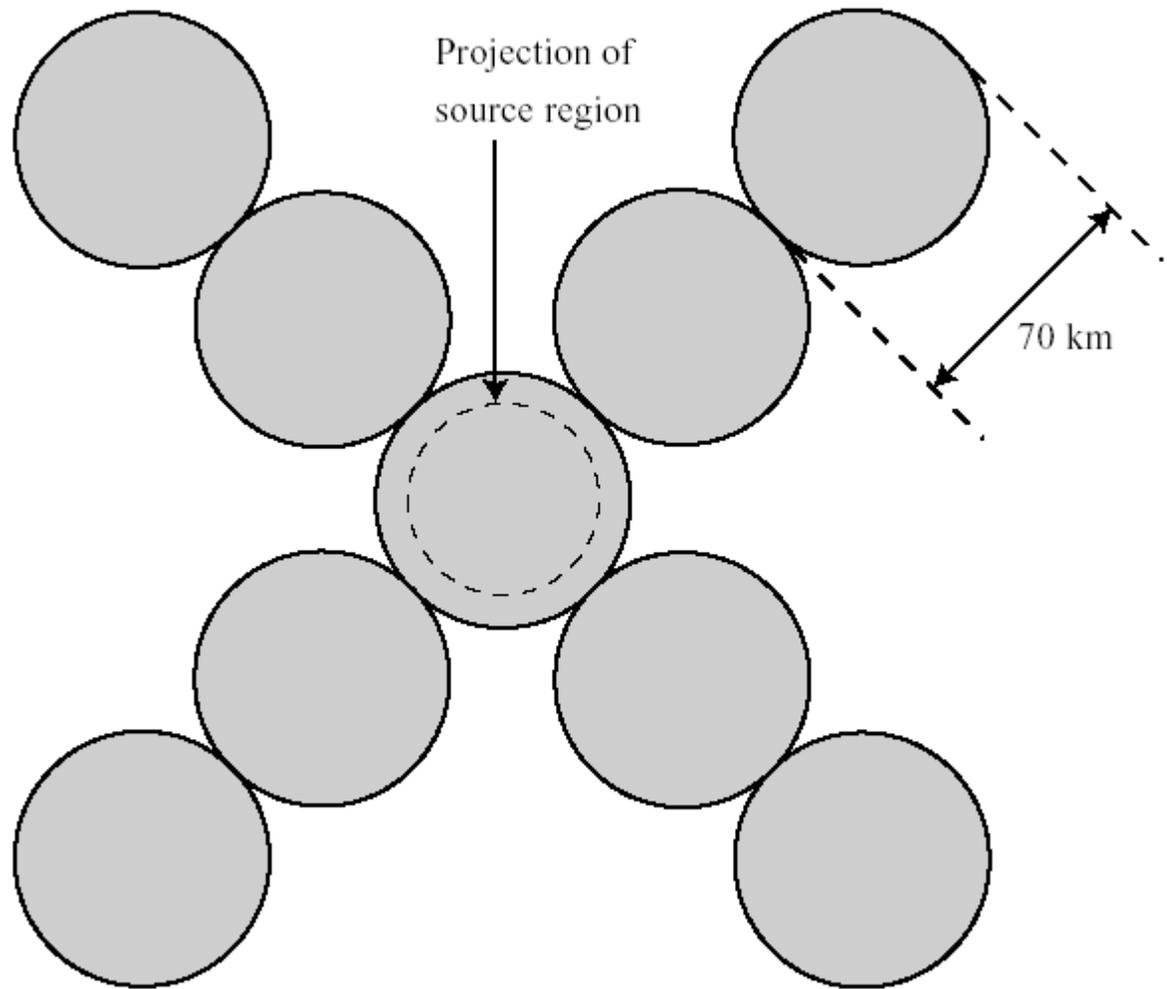
The dwell time of the HF beam at each location would be ~1 second. Thus the entire measurement sequence requires less than 10 minutes to complete. When the HF frequency is higher than 2.8 MHz, the HF beam width will decrease, as will the horizontal

scale of the heated region. In these cases we divide the heated volume into 500 sections as before so that the spatial resolution is inversely proportional to the frequency and always a fixed percentage of the diameter of the beam at ~ 80 km. Since it is possible that space charge effects may be important at all ELF frequencies, we monitor these effects by measuring the vertical component of *E* at each site. The relation between the vertical *E* and . is given by the relation

$$E_z = -\frac{(1 + \eta)}{4\pi\varepsilon_o} \int \frac{\rho\, z'}{R^3}\, dV'$$

where *z* is the vertical axis, *z* is the altitude of the charge, and . is a quantity that depends upon the local ground conductivity. For a highly conducting ground, . ~= 1. Since we know the values of *Ez* at the ground, (8) represents an integral equation for .. We solve it by the same procedure we used to arrive at (7). That is, we approximate the integral by a summation over 500 volume elements to create a matrix relationship:

$$\overline{E}_z = \overline{\overline{C}}\, \overline{\rho}$$

where *Ez* is a column vector containing the 500 measured values of *Ez* and . is a column vector containing the 500 unknown values of .. Inversion of (9) gives the relationship for .:

$$\overline{\rho} = \left[\overline{\overline{C}}\right]^{-1} \overline{E}_z$$

In general,   *J* can be expressed as the sum of two parts:

$$\vec{J} = \vec{J}_1 + \vec{J}_2$$

where . $J1 = 0, .J2 = 0$, and $J2$ is associated with the space charge .. The quantity $J1$ can always be found from (7), while $J2$ is found from (2):

$$\nabla \cdot \vec{J}_2 = -\frac{\partial \rho}{\partial t}$$

Since by definition $.J2 = 0$, we can express $J2$ as the gradient of a scalar F, i.e., : $J2 = .\Phi$.

Now (12) becomes similar to Poisson?s equation:

$$\nabla^2 \Phi = -\frac{\partial \rho}{\partial t}$$

Since the right hand side of (13) is known through (10), (13) can be solved numerically to find F, and then to find $J2$. Thus the complete current $J = J1 + J2$ can be found in the source region for any driving frequency in the ELF range.
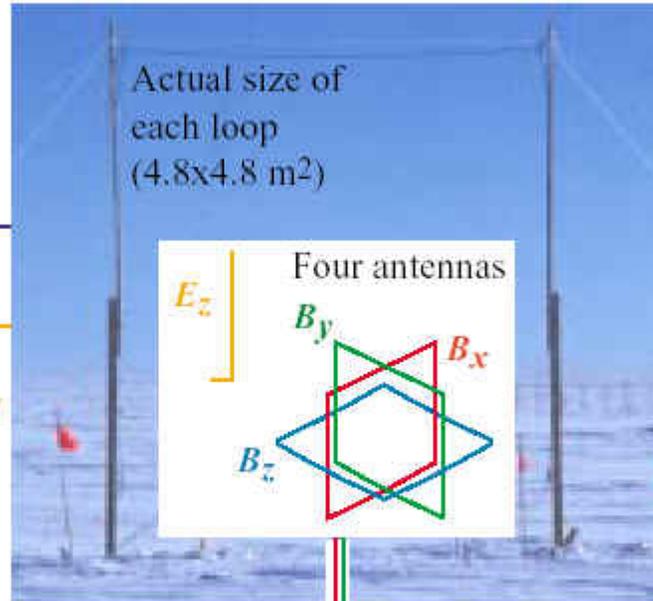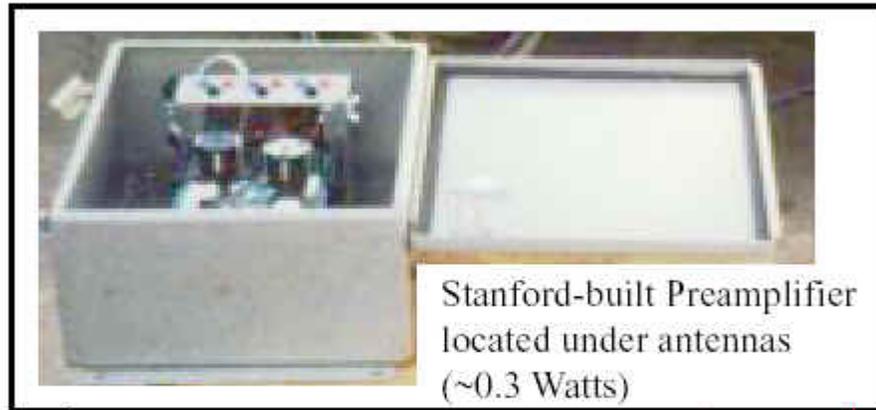
D. THE EQUIPMENT

At each site the ELF/VLF signals from the three orthogonal loop antennas and the vertical whip   antenna are fed into a four channel preamplifier box. The 4 outputs from the preamplifier are sent to a Stanford-built 4 channel presampling filter and clipper circuit where the signals are broadband filtered to remove high frequency noise and clipped to prevent saturation from impulsive signals (due to lightning discharges). The 4 signals are then fed into a programmable i386-Engine-M processor, which extracts the average variation of each field component over the course of a single cycle of the HAARP heater.
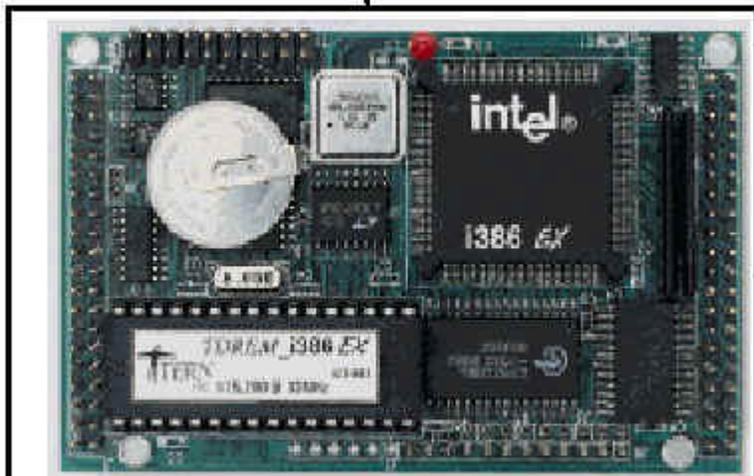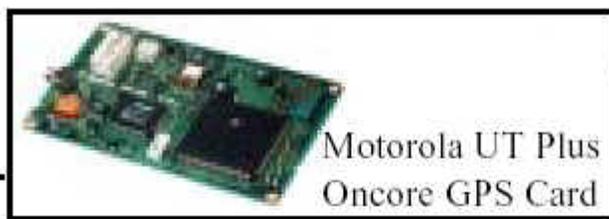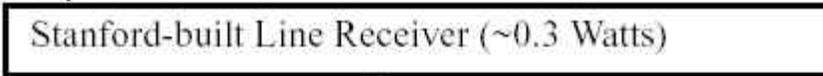
The HAARP transmission and modulation schedules are known *a priori* and the processor is programmed to process the data only during these times and at the specified frequencies, thus minimizing on-time for the processor (to save power) and data volume. The processed data is stored in flash memory cards. The stored data is downloaded (by connecting a portable NoteBook computer) from the memory cards during regular visits to the site. Any changes in recording schedules and frequencies are also downloaded to the programmable processor during these regular site visits.

The preamplifier is a wideband instrument (300 Hz to 90 kHz) with high linear dynamic range (~100 dB) and is similar in design to Stanford-built systems used worldwide for highly sensitive ELF/VLF measurements. For the interferometric measurement proposed here, the sampling rate of the i386 processor will typically be set at 10 kHz, providing the ability to measure signals in the frequency range of 300 Hz to 4 kHz. The processor will carry out ?on-board? analysis of the data as follows by partitioning data into sections of 1 second duration, and in each section determining the average variation of the field component over the course of a single cycle of the HAARP heater through a superposed epoch analysis.

The information concerning this average field variation will then be stored in flash memory. This procedure markedly improves the signal-to-noise ratio by which the field components can be determined and also greatly reduces the amount of data that must be subsequently stored.

B_z Signal

E_z signal

B_y Signal

B_x Signal

Actual size of each loop (4.8x4.8 m²)

Four antennas

E_z

B_y

B_x

B_z

Stanford-built Preamplifier located under antennas (~0.3 Watts)

~500 ft coaxial cable conveys power to preamplifier and relays wideband pre-amplified analog signal back to the i386 processor

Stanford-built Line Receiver (~0.3 Watts)

Motorola UT Plus Oncore GPS Card

Oncore GPS Antenna

Hawker Cyclon J-cell Batteries 8 amp-hr −50°C

i386-Engine-M, 33 MHz 32-bit Processor
100 kHz 16-bit A/D, 512 KB 16-bit EEPROM
Programmable in C/C++, 8-channel multiplexer

Fig. 3. System diagram of one of the nine identical ELF/VLF receivers constituting the proposed inteferometer array. At each site, the ELF/VLF signals from the 3 orthogonal loop antennas and the vertical whip antenna are fed into a Stanford-built 4 channel preamplifier box. The 4 outputs from the preamplifier are sent to a Stanford-built 4 channel line receiver where the signals are broadband filtered to remove high frequency noise and clipped to prevent saturation from impulsive signals (due to lightning discharges). The 4 signals are then fed into a programmable i386-Engine-M processor, which extracts the average variation of each field component over the course of a single cycle of the HAARP heater. The HAARP transmission and modulation schedules are known a priori and the processor is programmed to process the data only during these times and at the specified frequencies, thus minimizing on-time for the processor (to save power) and data volume. The processed data is stored in flash memory cards. The stored data is downloaded (by connecting a portable NoteBook computer) from the memory cards during regular visits to the site. Any changes in recording schedules and frequencies are also downloaded to the programmable processor during these regular site visits.

Logistics and General Operational Procedure

The logistics of the field deployment and use of the proposed ELF/VLF interferometer is envisioned to involve the following steps:

1) Identify nine sites that are electromagnetically quiet (away from power lines) and accessible by road (with car or snowmobile).

2) Visit each site and deploy the ELF/VLF antennas (see Figure 3). This deployment could be semi-permanent, and can be done in advance to save time.

3) Visit each site (this could also be done durign the previous visit) and deploy the system shown in Figure 3, except for batteries.

4) At this point, the ELF/VLF interferometer is in place and ready for measurement of HAARP signals. One day before the start of a HAARP experimental campaign, visit each site and connect the batteries.

5) During the experimental campaign, visit each site once every two days (40-hours; see subsection on Data Storage below) to download data from Flash Memory cards, by connecting them to the poratble NoteBook computer. Downloads of new recording schedules (based on new planned HAARP transmission schedules) into the i386 processor EEPROMare also done in these visits.

6) Visit each site once every five days (see subsection on Batteries) to replace batteries. Items (5) and (6) above will be continued until the end of the experimental campaign.

Stanford-built Preamplifier and Line Receiver

The Stanford-built preamplifier and line receivers are very similar in design to those previously constructed by Stanford University and currently in use at many sites worldwide. These systems have operated successfully in each case and planned goals were uniformly achieved. Thus, the construction of nine such units for the proposed ELF/VLF interferometer poses no schedule, cost, or performance risk. In past applications, the analog outputs from these units would be fed into an A/D board connected to a Pentium computer, with the digitized broadband signals recorded on hard disk and ultimately on CD-ROMs or digital tapes. The primary difference between the new systems proposed here and the previous systems is the fact that a low-power procesor (i386) is used instead of the Pentium computer and data is stored on Flash Memory cards instead of CD-ROMs, both features being necessary to facilitate battery-powered operation.

In general, it is important to note that line drivers and line receivers are required to drive (i.e., power is sent to the preamplifier from the line receiver) and receive (preamplified signal transmitted back to the line receiver) signals off on long lines. These units provide for correct cable termnation, common mode rejection, power-from-signal isolation, clipping to prevent saturation (due to impulsive signals produced by lightning discharges) and other important signal conditioning. When a wire of any length is used for signals of large dynamic range and significant bandwidth (in this connection ELF/VLF is extrememly wide bandwidth

compared to most things, covering, usually, three decades (30 Hz to 30 kHz) of frequency) it is necessary to have special terminations at both the send and receive ends.
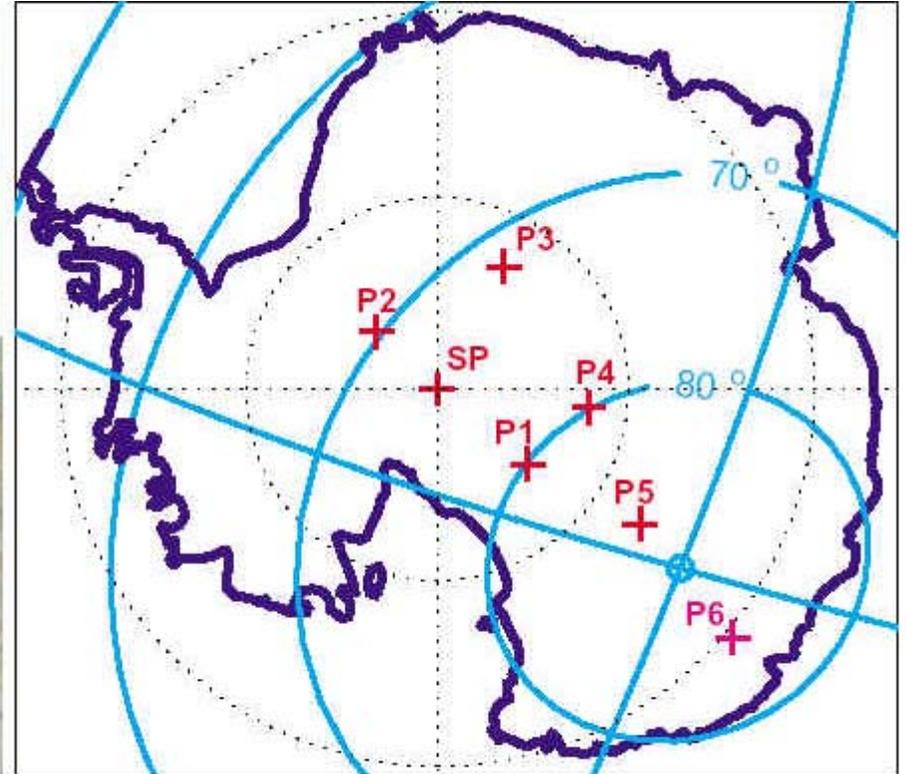
Fig. 4. Stanford ELF/VLF receivers at unmanned automatic geophysical observatory sites. This system, currently operational at five different remote high latitude Antarctic sites is currently deployed at the AGO sites P1, P2, P3,P4, and P5. It consists of a magnetic loop antenna (either a 1.7x1.7m or 4.9x4.9m square ? both shown in the photo above) connected to a preamplifier (grey box with sealed lid shown in lower left) buried immediately underneath, which is powered by and sends data over a ~500 ft coaxial cable (shown rolled up) to the station (shown in upper left), in which resides the main receiver unit (the box with the blue front panel) consisting of a line receiver, various fixed band filter channels, and a broadband snapshot system, as depicted in the block diagram. This ?low power? ELF/VLF system specially designed for unmanned sites with limited power nevertheless consumes ~6 to 7 W, depending on operational modes. The broadband snapshot system in these units (the upper left corner of blue box) has recently been redesigned to utilize the programmable i386-Engine-M processor, which also forms the basis for the individual elements of the proposed ELF/VLF interferometer system (see Figure 3).

i386-Engine-M Processor

The use of the programmable i386 processor also does not pose any risk since Stanford University instruments currently located at unmanned automatic geophysical observatories in Antarctica (see Figure 3) have recently been redesigned to use this processor for capturing wideband snapshots of ELF/VLF activity. As a result, expertise in the use and programming of this particular card for processing analog outputs from preamplifier systems already resides in our research group. The graduate student funded under the proposed program will take advantage of this expertise and will be responsible for programming the software interfaces for flexible use of the i386 processor for extraction of ELF/VLF waveforms at specific times and frequencies during which modulated heater transmissions will be carried out with the HAARP facility.

In terms of our application the i386 processor has the following key features:

Low power consumption: 1.9 Watts in normal operation, and 0.15 Watts in sleep mode. 512-KB 16-bit EEPROM, programmable in C/C++, with quick debugging/testing. 512-KB 16-bit SRAM, with memory expansion board available. 100 kHz 16-bit A/D, with

8-channel multiplexer.

These features allow for minimal power consumption, especially in view of the fact that the processor will need to be ON only during specified (a priori) periods of HAARP transmission/ modulation, and can be in the SLEEP mode at other times. On average, we expect the duty cycle of HAARP transmissions in any given targeted hour to be no more than 30-seconds every 5-minutes, which means that the processor can operate at an *average* power draw level of ~0.3 Watts. At other times, when no HAARP transmissions are made, the system will SLEEP while consuming only ~0.15 Watts.

Stable Time and Frequency Reference

The proposed VLF receiver incorporates a compact GPS receiver card as the source of a stable time and frequency reference. The power and size of GPS receivers has been shrinking rapidly, and the Motorola UT Plus Oncore card we propose to use operates at a power level of ~0.9 Watts. At first, this might seem to be a significant power draw, compared to the preamp/line receiver and the i386 systems. However, it should be noted that the ~1 *u*sec time resolution needed in an ELF/VLF receiver (note that the maximum bandwidth proposed is 100 kHz so that 1 *u*sec resolution is well enough) can be realized by using the GPS receiver only occasionally, for example once or twice per day, to synchronize a thermally isolated crystal resonator which is then the source for a timing generator and frequency reference. A thermally isolated, good quality crystal resonator has an Allen Deviation of typically better than 10-10, for 1000 to, 10,000 sec, which is about ~1 *u*sec/day. The drift due to aging is larger, about ~10 usec/day.

By synchronizing to GPS once or twice per day, the effects of drift and variation could easily be compensated to the precision needed by the ELF/VLF receiver. GPS satellite lock is achieved (with the Motorola UT Encore card) generally in at most ~4 minutes, so that the duty cycle of the GPS receiver would be 4 minutes every 12 hours, so that a ~0.9 W GPS card would only consume a negligible average power of only ~5 mW.

Data Storage on Flash Memory

The technology in FLASH memory has been leapfrogging its capacities with no sign of slowing down. Present commercially available memories have up to 190 Mbyte capacities, so that a few of these chips would have the capacity to store 1 Gbyte of data. The great advantage of FLASH memory is retention at zero power. The power used by these memories in writing to them is dependent on data rates, so that for the small few kHz bandwidths of ELF/VLF applications only ~1 mW is needed. For our application, we propose to use two Sandisk 160 MB flash memory cards at each site, for a total storage capacity of 320 MB. Within a few months, and certainly by program start (1 April 2000) we expect at least twice as much capacity to be available at the same cost.

The data storage requirements are obviously determined by the bandwidth and duty cycle of operation. As a benchmark, 10 kHz sampling rate at 16-bits allows for ~4 kHz bandwith and produces ~20 kBytes/s. At that rate, 320 MB of storage allows for continuous recordings of a single waveform for ~5.3 hours.

In practice, however, our expected duty cycle for HAARP transmissions in any given targeted hour will be no more than 30-seconds every 5-minutes (i.e., ~10%), so that 320 MB storage allows recordings of a single HAARP-induced waveform for ~53 hours, or more than two 24-hour days. With four channels (Bx, By, Bz, and Ez), and noting that typically HAARP operations will be conducted for periods no longer than ~8 hours/day, we can record 4-channels at 4 kHz bandwidth during HAARP transmissions (30-seconds every 5-minute, for 8-hours/day) for a period of ~40 hours. In view of the overall logistical approach described above, and with the distance between sites of ~70 km (see Figure 2), this provides ample time for visiting the sites, to download flash memories and replace batteries (if needed; see below).

The above data volume estimates are in fact quite conservative, and assume that the raw 16-bit waveforms of signalswould be retained with full 4 kHz bandwidth. The actual data requirements are likely be substantially lower due to the facts that:

The processor can carry out ?on-board? analysis of the data by partitioning data into sections of 1 second duration, and in each section determining the average variation of the field component over the course of a single cycle of the HAARP heater through a superposed epoch analysis. Only the information concerning this average field variation (rather than the full waveform) will have to be stored in flash memory. This procedure markedly improves the signal-to-noise ratio by which the field components can be determined and also greatly reduces the amount of data that must be subsequently stored. In cases where data volume is not a limitation, full waveforms can be retained and the superposed epoch procedure can be carried out after the data is extracted from Flash Memory.

In general, HAARP transmission schedule and modulatioin frequencies will be known in advance so that the waveform needs to be captured only in a narrow band (e.g., 400 Hz) centered around the ELF/VLF frequency used (e.g., 3 kHz), rather than the full 4 KHz bandwidth. This approach would relax data storage requirements by a factor of ~10.

Batteries

Based on the above discussion, the total average power consumption of each of the nine ELF/VLF interferometer elements is as follows:

Component Duty Cycle Average Power Consumption

Stanford-built Preamplifier 100% 0.3 Watts

Stanford-built Line Receiver 100% 0.3 Watts

i386-Engine-M Processor 30-s per 5-mins 0.3 Watts

Motorola Oncore GPS Card 4-min per 12-hrs 0.005 Watts

TOTAL 0.95 Watts

With a total continuous power consumption of only ~1Watt, the proposed ELF/VLF receiver system can be ideally powered by batteries. For this purpose, we propose to use batteries produced by Hawker, Inc., which are currently used in remote regions such as Antarctica. Our preliminary investigation indicates that their Cyclon series of the Hawker batteries works down to -65. C. To supply ~1 Watt for 24-hours at 4 Volts, we need ~6 amp-hours. The Hawker J-cell specifications, in the Cyclon series, is 8 amp-hours, at 2 V, in an approximately 5 cm diameter, 14 cm high, rigid plastic container that weighs 840 gm. For our purposes, we can connect two of these in series and then five such pairs in parallel to provide 30 amp-hours at 4 Volts, or 5-days of continuous power. The batteries would then weigh~8.4 kg, and would still be relatively easy to handle.

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Fig. 1. Schematic representation of the nine element ENIACarray proposed for the HAARP facility. The basic configuration is that of a cross with perpendicular arms. At each site the 4 channel VLF/ELF receiving system measures receiving system measures the signals on 3 orthogonal loop antennas and one vertical electric antenna. For clarity in the figure, only two loop antennas are shown at each site. The spacing between each site is ~70 km. The source region where the HF modulated auroral electrojet currents are located is in the 70-120 km altitude range. (Figure 1 on Page 6)

Last Updated: June 2001.