

HAARP

HF ACTIVE AURORAL RESEARCH PROGRAM

JOINT SERVICES PROGRAM PLANS AND ACTIVITIES

**AIR FORCE
GEOPHYSICS LABORATORY**

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HAARP

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HF ACTIVE AURORAL RESEARCH PROGRAM (HAARP)

EXECUTIVE SUMMARY

As described in the accompanying report, the HF Active Auroral Ionospheric Research Program (HAARP) is especially attractive in that it will insure that research in an emerging, revolutionary, technology area will be focussed towards identifying and exploiting techniques to greatly enhance C3 capabilities. The heart of the program will be the development of a unique high frequency (HF) ionospheric heating capability to conduct the pioneering experiments required under the program.

Potential Applications

An exciting and challenging aspect of ionospheric enhancement is its potential to control ionospheric processes in such a way as to greatly improve the performance of C3 systems. A key goal of the program is the identification and investigation of those ionospheric processes and phenomena that can be exploited for DoD purposes, such as those outlined below.

Generation of ELF waves in the 70-150 Hz band to provide communications to deeply submerged submarines. A program to develop efficient ELF generation techniques is planned under the DoD ionospheric enhancement program.

Geophysical probing to identify and characterize natural ionospheric processes that limit the performance of C3 systems, so that techniques can be developed to mitigate or control them.

Generation of ionospheric lenses to focus large amounts of HF energy at high altitudes in the ionosphere, thus providing a means for triggering ionospheric processes that potentially could be exploited for DoD purposes.

Electron acceleration for the generation of IR and other optical emissions, and to create additional ionization in selected regions of the ionosphere that could be used to control radio wave propagation properties.

Generation of geomagnetic-field aligned ionization to control the reflection, scattering properties of radio waves.

Oblique heating to produce effects on radio wave propagation at great distances from a HF heater, thus broadening the potential military applications of ionospheric enhancement technology.

Generation of ionization layers below 90 km to provide radio wave reflectors ("mirrors") which can be exploited for long range, over-the-horizon, HF/VHF/UHF surveillance purposes, including the detection of cruise missiles and other low observables.

Desired HF Heater Characteristics

A new, unique, HF heating facility is required to address the broad range of issues identified above. However, in order to have a useful facility at various stages of its development, it is important that the heater be constructed in a modular manner, such that its effective-radiated-power can be increased in an efficient, cost effective manner as resources become available.

Effective-Radiated-Powers (ERP) in Excess of 1 Gigawatt

One gigawatt of effective-radiated-power represents an important threshold power level, over which significant wave generation and electron acceleration efficiencies can be achieved, and other significant heating effects can be expected.

Broad HF Frequency Range

The desired heater would have a frequency range from around 1 MHz to about 15 MHz, thereby allowing a wide range of ionospheric processes to be investigated.

Scanning Capabilities

A heater that has rapid scanning capabilities is very desirable to enlarge the size of heated regions in the ionosphere.

Continuous Wave (CW) and Pulse Modes of Operation

Flexibility in choosing heating modes of operation will allow a wider variety of ionospheric enhancement techniques and issues to be addressed.

Polarization

The facility should permit both X and O polarization in order to study ionospheric processes over a range of altitudes.

Agility in Changing Heater Parameters

The ability to quickly change the heater parameters is important for addressing such issues as enlarging the size of the heated region in the ionosphere and the development of techniques to insure that the energy densities desired in the ionosphere can be delivered without self-limiting effects setting-in.

HF Heating Diagnostics

In order to understand natural ionospheric processes as well as those induced through active modification of the ionosphere, adequate instrumentation is required to measure a wide range of ionospheric parameters on the appropriate temporal and spatial scales. A key diagnostic for these measurements will be an incoherent scatter radar facility to provide the means to monitor

such background plasma conditions as electron densities, electron and ion temperatures, and electric fields, all as a function of altitude. The incoherent scatter radar facility, envisioned to complement the planned new HF heater, is currently being funded in a separate DoD program, as part of an upgrade at the Poker Flat rocket range, in Alaska.

For ELF generation experiments, the diagnostics complement would include a chain of ELF receivers, a digital HF ionosonde, a magnetometer chain, photometers, a VLF sounder, and a VHF riometer. In other experiments, in situ measurements of the heated region in the ionosphere, via rocket-borne instrumentation, would also be very desirable. Other diagnostics to be employed, depending on the nature of the ionospheric modifications being implemented, will include HF receivers, HF/VHF radars, optical imagers, and scintillation observations.

HF Heater Location

One of the major issues to be addressed under the program is the generation of ELF waves in the ionosphere by HF heating. This requires locating the heater where there are strong ionospheric currents, either at an equatorial location or a high latitude (auroral) location. Additional factors to be considered in locating the heater include other technical (research) needs and requirements, environmental issues, future expansion capabilities (real estate), infrastructure, and considerations of the availability and location of diagnostics. The location of the new HF heating facility is planned for Alaska, relatively near to a new incoherent scatter facility, already planned for the Poker Flat rocket range under a separate DoD program. In addition, it is desirable that the HF heater be located to permit rocket probe instrumentation to be flown into the heated region of the ionosphere. The exact location in Alaska for the proposed new HF heating facility has not yet been determined.

Estimated Cost of the New HF Heating Facility

It is estimated that eight to ten million dollars (\$8-10M) will provide a new facility with an effective-radiated-power of approximately that of the current DoD facility (HIPAS), but with considerable improvement in frequency tunability and antenna-beam steering capability. The facility will be of modular design to permit efficient and cost-effective upgrades in power as additional funds become available. The desired (world-class) facility, having the broad capabilities and flexibility described above, will cost on the order of twenty-five to thirty million dollars (\$25-30M).

Program Participants

The program will be jointly managed by the Navy and the Air Force. However, because of the wide variety of issues to be addressed, active participation of other government agencies, universities, and private contractors is envisioned.

HF ACTIVE AURORAL RESEARCH PROGRAM

The DoD HF Active Auroral Research Program (HAARP) is especially attractive in that it will insure that research in an emerging, revolutionary, technology area will be focussed towards identifying and exploiting techniques to greatly enhance C3 capabilities. The heart of the program will be the development of a unique ionospheric heating capability to conduct the pioneering experiments required to adequately assess the potential for exploiting ionospheric enhancement technology for DoD purposes. As outlined below, such a research facility will provide the means for investigating the creation, maintenance, and control of a large number and wide variety of ionospheric processes that, if exploited, could provide significant operational capabilities and advantages over conventional C3 systems. The research to be conducted in the program will include basic, exploratory, and applied efforts.

1. INTRODUCTION

DoD agencies already have on-going efforts in the broad area of active ionospheric experiments, including ionospheric enhancements. These include both space- and ground-based approaches. The space-based efforts include chemical releases (e.g., the Air Force's Brazilian Ionospheric Modification Experiment, BIME; the Navy's RED AIR program; and multi-agency participation in the Combined Release and Radiation Effects Satellite, CRRES). In addition other, planned, programs will employ particle beams and accelerators aboard rockets (e.g., EXCEDE and CHARGE IV), and shuttle- or satellite-borne RF transmitters (e.g., WISD and ACTIVE).

Ground-based techniques employ the use of high power, radio frequency (RF), transmitters (so-called "heaters") to provide the energy in the ionosphere that causes it to be altered, or enhanced. The use of such heaters has a number of advantages over space-based approaches. These include the possibility of repeating experiments under controlled conditions, and the capability of conducting a wide variety of experiments using the same facility. For example, depending on the RF frequency and effective radiated power (ERP) used, different regions of the atmosphere and the ionosphere can be affected to produce a number of practical effects, as illustrated in Table 1.

Because of the large number and wide variety of those effects, and because many of them have the potential to be exploited for important C3 applications, the program is focussed on developing a robust program in the area of ground-based, high power RF heating of the ionosphere.

Table 1. Summary of High Power RF Heating Effects.

Ionospheric Region	Altitude (km)	Perturbing Frequency	Practical Effects
-	20 - 70	1 - 100 MHz	- Electron density production
D	70 - 95	10 KHz - 30 MHz	- Pulsation to VLF generation - Increase electron energy - Nonlinear interactions - HF absorption - HF self-absorption
E	100 - 110	5 - 10 MHz	- Field aligned ionization (FAI) - Increase electron energy - Instability formation - VHF refraction
F	250 - 350	5 - 30 MHz	- HF-VHF-UHF refraction and backscatter - Increase electron energy - Field aligned ionization - Optical emissions - Plasma emissions - Instability formation
<p>Note 1. RF generation may be enhanced at certain geomagnetic latitudes.</p> <p>Note 2. Some effects may persist up to tens of minutes after the perturbing transmitter ceases operation.</p>			

To date, most DoD ionospheric heating experiments have been conducted to gain better understanding of ionospheric processes; i.e., they have been used as geophysical-probes. In this, one perturbs the ionosphere, then studies how it responds to the disturbance and how it ultimately recovers back to ambient conditions. The use of ionospheric enhancement to simulate ionospheric processes and phenomena is a more recent development, made possible by the increasing knowledge being obtained on how they evolve naturally. By simulating natural ionospheric effects it is possible to assess how they may affect the performance of DoD systems. From a DoD point of view, however, the most exciting and challenging aspect of ionospheric enhancement is its potential to control ionospheric processes in such a way as to greatly enhance the performance of C3 systems (or, to deny accessibility to an adversary). This is a revolutionary concept in that, rather than accepting the limitations imposed on operational systems by the natural ionosphere, it envisions seizing control of the propagation medium and shaping it to insure that a desired system capability can be achieved. A key ingredient of the DoD program is the goal of identifying and investigating those ionospheric processes and phenomena that can be exploited for such purposes.

2. POTENTIAL APPLICATIONS

A brief description of a variety of potential applications of ionospheric-enhancement technology that could be addressed in the DoD program are outlined below.

2.1. Geophysical Probing

The use of ionospheric heating to investigate natural ionospheric processes is a traditional one. Such research is still required in order to develop models of the ionosphere that can be used to reliably predict the performance of C3 systems, under both normal and disturbed ionospheric conditions. This aspect of ionospheric enhancement research is always available to the investigator; in effect, as a by-product of any ionospheric enhancement research, even if it is driven by specific system applications goals, such as discussed below.

2.2. Generation of ELF/VLF Waves

A number of critical DoD communications systems rely on the use of ELF/VLF (30 Hz-30 kHz) radio waves. These include those associated with the Minimum Essential Emergency Communications Network (MEECN) and those used to disseminate messages to submerged submarines. In the latter, frequencies in the 70-150 Hz range are especially attractive, but difficult to generate efficiently with ground-based antenna systems. The potential exists for generating such waves by ground-based heating of the ionosphere. The heater is used to modulate the conductivity of the lower ionosphere, which in turn modulates ionospheric currents. This modulated current, in effect, produces a virtual antenna in the ionosphere for the radiation of radio waves. The technique has already been used to generate ELF/VLF signals at a number of vertical HF heating facilities in the West and the Soviet Union. To date, however, these efforts have been confined to essentially basic research studies, and few attempts have been made to investigate ways to increase the efficiency of such ELF/VLF generation to make it attractive for communications applications. In this regard, heater generated ELF would be attractive if it could provide significantly stronger signals than those available from the Navy's existing antenna systems in Wisconsin and Michigan. Recent theoretical research suggests that this may be possible, provided the appropriate HF heating facility was available. Because this area of research appears especially promising, and because of existing DoD requirements for ELF and VLF, it is already a primary driver of the proposed research program.

In addition to its potential application to long range, survivable, DoD communications there is another potentially attractive application of strong ELF/VLF waves generated in the

ionosphere by ground-based heaters. It is known that ELF/VLF signals generated by lightning strokes propagate through the ionosphere and interact with charged particles trapped along geomagnetic field lines, causing them, from time-to-time, to precipitate into the lower ionosphere. If such processes could be reliably controlled, it would be possible to develop techniques to deplete selected regions of the radiation belts of particles, for short periods, thus allowing satellites to operate within them without harm to their electronic components. Many of the critical issues associated with this concept of radiation-belt control could be investigated as part of the DoD program.

2.3. Generation of Ionospheric Holes/Lens

It is well known that HF heating produces local depletions ("holes") of electrons, thus altering the refractive properties of the ionosphere. This in turn affects the propagation of radio waves passing through that region. If techniques could be developed to exploit this phenomena in such a way as to create an artificial lens, it should be possible to use the lens as a focus to deliver much larger amounts of HF energy to higher altitudes in the ionosphere than is presently possible, thus opening-up the way for triggering new ionospheric processes and phenomena that potentially could be exploited for DoD purposes. In fact, the general issue of developing techniques to insure that large energy densities can be made available at selected regions in the ionosphere, from ground-based heaters, is an important one that must be addressed in the DoD program.

2.4. Electron Acceleration

If sufficient energy densities are available in the ionosphere it should be possible to accelerate electrons to high energies, ranging from a few eV to even KeV and MeV levels. Such a capability would provide the means for a number of potentially interesting DoD applications.

Electrons in the ionosphere accelerated to a few eV would generate a variety of IR and optical emissions. Observation and quantification of them would provide data on the concentration of minor constituents in the lower ionosphere and upper atmosphere, which cannot be obtained using conventional probing techniques. Such data would be important for the development of reliable models of the lower ionosphere which are ultimately used in developing radio-wave propagation prediction techniques. In addition, heater generated IR/optical emissions over selected areas of the earth could potentially be used to blind space-based military sensors.

Electrons accelerated to energy levels in the 14-20 eV range would produce new ionization in the ionosphere, via collisions with neutral particles. This suggests that it may be possible to

"condition" the ionosphere so that it would support HF propagation during periods when the natural ionosphere was especially weak. This could potentially be exploited for long range (OTH) HF communication/surveillance purposes.

Finally, the use of an HF heater to accelerate electrons to KeV or MeV energy levels could be used, in conjunction with satellite sensor measurements, for controlled investigations of the effects of high energy electrons on space platforms. There already is indication that high power transmitters on space-craft accelerate electrons in space to such high energy levels, and that those charged particles can impact on the space-craft with harmful effects. The processes which trigger such phenomena and the development of techniques to avoid or mitigate them could be investigated as part of the DoD program.

2.5. Generation of Field Aligned Ionization

HF heating of the ionosphere produces patches of ionization that are aligned with the geomagnetic field, thus producing scattering centers for RF waves. Natural processes also produce such scatterers, as evidenced by the scintillations observed on satellite-to-ground links in the equatorial and high latitude regions. The use of a HF heater to generate such scatterers would provide a controlled way to investigate the natural physical processes that produce them, and could lead conceivably to the development of techniques to predict their natural occurrence, their structure and persistence, and (ultimately) the degree to which they would affect DoD systems.

One interesting potential application of heater induced field-aligned ionization is already a part of an on-going DoD (Air Force/RADC) research program, Ducted HF Propagation. It is known that there are high altitude ducts in the E- and F-regions of the ionosphere (110-250 km altitude range) that can support round-the-world HF propagation. Normally, however, geometrical considerations show that it is not possible to gain access to these ducts from ground-based HF transmitters. From time-to-time, however, natural gradients in the ionosphere (often associated with the day-night terminator) provide a means for scattering such HF signals into the elevated ducts. If access to such ducts could be done reliably, interesting very long range HF communications and surveillance applications can be envisioned. For example, survivable HF propagation above nuclear disturbed ionospheric regions would be possible; or, the very long range detection of missiles, breaking through the ionosphere on their way to targets, could be achieved. The use of an HF heater to produce field-aligned ionization in a controlled (reliable) way has been suggested as a means for developing such concepts, and will be tested in an up-coming satellite experiment to be conducted in during FY92. The experiment calls for a heater in Alaska to generate field-aligned ionization that will scatter HF signals from a nearby transmitter into elevated ducts. A

satellite receiver will record the signals to provide data on the efficiency of the field-aligned ionization as an RF scatterer, as well as the location, persistence, and HF propagation properties associated with the elevated ducts.

2.6. Oblique HF Heating

Most RF heating experiments being conducted in the West and in the Soviet Union employ vertically propagating HF waves. As such the region of the ionosphere that is affected is directly above the heater. For broader military applications, the potential for significantly altering regions of the ionosphere at relatively great distances (1000 km or more) from a heater is very desirable. This involves the concept of oblique heating. The subject takes on added importance in that higher and higher effective radiated powers are being projected for future HF communication and surveillance systems. The potential for those systems to inadvertently modify the ionosphere, thereby producing self-limiting effects, is a real one that should be investigated. In addition, the vulnerability of HF systems to unwanted effects produced by other, high power transmitters (friend or foe) should be addressed.

2.7. Generation of Ionization Layers Below 90 Km

The use of very high power RF heaters to accelerate electrons to 14-20 eV opens the way for the creation of substantial layers of ionization at altitudes where normally there are very few electrons. This concept already has been the subject of investigations by the Air Force (Geophysics Lab), the Navy (NRL), and DARPA. The Air Force, in particular, has carried the concept, termed Artificial Ionospheric Mirror (AIM), to the point of demonstrating its technical viability and proposing a new initiative to conduct proof-of-concepts experiments. The RF heater(s) being considered for AIM are in the 400 MHz-3 GHz range, much higher than the HF frequencies (1.5 MHz-15 MHz) suitable for investigating the other topics discussed in this summary. As such, the DoD program (HAARP) will not be directly involved with AIM-related ionospheric enhancement efforts.

3. IONOSPHERIC ISSUES ASSOCIATED WITH HIGH POWER RF HEATING

As illustrated in Figure 1, as the HF power delivered to the ionosphere is continuously increased the dissipative process dominating the response of the geophysical environment changes discontinuously, producing a variety of ionospheric effects that require investigation. Those anticipated at very high power levels (but not yet available in the West from existing HF heaters) are especially interesting from the point of view of potential applications for DoD purposes.

3.1. Thresholds of Ionospheric Effects

At very modest HF powers, two RF waves propagating through a common volume of ionosphere will experience cross-modulation, a superposition of the amplitude modulation of one RF wave upon another. At HF effective radiated powers available to the West, measurable bulk electron and ion gas heating is achieved, electromagnetic radiation (at frequencies other than transmitted) is stimulated, and various parametric instabilities are excited in the plasma. These include those which structure the plasma so that it scatters RF energy of a wide range of wavelengths.

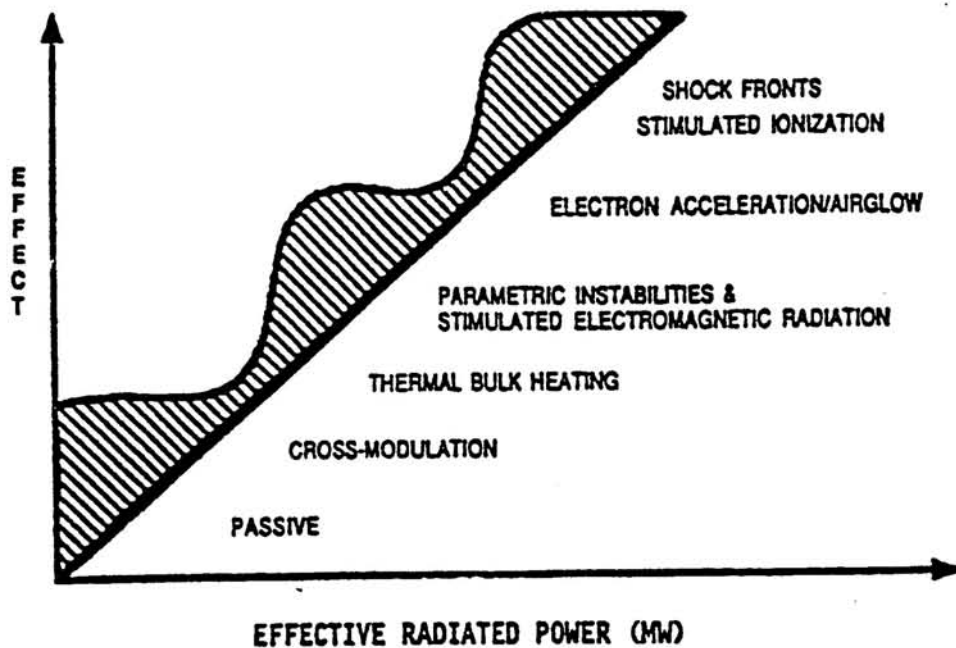


Figure 1. Thresholds of Ionospheric Effects as a Function of Heater ERP

There is also evidence in the West that at peak power operation parametric instabilities begin to saturate, and at the same time modest amounts of energy begin to go into electron acceleration, resulting in modest levels of electron-impact excited airglow. This suggests that at the highest HF powers available in the West, the instabilities commonly studied are approaching their maximum RF energy dissipative capability, beyond which the plasma processes will "runaway" until the next limiting process is reached. The airglow enhancements strongly suggest that this next process then involves wave-particle interactions and electron acceleration.

The Soviets, operating at higher powers than the West, now have claimed significant stimulated ionization by electron-impact ionization. The claim is that HF energy, via wave-particle interaction, accelerates ionospheric electrons to energies well in excess of 20 electron volts (eV) so that they will ionize neutral atmospheric particles with which they collide. Given that the Soviet HF facilities are several times more powerful than the Western facilities at comparable mid-latitudes, and given that the latter appear to be on a threshold of a new "wave-particle" regime of phenomena, it is believed that the Soviets have crossed that threshold and are exploring a regime of phenomena still unavailable for study or application in the West.

The Max Planck HF facility at Tromso, Norway, possesses power comparable to that of the Soviet high power heaters, yet has never produced airglow enhancements commonly produced by US HF facilities at lower HF power, but at lower latitudes. This is attributed to a present inadequate understanding of how to make the auroral latitude ionosphere sustain the conditions required to allow the particle acceleration process to dominate, conditions which are achieved in the (more stable) mid-latitude regions.

What is clear, is that at the gigawatt and above effective radiated power, energy density deposited in limited regions of the ionosphere can drastically alter its thermal, refractive, scattering, and emission character over a very wide electromagnetic (radio frequency) and optical spectrum. What is needed is the knowledge of how to select desired effects and suppress undesired ones. At present levels of understanding, this can only be done by: identifying and understanding what basic processes are involved, and how they interplay. This can only be done if driven by a strong experimental program steered by tight coupling to the interactive cycle of developing theory-model-experimental test..

3.2. General Ionospheric Issues

When a high-power HF radio wave reflects in the ionosphere, a variety of instability processes are triggered. At early times (less than 200 ms) following HF turn-on, microinstabilities driven by ponderomotive forces are excited over a large (1-10 km) altitude interval extending downwards from the point of HF reflection to the region of the upper hybrid resonance. However, at very early times (less than 50 ms) and at late times (greater than 10 s) the strongest HF-induced Langmuir turbulence appears to occur in the vicinity of HF reflection. The Langmuir turbulence also gives rise to a population of accelerated electrons. Over time scales of 100's of milliseconds and longer, the microinstabilities must coexist with other instabilities that are either triggered or directly driven by the HF-induced turbulence. Some of these instabilities are believed to be explosive in character. The dissipation of the Langmuir

turbulence is thought to give rise to meter-scale irregularities through several different instability routes. Finally, over time scales of tens of seconds and longer, several thermally driven instabilities can be excited which give rise to kilometer-scale ionospheric irregularities. Some of these irregularities are aligned with the geomagnetic field, while others are aligned either along the axis of the HF beam or parallel to the horizontal.

Recently, ionospheric diagnostics of HF modifications have evolved to the point where individual instability processes can be examined in detail. Because of improved diagnostic capabilities, it is now clear that the wave-plasma interactions once thought to be rather simple are in fact rather complex. For example, the latest experimental findings at Arecibo Observatory suggest that plasma processes responsible for the excitation of Langmuir turbulence in the ionosphere are fundamentally different from past treatments based on so-called "weak turbulence theory". This theoretical approach relies on random phase approximations to treat the amplification of linear plasma waves by parametric instabilities. Research in HF ionospheric modification during the period 1970-1986 commonly focussed on parametric instabilities to explain observational results. In contrast, there is increasing experimental evidence that the conventional picture is wrong and that the ionospheric plasma undergoes a highly nonlinear development, culminating in the formation of localized states of strong plasma turbulence. The highly localized state (often referred to as cavitons) consists of high-frequency plasma waves trapped in self-consistent electron density depletions.

It is important to realize that many different instabilities are simultaneously excited in the plasma and that one instability process can greatly influence the development of another. Studies of competition between similar types of instability processes and the interaction between dissimilar wave-plasma interactions are in the earliest stages of development. However, it is clear that the degree to which one instability is excited in the plasma may severely impact a variety of other HF-induced processes through HF-induced pump wave absorption, changes in particle distribution functions, and the disruption of other coherently-driven processes relying on smooth ionospheric electron density gradients. Because the efficiency of many instability processes is dependent on geomagnetic dip angle, the nature of instability competition in the plasma is expected to change with geomagnetic latitude. Indeed, observational results strongly support this notion. Consequently, it may be very difficult to extrapolate the observational results obtained at one geomagnetic latitude to another. Moreover, even at one experimental station, physical phenomena excited by a high-power HF wave is strongly dependent upon background ionospheric conditions. A classic illustration of this point may be found in Arecibo observations made when local electron energy dissipation rates are low. In this case, the ionospheric plasma literally

overheats due to the absence of effective electron thermal loss processes. The large (factor of four) enhancement in electron temperature that accompanies this phenomenon gives rise to a class of instability processes that is completely different from others observed under "normal" conditions where the ionospheric thermal balance is not greatly disrupted.

At ERPs greater than a gigawatt (greater than 90 dBW), ponderomotive forces are no longer small compared to thermal forces. This may qualitatively change the nature of the instability processes in the ionosphere. Experimental research in this area, however, must wait until such powerful ionospheric heaters are developed.

3.3. High Latitude Ionospheric Issues

Radio wave heating of the ionosphere at mid-latitudes (e.g., Arecibo and Platteville) has occurred under conditions where the background ionosphere (prior to turning on the heater) was fairly laminar, stable, fixed, etc. However, at high latitudes (i.e., auroral latitudes such as HIPAS and Tromso) the background ionosphere is a dynamic entity. Even the location of the aurora and the electrojet are changing as a function of latitude, altitude and local time. Moreover, the background E- and F-region ionosphere may not be laminar on scale sizes less than 20 km and less than 100 km, respectively. Rather, there is the possibility of E- and F-region irregularities (with scale sizes from cms to kms) occurring at various times due to (for example) electrojet driven instabilities in the E-region, and spread F or current driven instabilities in the F-region. High energy particles, e.g., from solar flares, may also lead to D-region structuring. In addition, connection to the magnetosphere via the high conductivity along magnetic field lines can play an important role. The theoretical understanding of high latitude ionospheric heating processes has been improving; however, given the dynamic nature of the high latitude ionosphere, it is important to diagnose the background ionosphere prior to the inception of any heating experiments. This diagnostic capability aids in determining long term statistics, as well as real-time parameters. While such diagnostics have been an integral part of the heating experiments at Arecibo and Tromso, HF heating experiments at HIPAS have been severely hampered by a lack of similar diagnostics.

4. DESIRED HF HEATING FACILITY

In order to address the broad range of issues discussed in the previous sections, a new, unique, HF heating facility is required. An outline of the desired capabilities of such a heater, along with diagnostics needed for addressing these issues are given in Table 2.


Technical/ Scientific Issues	Diagnostic	High Power Heater Capability	Geophysical Environment Desired
ELF Generation	ELF Receivers HF/VHF Radars Incoherent Scatter Radar	ELF, VLF Modulation Beam Motion Fast (within $\sim 40^\circ$ BW) ← { Real time measure of rapidly varying ionosph. feedback to heater? } →	At least modest current or $>5\text{mV/m}$ electric field
Electron Acceleration	Incoherent Scatter HF Receiver Optics, Imaging HF/VHF Radars Rocket	Maximum Power Frequency agility 2 Frequency	Smooth Ionosphere < few Rayleigh optical structure Plattville/ Tromso effect
Identification of Instability Processes	Incoherent Scatter Radar, HF Receiver HF/VHF Radar Optics Scintillation	Frequency Agility Steering Agility Multiple Freq./Fast Wide Frequency Range 2.8-15 MHz	Stable
Control of Instability Processes (Select, Mitigate, Exploit)	"	"	Stable for HF Induced Steady for Natural Mitigation
Particle Precipitation (Pitch Angle Scatter)	ELF, VLF Receivers Optics, Imaging HF Phase Sounder Riometer Imager VLF Phase	VLF Modulation 2 Frequency	Radiation Belt Particles ($L=4-6; 1.4$)
F Region Structuring (F Region Scatterers, e.g. Ducting)	Scintillation HF/VHF Radar Optics Incoherent Scatt. Radar	Maximum Power Frequency Agility	Smooth
Oblique	Midpath Diagnostics: HF Sounder Incoh. Scatt. Radar Electric Field End Path Diagnostics HF Receiver		Smooth Stable

Table 2. Desired Heater and Diagnostics Capabilities to Investigate Various Ionospheric Effects.

4.1. Heater Characteristics

The goals for the HF heater are very ambitious. In order to have a useful facility at various stages of its development, it is important that the heater be constructed in a modular manner, such that its effective-radiated-power can be increased in an efficient, cost effective manner as resources become available. Other desired HF heater characteristics are outlined below.

4.1.1. Effective-Radiated-Power (ERP). One gigawatt of effective-radiated-power (90 dBW) represents an important threshold power level, over which significant wave generation and electron acceleration efficiencies can be achieved, and other significant heating effects can be expected. To date, the Soviet Union has built such a powerful HF heater. The highest ERPs achieved by U.S. facilities is about one-fourth of that. Presently, a heater in Norway, operated by the Max Planck Institute in the Federal Republic of Germany, is being reconfigured to provide 1 gigawatt of ERP at a single HF frequency. The HAARP is to ultimately have a HF heater with an ERP well above 1 gigawatt (on the order of 95-100 dBW); in short, the most powerful facility in the world for conducting ionospheric modification research. In achieving this, the heated area in the F-region should have a minimum diameter of at least 50 km, for diagnostic-measurment purposes.

4.1.2. Frequency Range of Operation. The desired heater would have a frequency range from around 1 MHz to about 15 MHz, thereby allowing a wide range of ionospheric processes to be investigated. This incorporates the electron-gyro frequency and would permit operations under all anticipated ionospheric conditions. Multi-frequency operation using different portions of the antenna array is also a desirable feature. Finally, frequency changing on an order of milliseconds is desirable over the bandwidth of the HF transmitting antenna.

4.1.3. Scanning Capabilities. A heater that has scanning capabilities is very desirable in order to enlarge the size of heated regions in the ionosphere. Although a scanning range from vertical to very oblique (about 10 degrees above the horizon) would be desirable, engineering considerations will most likely narrow the scanning range to about 45 degrees from the vertical. The capability of rapidly scanning (microseconds time scale) in any direction, is also very desirable.

4.1.4. Modes of Operation. Flexibility in choosing heating modes of operation, including continuous-wave (CW) and pulsed modes, will allow a wider variety of ionospheric modification techniques and issues to be addressed.

4.1.5. Wave Polarization. The heater should permit both X and O polarizations to be transmitted, in order to study ionospheric processes over a range of altitudes.

4.1.6. Agility in Changing Heater Parameters. The ability to quickly change heater parameters, such as operating frequency, scan angle and direction, power levels, and modulation is important for addressing such issues as enlarging the size of the modified region in the ionosphere and the development of techniques to insure that the energy densities desired in the ionosphere can be delivered from the heater without self-limiting effects setting-in.

4.2. Heating Diagnostics

In order to understand natural ionospheric processes as well as those induced through active modification of the ionosphere, adequate instrumentation is required to measure a wide range of ionospheric parameters on the appropriate temporal and spatial scales.

4.2.1. Incoherent Scatter Radar Facility. A key diagnostic for these measurements will be an incoherent scatter radar facility to provide the means to monitor such background plasma conditions as electron densities, electron and ion temperatures, and electric fields, all as a function of altitude. In addition, the incoherent scatter radar will provide the means for closely examining the generation of plasma turbulence and the acceleration of electrons to high energies in the ionosphere by HF heating. The incoherent scatter radar facility, envisioned to complement the planned new HF heater, is currently being funded in a separate DoD program, as part of an upgrade at the Poker Flat rocket range, in Alaska.

4.2.2. Other Diagnostics. The capability of conducting in situ measurements of the heated region in the ionosphere, via rocket-borne instrumentation, is also very desirable. Other diagnostics to be employed, depending on the specific nature of the HF heating experiments, may include HF receivers for the detection of stimulated electromagnetic emissions from heater induced turbulence in the ionosphere; HF/VHF radars, to determine the amplitudes of short-scale (1-10 m) geomagnetic field-aligned irregularities; optical imagers, to determine the flux and energy spectrum of accelerated electrons and to provide a three-dimensional view of artificially produced airglow in the upper atmosphere; and, scintillation observations, to be used in assessing the impact of HF heating on satellite downlinks and in diagnosing large-scale ionospheric structures.

4.2.3. Additional Diagnostics for ELF Generation Experiments. These could include a chain of ELF receivers to record signal strengths at various distances from the heater; a digital HF ionosonde, to determine background electron density profiles in the E- and F-regions; a magnetometer chain, to observe changes in the earth's magnetic field in order to determine large volume ionospheric currents and electric fields; photometers, to aid in determining ionospheric conductivities and observing precipitating particles; a VLF sounder, to determine changes in the D-region of the ionosphere; and, a riometer, to provide additional data in these regards, especially for disturbed ionospheric conditions.

4.3. HF Heater Location

One of the major issues to be addressed under the program is the generation of ELF waves in the ionosphere by HF heating. This requires locating the heater where there are strong

ionospheric currents, either at an equatorial location or a high latitude (auroral) location. Additional factors to be considered in locating the heater include other technical (research) needs and requirements, environmental issues, future expansion capabilities (real estate), infrastructure, and considerations of the availability and location of diagnostics. The location of the new HF heating facility is planned for Alaska, relatively near to a new incoherent scatter facility, already planned for the Poker Flat rocket range under a separate DoD program. In addition, it is desirable that the HF heater be located to permit rocket probe instrumentation to be flown into the heated region of the ionosphere. The exact location in Alaska for the proposed new HF heating facility has not yet been determined.

4.4. Estimated Cost of the New HF Heating Facility

It is estimated that eight to ten million dollars (\$8-10M) will provide a new HF heating facility with an effective-radiated-power of approximately that of the current DoD facility (HIPAS), but with considerable improvement in frequency tunability and antenna-beam steering capability. The new facility will be of modular design to permit efficient and cost-effective upgrades in power as additional funds become available. The desired (world-class) facility, having the broad capabilities and flexibility described above, will cost on the order of twenty-five to thirty million dollars (\$25-30M).

5. PROGRAM PARTICIPANTS

The program will be jointly managed by the Navy and the Air Force. However, because of the wide variety of issues to be addressed, substantial involvement in the program by other government agencies (DARPA, DNA, NSF, etc.), universities, and private contractors is envisioned.

6. PLANS FOR RESEARCH ON THE GENERATION OF ELF SIGNALS IN THE IONOSPHERE BY MODULATING THE POLAR ELECTROJET

One of the initial objectives of the HF Active Auroral Research Program is the quantitative assessment of the potential of exploiting HF heating techniques to generate ELF signals in the ionosphere that can be used for communications to deeply submerged submarines. In that regard a number of ELF-related ionospheric and operational issues have been considered as part of the HAARP planning and implementation process. These are outlined below.

6.1. Ionospheric Issues as They Relate to ELF Generation

The dynamic role that the background ionosphere can play at high latitudes leads to some basic questions regarding heater-related ionospheric physics (prior to turning on the heater), as it pertains to the generation of ELF/VLF via modulation of the polar electrojet. For example, is enough known about the background "laminar" ionosphere? Given that the dominant ELF-producing heating theories require an electrojet (or at least a perpendicular electric field), what about the statistics of the E-region high latitude electrojet (i.e., location, strength, variability, etc.)? What is the geophysical structure and morphology of the high latitude D-region underneath the electrojet region? Also, what are those statistics for the site(s) that may be considered for a new heating facility? What about the naturally disturbed ionosphere (due to electrojet instabilities, spread F, magnetospheric particle precipitation, etc.) at high latitudes? Will these disturbances affect the ELF generation or propagation? Although most of the above questions are focused on ELF production by high power RF heating of the high latitude ionosphere, knowledge of the background laminar and disturbed ionosphere (the above questions) are important for any physical phenomena produced by heating at high latitudes.

6.1.1. Ionospheric Research Needs. For the background "laminar" ionosphere, data exist for the electrojet current, electric field, etc., over at least one complete solar cycle. However, the data have only been partially unfolded into formats that are useful in helping to assess the viability of reliably generating ELF by HF heating of the lower ionosphere. In addition, more analyses of the data must be done to make it more useful in the planning of future experimental programs, including the consideration of the location(s) of the heating facility that would be used to conduct them. More accurate models of the naturally disturbed ionosphere are needed, as well as better knowledge of the effects of those disturbances on heated regions of the ionosphere and ELF generation (e.g., the effects of geophysical-induced micropulsations on ELF wave phase stability, as seen at times during HIPAS experiments).

6.1.2. Ionospheric Research Recommendations. A relatively near-term solution is to unfold the existing data sets (e.g., data from an Alaskan magnetometer chain, Chatanika radar data and, possibly, Millstone Hill radar data) over a solar cycle (eleven year) period to obtain electrojet statistics. This will produce the location, strength, and variability (probability of occurrence) of the electrojet system and aid in the site location for a potential new facility. Research should be done which will look into the effects of natural disturbances on the heater-related effects one is trying to produce, e.g., effects of micropulsations on ELF phase stability, density depletion effects at F-region altitudes on the absorption of heater energy, the effects of geophysical-induced heat flows on ionospheric heating, etc.

6.2. HF-to-ELF Excitation Efficiency

ELF waves have been generated by modulating low altitude Hall currents using HF transmitters in the USSR, Tromso (Norway), Arecibo (Puerto Rico) and HIPAS (Alaska). However, the HF-to-ELF conversion efficiency is the critical factor in the design and implementation of a practical high power ionospheric ELF system. In a simplified fashion the HF to ELF conversion efficiency depends on:

- (i) Obtaining maximum magnetic dipole moment, $M = IL$, for a fixed HF power; where, I is the amount of the modified-region's current and L the linear dimension of the modified region; and
- (ii) The internal structure and orientation of the magnetic dipole moment be such as to have the optimum coupling efficiency to the earth-ionosphere waveguide.

Both factors have different physics scaling which result in distinct HF transmitter requirements, depending on whether the HF power absorption occurs at an altitude below 75-80 km or above it. The transition altitude of approximately 80 km corresponds to the altitude at which the electron neutral collision frequency in the modified region is approximately equal to the electron cyclotron frequency.

6.2.1. Low-Altitude Heating Issues. Some of the issues to be investigated with regard to the generation of ELF via HF heating of the ionosphere below 80 km include: (i) the efficiency of generating ELF by gyrofrequency heating; (ii) the development of techniques to increase that efficiency, such as enlarging the heated region by rapid scanning of the heater's antenna-beam (so-called "painting"); (iii) the parametric dependence of the generated ELF power on ambient and disturbed ionospheric conditions; (iv) quantification of the coupling efficiency of generated ELF in the ionosphere, into the earth-ionosphere

waveguide; and, (v) the identification and mitigation of possible self-limiting effects associated with very high power HF waves in the ionosphere.

6.2.2. Low-Altitude Heating Research Recommendations.

Substantial progress in addressing these issues can be achieved by utilizing existing HF heating facilities, such as HIPAS, with minimal modifications but with a well planned complement of diagnostics. The most important diagnostic equipment is a set of ELF receivers in the 30-200 Hz frequency range, located in the near- and far-fields of the heater generated ELF. Other diagnostic instrumentation, for measurement of ionospheric electric field and current profiles, and density and temperature profiles (both prior to- and during the heating), should also be employed.

Power and other upgrades of the HIPAS HF facility should be considered only following a comprehensive assessment of the results obtained using the current facility in such near-term studies as those outlined above.

6.2.3. High-Altitude Heating Issues.

Among the issues associated with the generation of ELF by high-altitude heating are: (i) the scaling of the strength of the generated ELF as a function of the incident HF heater power-density and frequency; (ii) the quantification and mitigation of self-limiting effects associated with the propagation of very high HF waves in the ionosphere; (iii) the degree to which efficiency increases can be achieved by exploiting antenna sweeping (painting) techniques; (iv) the possible deleterious effects on the ELF generation efficiency produced by patchy energy depositions in the ionosphere caused by non-linear effects (e.g., filamentation); (v) the coupling efficiency between the generated ELF in the ionosphere down-into the earth-ionosphere waveguide; and, (vi) the potential for increasing the ELF generation efficiency by other innovative concepts.

6.2.4. High-Altitude Heating Research Recommendations.

Investigation of the above issues requires the development of a new, unique, high frequency (i.e., in excess of 6-7 MHz), high ERP (between 90 and 100 dBW) facility. The facility should be scannable, be able to produce both polarizations, have frequency agility and be capable of pulse shaping. A modulation bandwidth of 10 kHz should suffice. Such a facility should be complemented by extensive diagnostic instrumentation and, if possible, be accessible to rocket experiments for in-situ diagnostics. The location of the facility should be chosen in accordance with the need to heat the ionosphere in regions where there are strong ionospheric currents and electric fields. Realistically the site would be selected by a trade off between optimization of electric-field access, facility costs, availability of a complement of diagnostics, and logistics.

6.3. Submarine Communication Issues Associated With Exploiting ELF Signals Generated in the Ionosphere by HF Heating

There are a number of issues, more specifically related to operational system requirements, that must be addressed in addition to the ionospheric-related issues discussed above. These are outlined below.

6.3.1. General Research Issues. For application to submarine communications, it is necessary to generate ELF signals in the frequency range of 70-150 Hz. To date, however, experiments on the generation of ELF in the ionosphere by HF heating have been conducted for frequencies below 50 Hz and above 200 Hz. Thus, it is essential that ELF generation in the 70-150 Hz frequency range be investigated.

The generation of ELF by ionospheric heating would become especially attractive for application to submarine communication if radiated powers on the order of 80-100 Watts could be achieved. Therefore, it is very important to investigate ionospheric heating techniques that may lead to greatly increased ELF-radiated powers. Since the efficiency of such ELF generation depends on the availability of the auroral electrojet, knowledge of its diurnal, seasonal, and other cyclic variations becomes essential as well.

In addition, the potential application of ionospheric generated ELF to submarine communications will require detailed knowledge of the characteristics of the "virtual" ELF antenna that is produced in the ionosphere by the heating process. Among the characteristics of interest are the pattern of the virtual ELF antenna, the degree to which that pattern can be controlled, and the antenna's bandwidth.

6.3.2. Specific ELF Systems Issues. Plans for research on the generation of ELF by HF heating of the ionosphere should be made in the context of the important system issues listed below:

- (1) operational coverage area (Atlantic/Pacific/Arctic/other);
- (2) location of potential HF heating transmitters;
- (3) size of the HF heating transmitters/facilities;
- (4) ELF data rates that can be achieved;
- (5) HF heater configurations (fixed/mobile/reconstitutable);
- (6) cost/performance tradeoffs;
- (7) HF/ELF interference/environmental effects; and,
- (8) compatibility with existing ELF system assets.

6.4. ELF System-Related Research Recommendations

A fully comprehensive assessment of the potential for efficiently generating ELF signals in the ionosphere by HF heating awaits the development of a suitable heating facility. Nevertheless, near-term, proof-of-concepts, experiments should be conducted, using existing facilities such as HIPAS. Among the important experiments that should be done are:

- (1) generation of ELF waves in the 70-150 Hz band;
- (2) evaluation of proposed techniques to increase the ELF radiated power;
- (3) assessment of various heating techniques such as continuous wave versus pulsed modulation to increase the ELF generation efficiency; and,
- (4) measurement of ELF signal levels at various distances from the transmitter.

7. SUMMARY OF HAARP INITIATION ACTIVITIES

A DoD steering group has been set-up to plan and initiate the HF Active Auroral Research Program (HAARP). A summary of their activities is outlined below.

7.1. HAARP Steering Group

<u>AIR FORCE:</u>	Dr. Herbert C. Carlson	(GL)
	Dr. Paul A. Kossey	(GL)
	Mr. John E. Rasmussen	(GL)
	Mr. Robert A. Skrivanek	(GL)
<u>DARPA:</u>	Dr. Larry Stotts	(ASTO)
<u>NAVY:</u>	Dr. Richard G. Brandt	(ONR)
	Dr. Bobby R. Junker	(ONR)
	Dr. Donald A. Miller	(NUSC)
	Dr. Sidney L. Ossakow	(NRL)
<u>OUSD(A):</u>	Colonel Ted S. Cress	(RAT/ELS)

7.2. Summary of HAARP Steering Group Activities and Schedule

13 December 1989	Navy-Air Force meeting at ONR to discuss mutual interests in carrying out a DoD program in the area of ionospheric modification. The need for a unique heating facility to conduct critical experiments relating to potential DoD applications was identified. A Navy-Air Force-DARPA program was proposed.
13 December 1989	Navy-Air Force personnel present their proposed DoD program to DARPA and DDRE representatives at a meeting at DARPA.
9-11 January 1990	Ionospheric Modification/ELF Workshop held at NUSC, attended by personnel from government agencies, universities, and the private sector (see Appendix B). The workshop provided an opportunity for broad-based inputs concerning research needs in ionospheric modification. In addition, potential systems applications requiring further research were defined, and the characteristics of a new, unique, HF heating facility were discussed and identified.

- 24 January 1990 Navy-Air Force meeting at the Geophysics Laboratory (Hanscom AFB, MA) to develop a plan to achieve DoD HAARP objectives.
- 7 February 1990 Written description of HAARP plans and objectives circulated to Navy, Air Force, and DARPA personnel for coordination.
- 12 February 1990 Meeting with DDR&E at ONR to present HAARP plan, and to discuss implementation approach.

APPENDIX A

HF Vertical Heating Facilities

SOVIET:

<u>LOCATION</u>	<u>FREQUENCY MHZ</u>	<u>EFFECTIVE RADIATED POWER (MW)</u>
NIIR (DUSHANBE)	1.35 4-5	1000 80
SURA	5-10	400
GORKIY	4-6	20
MONCHEGORSK	3.3	10

WESTERN:

ARECIBO, 'PUERTO RICO	3-15	80
FAIRBANKS, AK	2.85-4.9	80
PLATTEVILLE, CO (CLOSED)	5-10	250
TROMSO, NORWAY (NEW)	2.75-8 6	250 1000

APPENDIX B

Workshop on Ionospheric Modification and Generation of ELF

Thursday, 11 January 1990 (All Participants)

0830 Working Group Charters	Dr. Richard G. Brandt, ONR Dr. Herbert C. Carlson, GL
0900 Working Group Session	
- ELF-Related Ionospheric Physics	Dr. Sidney L. Ossakow, NRL
- ELF Receivers	Mr. Raymond Ingram, NUSC
- ELF Excitation Efficiency	Dr. Dennis Papadopoulos ARCO Power Tech, Inc.
- ELF Antennas and Propagation	Dr. Anthony J. Ferraro Penn State University
- ELF Systems Issues	Dr. Donald A. Miller, NUSC
- High Energy Ionospheric Modification	Dr. Herbert C. Carlson, GL
1200 Lunch	
1300 Working Group Reports	
1530 Review of Facility Requirements	Dr. Richard G. Brandt, ONR Dr. Herbert C. Carlson, GL
1630 Adjourn	

APPENDIX B

Workshop on Ionospheric Modification and Generation of ELF

Attendance Roster

<u>NAME</u>	<u>ORGANIZATION</u>	<u>PHONE NUMBER</u>
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APPENDIX B

Workshop on Ionospheric Modification and Generation of ELF

Attendance Roster (Cont)

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