Creation of visible artificial optical emissions in the aurora
by high-power radio waves

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Generation of artificial light in the sky by means of high-power radio waves interacting with the ionospheric plasma has been envisaged since the early days of radio exploration of the upper atmosphere, with proposed applications ranging from regional night-time street lighting to atmospheric measurements. Weak optical emissions have been produced for decades in such ionospheric 'heating' experiments, where they serve as key indicators of electron acceleration, thermal heating, and other effects of incompletely understood wave–particle interactions in the plasma under conditions difficult to replicate in the laboratory. The extremely low intensities produced previously have, however, required sensitive instrumentation for detection, preventing applications beyond scientific research.
Here we report observations of radio-induced optical emissions bright enough to be seen by the naked eye, and produced not in the quiet mid-latitude ionosphere, but in the midst of a pulsating natural aurora. This may open the door to visual applications of ionospheric heating technology or provide a way to probe the dynamics of the natural aurora and magnetosphere.

The most readily observed emissions produced in ionospheric heating are the 'forbidden' red and green lines from atomic oxygen at 630.0 and 557.7 nm, both common components of the natural aurora and airglow3. In almost all past experiments, artificial emissions have been produced by the interaction of radio waves with the ionospheric F
region, the long-lived primary ionospheric layer composed of atomic ions at an altitude of several hundred kilometres4. Only rarely have optical effects been reported from the ionospheric E region5, an ephemeral layer created from occasional meteoric ions or continuous solar illumination or auroral precipitation near an altitude of 100 km , where increased collisions with neutral molecules alter the behaviour of the plasma, and the proximity to the transmitter provides
a large inverse-square increase in power density5. Emission intensities achieved previously have typically ranged up to several hundred Rayleighs (1 R = 106 photons cm-2 s-1 integrated along a line of sight) for the more easily excited red line and tens of Rayleighs for the higher-energy green line. In all cases, intensities have remained far below the threshold for detection by the human eye, which
is given as 20 kR at 630 nm (ref. 2) towards the red end of the visible wavelength range, and 1 kR for 558 nm (ref. 6) near the peak
> sensitivity of the eye.
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We recently produced dramatically stronger artificial optical emissions bright enough to be visible to the naked eye in an experiment targeting the ionospheric E layer created by the natural aurora. The experiment was conducted on 10 March 2004, between 6–7 UT,
using the 960-kW transmitter array at the High Frequency Active Auroral Research Program (HAARP) facility near Gakona, Alaska (62.4°

N, 145.15° W). The HAARP transmitter was run in a 15-s cycle alternating between 7.5 s of full power and 7.5 s off. Four filtered optical imaging systems ranging from all-sky to telescopic were operated in synchronization with the transmitter on and off intervals.
Background conditions during the experiment period were characterized by aurora pulsating with apparent periods of 10 s in longitudinal bands running in the magnetic east–west direction over most of the sky, including the region within the transmitter beam (Fig. 1). The auroral precipitation created a blanketing E layer near an altitude of
100 km with critical frequencies ranging from 4–6 MHz.

For a period of approximately 10 min between about 06:40 and 06:50, a number of small speckles {Orbs FRJ } of enhanced green emission were observed with the HAARP telescope wide-field camera, which provided high-resolution
images of the region within the transmitter beam near magnetic zenith The speckles were present only during the image frames when the transmitter was on and were absent from exposures taken during the off periods. There is evidence of dynamic pulsations in the background aurora within this narrower field of view as well, such as the auroral bands that appear and disappear in the lower left corner of the images. The largest speckles are approximately one degree across.

Within a given frame the speckles { Orbs, FRJ } appear to be randomly distributed,
but upon closer examination of successive 'on' frames, some of the speckles often appear to be correlated with but displaced from those seen in the previous 'on' period. This suggests that some speckle features are in motion but may still retain coherence across multiple on–off cycles of the transmitter.

Calibrated average intensities for the background aurora within the transmitter beam were obtained from another imager, which made measurements at several different wavelengths once each minute. In spite of the
rapid pulsations in narrow bands and on 10-s
timescales, the average auroral brightness at 557.7 nm remained near 4 kR, with an increase to 5 kR near the time the speckles were observed.
This intensity calibration, applied to the high-resolution data in Fig. 2, indicates that the brightest speckles were approximately 4 kR in total intensity, well above the threshold for visibility and 1 kR or more above the darker auroral regions.

Given the unprecedented brightness of the speckles, we carried out a number of tests to rule out potential artefacts, including: repeating the transmission pattern at a different time to rule out radio-frequency (r.f.) interference with the camera electronics, verifying from radar records that no aircraft were in the area, and measuring the periods of white-light sources such as nearby communications towers and airport beacons. We attempted to reproduce the results whenever an aurora moved into range, but auroral events later in the experiment window never produced E layers of sufficient density to support significant transmissions at the original frequency again. More detailed analysis of the data revealed additional weak speckles earlier in the original 6-UT hour, at about 06:20 UT, when he transmitter was operated at a lower frequency (and lower effective power), and some of the brightest speckles were also identified in

data from one of the other lower-resolution camera systems operated from a separate building, eliminating any doubt that the speckles represent actual light from the sky.

Although visible levels of artificial optical emissions have not been reported previously, there have been other attempts made to stimulate the auroral E layer with radio waves. A similar experiment that used low-light television cameras and a 2-s on–off cycle but different

polarization reported an estimated modulation of less than 10 R, interpreted as radio-induced decreases in the green line emission7. Large-scale structural changes in the overhead aurora have been reported in conjunction with E-layer heating8, but the extremely small number of cases and the close similarity of the observed effects to naturally occurring processes make it difficult to assess the true influence of the radio waves on the auroral events. In contrast, the recent HAARP observations demonstrate clear on-off control of the > speckles over 50 or more complete cycles.

Potential sources of the observed bright speckles fall into two categories: production in the local E-region ionosphere by the transmitter beam, or indirect creation by modification of the auroral particle precipitation, which then produces the optical speckles in the same way as the background aurora. If the speckles are locally generated, the role of the natural aurora would probably be limited to creation of the E layer for the radio waves to interact with, and it might be possible to generate similar phenomena in non-auroral E layers independent of any specific on-off cycling, a potentially desirable condition for creation of visible artificial light. If, on the other hand, the speckles result from modification of the auroral particle population, perhaps through perturbations to currents flowing in the E layer or a wave resonance, we expect that the specific frequency of the on–off cycling relative to the natural pulsation frequencies might be a critical parameter, and experiments of this type could potentially become a new tool for exploration of time-dependent processes in the aurora and magnetosphere.

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References 1. Bailey, V. A. On some effects caused in the ionosphere by electric waves, Part II. Phil. Mag. 26(7), 425–453 (1938)
2. Bernhardt, P., Duncan, L. M. & Tepley, C. A. Artificial airglow excited by high-power radio waves. Science 242, 1022–1027 (1988)
3. Chamberlain, J. W. Physics of the Aurora and Airglow (International Geophysics Series Vol. 2, Academic, New York, 1961)
4. Rishbeth, H. & Garriot, O. K Introduction to Ionospheric Physics (Academic, New York, 1969)
5. Djuth, F. T. et al. Large airglow enhancements produced via wave-plasma interactions in sporadic E. Geophys. Res. Lett. 26, 1557–1560 (1999) | Article |
6. Omholt, A. The Optical Aurora 6 (Physics and Chemistry in Space Vol. 4, Springer, New York, 1971)
7. Sergienko, T., Kornilov, I., Belova, E., Turunen, T. & Manninen, J. Optical effects in the aurora caused by ionospheric HF heating. J. Atmos. Sol-Terr. Phys. 59, 2401–2407 (1997) | Article |
8. Blagoveshchenskaya, N. F. et al. Ionospheric HF pump wave triggering of local auroral activation. J. Geophys. Res. 106, 29071–29089 (2001) | Article |
9. Bauer, S. J. Physics of Planetary Ionospheres 82–95 (Physics and Chemistry in Space Vol. 6, Springer, New York, 1973)
10. Davis, N. The Aurora Watchers Handbook 58 (Univ. Alaska Press, Fairbanks, 1992)
11. Carlson, H. C. Jr & Egeland, A. in Introduction to Space Physics (eds Kivelson, M. G. & Russell, V.) 459–502 (Cambridge Press, New York, 1995)

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Complete HAARP Overview Below...

HAARP Executive Summary

HAARP

HF ACTIVE AURORAL RESEARCH PROGRAM

JOINT SERVICES PROGRAM PLANS AND ACTIVITIES

AIR FORCE
GEOPHYSICS LABORATORY

NAVY
OFFICE OF NAVAL RESEARCH

HF ACTIVE AURORAL RESEARCH PROGRAM (HAARP)

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HAARP -- HF Active Auroral Research Program

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 focused 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.

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 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 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 location 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 the 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 focused 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 (Dept. of Defense) 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., WISP 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 focused on developing a robust program in the area of ground-based, high power RF heating of the ionosphere.

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-30kHz) 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, any 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 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 emission, 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 spade- 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
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 an 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 (MU), 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
(unavailable)

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 'f 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 l0 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 accelerate electrons. Over
time scales op 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 modification 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 focused on parametric instabilities to explain observational results. In contrast, there is in increasing 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 op 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 diagnostic needed for addressing these issues are given in Table 2.

(Table 2 not available in this document)

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.

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 he 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 US. 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-measurement 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.

4.3. 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 atmospheric currents, either at an equatorial location or at 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.