The Future of the High frequency Active Auroral Research Program (HAARP)

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ABSTRACT

The HAARP facility, located in Gakona Alaska, is the world's premier laboratory for active experimentation in the ionosphere and upper atmosphere. Understanding the ionosphere is particularly important because it affects long-distance communication, navigation, and radar applications relying upon radio propagation through this ionized atmospheric region. The primary component of HAARP, the Ionospheric Research Instrument (IRI), is a phased array of 180 HF tower antennas spread across 33 acres and capable of radiating 3.6 MW into the upper atmosphere and ionosphere. The array is fed by five 2500 kW generators, each driven by a 3600 hp diesel engine (4 + 1 spare). Transmit frequencies are selectable in the range 2.8 to 10 MHz. HAARP is owned by the Space Vehicles Directorate of the Air Force Research Laboratory (AFRL/RV) in Albuquerque, NM. In 2013 AFRL/RV decided that they no longer needed the facility, and by prior arrangement, were prepared to remediate the site. In response to a letter writing campaign and petition by the scientific community, the Secretary of the Air Force directed that the demolition be postponed until May, 2015 to allow time for another federal agency, a consortium of academic or research institutions, or the University of Alaska, to build a plan to sustain the facility and preserve its capability to enable fundamental ionospheric research. For the past year the Geophysical Institute of the University of Alaska Fairbanks has been in active negotiations with the Air Force and a sustainment plan for HAARP, using a pay per use model may soon be approved and implemented preserving HAARP for future upper atmospheric investigations.

OVERVIEW

The HAARP facility, located in Gakona Alaska, is the world's premier laboratory for active experimentation in the ionosphere and upper atmosphere. Scientists at HAARP use high frequency (HF) radio transmitters to heat selected regions of the ionosphere and observe the effects. With a facility like HAARP, the ionosphere becomes a laboratory to study a range of physics phenomena. For traditional space research using ground-based observations or experiments on sounding rockets, it can take an extremely long time (days, weeks, years) to get the desired natural overhead conditions. Satellites can amass much larger databases but it is difficult to coordinate the satellite with the desired phenomena. With a facility like HAARP, it is possible to perform an experiment at

Figure 1 Overhead Photo of HAARP Courtesy of M. McCarrick

will to create plasma structures and irregularities; use the ionosphere like an antenna to excite low frequency waves; create weak luminous aurora-like glows; and a variety of other experiments. Ground-based instruments or satellite overflights are used to collect the necessary data for the investigation.

The primary component of HAARP is the Ionospheric Research Instrument (IRI), a phased array of 180 HF tower antennas spread across 33 acres and capable of radiating 3.6 MW into the upper atmosphere and ionosphere. The array is fed by five 2500 kW generators, each driven by a 3600 hp diesel engine (4 + 1 spare). Transmit frequencies can be chosen anywhere in the range 2.8 to 10 MHz and since the antennas are part of an array, the transmitted beam can take many shapes, can be scanned over a wide angular range (down to 30° deg. elevation angle) and multiple beams can be formed and steered. The facility employs 30 transmitter shelters each with six pairs of 10 KW transmitters (6 x 2 x 30 x 10) to achieve the 3.6 MW transmit power.

The facility is located at 62.39° N, 145.15° W in the subarctic which is an ideal location for a wide range of scientific experiments. The location is just south of the auroral region which allows active experiments outside of the aurora. During substorms HAARP's location is under the aurora or inside the auroral oval. The high latitude location is also ideal for experiments generating low frequency waves which propagate along magnetic field lines high into the magnetosphere.

Figure 2 HAARP Antennas Courtesy USRA

Figure 3 HAARP Antennas and Transmitter Shelters Courtesy USRA

Initiated in 1989 with congressional earmarks (~$180M), HAARP was completed around 2009 with additional investments of $110M from the Air Force Research Laboratory (AFRL), the Office of Naval Research (ONR) and Defense Advanced Research Program Agency (DARPA) and represents a total investment of ~$290M. HAARP is currently owned by the AFRL Space Vehicles Directorate (AFRL/RV) in Albuquerque NM.

There are two other ionospheric heaters in the world, EISCAT in Norway and Sura in Russia. The National Science Foundation is currently building a fourth hearter in Arecibo Puerto Rico. HAARP is by far the most powerful and capable heater in the world.

HAARP SCIENCE

A full discussion of the science capabilities, accomplishments and future science potential of HAARP is not practical here but the 2013 National Research Council Workshop Report: ***Opportunities for High-Power, High-Frequency Transmitters to Advance Ionospheric/Thermospheric Research*** (see below) is an excellent resource. As a scientific tool for active experimentation in the ionosphere HAARP has a number of characteristics that make it unsurpassed in the world including:

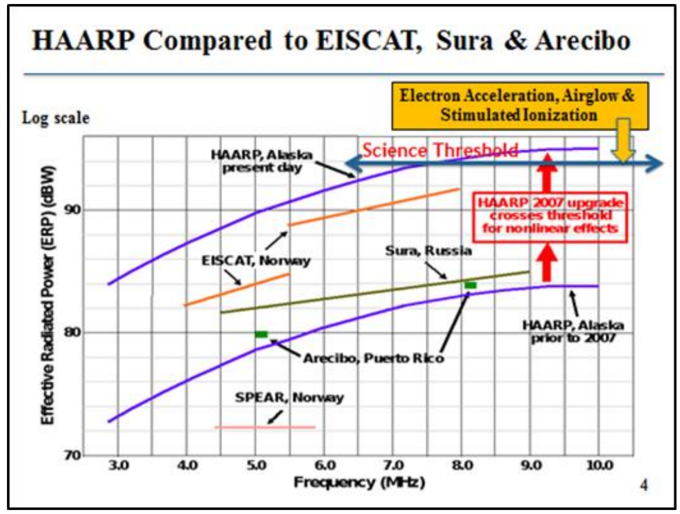

Figure 1 Comparison of Existing Ionospheric Heaters (Kennedy, 1998)

- Effective radiated power (ERP) = power x antenna gain;
- Steerability of the beam and ability to create multiple beams;
- Frequency range and ability to select frequency;
- Polarization control;
- Modulation control;
- Location – relative to the aurora and on high latitude magnetic field lines;
- Accessibility of the site from either Anchorage or Fairbanks Alaska.

A short summary of HAARP science highlights in a few topic areas includes:

RADIO SCIENCE: Production of artificial plasma layers to study radio frequency propagation at a range of frequencies from a few Hz to a few GHz (including GPS frequencies). Studies include guidance, redirection, enhancement and degradation and loss of signals.

MESOSPHERE-THERMOSPHERE DIAGNOSTICS: Production of artificial periodic irregularities; neutral density and temperature measurements and generation of optical emissions. Upper atmospheric heating has been used to change density, composition, neutral diffusion, thermospheric winds and potentially – drag on orbiting debris or satellites. HAARP can be used in studies of polar mesospheric clouds.

SPACE WEATHER: The use of HAARP to make comparisons quiet ionospheric conditions to substorms and mapping up into the plasmasphere. Use of the facility to study a variety of transient phenomena including subauroral polarization stream (SAPS); subauroral ion drift (SAID), high electron temperature regions and troughs, and ion-outflow-created atmospheric gravity waves.

MAGNETOSPHERE-RADIATION BELTS: This line of investigation primarily involves using the ionosphere in a variety of modes as a "virtual antenna" to inject a variety of waves including whistler waves, shear Alfvén, and magnetosonic waves and waves at frequencies down to a few Hz and study resonance and amplification effects. There are a wide range investigations of wave/particle interactions in the magnetosphere enabled by HAARP (Rietveld et al., 1989; Barr, 1998; Papadopoulos et al., 1990, 2005).

FUTURE SCIENCE POSSIBILITIES

Recent experiments at HAARP (Fallen et al., 2011) demonstrated experimental techniques to continuously generate artificial plasma ducts that extend from the upper ionosphere into the earth's magnetosphere. These plasma structures facilitate the ducting of VLF waves generated artificially either by, HAARP signals interacting with the ionosphere, from other ground based sources, or generated in space. This new discovery is relevant to the efforts to reduce high energy electrons in the radiation belts (see below).

Continued basic science efforts on this topic should reveal how this technique may be optimized for a variety of geophysical conditions. Measurements of duct geometry may then be used in conjunction with numerical models and simulation to estimate levels of VLF power density that may be deposited in the equatorial region of the earth's magnetosphere within the radiation belts. This efficient injection of artificially created VLF waves into the radiation belts acts to scatter and remove high levels of energetic electrons injected from high-altitude nuclear burst.

DOD APPLICATIONS

Interest by the DoD (AFRL, ONR and DARPA) in HAARP is obvious by the $105M they invested to complete and upgrade the facility. Historically, most of the applications of interest stem from the ability of HAARP to generate low frequency waves that propagate both within the Earth – atmosphere waveguide around the globe and which propagate upward along magnetic field lines into the magnetosphere. More recently the focus has been on using HAARP to stimulate artificial glows in the upper atmosphere and creating artificial plasma clouds.

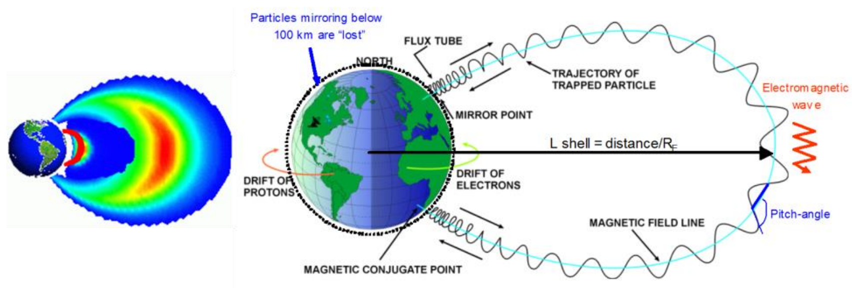

Figure 2 Radiation Belts and Trapped Electrons in Magnetic Flux Tubes

REDUCTION OF ELECTRONS IN THE SPACE RADIATION BELTS: The highest priority application for HAARP and the one stimulating most of the investment involves using low frequency waves to cause high energy million-electron-volt "killer" electrons in the magnetosphere to precipitate out. The Earth's natural radiation belts contain high energy electrons trapped in magnetic bottles (flux tubes) and propagating for extended periods from pole to pole spiraling along magnetic field lines. The density of these trapped particles can go up dramatically from a solar coronal mass ejection (SME) or from a manmade event like a high altitude nuclear burst. A 1000 fold electron density increase can easily be obtained from the latter and these electrons can persist for months or years in the radiation belts. These killer electrons can damage and destroy electronics in low Earth orbiting satellites and there is an estimated $100B of non-DoD satellites at risk.

Experiments with HAARP and other radio frequency transmitters have shown that a variety of low frequency waves can be generated in the ionosphere which propagate along magnetic field lines to interact with these trapped electrons. Wave-particle interaction occur which modify the angle between the trapped electron and the magnetic field line, the pitch angle. On subsequent reflections near either pole these electrons penetrate deeper into the upper atmosphere colliding with neutral atoms and molecules and are lost. This process reduces the density of electrons trapped in the radiation belts.

There have been a number of HAARP investigations on this topic sponsored by several agencies. Based on results observations and models, AFRL/RV built the DSX satellite to investigate the effect of emitting low frequency waves directly in space and will soon launch this vehicle soon to test the effect. Neither HAARP nor DSX provide a comprehensive solution for this problem but both provide valuable insights into the science of wave-particle interactions on the radiation belts.

SUBMARINE COMMUNICATION: The Navy's interest in HAARP was frequently related to using the ionosphere as a large antenna to excite extremely long wavelength (ELF) waves to propagate long distances and penetrate the oceans to communicate with submarines.

DETECTION OF CAVITIES IN THE EARTH: The same ELF waves that penetrate the oceans can also penetrate into the Earth's lithosphere and experiments with HAARP have been used to detect cavities; mines and caves underground.

OVER THE HORIZON RADAR: The current HAARP site was originally an over the horizon (OTH) radar site. OTH radar depends on reflecting HF waves off the ionosphere. Solar and geomagnetic activity produce problems for HF radar propagation in the Arctic. Auroral activity creates irregularities and bubbles in the ionosphere causing scintillation and loss of HF signals. Recent HAARP experiments (Pedersen et al., 2010) demonstrate the ability to create sustainable artificial plasma clouds or plasma balls at altitudes below the natural ionosphere which may be useable as an artificial mirror to reflect HF radar and other RF communication signals.

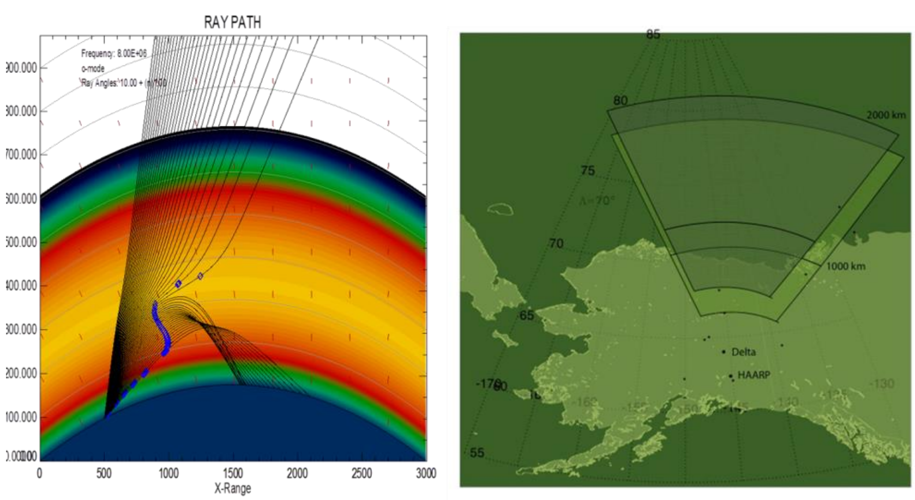

Figure 3 Ionospheric propagation of 8MHz rays and potential OTH footprint from HAARP Courtesy of Bill Bristow

As the sea ice in the Arctic continues to melt opening up polar navigation routes, there is increasing interest by the US Northern Command and NORAD in the possibility of deploying a system of OTH radars across North America for increased Arctic maritime domain awareness. HAARP may play an important role as an OTH test bed and demonstration platform for this new capability.

TRANSIONOSPHERIC RF PROPAGATION: As HAARP heats the ionosphere it can create bubbles and irregularities. These irregularities can then interfere with a wide range of space to ground RF propagation at frequencies up to 10 GHz. A facility like HAARP could be used to cause interference with communication signals, GPS navigation or blur space-based synthetic aperture radar.

LASER FUSION APPLICATIONS: Another application of an ionospheric heater is to use the natural ionosphere to perform nonlinear plasma experiments in unbounded plasma. The power levels of HAARP are small compared to those in fusion experiments but the lack of walls in the ionosphere, combined with HAARP's tunability and phase array transmissions allow a wide range of experimentation in parametric instabilities and nonlinear plasma physics.

THERMOSPHERIC HEATING EXPERIMENTS: Through coupling between the ionosphere and thermosphere it is possible to heat the neutral atmosphere above HAARP. This heating can be used to create density plumes and drive neutral waves over HAARP to test applications to increase drag on selected orbiting satellites or orbital debris.

HAARP GROUND-BASED DIAGNOSTICS

The IRI at HAARP creates the effects in the ionosphere but it is the diagnostic ground-based instruments which allow scientific investigations. The state of the diagnostic instruments at HAARP is in flux and many of the sensors have been temporarily removed. Most of the sensors are slated to be returned and restored to service during the spring/summer 2015. The discussion that follows lists the instruments that were traditionally resident at HAARP and used to support science and may represent the set of diagnostics later in 2015.

The primary diagnostic tool at HAARP is the digisonde. This instrument, basically a swept frequency HF radar, measures the bottom side of the electron layer in the ionosphere. Additional sensors at the facility include:

- All-sky Riometer
- Imaging Riometer (8 X 8 Array)
- Fluxgate Magnetometer
- Induction Magnetometer
- Optics
  - All-sky imager
  - Telescopic imager
  - Photometers
  - 14 ft Optical Dome
- Tomography Chain (Cordova -> Kaktovik)
- VHF Radar (139 MHz)
- MUIR (Modular UHF Ionospheric Radar
- Ionospheric Scintillation Receivers
  - SATSIN (offsite)
  - GPS-NOVATEL
  - Total Electron Content
- HF 2-30 MHz High Angle Receiving Antenna
- Scanning Doppler Interferometer (SDI)

Figure 4 HAARP Optics Facility

Figure 5 MUIR Radar

- Radio Background Receivers
  - Broadband ELF / VLF Receiver network.
  - SEE Receiver string.
  - HF to UHF Spectrum Monitor

Figure 6 HF High Angle Receive Array

NATIONAL ACADEMY OF SCIENCE INPUT

The National Research Council (NRC), the operating arm of the National Academy of Sciences has taken up the issue of HAARP twice over the past two years. In 2013 the NRC completed a Decadal Survey in Solar and Space Physics. One of the priority recommendations of that study included:

> **Priority** - ***Fully realize the potential of ionospheric modification techniques through collocation of modern heating facilities with a full complement of diagnostic instruments including incoherent scatter radars. This effort requires coordination between NSF and DOD agencies in planning and operation of existing and future ionospheric modification facilities.***

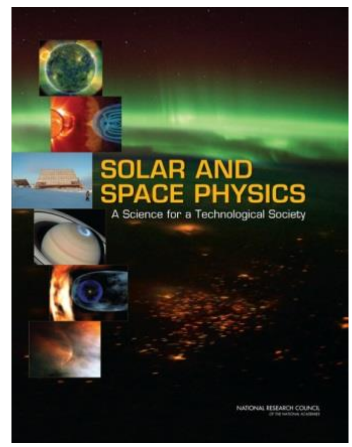

Figure 7 2013 Space Physics Decadal Study

In March 2013 in response to a request by AFRL and NSF the NRC conducted a workshop entitled: **Opportunities for High-Power, High-Frequency Transmitters to Advance Ionospheric/Thermospheric Research** focused primarily on HAARP. Topics addressed in that three day workshop included:

- Geospace and space weather;
- Stimulated emission and radiation belts;
- Radio science; and
- Communications.

NRC Workshops do not produce recommendations, but the NRC published a report containing 72 pages by 40+ scientists documenting past science results from HAARP and a wealth of prospects for future science from the facility.

The report reiterated the importance of co-locating an incoherent scatter radar to HAARP to maximize the science potential of the facility. The NRC report can be obtained at:

http://www.nap.edu/booksearch.php?booksearch=1&term=sale&record_id=18620

Figure 8 2013 NRC Workshop Report

NEED FOR AN INCOHERENT SCATTER RADAR

A diagnostic instrument noticeably missing from HAARP is an incoherent scatter radar (ISR). An ISR is one of the most powerful tools for studying the ionosphere from the ground. An ISR can routinely measure vertical profiles of electron density, electron and ion temperatures, bulk ion motion, ion masses, ion-neutral collision frequencies. Over the years there have been several plans to build an ISR at HAARP but because of funding variability for the facility it was never completed. There have been several studies, workshops and panels which made recommendations to install an ISR at HAARP, most notably the two NRC studies mentioned above but also a DoD sponsored panel in 2001 entitled HAARP "Future Directions" but usually called the "Tether Panel" after the chairman Dr. Tony Tether.

The NSF owns and operates a chain of ISRs from near the north magnetic pole to the magnetic equator at such sites as: Resolute Bay Canada; Sondrestrom Greenland; Millstone Hill Massachusetts; Arecibo Puerto Rico and Jicamarca Peru. Additionally, they own one more outside of that chain at Poker Flat Alaska about 300 miles north of HAARP. Older ISRs have a conventional radiating transmitter and dish reflector design, but two of the newer ISRs in Canada and Alaska are built with phased array transmitters and are far more flexible and capable. Both of these ISRs are called Advanced Modular Incoherent Scatter Radar (AMISR) and for distinction the Resolute Bay is commonly referred to as RISR and the Alaskan ISR is called the PFISR.

Figure 9 PFISR Incoherent Scatter Radar

The NSF PFISR is located on the property of the University of Alaska owned Poker Flat Research Range (PFRR) which is used by NASA to launch sounding rockets to study space physics in the arctic. The PFISR is employed for routine and campaign ionospheric science and frequently supports NASA sounding rocket launches. The radar consists of 128 identical panels which constitute the phased array. The MUIR radar at HAARP (Figure 9) is built with the same technology but with only 16 panels. That radar has some capability to sound the ionosphere but it does not have ISR capability. Expanding the MUIR to a total of 96 panels should give it ISR capability. There have been discussions of temporarily relocating PFISR to HAARP for a year, or two, to test out the heater/ISR combination to enable space research. Other options which have been discussed include reducing PFISR to 96 panels by transferring panels to HAARP and expanding the (adding panels) to the MURI array with a potential of ending up with two ISRs in Alaska.

EDUCATIONAL OPPORTUNITIES AT HAARP

With sponsorship from NSF and AFRL HAARP has provided numerous opportunities for graduate and undergraduate research projects and there are several ionospheric scientists working in the field who got degree in heater science with experiments at HAARP. For several years NSF and AFRL sponsored the Polar Aeronomy and Radio Science (PARS) summer school which gave undergraduates and graduate students opportunities to work with their advisors to perform science experiments at HAARP. This summer school also included tours and classes at the Geophysical Institute at the University of Alaska Fairbanks (UAF-GI) and tours of PFRR.

RECENT DEVELOPMENTS WITH HAARP

In 2012, anticipating budget cuts, AFRL/RV contacted the University Space Research Associates (USRA) and the UAF-GI to see if we could help them find a way to lower operating costs and/or divest themselves of management/operation of HAARP. USRA and UAF-GI formed a team and submitted a proposal to operate HAARP under an extended use lease arrangement which was not funded.

In 2013, after the release of the NRC workshop report and after a workshop sponsored by the Office of Science Technology Policy (OSTP), the UAF-GI proposed the creation of a Federal Facility Partnership for HAARP spreading the operating costs across five federal agencies (AFRL, ONR, DARPA, NSF and DOE), selling each a two-week campaign with an operating cost similar to what EISCAT charges customers. That proposal was not successful.

In July 2013, in response to a letter writing campaign by the scientific community; letters of support from leadership of the American Meteorological Society (AMS) and the Space Physics and Aeronomy Section of the American Geophysical Union (AGU/SPA); and a letter from U. S. Senator Lisa Murkowski; Air Force Secretary Deborah Lee James decided to postpone decommissioning plans for HAARP which had been scheduled for June 2014. She allowed time (May, 2015) for the "University of Alaska or a consortium of academic or research institutions" to develop a plan to take ownership of HAARP for the purpose of keeping the facility open covering operating costs from the user base.

In June 2014, DARPA completed a phase of the Basic Research on Ionospheric Characteristics and Effects (BRIOCHE) campaign and soon after the facility was placed in cold-storage. Transmitter tubes were removed from the transmitter shelters and moved into the heated main building to minimize heating costs for the winter. The diesel generators were winterized and many of the diagnostics were transported to AFRL at Kirtland AFB.

Since then negotiations have progressed well and the UAF-GI is working with AFRL/RV on a cooperative research and development agreement (CRADA) to transition ownership of the facility to the University of Alaska to allow the UAF-GI to bring it back on line for continued ionospheric, thermospheric and magnetospheric research. Current projections are that the UAF-GI will take ownership in the fall of 2015. Plans are being finalized to return the diagnostics to HAARP in the spring 2015. The UAF-GI is working to develop a plan to reduce the operating costs of the facility and is actively seeking customers, both domestically and internationally, to come to HAARP to do active experiments at the world's premier upper atmospheric active research facility.

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