An Ionospheric Modification Facility for the Magnetic Equator

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Summary

This is a conceptual proposal for the deployment of an ionospheric modification facility, also called and HF facility or ionospheric heater, near the geomagnetic equator. A heater is a powerful high-frequency (HF), or shortwave, radio transmitter that can be used to induce a number of phenomena in the ionospheric plasma. Some of these phenomena provide insights into complicated plasma physics processes that may occur elsewhere in nature but that are difficult or impossible to explore in the laboratory or numerically. Other HF-induced phenomena provide diagnostics of naturally-occurring ionospheric phenomena.

HF ionospheric modification may affect the propagation of radio signals passing through the modified region, which is how the phenomenon was first discovered (i.e. the Radio Luxembourg effect [*Bailey and Martyn*, 1934]). HF transmissions may modify plasma density, increase electron and ion temperatures (which is why they are called heaters), create field-aligned plasma density irregularities that may be interrogated by small coherent scatter radars, and generate VLF and ELF radiation, which has practical societal utility (e.g. in underwater communications and underground remote sensing). By inducing turbulence, and through other processes, they add energy to electrostatic ion-acoustic and Langmuir modes that may be observed by incoherent scatter. These processes also induce optical and radio emissions that may be observed from the ground, and cause electron acceleration, although the detailed mechanism is unclear.

Heaters have been deployed in Plateville, Colorado, Fairbanks and Gakona, Alaska, Islote and Esperanza, Puerto Rico, Tromsø and Longyearbyen, Norway, Kharkov, Ukraine, and at Nizhniy Novgorod and other locations in Russia. These are all high- and middle-latitude sites. However, it has been suggested that the most spectacular heater-induced phenomena may be waiting to be discovered at low latitudes, under the geomagnetic equator.

Because of the close connection between heating effects and electrostatic waves, heaters are most productive when located close to an incoherent scatter radar. We propose that an equatorial HF facility should consequently be installed close to the Jicamarca Radio Observatory near Lima, Peru. Some initial work toward this end is already being performed.

Advancing solar and space physics

Ionospheric modification provides a powerful tool for exploring both artificially-driven plasma physics and natural aeronomic processes in the upper atmosphere, and permits controlled, repeatable experiments, as opposed to making indirect inferences from large sets of disconnected observations. Consequently, hypotheses can be posed and tested, and experiments refined and repeated, so as to achieve rapid closure of existing science problems as well as the discovery of new ones (see reviews by *Duncan and Gordon* [1982], *Frolov et al.* [1997], and *Gurevich* [2007]).

In the ionosphere, a pump electromagnetic wave emitted from a high-power HF transmitter decays parametrically into a high-frequency byproduct wave (Langmuir, electron Bernstein/upper hybrid) and a low frequency byproduct wave (lower hybrid, ion acoustic, ion Bernstein, purely growing). Some of these byproducts can be observed directly using incoherent scatter radar (ISR), which is the most incisive diagnostic available for studying heater-induced phenomena. Others result in the stimulated emission of electromagnetic waves (SEE), which can then be observed on the ground with simple HF receivers. While linear theory predicts the onset and early behavior of the waves produced in heating experiments, turbulence paradigms involving wave trapping and caviton production and collapse are required to account for the complex electrostatic (ISR) and electromagnetic (SEE) spectra that are observed.

Another feature of ionospheric modification experiments is electron heating and suprathermal electron production and electron acceleration. Instabilities driven by the pump wave heat the electrons up to about 3500 K, which can result in ion upwelling, and ion temperatures may increase by up to a few hundred K [*Rietveld et al.*, 2003]. Although the specific mechanisms involved are still unresolved, heater-induced plasma instabilities are also known to accelerate electrons up to 60 eV or more [*Gustavsson et al.*, 2005]. These electrons collide with oxygen atoms and nitrogen molecules and produce optical emissions much as natural electron impact from precipitation does in the aurora. Both thermal and suprathermal processes are believed to be at work, with 630-nm (red line) excitation being accessible through direct electron heating and 557.7-nm (green line) excitation through electron acceleration. Suprathermal electrons can be diagnosed both through incoherent scatter and optical techniques. Coordinated experiments provide the most direct path towards resolving the processes involved in electron acceleration.

A signature feature of ionospheric modification experiments is the production of small-scale artificial field-aligned plasma density irregularities (AFAIs) just below the HF reflection height [*Fialer*, 1974; *Minkoff et al.*, 1974]. The mechanism responsible is the thermal parametric instability (linear regime) [e.g., *Fejer*, 1979] followed by the resonance instability (nonlinear regime) [e.g., *Vas'kov and Gurevich*, 1977]. Using spaced-receiver radar imaging techniques, it is possible to generate three-dimensional radar images of the heater-induced irregularities with excellent spatial and temporal resolution (of the order of a second and a few hundred meters, respectively) [e.g. *Nossa et al.*, 2009]. AFAIs offer an incisive diagnostic of both ionospheric modifications and naturally occurring processes. Ionospheric heating effectively "shines a light" on existing ionospheric density layers, which can then be monitored and analyzed in much greater detail than conventional remote sensing techniques generally afford (e.g. Figure 1).

Another method for monitoring the background ionosphere using ionospheric modification was introduced by *Bernhardt et al.* [2003] in experiments on sporadic-E ionization layers at Arecibo. The method, termed "radio-induced aurora" or RIA, combines ionospheric modification with optical imaging. The idea involves emitting pump-mode radiation at a frequency below the F region peak frequency. Where there are no sporadic E layer patches, the radiation propagates into the F region and produces red line emissions at the F region interaction height. Where there are sporadic E layer patches the pump-mode radiation interacts in the E layer, producing gaps or "shadows" in the red line emissions and green line emission at E region altitudes. Airglow imagers can detect both phenomena, leading to spatial maps of the E layer structure in two horizontal dimensions.

Among the more practical applications of ionospheric modification are the generation of radio signals in the VLF (3 –30 kHz), ULF (300 – 3000 Hz), and ELF (3 – 30 Hz) bands [*Ferraro et al.*, 1982]. Such signals are useful for undersea communications (i.e. with submarines) and subsurface imaging, both having strategic significance for the nation. Conventional antennas used in these bands are electrically short by necessity (compared to a wavelength) and therefore inefficient. Using HF transmissions we may attempt to alter ionospheric currents (periodically in time and perhaps also in space) and thereby cause them to radiate. Most efforts to date have involved the auroral electrojet current, although emissions can also be caused by driving diamagnetic currents or currents associated with the pondermotive force.

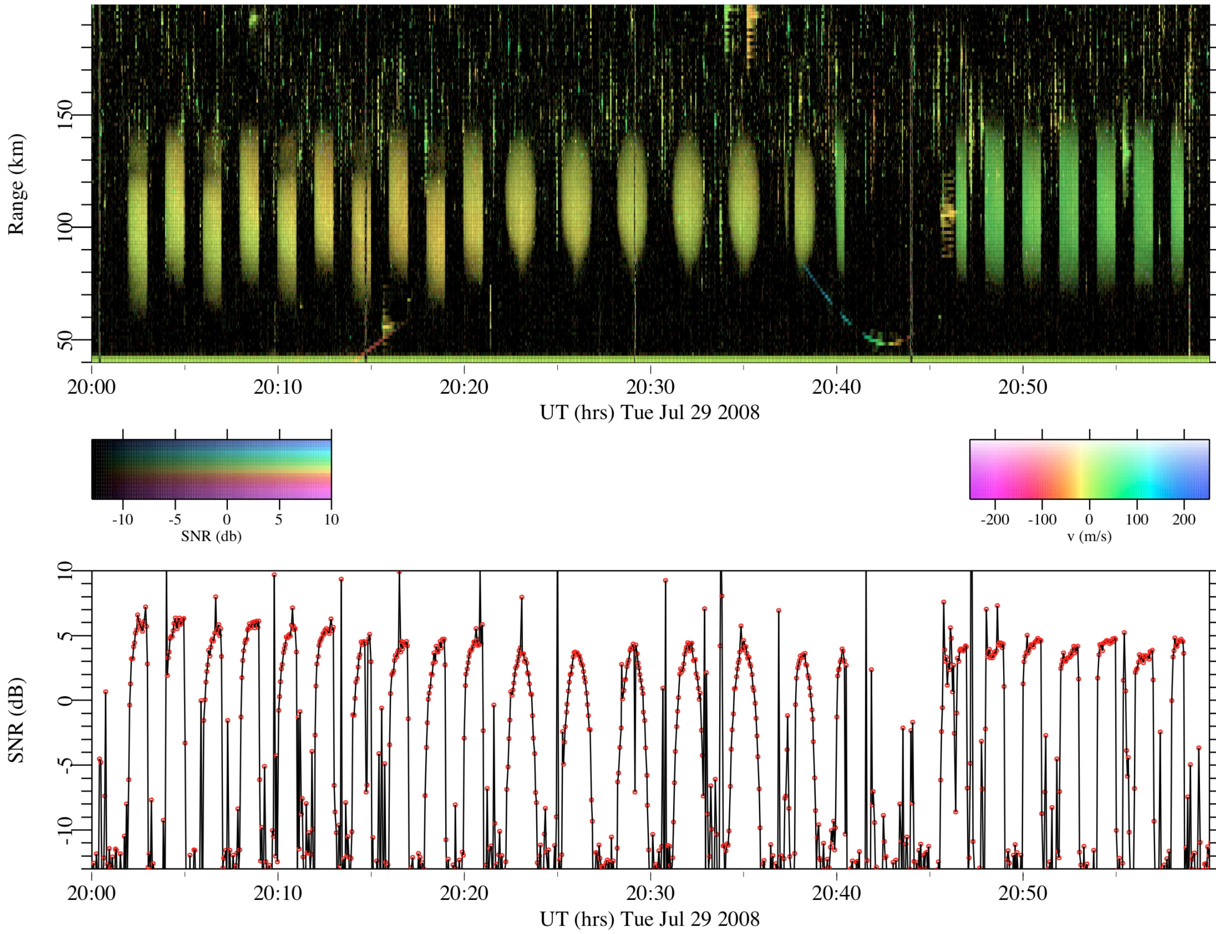

Figure 1. UHF radar range-time Doppler and SNR plots for three different experiments at HAARP during the summer of 2008. The morphology of the generated echoes changes depending on the parameters used. The experiments are repeatable, creating unique conditions for studying plasma physical and natural phenomena (from *Nossa et al.* [2009]).

Science investigations along many of the lines outlined above could also be conducted with a heating facility near the geomagnetic equator. More importantly, a number of new and potentially spectacular phenomena could also be explored. Some of these were first described in a review paper by *Erukhimov et al.* [1997], while others are derived from years of experience at HAARP, Jicamarca, and elsewhere. The most obvious objectives of an equatorial heater are outlined below.

Artificial periodic irregularities

A standing wave pattern is formed where the transmitted HF wave reflects back to Earth, creating nonuniform heating and quasiperiodic density irregularities. These irregularities can be probed using low-power HF waves at and close to the pump frequency. A modern ionosonde can be used for this purpose. By timing the irregularity onset and decay times, relaxation processes, state parameters, and transport coefficients can be determined for the natural atmosphere.

At middle and high latitudes, a given geomagnetic field line may connect, or short-circuit, the artificial irregularities, subjecting them to rapid dissipation by parallel ambipolar diffusion, particularly in the F region. This limits the utility of the technique as a practical diagnostic. At the magnetic equator, however, the artificial irregularities will form orthogonally to the geomagnetic field. Dissipation in the F region will then be limited by the electron cooling rate, which is very slow.

Erukhimov et al. [1997] estimated that the artificial irregularity amplitude will then be three to four orders of magnitude larger than for comparable high-latitude experiments, approaching something like 10% RMS for a heater with an effective radiated power of 100 MW. This would be a dramatic effect and would offer a versatile, cost-effective, exploratory tool for equatorial aeronomy.

Triggering equatorial spread F

Equatorial spread F (ESF) has been the cause celebre of equatorial aeronomy since its discovery over 70 years ago. The term refers to ionospheric interchange instabilities that occur frequently after sunset at latitudes between the Appleton ionization anomalies, generating ionospheric irregularities which evidence themselves through radar scatter and clutter, optical signatures, and radio scintillation and refraction. ESF disturbs operational communication and navigation systems, including GPS, and interferes with SAR imagery. Forecasting ESF is a priority of the National Space Weather Program and the Air Force C/NOFS satellite program. Forecasting efforts have proceeded slowly, however, and undetected triggers or inhibitors are often suspected to be at work.

Ionospheric modification offers a means of experimenting with ESF triggering processes and testing the sensitivity of the stability of the ionosphere to different perturbations. Electron heating in F-region modification experiments is due mainly to anomalous absorption associated with the excitation of plasma instabilities. The subsequent effect on the plasma number density in the lower F region is mainly controlled by photochemistry and depends on the altitude and the temperature dependence of the recombination coefficient. Since the recombination rate is a decreasing function of temperature, the tendency is for electron density to actually increase during heating experiments there, whereas density decreases during heating at higher altitudes.

Allen et al. [1974] reported being able to induce spread F reproducibly in their mid-latitude heating experiments. During heating experiments at Arecibo *Djuth et al.* [1987] measured large temperature and density perturbations that they attributed to the pre-existence of marginal dynamical instability in the ionosphere. At equatorial latitudes instability triggering is likely to have the most dramatic and consequential results, which could then be systematically investigated.

Parametric decay instabilities

Two classes of plasma instabilities occur during ionospheric modifications: (a) parametric decay instabilities, which occur where the HF pump frequency matches the plasma frequency, and (b) thermal parametric instabilities, which occur at somewhat lower altitudes where the pump frequency matches the upper hybrid frequency. The former drives Langmuir and ion acoustic waves and gives rise to Langmuir turbulence, electron acceleration, and related processes. The latter produces stimulated radio emissions and artificial field-aligned plasma density irregularities (AFAIs). One effect of AFAIs is to scatter away the incident pump radiation, causing anomalous absorption and inhibiting the growth of the parametric decay instabilities above, which as a result become difficult to study after the irregularities emerge.

At the magnetic equator, O-mode HF pump waves emitted strictly vertically will propagate in the quasitransverse mode, and the wave electric field will consequently be parallel to the geomagnetic field. Without a transverse electric field component, the pump wave will not be able to excite thermal parametric instabilities, and AFAIs will not be created. For HF rays having slightly off-vertical incidence, the HF waves will be quasi-longitudinal, and irregularity excitation will occur as it does at middle and high latitudes. However, there will be a narrow cone directly over the heating facility through which HF radiation will be able to propagate directly through to the reflection height. Parametric decay instabilities will be driven continuously within that cone, offering a new means of studying their long-term behavior and evolution.

Equatorial electrojet current modulation

Attempts to generate low-frequency radio waves at high latitudes with HF heating have suffered from the unpredictability of the auroral electrojet as well as from the adverse effects of particle precipitation and deviative absorption, which prevents the pump power from reaching the electrojet current. The equatorial electrojet, meanwhile, exhibits extremely reliable diurnal behavior, and low-latitude heating experiments do not suffer from the effects of precipitation. Preliminary tests carried out in the 1980's using the Jicamarca 50-MHz radar as an underdense heater demonstrated the plausibility of VLF generation using the equatorial electrojet. The installation of a heating facility would provide a full experimental and operational capability.

Other factors also suggest that the equatorial electrojet is more suitable for low-frequency wave emission than the auroral electrojet. *Papadopoulos* [2008] discuss how the radiation generated in the equatorial electrojet will couple much more efficiently into the Earth-ionosphere waveguide than radiation generated at high latitudes, which tends to couple into the magnetosphere. *Lehtinen and Inan* [2009] conducted full-wave numerical simulations of VLF/ELF emissions generated by a heater at the geomagnetic equator that show all of the radiated power contained within the Earth-ionosphere waveguide and a total generated energy flux 30 times greater than predicted for the auroral electrojet case under comparable conditions. The emitted radiation was furthermore directional, implying still higher effective radiated power by comparison. The equatorial electrojet contains a significant vertical current component which, when modulated, acts like a vertical dipole element, which is well suited for exciting the Earth-ionosphere waveguide.

The aforementioned predictions are remarkable and suggest that an important operational capability could emerge from an equatorial heater. From a space physics perspective, the scientific utility of the heater would come from testing theories and exploring the related plasma physics.

Modification of equatorial irregularities

A heater at the equator will be very useful for performing controlled experiments of equatorial mesospheric and 150-km irregularities. In the case of mesospheric echoes, for example, one can determine whether or not charged particles play an active role. Recent radar studies of 150-km echoes indicate the presence of both field-aligned irregularities and naturally-enhanced ion-acoustic waves [e.g., *Chau et al.,* 2009]. Moreover, the modulation of these echoes by extreme ultraviolet solar radiation indicates the presence of Langmuir turbulence, the controlled investigation of which would be another promising area of study for an equatorial heater.

Cost estimate

We have estimated the cost of a 100-MW ERP-class heating facility able to generate the heater-related phenomena described here, and comparable to the former HIPAS (Alaska), existing SPEAR (Norway), and new Arecibo systems. The cost estimates have been obtained with the help of colleagues and contractors constructing the new Arecibo heater, modified for local conditions in Peru. The main estimated costs are: (1) antenna and transmitter design and prototype construction and testing (~$500,000), (2) final system construction and installation, including building and land preparation (between $4 and $8 million USD, depending on the transmitter option selected).

Preliminary studies indicate that a suitable array would consist of 6x6 cross-polarized log-periodic antennas. The design will utilize distributed, custom-made, solid-state, roughly 10-kW transmitters. Given the high efficiency expected from this transmitter system, and the total transmitter power, diesel or natural gas generators would be used. The expected operational cost, assuming 150 transmitting hours per year, would be around $100,000/year.

Benefits

Below we describe some of the practical benefits to the scientific and broader communities.

Previous studies

The proposed concept has not been identified in previous NRC decadal surveys.

Significant contributions to panel themes

The proposed ground-based instrument provides significant contributions to the Atmosphere-Ionosphere-Magnetosphere Interactions panel theme as well as coupling to other themes.

Important science questions

This project addresses some of the most pressing basic science questions in AIM including the physics behind electron acceleration, wave-wave coupling, and ionospheric instabilities. It also has the potential of providing a new diagnostic of ionospheric parameters, rate constants, and transport coefficients, adding to and going beyond what incoherent scatter techniques currently provide.

Societal benefits and operations

Low-frequency electromagnetic waves can play an important role in submarine communication and subsurface remote sensing, and an equatorial heater represents a cost-effective means of achieving these capabilities. Forecasting of equatorial spread F is important to a number of space weather interests, and controlled, repeatable ionospheric experiments may accelerate progress in this area.

Other systems and programs complemented

This project complements existing ionospheric modification programs underway in Europe, Alaska, and Puerto Rico. A significant community of users surrounding the annual Radio Frequency Ionospheric Interactions ("Santa Fe") Workshop and Polar Aeronomy and Radio Science (PARS) summer school already exists. Likewise, the project builds on existing infrastructure at Jicamarca and on the close ties between NSF, Cornell University, and the Peruvian Geophysical Institute (IGP).

Affordability

This project leverages existing infrastructure in Peru, and experience and design know-how developed through Arecibo's recent heater deployment, which included the involvement of some IGP personnel. The cost will be very modest compared to previous heater projects.

Readiness

As described above, ionospheric heating is a well-known field. The novelty of the proposed idea relies on the location, i.e. under the magnetic equator. The main challenge would be to keep within a reasonable budget. Personnel and companies involved in the construction of the Arecibo heater would join the scientific and technical expertise at the Jicamarca Radio Observatory to carry out the construction and installation of the equatorial heater. Operation of the proposed heater could be handled in the same way as for the Jicamarca Radio Observatory, which has been jointly operated by the Peruvian Geophysical Institute, Cornell University, and NSF for over 30 years.

International plans and activities

The proposed heater would attract broad international participation. For example, both Western and Eastern Europe have long traditions in this field, and a correspondingly large community of interested and participating experimentalists and theorists.

References

Allen, E. M., G. D. Thome, and P. B. Rao, HF phased array observations of heater-induced spread F, Radio Sci., 9, 905–916, 1974.

Bailey, V. A., and D. F. Martyn, Influence of electric waves in the ionosphere, Phil. Mag., 22, 369, 1934.

Bernhardt, P. A., N. A. Gondarenko, P. N. Guzdar, F. T. Djuth, C. A. Tepley, M. P. Sulzer, S. L. Ossakow, and D. L. Newman, Using radio-induced aurora to measure the horizontal structure of ion layers in the lower thermosphere, J. Geophys. Res., 108(A9), 1336, doi:10.1029/2002JA009,712, 2003.

Chau, J. L., R. F. Woodman, M. A. Milla, E. Kudeki, Naturally enhanced ion-line spectra around the equatorial 150-km region, Annales Geophysicae Vol. 27, 933–942., 2009.

Djuth, F. T., B. Thid´e, H. M. Ierkic, and M. P. Sulzer, Large F-region electron temperature enhancements generated by high-power HF radio waves, Geophys. Res. Lett., 14, 953–956, 1987.

Duncan, L. M., and W. E. Gordon, Ionospheric modification by high power radio waves, J. Atmos. Terr. Phys., 44(12), 1009–1017, 1982.

Erukhimov, L. M., N. A. Mityakov, and B. Thid´e, On the excitation of the ionosphere by high-power radio waves in the geomagnetic eqautor region, Radiophys. Quantum Electron. (Engl. Trans.), 40, 165, 1997.

Fejer, J. A., Ionospheric modification and parametric instabilities, Rev. Geophys. Space Phys., 17, 135–153, 1979.

Ferraro, A. J., H. S. Lee, R. Allshouse, K. Carroll, A. A. Tomko, F. J. Kelly, and R. G. .Joiner, VLF/ELF radiation from the ionospheric dynamo current system modulated by powerful HF signals, J. Atmos. Terr. Phys., 44(12), 1113–1122, 1982.

Fialer, P. A., Field-aligned scattering from a heated region of the ionosphere – observations at HF and VHF, Radio Sci., 9, 923–940, 1974.

Frolov, V. L., L. M. Erukhimov, S. A. Metelev, and E. N. Sergeev, Temporal behavior of artificial smallscale ionospheric irregularities: review of experimental results, J. Atmos. Sol. Terr. Phys., 18, 2317–2333, 1997.

Gurevich, A. V., Nonlinear effects in the ionosphere, Uspekhi Fizicheskikh Nauk., 177(11), 1145–1177, 2007.

Gustavsson, B., et al., The electron distribution during HF pumping, a picture painted with all colours, Ann. Geophys., 23, 1747–1754, 2005.

Lehtinen, N. G., and U. S. Inan, ELF/VLF wave radiation produced by an equatorial ionospheric heater, oral presentation at National Radio Science Meeting; Boulder, CO; Abstract HG2-9, January 5–8, 2009.

Minkoff, J., P. Kugelman, and I. Weissman, Radio-frequency scattering from a heated ionospheric volume, 1, VHF/UHF field-aligned and plasma line backscatter measurements, Radio Sci., 9, 941–955, 1974.

Nossa, E., D. L. Hysell, C. T. Fallen, and B. J. Watkins, Radar observations of artificial E-region field-aligned irregularities, Ann. Geophys., 27, 2699–2719, 2009.

Papadopoulos, K., Pulsed artificial electrojet generation, AGU, FallMeet. Suppl., Abstract SA42A-01, 2008.

Rietveld, M., M. Kosch, N. Blagoveshchenskaya, V. Kornienko, T. Leyser, and T. Yoeman, Ionospheric electron heating, optical emissions and striations induced by powerful HF radio waves at high latitudes: Aspect angle dependence, J. Geophys. Res., 108, 1141, doi:10.1029/2002JA009,543, 2003.

Vas'kov, V. V., and A. V. Gurevich, Resonance instability of small-scale plasma perturbations, Sov. Phys. JETP Engl. trans., 46, 487–494, 1977.