HAARP, the most powerful ionosphere heater on Earth

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When stimulated with high-intensity radio waves, the ionosphere responds with baffling and beautiful displays.

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Our modern world of Wi-Fi, smartphones, and location apps relies on radio waves to link up all our gadgets. Most of us, though, are unaware that the ionosphere high above Earth affects the location services in our phones and the directions relayed by the navigation units in our cars. The complex dynamics of the ionospheric plasma, a gas of electrons and ions enveloping our planet, can be studied by research facilities such as the High Frequency Active Auroral Research Program (HAARP), located in Alaska. During the past 15 years, HAARP has produced many interesting and unexpected results, perhaps most spectacularly the production of an artificial ionospheric plasma generated by radio waves.

Atmospheric shrapnel

The ionosphere is the region of the upper atmosphere characterized by a large population of free electrons and ions—the atmospheric shrapnel that arises when UV photons from the Sun knock electrons from atmospheric gas. (For a tour of the upper atmosphere, see the Quick Study by John Emmert, Physics Today, December 2008, page 70.) Its density is controlled by the relative rates of ion production and the recombination of ions with electrons to re-create neutral molecules. The ionosphere begins at an altitude of about 70 km, reaches a peak daytime density of something like a million particles per cubic centimeter near 250 km, and tapers off above that altitude to blend into the much more rarefied plasmasphere, magnetosphere, and solar wind.

The ionospheric plasma can distort and delay satellite communications and navigation signals passing through it; indeed, the primary practical motivation for studying the ionosphere is to get a handle on those effects. At the low power of day-to-day devices, the ionospheric plasma can alter radio waves, but the plasma itself is unaffected. At high enough power densities, however, radio waves can affect the plasma and generate feedback between the waves and plasma, a phenomenon that offers a unique means—so-called ionospheric heating—of studying the ionosphere.

The HAARP facility began operating in 1999 with a 6 × 8 array of transmitting antennas that, in total, produced 960 kW of RF power—about the same as generated by 10 AM radio stations. (The figure shows today's 12 × 15 array.) The HAARP beam is broad like a flashlight's, not narrow like a laser's, but it can be electronically steered anywhere within 30° of zenith—that is, local vertical—and it can operate at 3–10 MHz. Its powerful radio waves drive ionospheric electrons back and forth in what are called plasma waves. As those driven electrons collide with each other and with background species, their temperature goes up, which is why HAARP is called a heater.

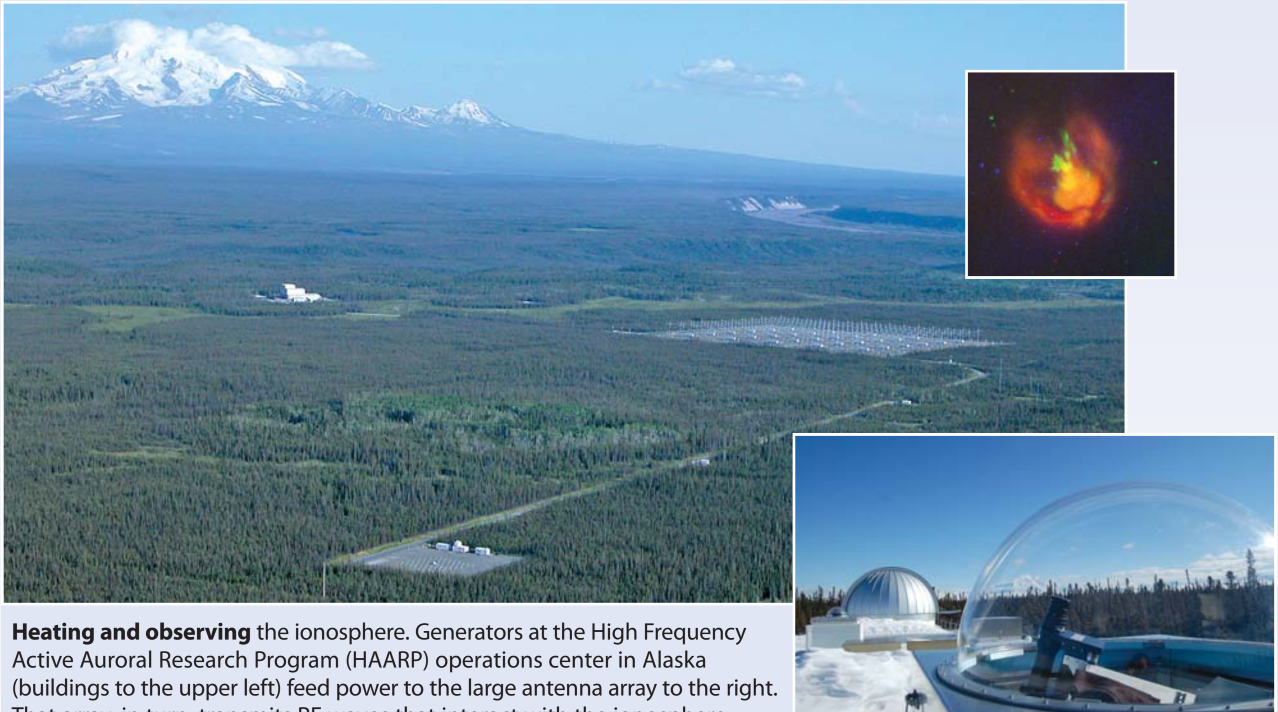
A series of unexpected events

Just as an opera soprano needs to sing at just the right frequency to break a glass, so a heater must target frequencies that match the natural plasma resonances in the ionosphere. Primary targets include the plasma frequency, a function of electron density; multiples of the cyclotron frequency of electrons spiraling around the magnetic field; and hybrid resonances that combine those fundamental frequencies.

Measurements of optical emissions excited by heated electrons yielded HAARP's first unexpected result. Spotting such emissions at all was a feat, inasmuch as 20 years of attempts to do so at the EISCAT (European Incoherent Scatter) heater in Norway's Arctic had been unsuccessful; in fact, HAARP scientists had been warned that looking for optical emissions would be a waste of time. Nevertheless, images recording the red 630.0-nm oxygen line revealed a faint blob turning on and off in sync with the heater; that could only mean HAARP had heated the electrons and excited the oxygen. The airglow showed an unexpected enhancement well away from the beam center, at the magnetic zenith—that is, the direction of the magnetic field. The obvious next step was to point the beam toward the magnetic zenith, which at HAARP is about 15° south-southwest of vertical. When the experiment was finally performed in 2002, as the HAARP array swung the beam through the magnetic zenith, the blob lit up and was 10 times as bright as airglow in any other location. A variation of that magnetic zenith effect had been previously observed at EISCAT, but neither the EISCAT nor HAARP version of the effect had been predicted and neither is fully understood.

Thanks to its frequency agility, the HAARP antenna can heat the ionosphere at specific altitudes where the transmission frequency simultaneously matches two resonances. In 2004, experiments exploiting that possibility produced green-line oxygen emissions at 557.7 nm. (The figure shows an airglow with red and green oxygen emission.) Those lines come from an excited state with an energy 4 eV above the ground-state energy; evidently, by "surfing" plasma waves, the electrons accelerated to energies well beyond the thermal energy. Another HAARP experiment in the same series heated an ephemeral ionospheric layer produced by an aurora; the resulting green spots were as bright as the aurora itself. Those extremely bright spots have since been reproduced but are not yet explained.

In 2007 HAARP expanded to its full design capability of 12 × 15 antennas and 3.6 MW of total power. During its first postexpansion science campaign, in February 2008, my colleagues and I obtained optical images with strange, unpredicted rings around the airglow spot. We hypothesized that if the plasma in the center of the beam were slightly enhanced



Heating and observing the ionosphere. Generators at the High Frequency Active Auroral Research Program (HAARP) operations center in Alaska (buildings to the upper left) feed power to the large antenna array to the right. That array, in turn, transmits RF waves that interact with the ionosphere. Shelters down the road from the array house optical instruments for observing the resulting excitations; one of the instruments is visible through the clear dome in the lower inset. (Backdrop photo by A. Lee Snyder; inset photo by Robert Esposito.) The red and green regions in the upper inset (courtesy of Jeffrey Holmes) represent regions of the ionosphere in which oxygen atoms excited by ionospheric heating relax to lower-energy states. Behind the HAARP site rises Mount Drum.

in density relative to the background ionosphere, the density gradient could divert rays away from the center of the beam toward the location where the ring was observed. Careful examination of echoes from radio waves bounced off the ionosphere turned up evidence for a density-enhancing artificial plasma layer just below the natural ionosphere. Moreover, simulations of RF waves propagating through the observed layer put additional power right where the rings were seen.

We had not expected such artificial ionization to be possible, but we followed up with new experiments designed to optimize ionization production. In March 2009, just over 10 years after we were told that looking for airglow was futile, I stepped outside with a couple of coworkers during an ionization experiment and marveled at the light—visible with unaided eyes—from an artificial ionospheric plasma produced and sustained by radio waves transmitted from the ground.

In addition to generating unexpected phenomena, HAARP scientists used and further developed a diagnostic technique pioneered at EISCAT: stimulated electromagnetic emissions. The effect arises when plasma waves stimulated by the heater regenerate radio waves that are received on the ground as a complex spectrum of narrow peaks and broad bumps on either side of the transmission frequency. Some of those depend not only on electron density but also on ion mass, magnetic field strength, or other parameters. Thus the stimulated emissions provide a potentially powerful tool for analyzing conditions in the heated volume.

A zoo of plasma waves

Admittedly, research at HAARP has not directly contributed to new corrections for ionospheric effects on navigation or communications systems. Instead, the many surprises encountered in HAARP experiments have made abundantly clear the need for quantitative predictive theory and modeling in the field of high-power RF-wave propagation. The complex equations describing plasma waves imply a whole zoo of wave modes that could potentially be excited by a transmitter.

But no one can predict with certainty whether a particular wave mode will absorb half the transmitted energy or only one part in a million. For example, observed artificial plasma production accounts for only about 5% of the energy available from the beam; some of the remaining 95% undoubtedly excites other modes that might mislead researchers into wrongly identifying the cause of the ionization. Stimulated electromagnetic emissions hold the greatest promise for helping scientists determine which wave modes are active during actual experiments.

An interesting and still unexplored aspect of artificial ionization is the complex interplay between the plasma created by radio waves and the bending or reflecting of radio waves by that plasma. As food for thought, have a look at the video that accompanies the online version of this Quick Study. You'll see a wide range of spots, turbulence, and sharp gradients—despite the smoothly varying beam. If we are ever to develop practical applications of heating technology, we'll need to find mathematical solutions describing the evidently complex feedback process.

In August 2015 the HAARP facility was transferred from the US Air Force to the University of Alaska so that HAARP scientists could continue their investigations of fundamental plasma physics in an academic environment.

Additional resources

▶ F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion, Volume 1: Plasma Physics*, 2nd ed., Springer (2006).
▶ B. Freeman, "HAARP scientists create mini ionosphere," *Armed with Science* blog (27 February 2010).
▶ N. Rozell, "HAARP again open for business," University of Alaska Fairbanks online news story (3 September 2015). ■