REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-01-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
30-01-2010	REPRINT	

4. TITLE AND SUBTITLE
Creation of artificial ionospheric layers using high-power HF waves

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

5d. PROJECT NUMBER
2311

5e. TASK NUMBER
SD

5f. WORK UNIT NUMBER
A4

6. AUTHORS
T. Pedersen
B. Gustavsson*
E. Mishin
E. Kendall**
T. Mills
H. C. Carlson@
A. L. Snyder@@

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory /RVBXI
29 Randolph Road
Hanscom AFB, MA 01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RV-HA-TR-2011-1031

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBXI

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; distribution unlimited.

20110627115

13. SUPPLEMENTARY NOTES
Reprinted from *Geophysical Research Letters,* Vol. 37, L02106, doi:10.1029/2009GL041895, 2010 ©2010, American Geophysical Union
*InfoLab21, Lancaster Univ., Lancaster, UK. **SRI International, Menlo Park, CA @AFOSR, Arlington, VA @@NWRA, Stockton Springs, ME

14. ABSTRACT
We report the first evidence of artificial ionospheric plasmas reaching sufficient density to sustain interaction with a high-power HF pump beam produced by the 3.6 MW High-Rrequency Active Auroral Program (HAARP) transmitter in Gakona, Alaska. The HF-driven ionization process is initiated near the 2nd electron gyroharmonic at 220 km altitude in the ionospheric F region. Once the artificial plasma reaches sufficient density to support interaction with the transmitter beam it rapidly descends as an ionization wave to ~150 km altitude. Although these initial artificial layers appear to be dynamic and highly structured, this new ability to produce significant artificial plasma in the upper atmosphere opens the door to a new regime in ionospheric radio wave propagation where transmitter-produced plasmas dominate over the natural ionospheric plasma and may eventually be employed as active components of communications, radar, and other systems.

15. SUBJECT TERMS
Ionosphere Polar regions High Latitudes Ionospheric irregularities Plasma processes
Active experiments Ionospheric scintillation Equatorial ionosphere HF heating

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Todd R. Pedersen
UNCL	UNCL	UNCL	UNL	5	19B. TELEPHONE NUMBER *(Include area code)*

GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L02106, doi:10.1029/2009GL041895, 2010

Creation of artificial ionospheric layers using high-power HF waves

T. Pedersen,[1] B. Gustavsson,[2] E. Mishin,[1] E. Kendall,[3] T. Mills,[1] H. C. Carlson,[4] and A. L. Snyder[5]

Received 24 November 2009; revised 23 December 2009; accepted 5 January 2010; published 30 January 2010.

[1] We report the first evidence of artificial ionospheric plasmas reaching sufficient density to sustain interaction with a high-power HF pump beam produced by the 3.6 MW High-Frequency Active Auroral Program (HAARP) transmitter in Gakona, Alaska. The HF-driven ionization process is initiated near the 2nd electron gyroharmonic at 220 km altitude in the ionospheric F region. Once the artificial plasma reaches sufficient density to support interaction with the transmitter beam it rapidly descends as an ionization wave to ~150 km altitude. Although these initial artificial layers appear to be dynamic and highly structured, this new ability to produce significant artificial plasma in the upper atmosphere opens the door to a new regime in ionospheric radio wave propagation where transmitter-produced plasmas dominate over the natural ionospheric plasma and may eventually be employed as active components of communications, radar, and other systems. **Citation:** Pedersen, T., B. Gustavsson, E. Mishin, E. Kendall, T. Mills, H. C. Carlson, and A. L. Snyder (2010), Creation of artificial ionospheric layers using high-power HF waves, *Geophys. Res. Lett.*, *37*, L02106, doi:10.1029/2009GL041895.

1. Introduction

[2] The ionospheric plasma a few hundred kilometers above the earth's surface acts as a reflector for radio waves in the HF frequency range, enabling long-distance radio communications, over-the-horizon radar, and other technologies of growing importance for national security and counter-terrorism applications [*McNamara*, 1991]. However, the natural diurnal, seasonal, and solar-driven variability of the ionosphere imposes severe limitations on operation of such systems. Concepts to actively control radio propagation by using high-power electromagnetic waves to ionize the gasses in the upper atmosphere and create artificial ionospheric plasma have been discussed for decades [e.g., *Koert*, 1991], but have never been demonstrated due to the large electric field thresholds required for conventional or even runaway breakdown [*Gurevich and Zybin*, 2005]. Recent advances in high-power HF excitation of the ionosphere made possible by completion of the High-Frequency Active Auroral Research Program (HAARP) transmitter facility, however, have made production of significant artificial ionospheric plasma possible for the first time, opening the door to practical exploration of these concepts.

[3] Electromagnetic waves with ordinary (O) mode polarization are reflected from plasmas at the point the transmitted wave frequency f_T equals the local plasma frequency $f_p \approx 9\sqrt{N_e}$ kHz (for N_e in cm^{-3}), which depends only on the plasma density N_e. High-power radio waves can transfer significant energy to the ionospheric plasma when f_T matches plasma eigen-frequencies near f_p, the upper hybrid frequency $f_{uh} = \sqrt{f_p^2 + f_{ce}^2}$, or multiples of the electron gyro frequency f_{ce}. This energy can heat the ionospheric electron population to thousands of Kelvin above ambient and also accelerate electrons to suprathermal energies in the range of a few to few dozen eV. Suprathermal electrons excite optical emissions upon impact with the neutral gasses [*Bernhardt et al.*, 1988], and can actually create new plasma when their energy exceeds the ionization potentials of the gasses (~12–18 eV) [*Gustavsson et al.*, 2006].

[4] Based on energy budget estimates, creation of artificial ionization by HF heating has been predicted to occur when power densities in the HF beam reach 1 GW effective radiated power (ERP), similar to that of the solar extreme ultraviolet flux creating the natural ionosphere [*Carlson*, 1993]. However, the effects of ionization production have generally been too small to be detectable in the ionosphere until the recent upgrade of the HAARP facility in Gakona, Alaska (62.4° N 145° W) to 3.6 MW power, providing ERP in the range of 400–4000 MW. Initial experiments after the upgrade showed indications of enhanced plasma densities near 200 km altitude on the bottomside of the ionospheric F region, which apparently de-focused the transmitter beam into a ring surrounding a bright central spot visible in optical measurements [*Pedersen et al.*, 2009]. In this report we present the first evidence of artificial ionization reaching the threshold of self-perpetuation, where the artificial plasma becomes sufficiently dense to sustain interaction with the transmitter beam. This breaks the dependence on the natural ionosphere and allows the artificial plasma to descend as an ionization "wave" toward higher power densities closer to the transmitter, forming a glowing artificial layer near 150 km altitude in the ionospheric "valley" region, a minimum in natural plasma density.

2. Observations

[5] The most pronounced cases of artificial layer formation in the valley region occurred between 4–6 UT on March 17, 2009, corresponding to twilight and early evening hours

[1]Space Vehicles Directorate, Air Force Research Laboratory, Hanscom AFB, Massachusetts, USA.
[2]InfoLab21, Lancaster University, Lancaster, UK.
[3]SRI International, Menlo Park, California, USA.
[4]Air Force Office of Scientific Research, Arlington, Virginia, USA.
[5]Northwest Research Associates, Stockton Springs, Maine, USA.

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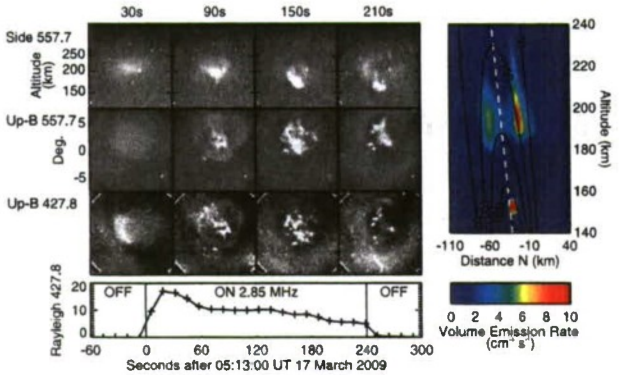

Figure 1. (left) Images of artificial optical emissions as viewed from the remote site at 557.7 nm (top, with altitudes along the HAARP field line indicated), and from the HAARP site looking up the field line with high resolution at 557.7 nm (2nd row) and 427.8 nm (3rd row). Average calibrated intensities at 427.8 nm for the central region of the images are shown in the 4th row as a function of seconds after the transmitter turned on at 5:13:00 UT. (right) The 557.7 nm images for 210s have been combined using a tomographic algorithm to provide a cross-section of the optical volume emission rate in the magnetic meridian plane. The HAARP magnetic field line and contours of nominal transmitter power in percent relative to peak power at 230 km altitude have been superimposed on the tomographic cross section.

in Alaska local time. The transmitter was pointed at the magnetic zenith (az = 202° el = 76°) and operated with O-mode polarization at full power of ~440 MW ERP alternating between 4 min at full power and 4 min off to allow recovery from artificially induced effects. The transmitter frequency alternated between 3.16 and 2.85 MHz every other "on" period to compare effects away from and near $2f_{ce}$. After 05:05 UT the ionospheric critical frequency $f_O F_2$ dropped below 3.16 MHz and only 2.85 MHz was utilized. The transmitter beam had a full width at half maximum of 18 degrees along the magnetic meridian at 2.85 MHz. Optical observations were carried out with a remote wide-field imager located ~160 km N of HAARP, and with multiple wide- and narrow-field systems at the HAARP site observing 557.7 nm emissions from the ^1S state of atomic oxygen corresponding to >4 eV electron energy and 427.8 nm N_2^+ emissions indicating ionization production at >18 eV. Figure 1 shows a series of optical images viewed obliquely from the remote site at 557.7 nm (top row) and looking up the magnetic field from HAARP (557.7 and 427.8 nm in the 2nd and 3rd rows) during an artificial layer creation event from 05:13-05:17 UT. Emission intensities averaged over the central part of the 427.8 nm images are shown in the fourth row.

[6] Early in the period, the optical emissions are diffuse and roughly proportional to the transmitter beam intensity. In the second minute, the diffuse emissions have organized themselves into a sharp-edged central disk with indications of a ring surrounding it. Very bright field-aligned filaments begin to appear in the center of the disk and descend in altitude. In the 3rd minute, the filaments are very intense and the emissions have descended to nearly 150 km altitude. The central region immediately surrounding the filaments also begins to grow dark, a trend which reaches its extreme in the 4th minute, where emissions in the center of the beam have formed a bright spot near 150 km altitude, leaving an empty ring near 200 km. The localized spot and ring are clearly shown in a cross section through a tomographic reconstruction generated from 557.7 nm images from the 2 sites (Figure 1, right). The magnetic field line and nominal contours of transmitter beam power in percent relative to 230 km altitude at the beam center have been superimposed on the cross section.

[7] Although the accelerated electrons exciting the optical emissions can travel ~10 km or so along the magnetic field from their source, the isolated spot near 150 km in the beam center indicates that a strong interaction with the 2.85 MHz transmitter beam is taking place at this altitude. Note that the natural plasma density at that altitude at this time of night is below 2.5×10^4 cm^{-3} or ~200 kHz, an order of magnitude too low for interaction.

[8] Ionograms recording the apparent range of points where the plasma frequency matches the swept ionosonde probe frequency were acquired at 1 min intervals throughout the experiment. Ionograms just before and during a transmitter "on" cycle that started at 05:21 UT are displayed in Figure 2. The "off" ionogram (Figure 2, left) shows only the background F-region ionosphere, which peaks near 250 km. Densities below ~200 km virtual height are below the 1 MHz detection threshold in the mode utilized. After several minutes of heating, however (Figure 2, middle), clear layers of new echoes are seen at ~200 km and 160 km virtual range, closely corresponding to the observed optical structures. Although the HAARP transmitter interferes with ionosonde reception near f_T, X-mode echoes (green) reflect from the same density levels at higher frequencies above this gap, and can be related to O-mode echoes by the expression $f_x = \frac{f_{ce}}{2} + \sqrt{f_o^2 + \left(\frac{f_{ce}}{2}\right)^2} \approx f_o + \frac{f_{ce}}{2}$. This indicates that the O-mode critical frequency in these layers reached 2.6 and 3.0 MHz. True height profiles inverted from these traces using the University of Massachusetts Lowell SAO Explorer program are shown in the right panel, although

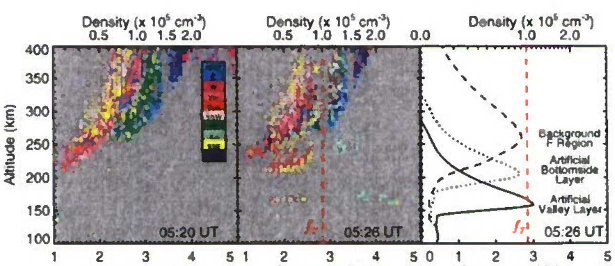

Figure 2. (left) Ionogram showing only background F-region echoes while the transmitter was off. (middle) After several minutes of heating, the interaction region descends to lower altitudes, and two lower layers of echoes become apparent near 160 and 200 km virtual height. (right) Using both the O-mode (red and pink) and X-mode (green) echoes allows the gap resulting from interference at the transmitter frequency to be bridged and density true height profiles to be determined for the various layers.

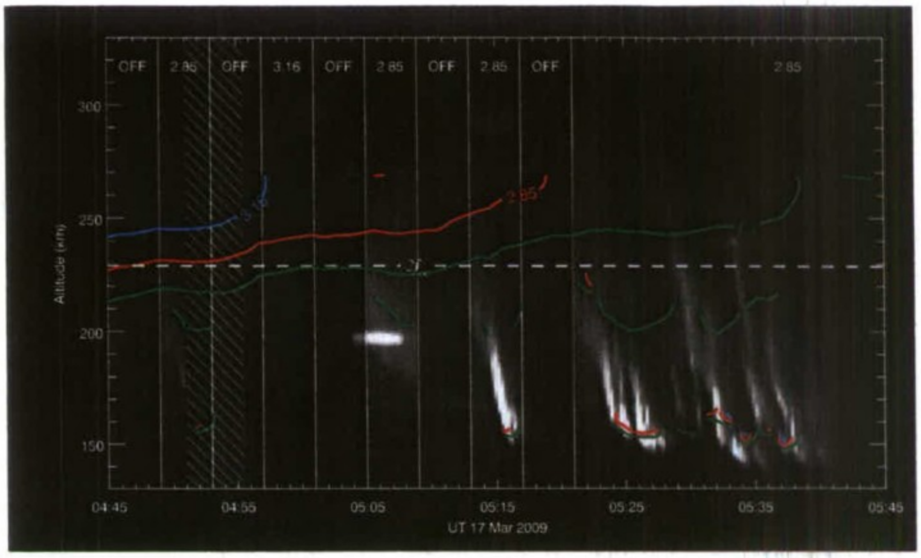

Figure 3. Time-vs-altitude plot of 557.7 nm optical emissions along the HAARP field line with contours showing the altitudes where f_p = 3.16 MHz (blue), f_p = 2.85 MHz (red), f_{uh} = 2.85 MHz (green), and $2f_{ce}$ = 2.85 MHz (dashed white). Horizontal blips such as the one seen near 200 km altitude at 5:05 UT are stars passing through the view.

the top sides of the profiles are extrapolated by the software and are not observable with the ionosonde technique. The inescapable conclusion from the combined optical and ionosonde measurements is that artificial ionospheric layers were produced at 200 and ~150 km altitude, and that the density in the lower of the layers actually exceeded both f_T and the background $f_O\ F_2$.

[9] This phenomenon was reproduced on multiple nights, but in the following section we present a broader view of several repetitions of the experiment on the night of March 17. Figure 3 shows sequential altitude profiles extracted from the oblique optical images along the projection of the HAARP magnetic field line, overlaid with contours of plasma frequency obtained by inversion of the 1-min ionograms.

[10] On this night, artificial optical emissions at 557.7 nm were first detected above the twilight during a 4-min "on" period at 04:49 UT at 2.85 MHz, but a gap in the optical data prevented full analysis of this period. Nevertheless, the ionosonde recorded increased densities on the bottomside and in the valley region as evidenced by descending contours of f_{uh} on the bottomside and 2.85 MHz in the valley region. Transmissions away from $2f_{ce}$ at 3.16 MHz were attempted in 3 experiment cycles prior to 04:45 UT, but produced no significant effects and were discontinued after the 4th cycle at 04:57 UT. At 2.85 MHz at 05:05 UT, however, strong emissions started out as a diffuse glow, then gathered into the spot-within-ring bullseye structure while gradually descending in altitude. Ionograms showed a secondary bottomside layer gradually descending, with the contour of f_{uh} approaching 200 km.

[11] The next "on" period starting at 05:13 UT corresponds to the images presented in Figure 1: initial development is similar to the previous period for the first 2 min., with a secondary layer again descending near 200 km at ~240 m/s. As the emissions reached 180 km altitude, however, the 557.7 nm intensity suddenly increased by a factor of 6 and the rate of descent rose to ~260 m/s, with the interaction region descending to ~150 km altitude over the next 90 seconds or so. Here the ionograms indicated the presence of plasma density up to 3.1 MHz, well in excess of f_T. During the 4th minute, the emissions appear to quench themselves somewhat and retreat in altitude before the end of the transmission. During a continuous "on" period beginning at 05:21UT, the same pattern is realized, with the emissions brightening at about 180 km and rapidly descending to ~150 km. In this case the emissions appear to quench themselves several times, initiating the descending process over again from higher altitudes, although some of the apparent vertical motion in the optical data toward the end of the period represents horizontal displacement. The ionosonde data indicate that artificially produced plasma density in excess of the 2.85 MHz transmitter frequency was present most of the time optical emissions were seen near 150 km altitude, as shown by the red contours between 150 and 160 km altitude. Once the background ionosphere had decayed below f_{uh} at about 05:40 UT, production of both optical emissions and artificial ionospheric layers ended. Just prior to the end of the optical emissions, the authors present at HAARP during the experiment went outside and were able to observe the artificial optical emissions with the naked eye, an indicator of the extraordinary intensity of the emissions produced [cf. *Pedersen and Gerken*, 2005].

3. Discussion

[12] We interpret these observations as follows: near the double resonance where f_T simultaneously matches both f_{uh} and $2f_{ce}$, electrons are efficiently accelerated [e.g., *Kosch et al.*, 2007] and ionize the neutral gas, adding to the ambient plasma density. This pushes the density contours down over a few minutes to form a descending artificial ionospheric layer near 200 km, sufficiently dense to sustain interaction at f_{uh} but not f_p. This part of the process was seen in each of the

2.85 MHz cases on March 17 as well as earlier experiments, and appears in ionograms as a secondary bottomside layer.

[13] As the interaction altitude descends, the power density in the transmitter beam goes up as $\frac{1}{r^2}$, already reaching 132% at 200 km compared to 230 km. This process continues until about 180 km (163% power), when the plasma frequency in the descending layer reaches f_T. This would correspond to formation of the bright field-aligned structures in the optical images. Stimulation of the plasma resonance now becomes possible, providing an additional potential mechanism for accelerating even more electrons. Propagation of transmitter power to altitudes above the artificial layer is now blocked in the center of the beam, with any HF power not absorbed being reflected back down and adding to the field strength below the reflection point. With this new electron source, the localized artificial plasma now becomes completely self-sustaining, and rapidly propagates downward as an ionization wave front toward the transmitter, appearing as a layer of echoes in the ionograms near 150 km. For a realistic density gradient of 10^5 cm^{-3} over 10 km, the observed propagation implies an ionization production rate in excess of losses by about 2.6×10^3 cm^{-3} s^{-1}. The descent of the artificial ionization stalls at ~150 km altitude, near the transition from atomic oxygen to short-lived molecular ions, which decay at rates exceeding even the enhanced ionization production rate, now driven by 235% nominal transmitter power.

[14] The complete quenching of the artificial ionization upon reaching ~150 km altitude is more difficult to explain, but as seen in the 427.8 nm intensity (Figure 1, bottom), the overall ionization rate averaged over the central region of the beam appears to go down steadily as the central region descends in altitude, and the matching frequency for $2f_{ce}$ increases to ~2.95 MHz at 150 km altitude. Excitation near the $2f_{ce}$ resonance has a significant frequency dependence [*Mishin et al.*, 2005; *Kosch et al.*, 2007]. This likely reduces the efficiency of electron acceleration even at higher power levels and contributes to the artificial plasma density production balance changing over from a net surplus evidenced by downward motion of the layer to a net loss, which rapidly leaves it unable to interact with the transmitter beam and maintain itself. This can be tested in future experiments by increasing the transmitter frequency as the layer drops to maintain f_T near $2f_{ce}$. In any case, as seen in the period after 5:21 UT when the transmitter remained on continuously, the interaction quenches itself after a few minutes at 150 km and starts over again near f_{uh} in the background ionosphere. When f_{uh} is no longer available due to decay of the background, the process is no longer able to restart itself.

[15] We note that while we have discussed evolution of the artificial ionization in terms of altitude, there is a parallel spatial evolution occurring simultaneously, with the bright filaments appearing away from the beam center and generally moving inward before extinguishing themselves. Also, although we have referred to the regions of artificially enhanced plasma density as "layers," based on their appearance in the ionosonde data, the optical images clearly show a high degree of spatial structure, with the areas of greatest density enhancement likely located inside the very bright field-aligned filaments a few km in diameter.

[16] While the exact mechanisms producing the artificial ionization layers in these experiments remain to be determined and the patchy and unstable nature of the enhancements pose difficulties to be overcome before practical applications become feasible, these experiments have demonstrated the first production of self-sustaining artificial ionospheric plasma and represent a major breakthrough laying the groundwork for a variety of controlled near-space radio applications based on a new technology of artificial ionospheric plasma production.

[17] **Acknowledgments.** HAARP is a Department of Defense program operated jointly by the U. S. Air Force and U.S. Navy. Work at AFRL was supported by the Air Force Office of Scientific Research. We thank the HAARP program for transmitter time, the operators and crew of the HAARP facility and remote optical site for their support, and L. McNamara for helpful discussions.

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H. C. Carlson, Air Force Office of Scientific Research, 875 N. Randolph St., Arlington, VA 22203, USA.

B. Gustavsson, InfoLab21, Lancaster University, South Drive, Lancaster LA1 4WA, UK.

E. Kendall, SRI International, 333 Ravenswood Ave., Menlo Park, CA 94025-3493, USA.

T. Mills, E. Mishin, and T. Pedersen, Space Vehicles Directorate, Air Force Research Laboratory, 29 Randolph Rd., Hanscom AFB, MA 01731, USA.

A. L. Snyder, Northwest Research Associates, 22 Black Rd., Stockton Springs, ME 04474, USA.