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MULTISITE OPTICAL IMAGING OF ARTIFICIAL IONOSPHERIC PLASMAS (POSTPRINT)

Todd R. Pedersen, et al.

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Interim Report

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Artificial ionospheric plasmas are formed on the bottom side of the natural ionospheric F region during high-power high-frequency (HF) heating experiments and descend to altitudes as low as 140 km before disappearing. Optical emissions produced during these events often exhibit bull's-eye structures, where the artificial plasma is thought to form a central spot that diverts or blocks HF waves to form an empty ring of emissions from the natural ionosphere at higher altitudes. We present multisite image data showing that, in some cases, both the spot and rig represent distinct artificial plasma layers.

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Multisite Optical Imaging of Artificial Ionospheric Plasmas

Todd R. Pedersen, Jeffrey M. Holmes, Bjorn Gustavsson, and Travis J. Mills

***Abstract*—Artificial ionospheric plasmas are formed on the bottom side of the natural ionospheric F region during high-power high-frequency (HF) heating experiments and descend to altitudes as low as 140 km before disappearing. Optical emissions produced during these events often exhibit bull's-eye structures, where the artificial plasma is thought to form a central spot that diverts or blocks HF waves to form an empty ring of emissions from the natural ionosphere at higher altitudes. We present multisite image data showing that, in some cases, both the spot and ring represent distinct artificial plasma layers.**

***Index Terms*—Ionosphere, optical imaging, plasma density, radio propagation.**

ARTIFICIAL IONOSPHERIC plasmas are localized regions of enhanced plasma density observed descending from the background natural ionosphere within the beam of a high-power high-frequency (HF) transmitter, particularly when the transmitter frequency is near the second harmonic of the electron gyrofrequency $(2f_{ce})$. Recently discovered at the High-Frequency Active Auroral Research Program (HAARP) facility in Gakona, Alaska (62.4° N 145° W) after the transmitter reached full 3.6-MW power, these plasmas appear in ionosonde measurements as distinct layers of echoes below those from the natural ionosphere, in regions of otherwise much lower plasma density [1]. Although the plasma production mechanism remains uncertain, a critical aspect of the artificial plasmas is that they are dense enough to interact directly with the HF waves and draw energy from the transmitter beam until eventually losing critical density and disappearing at altitudes near 150 km [1], [2]. Absorption of power within the plasma results in enhanced yet generally subvisual optical emissions excited by the impact of thermal and accelerated electrons [3]. Imaging of these emissions from multiple ground sites played a key role in the discovery of the plasmas and in the realization that they were self-sustaining layers dependent on the transmitter. In particular, in [1], optical emissions formed a bull's-eye pattern when seen from below, but remote images showed the artificial plasma in the center of the bull's-eye to be ∼50 km below the ring, which resulted from excitation of the natural ionosphere. In this paper, we present multisite images of an artificial ionospheric plasma which shows both the spot and ring to be distinct artificial layers.

The experiment was carried out on November 19, 2009, between 02:26 UT and 02:43:50 UT. Optical images were acquired at the HAARP site at 557.7 nm (O ^{1}S, excited by electrons > 4.19 eV) with a 1″ Princeton Instruments Versarray 1340 × 1300 pixel camera equipped with all-sky [180° field of view (FOV)] telecentric optics built by Keo Consultants and a 2-nm narrow-band filter. The detector was binned to 335 × 325 pixel resolution to enhance signal to noise and integrated for 5 s at a temperature of −40 °C. A second system located 160 km north of the HAARP near Delta Junction used an Apogee Alta E47 1/2″ 1024 × 1024 pixel CCD detector binned to 256 × 256 pixels and integrated for 13 s at −40 °C. This system viewed a field-broadening mirror through a 50-mm f/1.2 Nikon lens and a 10-nm filter centered at 560 nm, providing an effective FOV of ∼70°, which was centered at 45° elevation 180° azimuth. The HAARP HF transmitter was pointed vertically and operated at 3.6 MW (∼440 MW effective radiated power) in a frequency sweep mode from 2.85 to 2.95 MHz designed to match $2f_{ce}$ in the artificial plasma as it descended to altitudes of stronger magnetic field and higher gyrofrequency. The transmitter parameters and plasma density contours for this period are available in [2].

Fig. 1 shows a schematic of the observation setup and image data, shown in false color approximating the actual wavelength, from the remote system looking obliquely (upper left, acquired at 02:36:15 UT) and the HAARP imager looking up (top center, acquired at 02:36:07 UT). Note that the actual FOV in the image data is much broader than the notional lines of sight in the diagram. The up-looking image from the HAARP shows a partial but well-defined spot and a concentric ring separated by a pronounced dark gap. The oblique image of the same structure also shows a clear gap, but the gap is much wider at the top of the image and disappears near the bottom. This is consistent with a geometry similar to an inverted top hat, where the central spot forms a lower layer corresponding to the top of the hat, while the ring forms another layer at higher altitude corresponding to the brim of the hat. Triangulation of multiple points within both the ring and the spot over ∼15 min of the experiment shows the spot to be ∼15 km below the ring, a separation which was maintained from the initial formation near 200-km altitude to the final decay at 145 km as the structure descended steadily at ∼75 m/s. At the time of these

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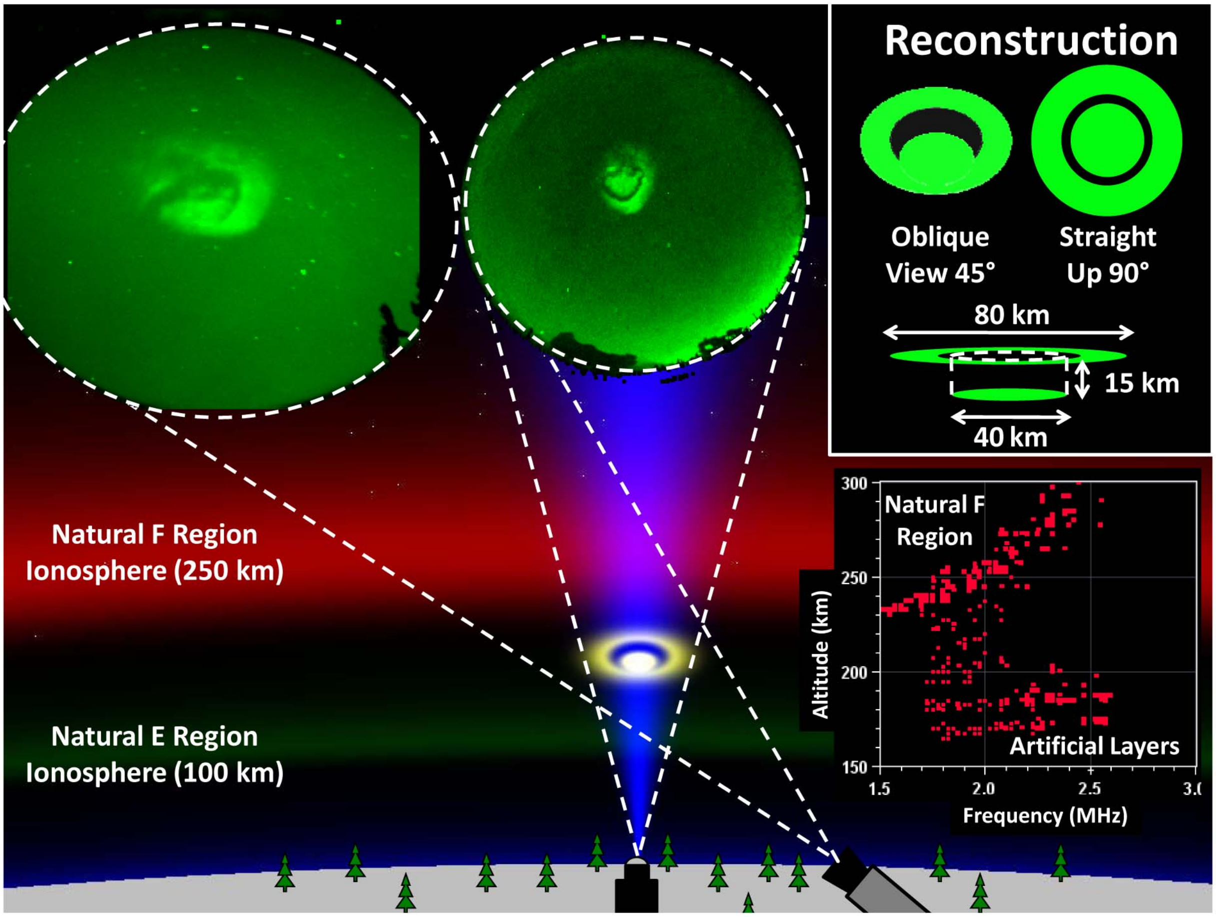

Fig. 1. Observation geometry and image data from two low-light imaging systems capturing 557.7-nm emissions from a bull's-eye-shaped artificial ionospheric plasma over the HAARP facility. A reconstruction based on the image data shows the central spot and the ring to form two distinct artificial layers separated in altitude by ∼15 km, which matches closely the multiple layers seen in ionosonde echoes (lower right).

images, the spot altitude was ∼160 km, and the ring was at ∼175 km. Fitting of circles to the spot, gap, and ring in the up-looking image gives radii of ∼6.4° for the edge of the spot, ∼8° for the inner edge of the ring, and ∼13° for the overall distribution. These compare to the 10° N-S and 8° E-W half-power half widths for the transmitter beam, shown in blue in the diagram. At the triangulated 160–175-km altitude for the images shown, the central spot is ∼40 km in diameter, while the inner edge of the ring is ∼50 km in diameter, and the outer edge of the entire pattern is ∼80 km in diameter.

The fact that the dark gap remains distinct even though it is less than 2° or ∼5 km wide indicates that the optical emissions originate in relatively thin layers and do not have large extent along the magnetic field. The inverted top-hat geometry reconstructed from these optical images sheds new light on the ionosonde data (lower right), which showed two artificial layers ∼15–20 km apart in altitude during this period.

In conclusion, multisite optical imaging has demonstrated that artificial ionospheric plasmas can take the form of two distinct layers in a 3-D inverted top-hat configuration. Accurate determination of the properties of such plasmas is essential for the development of practical applications such as enhanced over-the-horizon radar propagation.

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