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Ionospheric Duct Formation at the HAARP HF Facility in Alaska Using Pencil and Twisted Beams

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The F-Region ionosphere plays a crucial role in the propagation of whistler waves along magnetic field lines, particularly when these waves interact with energetic particles in the Earth's magnetosphere. Ionospheric ducts, which guide waves into the radiation belts, can be created by high-powered, localized High Frequency (HF) heating of F-Region plasma on the bottom of the ionosphere. This heating causes the F-region plasma to move along magnetic field lines in response to the pressure increase from the elevated electron temperatures, forming a field-aligned structure that can guide whistler waves.

The high-power, HF radio beam modes have different shapes based on the phasing of the HAARP array of 12 x 12 crossed dipoles. When all the dipoles are driven in phase, a pencil beam is formed with a Gauss-Laguerre shape designation of L=0. Previous research, including studies using the High-frequency Active Auroral Research Program (HAARP), has successfully demonstrated ionospheric duct formation with L=0 configurations [1]. These HF beams generate ducts with a central, high-density region that guides whistler waves along the magnetic field lines into the magnetosphere. However, 180-degree phasing of the complementary elements on both sides of the array center cancels the signal at the middle of the beam making a “donut pattern” with a hole in the middle. This Gauss-Laguerre configuration has L=1 and is often referred to as a “twisted beam”. Such a beam has not been previously explored for field-aligned duct formation and could offer new insights into how wave propagation might be influenced by the duct's structure. Experiments using the "twisted beam" to create ionospheric ducts were carried out in January 2025 with a variety of excitations to produce whistler guiding structures with different characteristics. The twisted beam is generated by setting the phase of each transmitter in the HAARP array to correspond to its azimuthal position relative to the array's center. This leads to an on-axis cancellation that results in a hollow structure [2]. This could, in theory, create a duct with a reduced density in the center and enhanced densities at the edges, potentially altering how whistler waves are guided through the ionosphere.

These ducts serve as field-aligned channels, guiding VLF waves into the magnetosphere. The ducts' density profiles and their ability to guide waves depend on various factors, including duct width, duct enhancement factor, and the location of plasmapause with respect to the duct location. While L=0 enhancement-ducting has been previously studied [1], they fail to guide whistlers with frequencies greater than one-half the local gyro-frequency. This experiment focuses on the potential for L=1 enhancement and depletion-ducting to guide whistlers with frequencies up to the gyro resonance. The application of twisted beams allows the generation of tubular ducts with unique guiding properties for frequencies above and below one-half the electron gyro frequency. VLF waves propagating above and below the gyro frequency respectively can be trapped by the enhanced densities at the edges and the depletion duct at the center. The expectation is that L=1 ducts could exhibit different density profiles, widths, and guiding capabilities than the usual L=0 ducts, which may open up new possibilities for better understanding whistler wave propagation into the magnetosphere.

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2. S. J. Briczinski, P. A. Bernhardt, C. L. Siefring, S.-M. Han, T. R. Pedersen, and W. A. Scales, “'Twisted Beam' SEE Observations of Ionospheric Heating from HAARP,” *Earth, Moon, and Planets*, 116, 1, February 2015, pp. 55-66, doi:10.1007/s11038-015-9460-3.