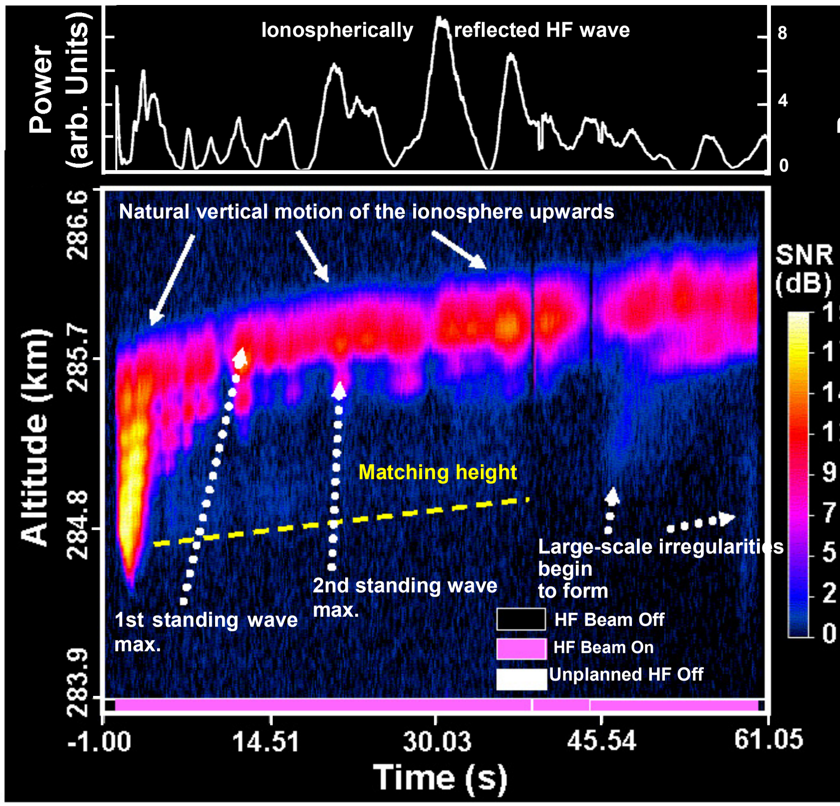
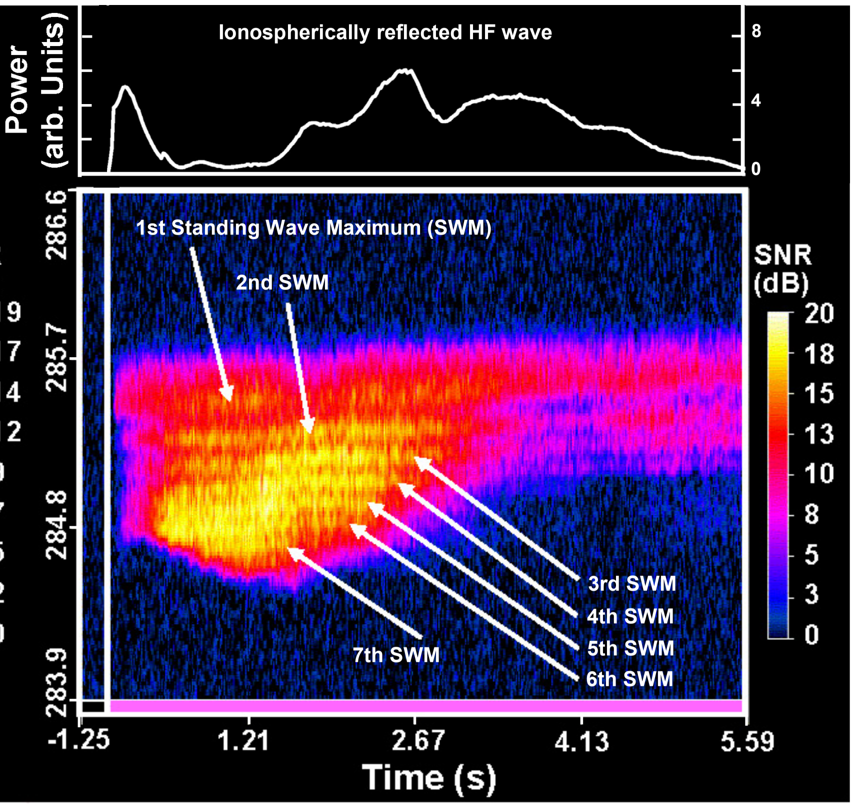
Temporal Development of HF-Excited Langmuir and Ion Turbulence at Arecibo



Excitation of Langmuir turbulence in the Arecibo ionosphere after a cold turn-on of the HF beam in a smooth, stratified, stable plasma. The first minute of ionospheric modification is presented along with supplemental annotations of important features.



Expanded view of the early time development of the HF-induced turbulence. SWM refers to the standing wave maxima of the high-power HF wave near the point of ionospheric reflection

Introduction: Arecibo Observatory (AO) will initiate experiments entailing the transmission of high-frequency (HF), high-power radio waves in early 2015. The basic concept is to perform plasma physics and aeronomy experiments in the laboratory-without-walls environment of space. Arecibo has a rich history of performing such experiments and is the premier site for studying plasma turbulence because of its powerful 430 MHz incoherent scatter radar. HF modification experiments were initiated at AO in 1970 with the aid of a log periodic antenna suspended above the incoherent scatter radar reflector dish (305 m in diameter). On-site HF experiments at AO ended in 1979, and a new HF facility was constructed at a site located approximately 17 km northeast of AO near the coastal town of Islote. The Islote facility HF antenna consisted of a 4 × 8 array of inverted (downward firing) log periodic antennas, with the longest array dimension oriented in the geographic east-west direction. This facility generated ~40 MW effective radiated power (ERP) across a frequency band from 3.175 to 8.175 MHz. From 1994 through May 1997 this facility along with the Arecibo radar were shut down for the installation of the Gregorian feed system at AO. The Gregorian feed greatly improved the measurement flexibility of all projects involving the Arecibo dish, including 430 MHz radar measurements. Also during this period, the Islote transmission lines were upgraded, and a "true" 80 MW ERP was subsequently available for HF experiments. The upgraded Islote facility began operations in June 1997, and the last experiments were performed in February 1998. Hurricane Georges destroyed the facility in September 1998. Since then there has been no HF facility at Arecibo. However, a new facility with an antenna consisting of six crossed dipoles near the surface of the Arecibo dish and a suspended cassegrain reflector is scheduled to start operations in early 2015. This facility transmits up to 230 MW ERP, which is much greater than in the past.

More than 40 observing proposals from the scientific community have already been approved for observing time with the HF facility, and there is a continuous stream of additional observing proposals that are being submitted at each of the two Arecibo proposal submission deadlines (March and September). It is clear that this facility has broad community support. As in the past, the Arecibo HF experiments are expected to yield a large number of discoveries and many journal publications written by scientists from a variety of organizations (e.g., universities, colleges, Federal laboratories and agencies, private companies, Federally-funded R&D centers, and independent and retired scientists).

The paper below has been submitted to the journal *Earth, Moon, and Planets* for publication; it discusses the current state of our knowledge in the area of plasma turbulence excited with the Arecibo HF facility. We seek to introduce new researchers to the processes by which Langmuir wave and ion wave turbulence is excited in the ionospheric *F* region above Arecibo Observatory. We also present Arecibo 430 MHz radar results obtained in the past to illustrate what is currently known about the excitation process and what is not. Measurements are suggested to help resolve key outstanding issues in anticipation of the start-up of the new HF facility. Finally, attempts are made to project the new physics that will become available with the resumption of HF operations.

Summary: The Arecibo high-power, high-frequency (HF) facility and 430 MHz radar are used to examine the temporal development of the HF-induced Langmuir and ion turbulences from 1 ms to many minutes after the turn-on of the HF beam in the *F* region. All HF observations begin in a smooth, stratified, stable plasma. "Cold start" HF transmissions are employed to avoid remnant irregularities from prior HF transmissions. HF-excited plasma line (HFPL) and ion line echoes are used to monitor the evolution of the turbulence. In the evening/nighttime the HFPL develops in three reproducible stages. Over time scales of 0 to 10–20 ms (possibly 40 ms), the smooth plasma conditions are maintained, and the results are consistent with theoretical models of the excitation of strong Langmuir turbulence near HF reflection. This entails the initiation of the so-called "caviton production cycle." The turbulence from the parametric decay instability is detected at lower altitudes where the radar wave vector matches those of the HF-enhanced waves. The data suggests that the two processes coexist in the region in between. After ~40 ms the "overshoot process" begins and consists of a downward extension of the HFPL from the HF reflection region to heights ~1.1 km below followed by a retreat back to the reflection region. The whole overshoot process takes place over a time scale of ~3 s. Thereafter the echo remains near HF reflection for 20 to 90 s after HF turn-on. The HFPL echo subsequently breaks up into patches because of the formation of large-scale electron density structures in the plasma.

Arecibo's new HF facility offers scientists opportunities not only to resolve past HFPL issues but also to explore instabilities in a higher HF power regime. In addition, Arecibo Observatory now operates with dual radar beams allowing HF–induced suprathermal electron fluxes traveling along geomagnetic field lines to be simultaneously measured above and below the region of Langmuir turbulence at early and late times in the modification process. This arrangement is ideal for testing the prediction of *Carlson et al.* [1982] that "Any flux initially directed down will produce a steady state flux in both directions, about one-third of the total flux at any level being backscattered up towards the source region." This statement applies to altitudes below ~300 km. Alternatively HFPLs/HFILs can be simultaneously measured along with one receiver channel dedicated to measurements of suprathermal electron fluxes. Observations of this type make it possible to test and refine kinetic simulations of HF-induced turbulence [e.g., the QZAK model developed by *DuBois et al*.]. One model prediction is that suprathermal electrons generated by caviton burn–out regulate turbulence levels in the plasma. Accurate predictions of suprathermal fluxes will greatly aid aeronomy studies of electron transport, electron loss, and thermal energy balance in the upper atmosphere. HF-generated suprathermal electron fluxes offer a simple, reliable, and repeatable source flux for studies of the upper atmosphere. In general, one can expect many pioneering investigations to be performed with the new AO facility as spin-offs of the HFPL and related suprathermal electron science.