# Whistler Wave Interactions with Space Plasmas during HF Heating of the Ionosphere at Arecibo

M. C. Lee[1], M. J. Starks[1], W. J. Burke[2], S. P. Kuo[3]
M. P. Sulzer[4], R. J. Riddolls[1], A. X. Zhang[1]

We demonstrate that signals at 28.5 kHz emitted from the Naval (NAU) transmitter in Puerto Rico effectively couple into ionospheric ducts, induced/enhanced by the Arecibo HF heater, and propagate into the conjugate hemisphere as ducted whistlers. Also presented are suspected radar detections of whistler-triggered electron precipitation events. NAU-generated whistlers have intensities sufficient to parametrically excite lower hybrid waves and 10-m scale ionospheric irregularities over Arecibo. Subsequent heating of electrons and ions by the lower hybrid waves yields a chain of ionospheric plasma effects, such as airglow, short-scale density depletions, and plasma line enhancements in a range of altitudes which far exceeds that affected by the HF heater. Whistler contamination from NAU overriding some heater-induced effects may account for apparent discrepancies between results reported from Arecibo and other heater sites.

1. Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

2. Air Force Research Laboratory, Hanscom Air Force Base, Massachusetts 01731.

3. Polytechnic University, Farmingdale, New York 11735.

4. Arecibo Observatory, Arecibo, Puerto Rico 00612.

## 1. Introduction

Intense VLF whistler waves from transmitters or lightning discharges parametrically excite lower hybrid waves and field-aligned zero-frequency plasma density irregularities in the ionosphere [*Lee and Kuo*, 1984]. The excited ionospheric density irregularities have scale sizes of ~10 m and align with the geomagnetic field lines to form filaments. The lower hybrid waves can accelerate electrons and ions along and across the geomagnetic field, respectively, generating non-Maxwellian distribution functions [*Lynch et al.*, 1994] capable of exciting airglow. In fact, airglow effects were observed in coincidence with the operational cycles of a VLF transmitter [*Chmyrev et al.*, 1976], and lower hybrid waves were detected over a powerful VLF transmitter [*Bell et al.*, 1991]. The mechanism described by *Lee and Kuo* [1984] provides a basis for understanding explosive spread F phenomena [*Liao et al.*, 1989] and the spectral broadening of VLF waves during transionospheric propagation [*Groves*, 1988; *Dalkir et al.*, 1992].

A Naval VLF transmitter code-named NAU, located at Aguada, Puerto Rico, emits VLF waves at a power and frequency of 100 kW and 28.5 kHz, respectively. Although the NAU transmitter operates exclusively for Naval communications rather than for scientific research, its proximity to the Arecibo HF heater facility offers opportunities to conduct controlled studies of whistler-induced ionospheric plasma effects. Both the VLF and HF sources are located near the $L = 1.35$ magnetic field line, and are magnetically conjugate to Trelew, Argentina. The Arecibo HF heater can be used to either create or enhance ionospheric ducts for conjugate whistler propagation experiments. The purpose of this paper is to present evidence that VLF waves can effectively couple into ionospheric ducts, induced/enhanced by the Arecibo HF heater, and propagate into the conjugate ionosphere as ducted whistlers. Furthermore, extensive ionospheric effects caused by the whistler waves may contaminate and actually override some of those induced by the HF heater. Relying on HF wave-induced, rather than naturally occurring, ionospheric ducts has been characteristic of our ducted whistler experiments at Arecibo [*Lee et al.*, 1992; *Starks*, 1999].

Experimental results presented in Section 2 show that the powerful HF waves create plasma environments which increase the efficiency of conversion of incident VLF waves into ducted whistlers. Subsequent interactions of the ducted 28.5 kHz whistlers with energetic electrons trapped in the radiation belts may have caused some to precipitate into the atmosphere over Arecibo. Ionospheric plasma disturbances induced by NAU 28.5 kHz transmissions may affect those generated by the HF heater wave, as elucidated in Section 3. We suggest that conditions provided by the nearby NAU transmitter may explain some observations at Arecibo, which are difficult to ascribe solely to the HF heater.

## 2. Arecibo Experiments

We conducted experiments at Arecibo from July 22 to August 1, 1997, using the newly upgraded 430 MHz diagnostic radar and the HF heater. These experiments investigated ionospheric plasma effects caused by the HF heater waves and the ducted 28.5 kHz whistlers. During continuous wave (CW) heating of the ionosphere by O-mode HF waves, large-scale ionospheric plasma turbulence was generated in the forms of sheet-like ionospheric density irregularities [*Lee et al.*, 1998a], depleted magnetic flux tubes [*Lee et al.*, 1999], and rising plasma bubbles [*Lee et al.*, 1998b]. The sheet-like density irregularities are parallel to the magnetic meridional plane, and can extend to a large distance beyond the HF wave-heated ionospheric region as "ionospheric ducts", acting as a multi-parallel-plate waveguide for whistler wave propagation. The sheet thickness is ~1 km, and the separation between adjacent structures is several km. The linear dimension of these ducts is significantly larger than the several hundred-meter wavelength of 28.5 kHz whistlers in the ionosphere. *Lee et al.* [1992] proposed that heater-generated large-scale ionospheric irregularities could support ducted whistler mode propagation from Arecibo to Trelew along the L = 1.35 shell (viz., magnetic flux tube).

This concept is illustrated in Figure 1. A high power 3.175 MHz radio wave injected vertically from the Arecibo HF heater generates ionospheric density irregularities with scale lengths ranging from tens of centimeters to a few kilometers. While short-scale ($\leq 1$ m) irregularities were excited in a fraction of a second, large-scale ($\geq 100$ m) sheet-like irregularities formed in minutes and ionospheric depletions subsequently developed along the geomagnetic field. Some fraction of the wave power emitted by the NAU transmitter impinges on the lower boundary of the ionosphere, and is reflected as subionospheric signals for propagation in the Earth-ionosphere waveguide. In the presence of HF-enhanced ionospheric irregularities, the VLF waves partially scatter into the ionospheric ducts, then propagate as whistlers from Arecibo to the conjugate locations near Trelew. Whistler-electron interactions in the radiation belts can cause trapped electrons to precipitate into the atmosphere.

During the period between 21:15 and 23:30 LT on July 24, 1997, 28.5 kHz signals were continuously recorded at Trelew, while the HF heater operated at Arecibo. Figures 2a and 2b provide experimentally measured transit times and intensities of 28.5 kHz waves, respectively. For the first 28 minutes (Period A), the HF heater operated in a 20 ms on/980 ms off pulsing sequence, injecting X-mode waves at 5.1 MHz. The heater turned off at 21:43 for 11 minutes (Period B). Operations resumed at 21:54 transmitting CW O-mode waves at 3.175 MHz for 31 minutes (Period C). From 22:25 until 23:13 (Period D) the heater switched to 20 msec on/980 msec off pulsed O-mode. At 23:13 the heater transmitted CW X-mode until the end of the ducted 28.5 kHz wave recording (Period E).

Figure 2a shows that between Period A and Period C measured transit times of NAU signals from Puerto Rico to Trelew decreased from 0.90 to 0.16 s. Figure 2b shows that during the same interval the received intensities nearly doubled. The detail of experimental techniques and data analyses is given in *Starks and Lee* [1999]. The observed transit times are much greater than the 30 ms required for the VLF signal to propagate from Puerto Rico to Trelew in the Earth-ionosphere waveguide. This suggests that the conjugate propagation of the 28.5 kHz NAU signal was in the whistler mode during Period B, along a duct at the $L = 1.35$ shell (for a group delay of 0.16 s) induced or enhanced by the CW O-mode heater wave, while the whistler propagated along naturally occurring ducts at higher L shells (e.g., a group delay of 0.42 s corresponding to $L = 2.4$) during Period A. Signals coupled more efficiently into the heater-induced/enhanced duct and so were detected preferentially by the conjugate receiving system. The $L = 1.35$ duct apparently was not well-maintained during Period D, when the heater reverted to pulsed O-mode. Detectable local ducting ceased entirely by Period E.

Displayed in Figure 2c are range-time-intensity (RTI) plots of the Arecibo radar backscatter power measured from 21:30:19 to 23:19:32 LT. Between 22:00:48 to 22:47:33 LT a radar data gap occurred. In this display a gray scale is used with bright and dark regions corresponding to strong and weak backscattered power, respectively. The top and bottom panels of Figure 2c show ionospheric features in the F region near the reflection height of the HF heater and at lower altitudes, respectively. No measurable backscatter came from intervening altitudes. The reflection heights of the 3.175 MHz heater wave were about 230 and 255 km in Periods C and D, respectively, as indicated by bright lines. The nighttime ionosphere usually contains few free electrons at D- and E-region altitudes. We note, however, that layered structures appeared episodically between 60 and 120 km. The two continuous bright lines near 100 and 110 km represent backscattered power from persistent sporadic E layers. Discrete bright vertical lines (e.g., around 21:38, 21:44, 21:48, 21:52, 22:55, 23:00) are signatures of meteor-produced ionization [*Zhou and Mathews*, 1994]. The most intriguing feature is associated with brief, horizontal dashed lines, recorded in Periods A, D, and E, in the 60–80 km altitude range. Their shapes are different from the V- or U-shaped lines characteristic of backscatter from ships or airplanes [*Zhou and Mathews*, 1994]. One such example appears near 22:50 LT. We believe that the horizontal dashed lines come from thin ionization layers produced as ∼250 keV electrons, precipitated from the radiation belts by ducted 28.5 kHz whistlers, were stopped in the atmosphere.

Arecibo is situated at the footprint of the L = 1.35 magnetic flux tube, and just to the west of the longitude sector containing the South Atlantic Anomaly. Eastward-drifting quasi-trapped electrons undergo maximum precipitation in this longitude sector where the atmospheric loss cone is large and the magnetic field is weak [cf. Figure 1 of *Luhmann and Vampola*, 1977]. Precipitation would result from the pitch-angle scattering of marginally trapped electrons by 28.5 kHz whistlers, introduced into the radiation belt through naturally occurring or heater-enhanced ionospheric ducts. Electron precipitation from a continuous 28.5 kHz transmission is expected to be brief or episodic, due to the relatively small inhomogeneity in the pitch angle distribution of energetic electrons that are gradient-curvature drifting across the Arecibo flux tube. Observations of such wave-particle interactions are not unprecedented. During the stimulated emission of energetic particles (SEEP) experiments conducted with the S-81 satellite, *Imhof et al.* [1983] observed the controlled precipitation of energetic electrons from the magnetosphere in response to modulated bursts of 17.8 kHz radiation from the NAA transmitter in Cutler, Maine. During other SEEP experiments precipitating electrons with $E > 45$ keV were detected in conjunction with VLF radiation bursts from the Siple station in Antarctica [*Imhof et al.*, 1989] and lightning [*Inan et al.*, 1989]. Measurements from the SAMPEX satellite, available at *http : //cdaweb.gsfc.nasa.gov/cdaweb/istp_public/*, indicate that the inner radiation belt contained significant fluxes of energetic electrons at the time of the Arecibo experiments.

## 3. Whistler Wave-Induced Ionospheric Effects

The NAU 28.5 kHz transmitter in Puerto Rico emits at 100 kW. If only a few percent of the radiated power couples into the ionosphere, the electric field amplitudes of whistler waves would reach tens of mV/m in the ionosphere. Such an intense whistler wave can parametrically excite lower hybrid waves and zero-frequency field-aligned density irregularities in a few seconds [*Lee and Kuo*, 1984]. As discussed below, significant ionospheric effects may be caused by both the excited lower hybrid waves and ionospheric density irregularities which can contaminate or override the HF heater wave-induced effects.

### (A) Ionospheric Density Irregularities

During a sounding rocket flight through the Arecibo heater beam, *Kelley et al.* [1995] detected patches of filament-like ionospheric irregularities. Mean density depletions of 6% were observed both above and well-below the reflection height of the 5.1 MHz O-mode heater. The wavenumber spectrum of the irregularities had a local maximum, corresponding to a wavelength of ∼15 m. Irregularity patches were separated by a few kilometers. Some striking features probably cannot be explained by a mechanism [*Gurevich et al.*, 1995] as resulting solely from heater-induced processes. For example, it is puzzling why ∼15-m scale plasma depletions should be detected in patches above and below the heater wave's reflection height and well-removed from the region of intense wave-plasma interactions [*Kelley et al.*, 1995].

Sheet-like ionospheric irregularities, generated during O-mode heater emissions at Arecibo, can guide the 28.5 kHz waves causing them to propagate in the ionosphere as ducted whistlers. The amplitudes of NAU whistlers are sufficient to excite lower hybrid waves and zero-frequency ionospheric density irregularities along their propagation paths. From whistler and lower hybrid wave dispersion relations, we calculate that the scale length of the excited ionospheric irregularities is ~14 m. Small-scale filament-like irregularities are thus produced by the 28.5 kHz whistler wave, and are embedded in the large-scale irregularity sheets generated by the HF heater wave. Concurrently excited lower hybrid waves are also effective heaters of electrons (ions) along (across) the magnetic field, leading to still-deeper plasma depletions.

We suggest that the 28.5 kHz whistlers produced ~15-m scale irregularities with deep density depletions along their propagation paths, during ionospheric HF heating periods. The heater-induced large sheets of irregularities act as ionospheric ducts that separate whistler-induced filaments into patches. This scenario explains the main features of filamentary ionospheric irregularities measured by the rocket-borne instrument [*Kelley et al.*, 1995]. The proximity of a VLF transmitter such as NAU to an ionospheric heater such as Arecibo is unique. This unique proximity must be considered in trying to account for some apparent discrepancies between results of similar heater experiments conducted at Arecibo and Tromso. In spite of the Tromso heater being the more powerful, it induced small-scale ionospheric irregularities with density depletions of ~1%, compared with the 6% at Arecibo.

### (B) Suprathermal Electrons and Plasma Lines

Diagnostic measurements by the Arecibo 430 MHz radar made during nighttime HF heater experiments showed that backscatter radar echoes from enhanced Langmuir waves (plasma lines) occurred over a broad range of altitudes [*Carlson et al.*, 1982]. It is reasonable to assume that these enhanced plasma lines were caused by energetic electrons. Enhanced downshifted plasma lines correspond to upgoing Langmuir waves excited by upgoing electron fluxes. They extended from 250 km to nearly 450 km, well away from the heater reflection height of ~285 km. *Carlson et al.* [1982] thus concluded that large fluxes of suprathermal electrons with energies >20 eV must have been accelerated by the Arecibo heater wave.

We note several unusual features of these plasma lines that may not be directly related to the HF wave effects during the 3 min on/3 min off experimental cycles [*Carlson et al.*, 1982]. Plasma line intensities and deduced electron fluxes did not exhibit strong dependences on the HF power density incident on the ionosphere. When the heater turned off, the intensities of bottomside plasma lines quickly weakened, but still exceeded background thermal levels by factors of 2 to 4. At topside altitudes, plasma line intensities were nearly independent of the phase of the heater's operational cycle. *Carlson et al.* [1982] also pointed out that nighttime plasma lines at Arecibo often mildly exceed thermal levels, indicating the presence of weak fluxes of ∼10 eV electrons overhead.

Since the NAU transmitter operates routinely for communication purposes, it appears likely that 28.5 kHz whistlers can be partially responsible for enhanced plasma lines observed during ionospheric heating experiments. The 3 min on/3 min off sequencing of the heater during these experiments is barely sufficient to excite large-scale ionospheric irregularities, which can couple the 28.5 kHz wave into the heater-induced/enhanced ionospheric ducts. However, lower hybrid waves excited by the 28.5 kHz whistler waves can effectively accelerate electrons. Consequently, a broad altitude range of plasma lines is created in the wake of the whistler wave. When the heater turned off, the electron acceleration directly caused by the HF wave-excited instabilities ceased. However, the 28.5 kHz waves preserved deteriorating ducts after the heater turned off, by continuing to excite lower hybrid waves that maintained relatively weak electron fluxes and consequent plasma lines. The excitation of lower hybrid waves, and the generation of energetic electrons and plasma lines, depends on the intensity of the whistler wave. These processes are unaffected by the HF heater power, as long as the 28.5 kHz wave is guided by ionospheric ducts. Thus, even after ionospheric heating activities ceased, 28.5 kHz whistlers, supported by naturally occurring ionospheric ducts, were able to continue producing weak fluxes of suprathermal electrons over Arecibo.

### (C) Anti-Stokes Langmuir Waves

Radar-detected Langmuir waves near the reflection height of the HF heater wave can have both broad cascading and narrow frequency-upshifted spectra. The cascading portions of Langmuir wave spectra are manifestations of the parametric decay instability (PDI). *Kuo and Lee* [1992] suggested that frequency-upshifted waves result from the scattering of the PDI-excited Langmuir waves by density fluctuations associated with lower hybrid waves. In other words, the frequency-upshifted Langmuir waves are anti-Stokes modes in nature. The measured frequency shift of anti-Stokes Langmuir waves versus the

HF heater wave frequency, obtained from our 1991 ionospheric heating experiments at Arecibo, is displayed in Figure 1b of *Lee et al.* [1997].

It is natural to ask how the lower hybrid waves, excited by 28.5 kHz whistlers, affect the HF wave-enhanced Langmuir waves. Can we detect anti-Stokes Langmuir waves with a frequency shift of 28.5 kHz using the Arecibo 430 MHz radar? The answer is indicated in Figure 1b of *Lee et al.* [1997]. As expected from theory, we see that the measured frequency shift is inversely proportional to the heater wave frequency. To detect anti-Stokes Langmuir waves with a frequency shift of 28.5 kHz, the HF heater must operate at frequencies exceeding 10 MHz. This would also require the ionosphere to have a peak plasma frequency $>$ 10 MHz. While this may be achievable at periods of the solar maximum, it did not happen in the local ionosphere during any of our experiments.

In conclusion, our experiments demonstrated that HF heater-generated/enhanced ionospheric ducts support whistler propagation between two hemispheres along local magnetic flux tubes. Intense whistlers can significantly modify the ionospheric plasma to override some of HF heater-induced effects. To guard against misinterpreting Arecibo measurements or inappropriately comparing them with results from other sites, caution must be exercised. The proximity of NAU to Arecibo may provide critically different ionospheric conditions.

## Acknowledgements

This work was supported by the Air Force Office of Scientific Research through grant F49620-98-1-0389 to the Massachusetts Institute of Technology (MIT), by Task 2311G5 and the HF Active Auroral Research Program [HAARP] at the Air Force Research Laboratory, and by the National Science Foundation through grant ATM-9812154 to the Polytechnic University. The Arecibo Observatory has been operated by Cornell University under the sponsorship of the National Science Foundation. M.J. Starks was supported by the Air Force Senior Knight Program for his doctoral research at MIT.

## References

Bell, T. F., U. S. Inan, V. S. Sonwalker, and R. A. Helliwell, DE-1 observations of lower hybrid waves excited by VLF whistler mode waves, *Geophys. Res. Lett.*, 18, 393, 1991.

Carlson, H.C., V.B. Wickwar, and G.P. Mantas, Observations of fluxes of suprathermal electrons accelerated by HF excited instabilities, *J. Atmos. Terr. Phys.*, 44, 1089, 1982.

Chmyrev, V.M., V.K. Roldugin, I.A. Zhulin, M.M. Mogilevskii, V. I. Di, V.K. Koshelevskii, V.A. Bushmarin, and O.M. Raspopov, Artificial injection of very low frequency wave into the ionosphere and the magnetosphere of the earth, *JETP Lett.*, 23, 49, 1976.

Dalkir, Y.R., M.C. Lee, K.M. Groves, and S.P. Kuo, A mechanism responsible for the observation of symmetric lower hybrid sidebands and a low frequency mode in the upper ionosphere, *J. Geophys. Res.*, 97, 17995, 1992.

Groves, K.M., M.C. Lee, and S.P. Kuo, Spectral broadening of VLF radio signals traversing the ionosphere, *J. Geophys. Res.*, 93, 14683, 1988.

Gurevich, A.V., K.P. Zybin, and A.V. Lukyanov, Stationary striations developed in the ionospheric modification, *Phys. Rev. Lett.*, 75, 2622, 1995.

Imhof, W. L., J. B. Reagan, H. D. Voss, E. E. Gaines, D. W. Datlowe, J. Mobilia, R. A. Helliwell, U. S. Inan, and J. Katsufrakis, Direct observations of radiation belt electrons precipitated by controlled injection of VLF signals from a ground-based antenna, *Geophys. Res. Lett.*, 10, 361, 1983.

Imhof, W. L., H. D. Voss, J. Mobilia, M. Walt, U. S. Inan, and D. L. Carpenter, Characteristics of short duration electron precipitation bursts and their relationship to VLF wave activity, *J. Geophys. Res.*, 94, 10079, 1989.

Inan, U. S., M. Walt, H. D. Voss, and W. L. Imhof, Energy spectra and pitch angle distributions of lightning-induced precipitation: Analysis of an event observed on the S-81 (SEEP) satellite, *J. Geophys. Res.*, 94, 1379, 1989.

Kelley, M.C., T.L. Arce, J. Salowey, M. Sulzer, W.T. Armstrong, M. Carter, and L.M. Duncan, Density depletion at the 10-m scale induced by the Arecibo heater, *J. Geophys. Res.*, 10, 17362, 1995.

Kuo, S.P., and M.C. Lee, A source mechanism producing HF-induced plasma lines (HFPLs) with up-shifted frequencies, *Geophys. Res. Lett.*, 19, 249, 1992.

Lee, M.C., and S.P. Kuo, Production of lower hybrid waves and field-aligned plasma density striations by whistlers, *J. Geophys. Res.*, 89, 10873, 1984.

Lee, M.C., K.L. Koh, K.D. Vilece, S. Basu, K.M. Groves, and M.P. Sulzer, Generation of artificial ionospheric ducts for guided VLF wave propagation, *Proc. International Beacon Satellite Symposium*, Cambridge, Massachusetts, 1992.

Lee, M.C., R.J. Riddolls, K.D. Vilece, N.E. Dalrymple, M.J. Rowlands, D.T. Moriarty, K.M. Groves, M.P. Sulzer, and S.P. Kuo, Laboratory reproduction of Arecibo experimental results: HF wave-enhanced Langmuir waves, *Geophys. Res. Lett.*, 24, 115, 1997.

Lee, M.C., R.J. Riddolls, W.J. Burke, M.P. Sulzer, S.P. Kuo, and E.M.C. Klien, Generation of large sheet-like ionospheric plasma irregularities at Arecibo, *Geophys. Res. Lett.*, 25, 3067, 1998a.

Lee, M.C., R.J. Riddolls, W.J. Burke, M.P. Sulzer, E.M.C. Klien, M.J. Rowlands, and S.P. Kuo, Ionospheric plasma bubble generated by Arecibo heater, *Geophys. Res. Lett.*, 25, 579, 1998b.

Lee, M.C., E.M.C. Klien, W.J. Burke, A.X. Zhang, R.J. Riddolls, S.P. Kuo, M.P. Sulzer, and B. Isham, Augmentation of natural ionospheric plasma turbulence by HF heater waves, *Geophys. Res. Lett.*, 26, 37, 1999.

Liao, C.P., J.P. Freidberg, and M.C. Lee, Explosive spread F caused by lightning-induced electromagnetic effects, *J. Atmos. Terr. Phys.*, 51, 751, 1989.

Luhmann, J.G., and A.L. Vampola, Effects of localized sources on quiet time plasmasphere electron precipitation, *J. Geophys. Res.*, 82, 2671, 1977.

Lynch, K.A., R.L. Arnoldy, P.M. Kintner, and J.L. Vago, Electron distribution function behavior during localized transverse ion acceleration events in the topside auroral zone, *J. Geophys. Res.*, 99, 2227, 1994.

Starks, M.J., Measurements of the conjugate propagation of VLF waves by matched filter and application to ionospheric diagnosis, Department of Electrical Engineering and Computer Science, Sc.D. Dissertation, Advisor: M.C. Lee, M.I.T., 1999.

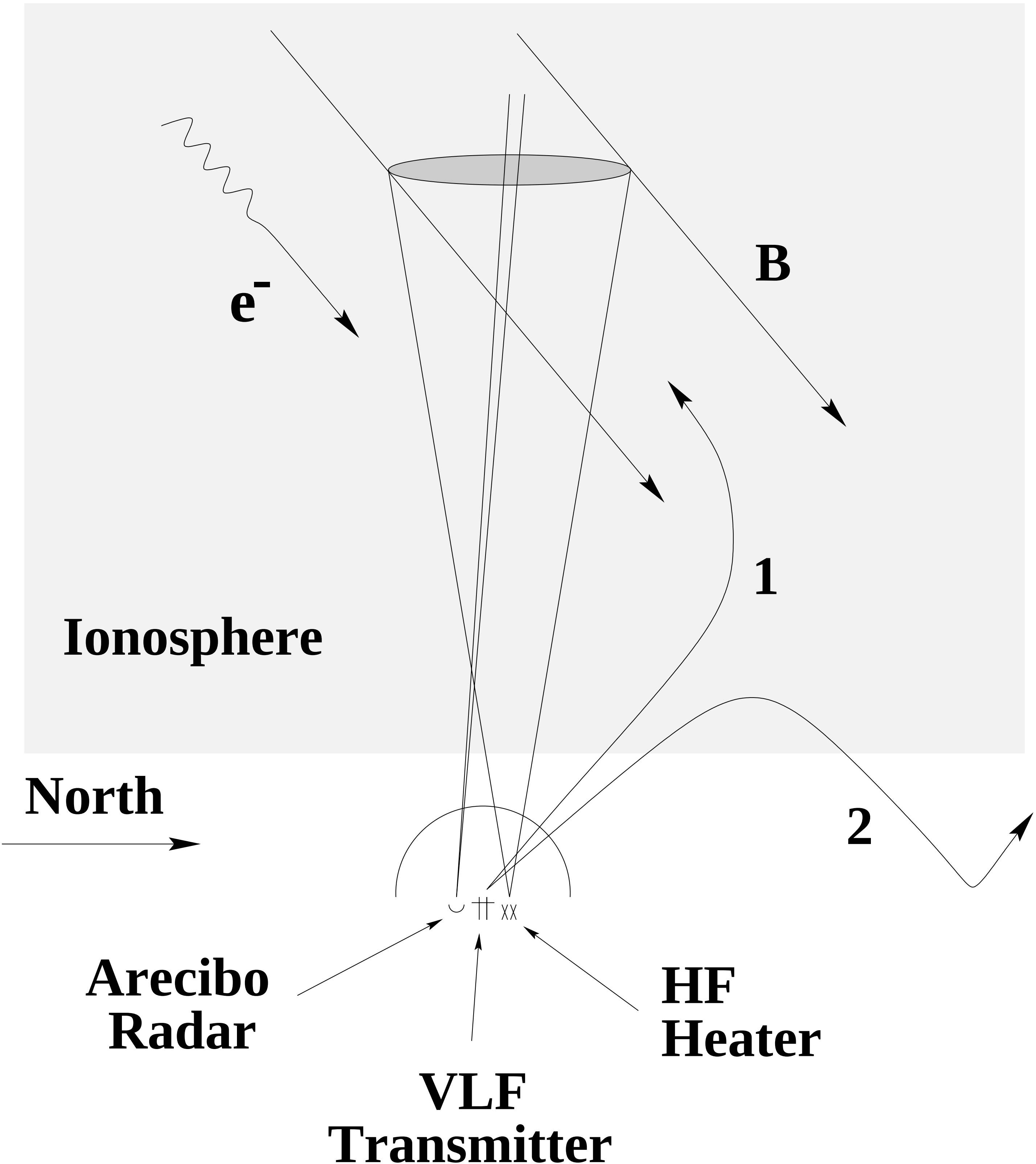
Starks, M.J., and M.C. Lee, Matched filtering for the measurements of ducted VLF emissions, submitted to *Radio Sci.*, 1999.

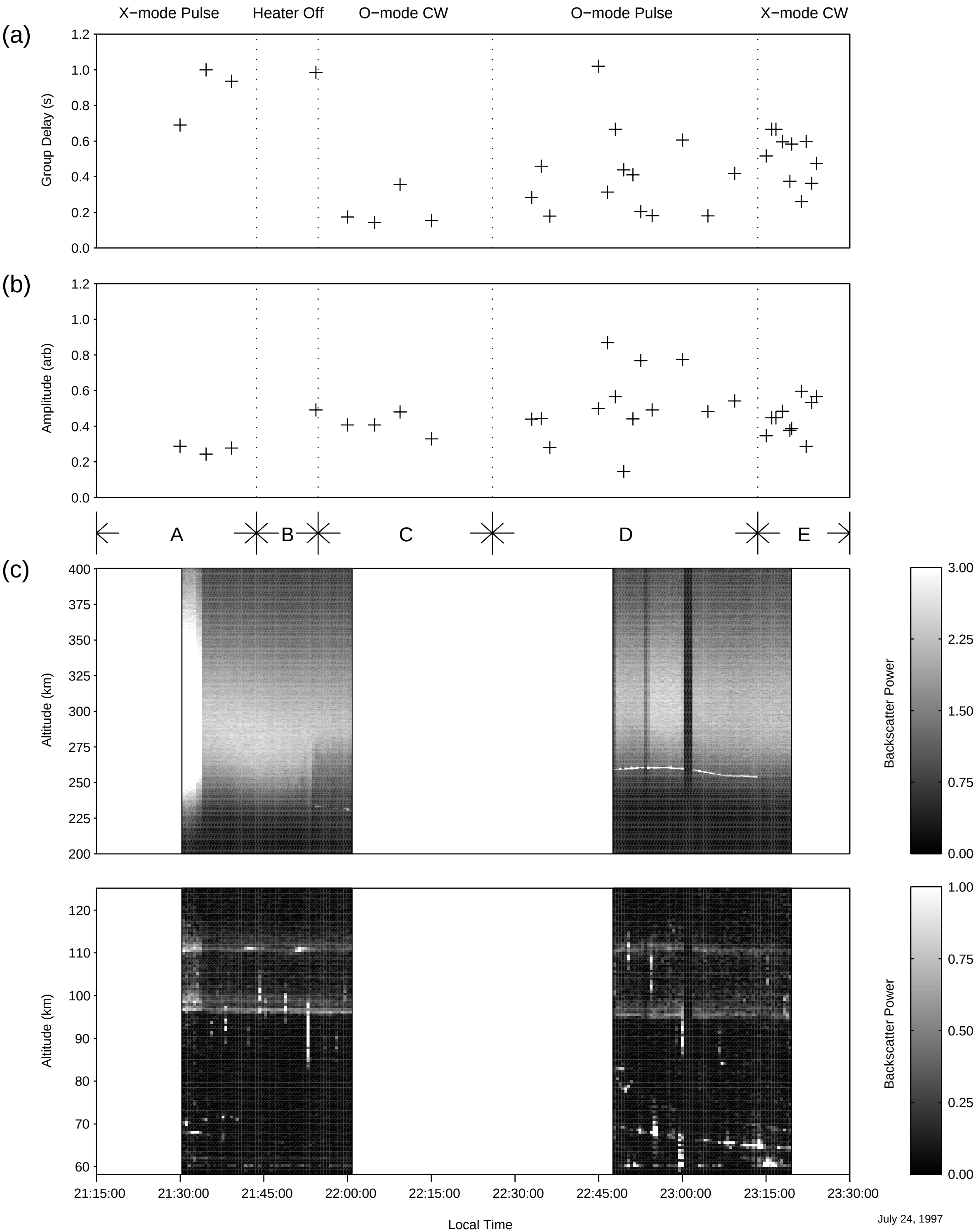
Zhou, Q. and J.D. Mathews, A spectral technique for the detection and correction of coherent interference effects on incoherent scatter radar power profiles, *Radio Sci.*, 29, 1173, 1994.

# Figure Captions

Figure 1. Schematic illustration of the HF ionospheric heating, the coupling of the 28.5 kHz wave into ionospheric ducts, and the radar diagnoses of the induced ionospheric effects. Ducted whistler and subionospheric VLF wave propagation paths are labeled by 1 and 2, respectively.

Figure 2. (a) Transit times and (b) intensities of the 28.5 kHz wave recorded at Trelew (Argentina), the geomagnetic conjugate point of Arecibo (Puerto Rico); (c) RTI plot of radar backscatter power showing ionospheric features in the F region and suspected events of whistler-triggered particle precipitation into the lower ionosphere over Arecibo.


B
e-
1
Ionosphere
North
2
Arecibo Radar
VLF Transmitter
HF Heater


X−mode Pulse
Heater Off
O−mode CW
O−mode Pulse
X−mode CW
(a)
Group Delay (s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
(b)
Amplitude (arb)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
A
B
C
D
E
(c)
Altitude (km)
200
225
250
275
300
325
350
375
400
Backscatter Power
0.00
0.75
1.50
2.25
3.00
Altitude (km)
60
70
80
90
100
110
120
Backscatter Power
0.00
0.25
0.50
0.75
1.00
21:15:00
21:30:00
21:45:00
22:00:00
22:15:00
22:30:00
22:45:00
23:00:00
23:15:00
23:30:00
Local Time
July 24, 1997