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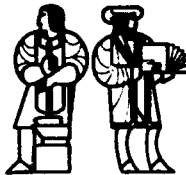
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13. ABSTRACT (Maximum 200 words) Since 1 October 1991, Dr Min-Chang Lee and his students at MIT and Boston Univ., have conducted experimental and theoretical research aimed at investigating ionospheric plasma disturbances which can significantly affect radio wave propagation from satellite communications systems. His efforts have developed a theory to explain reflectivity of radio waves from lightning induced plasmas. In addition, his research has focused on enhanced radar backscatter, source mechanisms for generating symmetric lower hybrid sidebands in the upper ionosphere, and the characteristics of the HF enhanced plasma lines. .					
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AFOSR-TR- 93 0090

To: Dr. Jim Kroll, Program Manager, AFOSR
From: Prof. Min-Chang Lee
Date: August 1, 1993
Re: Progress Report on Sponsored Research Programs titled "Source Mechanism and Radio Effects of Ionospheric Plasma Disturbances" (AFOSR-92-0001) and "Studies of Enhanced Radar Backscatter" (F49620-92-J-0297)

Over the past year the following research subjects have been investigated: (1) Radar studies of lightning-induced plasmas with potential applications to radio communications and space surveillance, (2) enhanced radar backscatter, (3) source mechanism generating symmetric lower hybrid sidebands and low-frequency modes in the upper ionosphere, and (4) the spectral characteristics of the HF enhanced plasma lines (HFPLs). Research results are briefly summarized below.

Reflection of radio waves from turbulent plasma layers was investigated with potential applications to radio communications and space surveillance. In addition to theoretical analyses of the problem [Dalkir and Lee, 1993], simulation experiments with lightning-induced plasmas were conducted on campus with the MIT S-band, C-band, and the Millstone UHF radars (see Figure 1) [Dalkir et al., 1993]. The volume reflectivity of the lightning-induced plasmas averaged over several hundreds of radar points, exhibits an inverse square wavelength ($1/\lambda^2$) dependence (see Figure 2) which can be successfully accounted for by the following model. The lightning plasma is modelled as a cylinder of ionized gas (see Figure 3) that is overdense, or perfectly reflecting, to the radio frequencies in our experiments. The surface of the plasma is rough, with a power-law irregularity spectrum. This lightning induced plasma model is applied to the problem of radio wave reflection from an artificially produced plasma patch in the atmosphere (see Figure 4). Both the monostatic (backscatter) and bistatic (specular) geometries are analyzed. The monostatic geometry may be used to diagnose the structure of the plasma patch once it is created; the bistatic geometry is relevant to radio communications applications. The

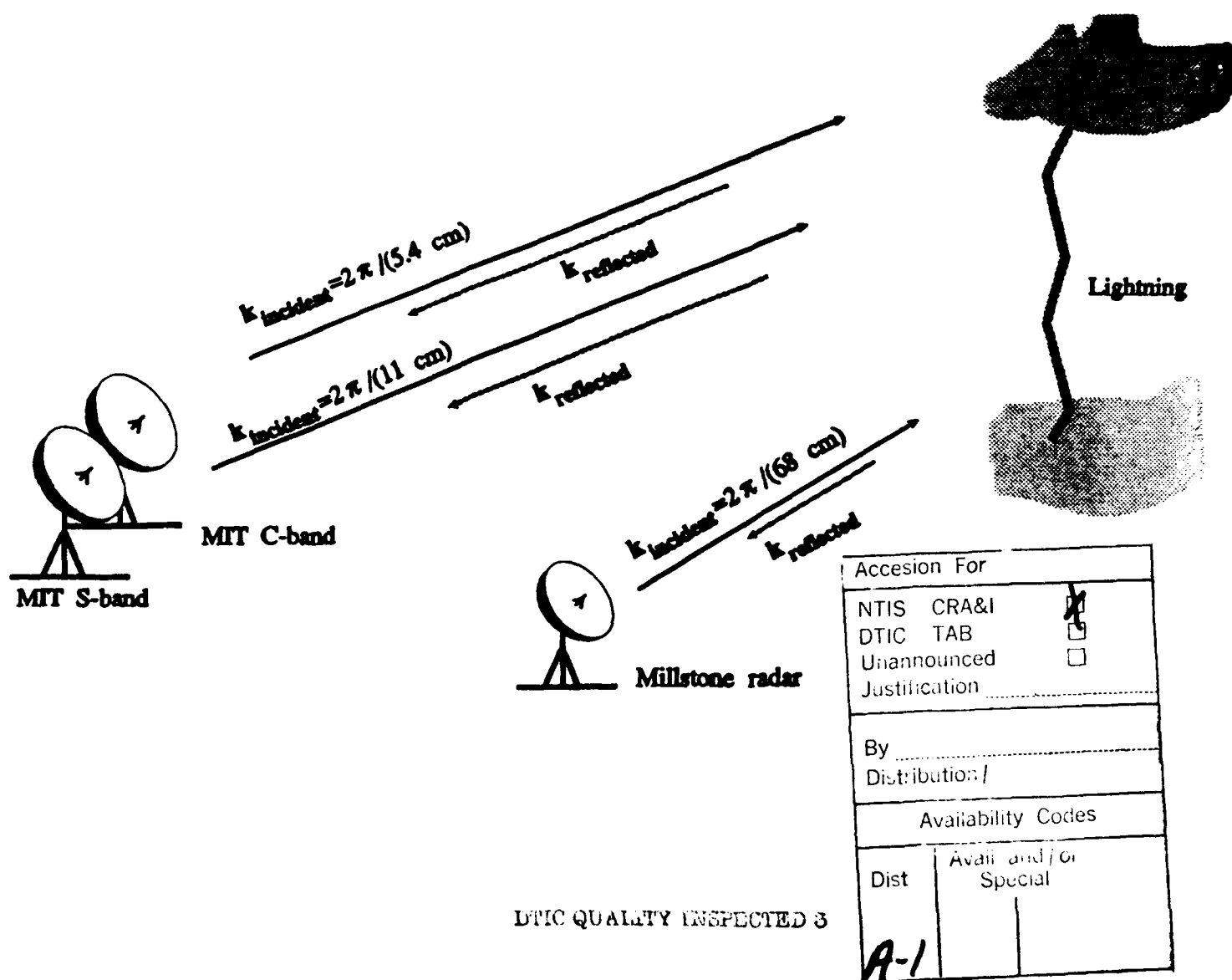


Fig. 1. Schematic representation of lightning backscatter experiments. The plasma cylinders created through air breakdown around the lightning discharges is diagnosed with the MIT C-band, S-band and Millstone UHF radars. For simplicity, only one lightning discharge is shown; in actuality, the experiments were carried out separately in different thunderstorms.

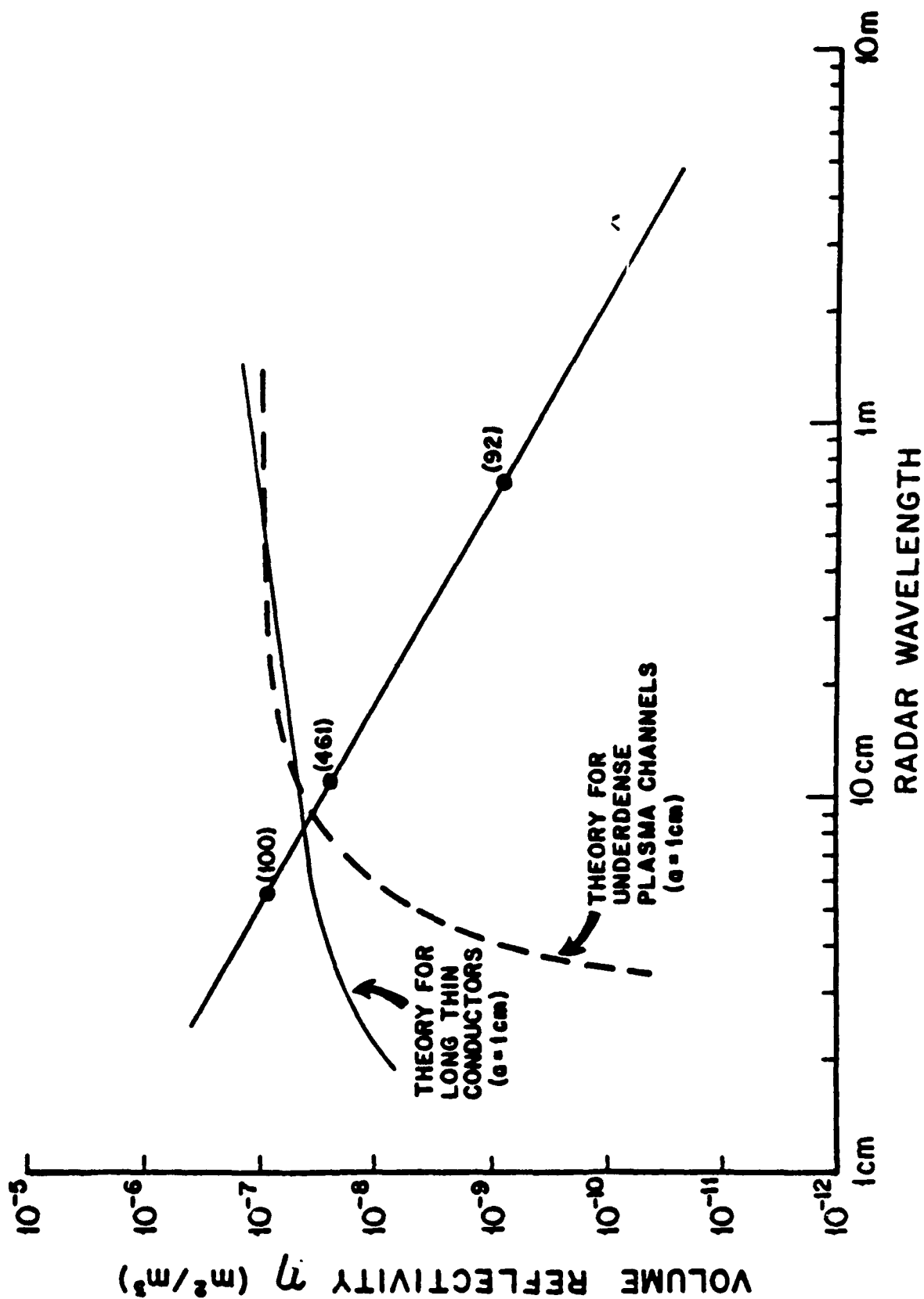


Fig. 2. Summary of experimental results. The average volume reflectivity at $\lambda = 5.4$,

11 and 68 cm is plotted. The numbers in parentheses indicate the number of data points

collected. The wavelength dependence predicted by the theory of long thin conductors,

and underdense plasma channels is also indicated on the figure. Neither existing model

fits the data of the present study, which exhibit a clear $1/\lambda^2$ dependence.

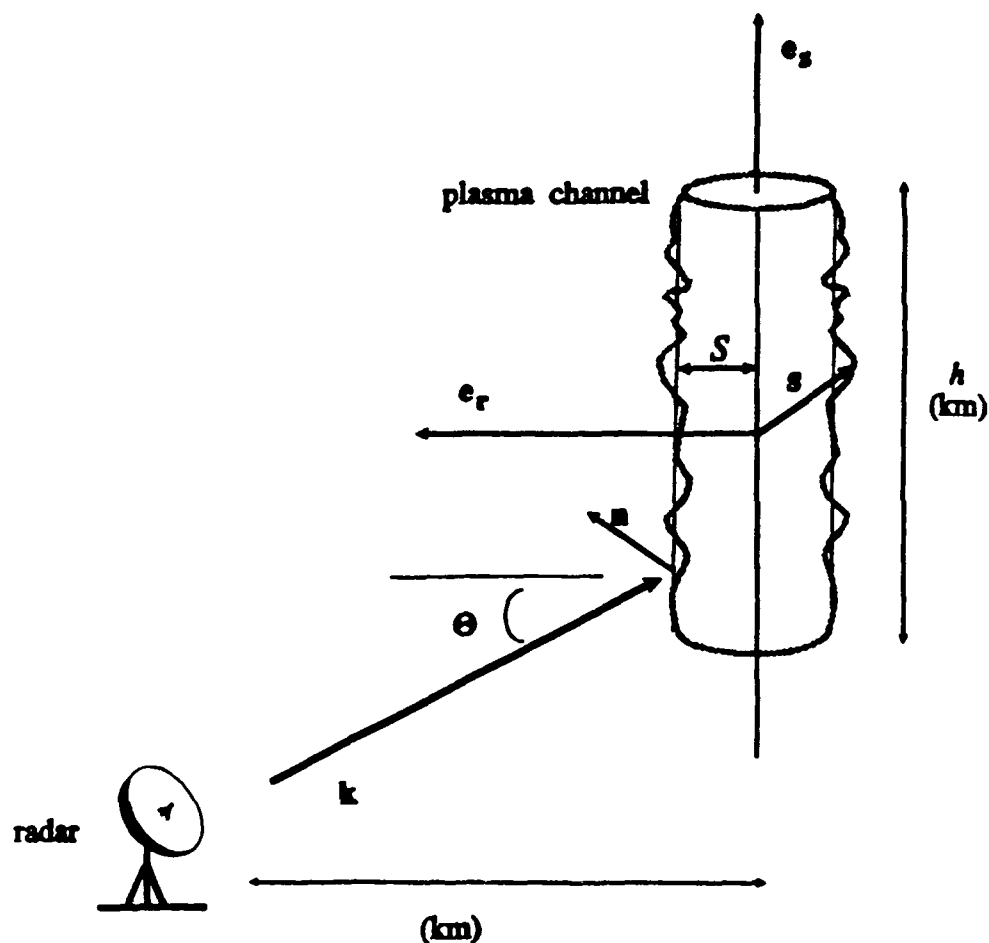


Fig. 3. Schematic representation of overall scattering geometry. The transmitter is located a few kilometers from the lightning activity. Radio signals with wave vector $\mathbf{k}$ are incident on the plasma surface at an angle θ to the horizontal. The z axis is taken to be along the axis of symmetry of the plasma channel, which is approximately perpendicular to the ground. The position vector $\mathbf{s}$ extends from the origin of the coordinate system to the surface of the lightning-induced plasma; $\mathbf{n}$ is the local normal vector to the surface. h is the vertical extent of the plasma, which is estimated to be on the order of kilometers.

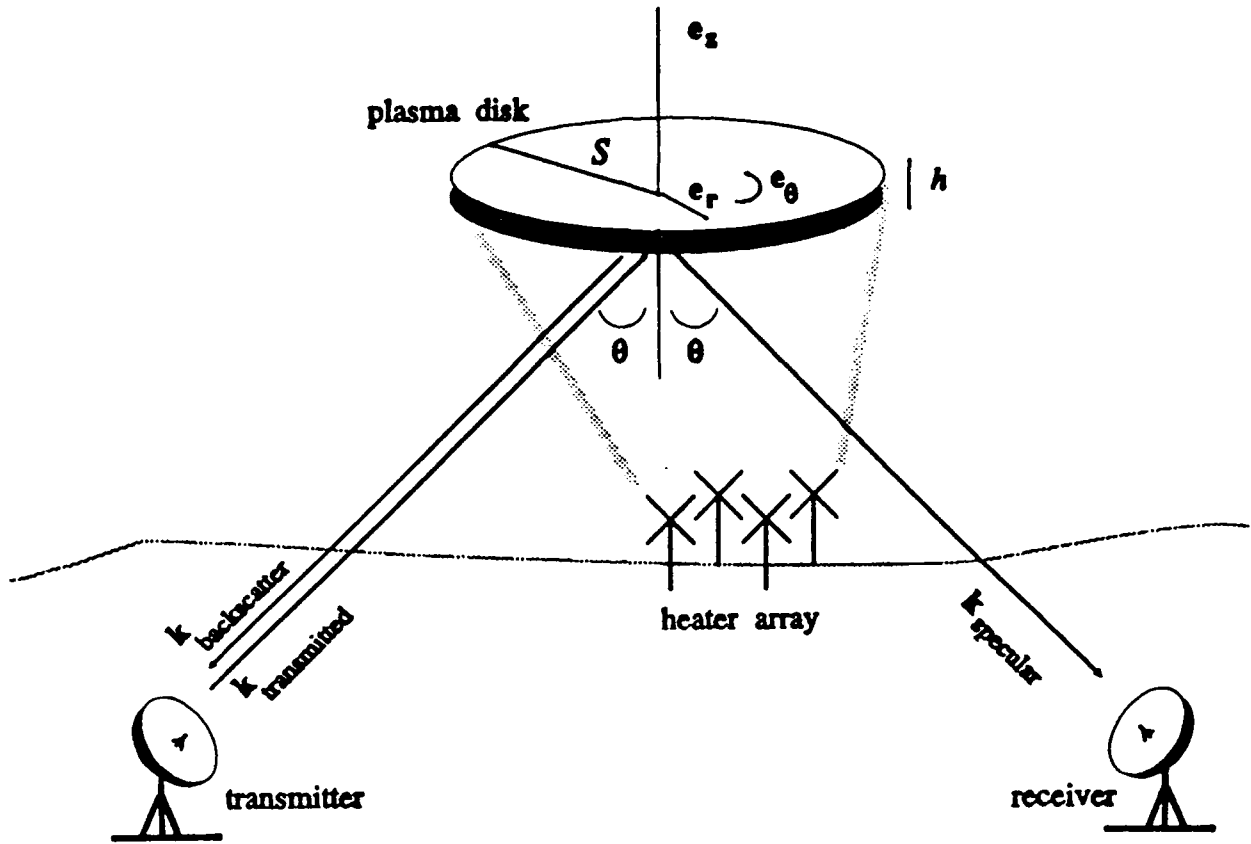


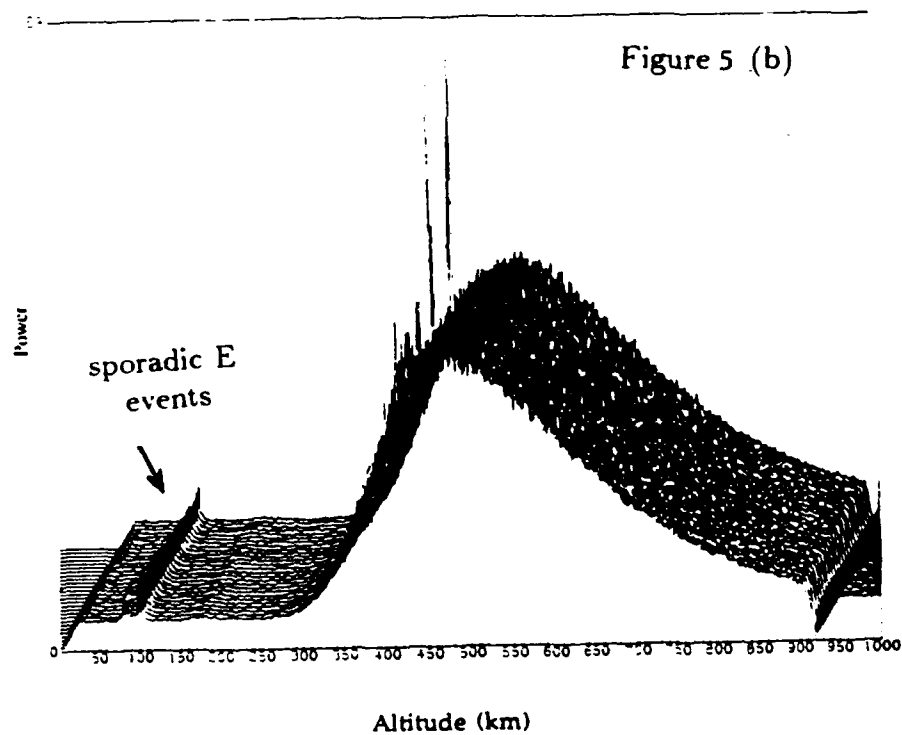
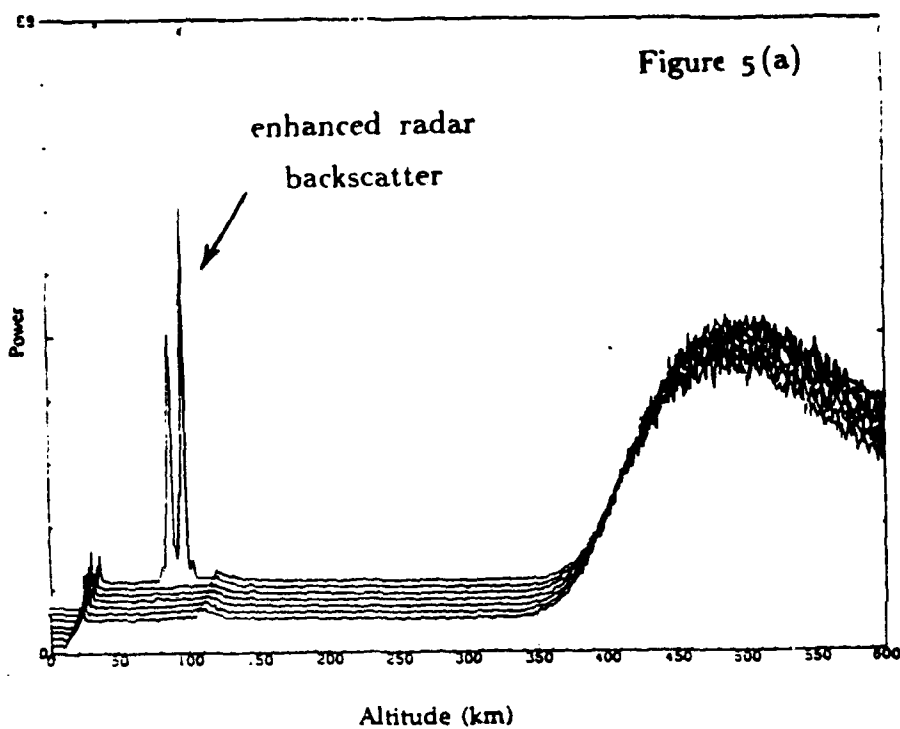
Fig. 4. Geometry of radio wave scattering from a pancake-like plasma of radius S and height h . The heater array "paints" the plasma patch through air breakdown in the beam cross-section. The transmitted wave is incident on the plasma at the origin of a cylindrical coordinate system. In the backscatter geometry used in radio diagnostics, $k_{\text{backscatter}} = -k_{\text{transmitted}}$. In radio communication applications, the reflected wave is in the k_{specular} direction. Note that the scattering surface is not flat, but irregular in the e_z direction (not pictured).

scattered power for both a power-law and Gaussian irregularity spectra is derived. It is found that higher frequencies are preferentially scattered into the specular direction by the plasma patch. The results therefore indicate that the plasma patch may be an efficient means of reflecting high frequency radio waves as intended [Y.R. Dalkir, M.S. Thesis, MIT, 1993].

Large enhancements of the incoherent radar backscatter echoes around 90 km were frequently seen at Arecibo during our heating experiments. Shown in Figure 5 (a) is such an event recorded on July 16, 1991, which is apparently different from the sporadic E events given in Figure 5 (b). Our statistical study of these enhanced radar backscatter (ERB) events over the past two years at Arecibo has indicated that they are plasma layers possibly caused by meteors or HF wave triggered particle precipitation. Auto-correlation function (ACF) measurements of radar echoes, can further distinguish one from the other. Our preliminary data analysis and theoretical consideration suggest tentatively a scenario of the VLF (whistler) wave triggered particle precipitation at Arecibo as follows. Arecibo, Puerto Rico is located near the footprint of the geomagnetic flux tube at $L = 1.47$. Kilometer (and larger)-scale field aligned waveguides can be generated by the Arecibo HF heating facility, guiding favorably VLF (whistler) waves from the lower ionosphere into the radiation belts (see Figure 6). The VLF (whistler) waves can be those produced by lightning or injected from a nearby naval transmitter operated at 28.5 KHz. Whistler wave-particle interactions in the radiation belts can potentially lead to particle precipitation, causing anomalous ionization in the lower ionosphere [Lee et al., 1992; K.M. Vilece, M.S. Thesis, MIT, 1992].

A source mechanism has been proposed to explain the observation of a low- frequency (~ 500 Hz) mode in conjunction with symmetric sidebands, displaced by approximately 500 Hz off the carrier frequency of an injected VLF wave from a ground-based transmitter [Dalkir et al., 1992]. These plasma modes were detected by satellite-borne instruments in the VLF wave injection experiments at the Komsomolsk-on-Amur Alpha station [Sotnikov et al., 1991]. Our theoretical analysis shows that the injected VLF wave parametrically excites a purely growing mode and both the Stokes and the anti-Stokes sidebands of the lower hybrid waves. The Doppler shifted frequencies of these modes resulting from the satellite motion adequately account for both the sidebands and the low frequency mode observed in the experiments.

We have conducted ionospheric heating experiments at Arecibo, using both vertically and obliquely injected HF waves to study the spectral characteristics of the HF enhanced



Figures 5 (a) Large enhancement of incoherent radar backscatter echoes around 90 km during heating experiments at Arecibo on July 16, 1991.

5 (b) Typical sporadic E event at Arecibo.

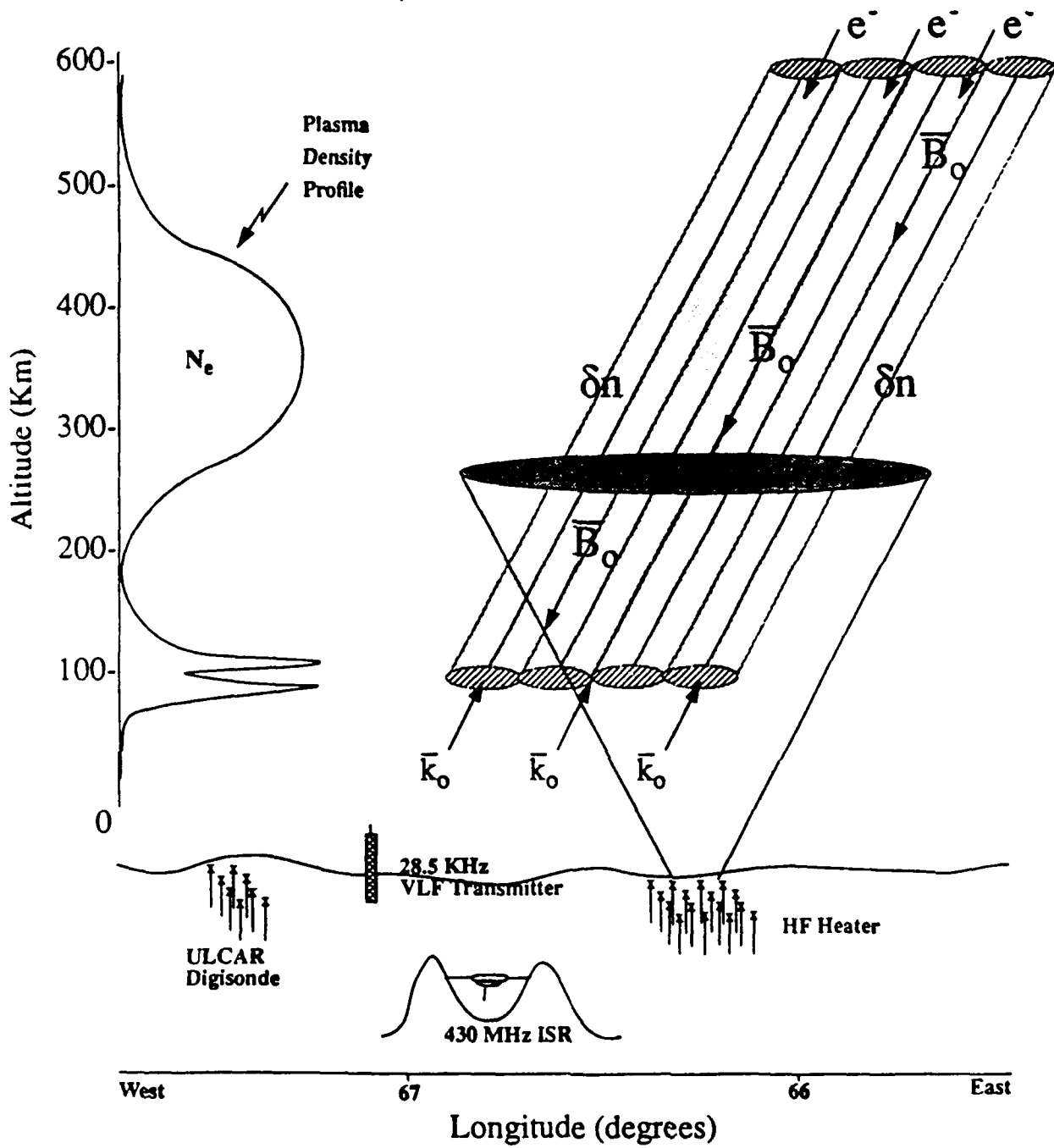


Figure 6. Locations of HF heater, 430 MHz radar, digisonde, VLF transmitter at 28.5 kHz in our heating experiments at Arecibo, Puerto Rico.

Langmuir waves. During the vertical heating experiments, the cascading spectra of Langmuir waves due to the PDI (parametric decay instability) were constantly observed [see Figure 7 (a)]. This broad cascading spectrum cannot be produced "directly" by PDI. The filamentation instability of the PDI-produced Langmuir waves, however, generates obliquely propagating Langmuir waves that can be subsequently scattered off meter-scale field-aligned density irregularities to yield these observed HF enhanced plasma lines at Arecibo [Kuo et al., 1993]. Occasionally seen was a relatively weak and narrow band of Langmuir waves whose frequencies are greater than the HF heater frequency by tens of kHz known as free modes [e.g., Chung et al., 1990; DuBois et al., 1991; Fejer et al., 1992] or anti-Stokes modes [Kuo and Lee, 1992; Lee et al., 1992] in the literature. As shown in Figures 7 (b) these Langmuir waves are frequency-upshifted by approximately 50 kHz for the HF heater operated at 8.175 MHz. Measurements of the frequency shifts of the free modes/anti-Stokes modes were made for three heater frequencies: 5.1 MHz, 7.4 MHz, and 8.175 MHz as displayed in Figure 8. The solid line is the theoretical result [Lee et al., 1992 & 1993; Kuo and Lee, 1992], which is described briefly below.

The observation of these frequency upshifted Langmuir waves is explained by a non-linear scattering process, whereby the source Langmuir waves generated by PDI along the geomagnetic field are scattered off the density fluctuations associated with the existing lower hybrid waves. These lower hybrid waves can be generated by lightning-induced VLF (whistler) waves via parametric instabilities [Lee and Kuo, 1984; Kelley et al., 1984] or a scattering process discussed in Groves et al. [1988]. The resulting frequency upshifted (anti-Stokes) Langmuir waves are resonant (i.e., normal) modes, viz., they satisfy the dispersion relation for Langmuir waves propagating obliquely across the geomagnetic field. The frequency downshifted (Stokes) modes, by contrast, are nonresonant, and are thus greatly reduced in intensity compared with the frequency upshifted modes. This theoretical expectation agrees with the observation that no corresponding frequency downshifted modes were detected by the Arecibo 430 MHz radar [see Figures 7 (b)].

Our oblique ionospheric heating experiments were carried out at Arecibo during August 7-12, 1992. Distinctively different spectra of the HF enhanced Langmuir waves were observed as displayed in Figure 9. An intense broad spectrum of decay modes clearly overrides the cascading spectrum of PDI, indicating that other plasma process(es) have overshadowed the weakly excited PDI during our oblique heating experiments [Lee et al., 1993]. Further investigation of this phenomenon will be conducted.

The outcome of the afore-mentioned research work leads to the publication and sub-

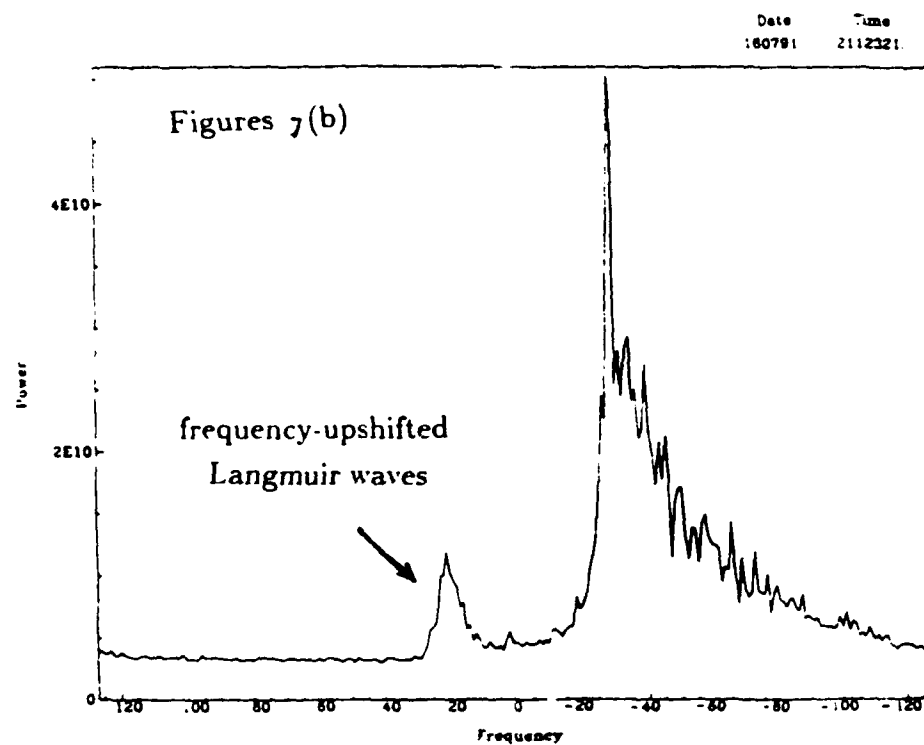
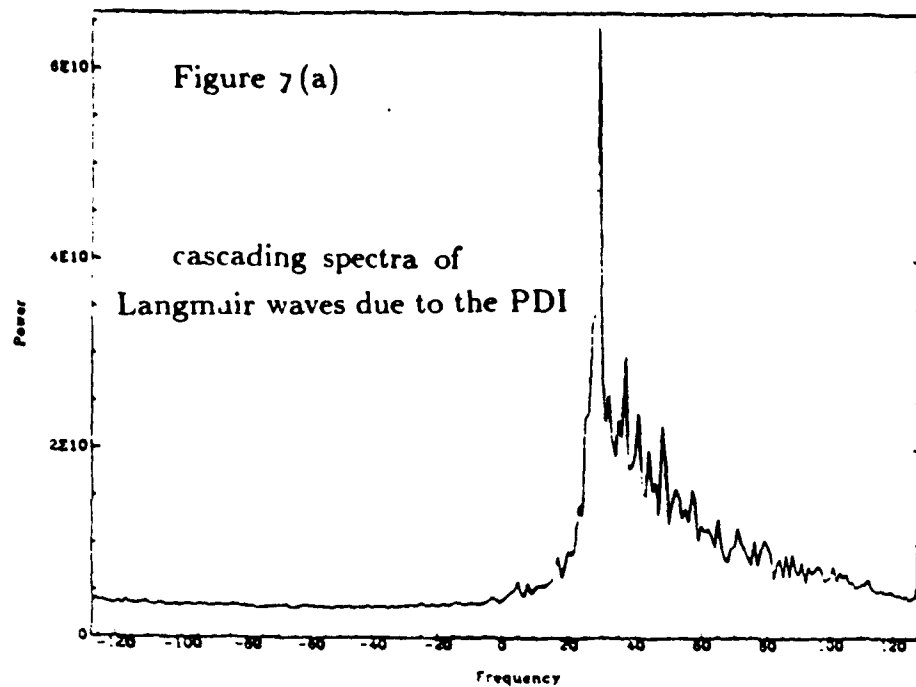


Figure 7. (a) Cascading spectra of Langmuir waves due to PDI, (b) Frequency upshifted Langmuir waves, during vertical heating experiments at Arecibo with HF heater operated at 8.175 MHz.

Anti-Stokes Langmuir Mode: Experimental Results vs. Dispersion Relationship

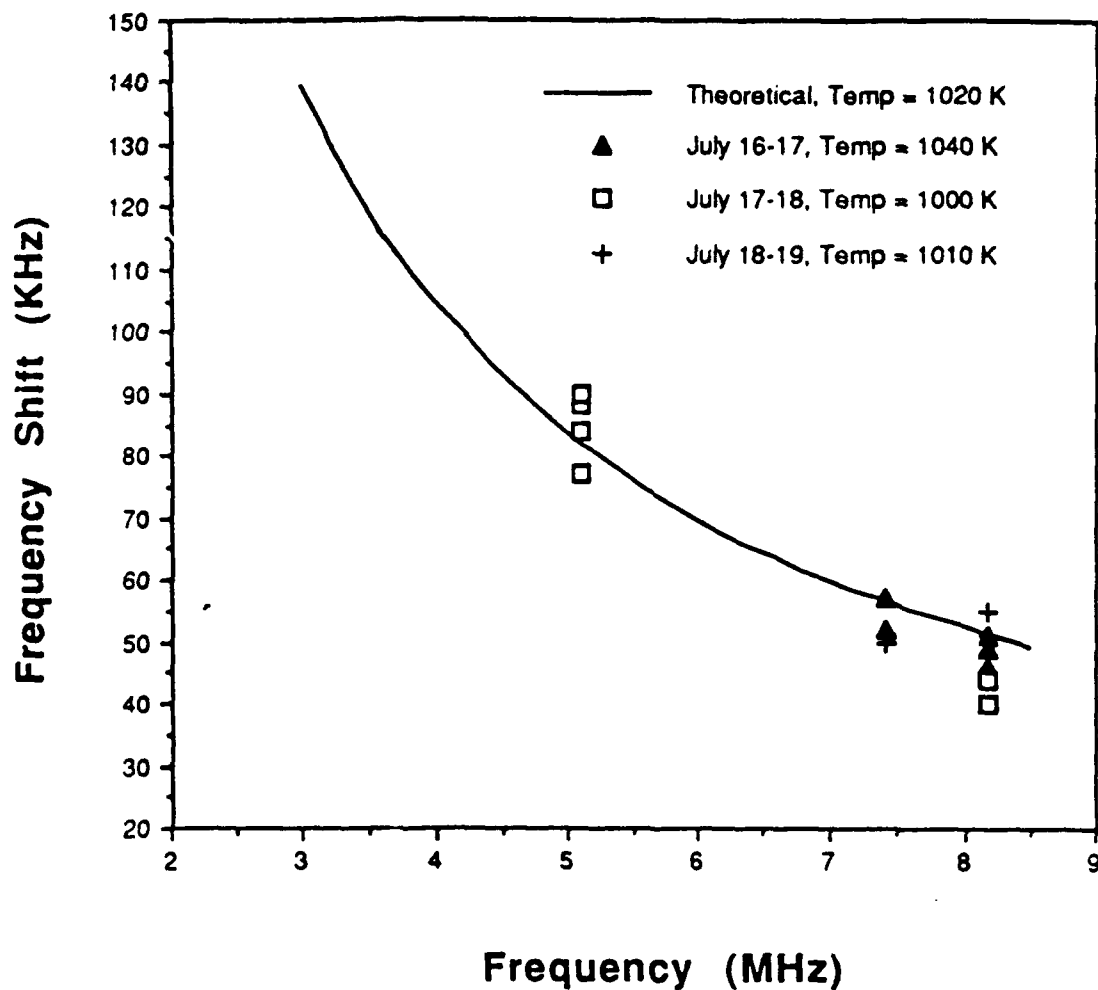
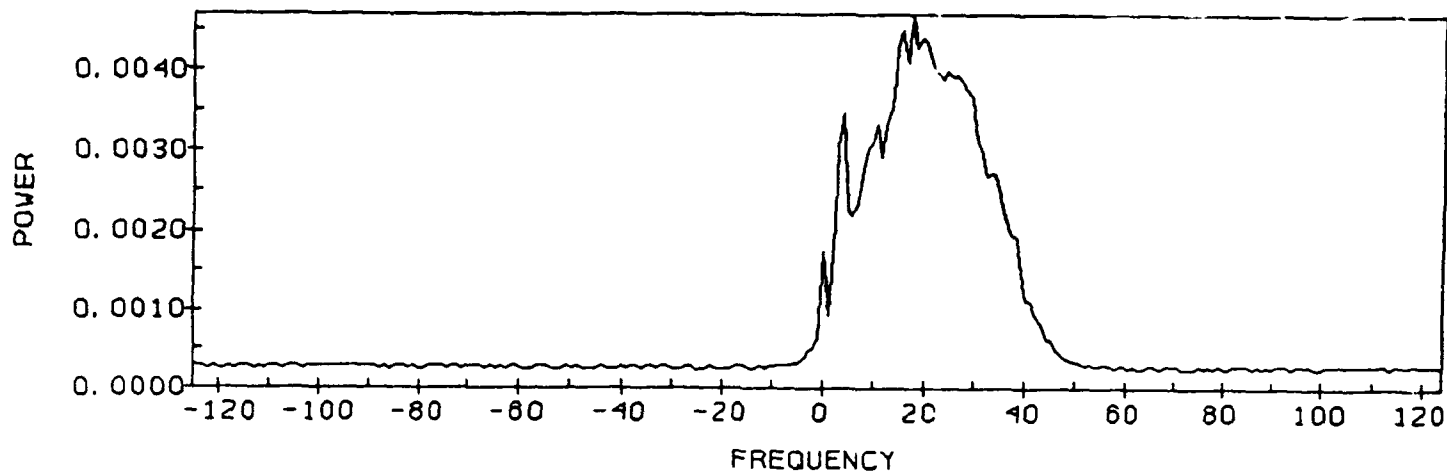
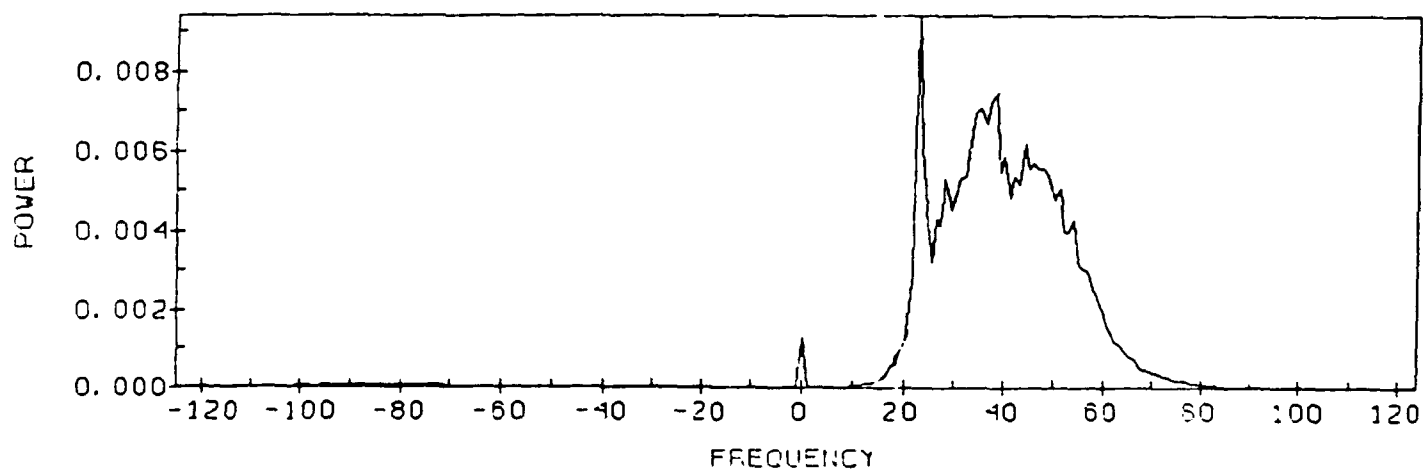


Figure 8, Measurements of the frequency shifts of the anti-Stokes Langmuir waves for three heater frequencies 5.1 MHz, 7.4 MHz, and 8.175 MHz in Arecibo experiments during July 16-19, 1991.



TI= 157456 DA= 60892 AZ= 376.0 ZA= 16.0



TI=2105565 DA=100892 AZ= 376.0 ZA= 16.0

Figure 9. Spectra of Langmuir waves during oblique heating experiments carried out during August 7-12, 1992.

mission of eight (8) journal articles and nine (9) proceedings papers. Seventeen (17) papers have been presented at conferences/symposiums. Two (2) graduate theses and one (1) undergraduate thesis have been accomplished. The paper entitled "Radar studies of lightning induced plasmas with potential applications to radio communications and space surveillance" by Y.R. Dalkir and M.C. Lee won the 1st position in the 1992 URSI Student Prize Paper Contest held at the National Radio Science Meeting, Boulder, Colorado, January 5-8, 1993. A xerox copy of the award certificate is attached in the Appendix. Listed below are the main publications.

(A) Technical Articles:

(1) "A mechanism responsible for the observation of symmetric lower hybrid sidebands and a low frequency mode in the upper ionosphere" by Y.R. Dalkir, M.C. Lee, K.M. Groves, and S.P. Kuo", **Journal of Geophysical Research**, 97, 17195, 1992.

(2) "A source mechanism producing HF-induced plasma lines (HFPLs) with upshifted frequencies" by S.P. Kuo and M.C. Lee, **Geophysical Research Letters**, 19, 249, 1992.

(3) "Nonlinear ionospheric propagation effects of UHF radio signals" by K.M. Groves, M.C. Lee, and J.C. Foster, in **Physics of Space Plasmas**, Scientific Publishers, Cambridge, MA, No. 11, 377, 1992.

(4) "On the spectral characteristics of the Langmuir mode waves produced by RF heating of ionospheric plasmas" by M.C. Lee, Y.R. Dalkir, D.T. Moriarty, K.D. Vilece, K.M. Groves, M.P. Sulzer and S.P. Kuo, accepted for publication in **Physics of Space Plasmas**, Scientific Publishers, Cambridge, MA, No. 12, 1993.

(5) "The role of nonlinear beating currents in the theory of parametric instabilities" by S.P. Kuo, M.C. Lee and J.A. Fejer, **Journal of Geophysical Research**, 98, 9515, 1993.

(6) "On the altitude of HF-enhanced plasma lines (HFPLs)" by S.P. Kuo, J. Huang and M.C. Lee, accepted for publication in **Journal of Geophysical Research**, 98, 11671, 1993.

(7) "Radar studies of lightning-induced plasmas with potential applications to radio communications and space surveillance" by Y.R. Dalkir and M.C. Lee, accepted for publication in **Radio Science**, 1993.

(8) "Radio reflectivity of lightning-induced plasmas" by Y.R. Dalkir, M.C. Lee and E.R. Williams, accepted for publication in **Journal of Geophysical Research**, 1993.

(9) "Generation of artificial ionospheric ducts for guided VLF wave propagation" by M.C. Lee, S. Basu, K.M. Groves, K.L. Koh, M.P. Sulzer and K.D. Vilece, **Proceedings of 1992 International Beacon Satellite Symposium**.

(10) "Frequency-upshifted Langmuir waves produced by RF heating of ionospheric plasmas" by M.C. Lee, Y.R. Dalkir, K.M. Groves, S.P. Kuo, M.P. Sulzer, and K.D. Vilece, **Proceedings of 1992 International Beacon Satellite Symposium**.

(11) "Scintillation effects on incoherent scatter radar observations of enhanced ion acoustic waves" by K.M. Groves, M.C. Lee, J.C. Foster, and F.T. Djuth, **Proceedings of 1992 International Beacon Satellite Symposium**.

(12) "Ionospheric heating experiments at Arecibo using vertically and obliquely transmitted HF waves" by M.C. Lee, M.P. Sulzer, K.M. Groves, S.P. Kuo, D.T. Moriarty, J.L. Scali and B.W. Reinisch, **Proceedings of 1993 Ionospheric Effects Symposium**.

(B) Graduate Theses:

(1) K.D. Vilece, "Experimental study of anti-Stokes Langmuir modes and particle precipitation produced by RF heating of ionospheric plasmas", M.S. Thesis, Department of Nuclear Engineering, **M.I.T.**, May, 1992.

(2) Y.R. Dalkir, "Radio wave interactions with plasmas in the atmosphere", M.S. Thesis, Department of Electrical Engineering and Computer Science, **M.I.T.**, May, 1993.

(C) Undergraduate Thesis:

(1) M.J. Starks, "Artificial communication paths: table-top demonstration and experiments at Arecibo", B.S. Thesis, Department of Electrical, Computer, and Systems Engineering, **B.U.**, May, 1993.

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