

INVERSION OF ARECIBO INCOHERENT SCATTER RADAR CODED  
LONG PULSE BACKSCATTER SPECTRA

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BY

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THESIS

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# ABSTRACT

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# CHAPTER 1

## INTRODUCTION

Large power VHF/UHF radar systems used with very large gain antennas in ionospheric research are known as incoherent scatter radar (ISR). The highest sensitivity ISR in operation in the world today is located at the Arecibo Observatory in Puerto Rico, and this thesis presents the coded long pulse (CLP) spectral estimation and analysis using measurement data from the Arecibo ISR from ionospheric altitudes above about 75 km.

The mechanism underlying incoherent scattering in ISR operations is the “dipole radiation” of each free electron in the ionosphere made to oscillate by the transmitted radar pulse – this is known as the Thomson scattering process. The density of Thomson scattering free electrons in the ionosphere fluctuates as a superposition of electron density waves propagating in all directions across a broad spectrum of wavelengths with propagation velocities governed by the Langmuir and ion-acoustic wave dispersion relations. An ISR will only detect the superposition dipole radiation (Thomson scattering) signals of the electrons “belonging to” density waves whose wavefronts are perpendicular to the radar beam since scattering from electrons of waves propagating in other directions will be self-cancelling due to the destructive interference. Furthermore, only the scattering of the electrons of waves with a wavelength equal to one half of the wavelength of the transmitted radar pulse will not self-cancel – this wave component solely responsible for the backscattered radar signal is called the “Bragg wave”. The operation frequency of the Arecibo ISR is 430 MHz, which corresponds to about 70 cm wavelength, and 35 cm Bragg wavelength, meaning that Arecibo ISR will only detect signals returned from 35 cm wavelength electron density waves which are propagating parallel or anti-parallel to the direction of radar beam. The Arecibo ISR signal spectrum will then exhibit a pair of peaks up-shifted from 430 MHz, each one caused by 35 cm Bragg waves propagating toward the radar at the ion-acoustic velocity  $C_s$  as well as the plasma-wave phase

shift speed  $\omega_p/k_B$ , respectively, where  $\omega_p$  is the plasma frequency and  $k_B$  is the Bragg wavenumber, in addition to a pair of down-shifted peaks caused by the same waves propagating in the opposite direction. The slower phase velocity peaks in the ISR spectrum relate to ion-acoustic waves in the ionospheric plasma while the fast phase velocity peaks represent electron plasma (Langmuir) waves. Landau damping and collisional damping of the scattering density waves will contribute to the broadening of each of these spectral peaks. The broadened low-frequency ion-acoustic peaks will tend to merge together to form the “double humped” ion-line feature of the ISR spectrum. The shape of this “double-humped” ion-line component has been derived by *Kudeki and Milla* [2011], and is essentially a superposition of electron and ion velocity distribution functions scaled by  $k_B$  and frequency-dependent weighting coefficients describing the collective interactions of ionospheric charged particles (electrons and ions) via polarization electric fields that they cause.

(Next we describe coded long pulse here, can borrow something from senior thesis)

There are six additional chapters in this thesis:

- Chapter 2 introduces basic concepts about the ionosphere and presents the derivation of the model equation of the spectrum of the electron density fluctuations causing the radar backscatter – a convolutionally distorted version of the spectrum also models the backscattered radar signal spectrum that can be computed from the sampled radar data.
- Chapter 3 describes the configuration of the Arecibo ISR system and the technologies utilized in the experiment using CLP data collection mode.
- Chapter 4 presents the computation of ISR ion-line power spectrum from CLP raw voltage data using fast Fourier transform (FFT) and point spread function (PSF) that is used in inversion of convolutionally distorted power spectra.
- Chapter 5 presents the details of the theory of ion-line spectrum including the electron and ion Gordeyev integral that involves the effects of Coulomb collision, ion-neutral collision, geomagnetic fields, and magnetic aspect angle, followed by the computation of such model using chirp-z algorithm.

- Chapter 6 presents the inversion of electron and ion temperatures from CLP ion-line power spectra using independent fitting and profile fitting techniques. The inversion of ion velocity from auto-correlation function (ACF) of power spectra and the inversion method of electron density and radar system calibration from ion-line power spectra are discussed.
- Chapter 7 presents the conclusions of this study and the future directions of improving current inversion algorithm.

# CHAPTER 2

## THE IONOSPHERE AND THE THEORY OF IONOSPHERIC INCOHERENT SCATTERING

### 2.1 Earth's Ionosphere

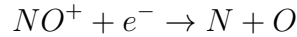
Earth's upper atmosphere is a partially ionized and electrically conducting plasma above about 50 km altitude. This deep layer of the atmosphere is called the “ionosphere” and blends into Earth's “magnetosphere” above an altitude of about 1000 km as a magnetized plasma and into the “solar wind” beyond.

Two types of classification are used to describe the properties of the ionosphere:

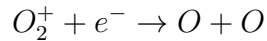
- Temperature profile: As shown in Figure ?? on the left, atmospheric temperature will decrease with height at an approximately constant rate below an altitude of about 10 km in a region known as the troposphere. Above the troposphere the temperature will increase with height throughout a region known as the stratosphere. The region of decreasing temperature above the stratosphere is known as the mesosphere, above which lies a region of increasing temperature known as the thermosphere. Stratospheric temperature increase is due to the absorption of the ultraviolet portion of the solar radiation by ozone. Mesospheric temperature decrease with height above 50 km is caused by radiative cooling whereas thermospheric temperature increase is caused by daytime absorption of solar photons in UV and EUV frequency bands.
- Plasma density profile: This characteristic is defined as the number of free electrons per unit volume. As shown in Figure ?? on the right, ionospheric plasma density reaches its peak value at a few hundred kilometers altitude and exhibits substantial variation depending on daytime (solid curve) and nighttime (dashed curve) conditions. The daytime

profile represents an equilibrium between the photo-ionization rate and recombination rate of plasma production and decay. In daytime, the solar spectrum is incident on a neutral atmosphere whose electron density increases exponentially with decreasing altitude. Since the photons are absorbed in the process of photoionization, the incoming beam itself decreases in intensity as it penetrates the atmosphere. The combination of decreasing solar flux increasing neutral density, and diffusion provides a simple explanation for the basic large scale vertical layer of ionization [Kelley, 2009]. From 60 km to 90 km altitude is the D region, from 90 km to 150 km is the E region, and beyond 150 km lies the F region. Peak plasma density occurs in the F region. The ion composition differs among regions; at lower altitudes, namely in the D region, it is less affected by the solar radiation. Therefore, there is a large number of neutral particles in the lower altitude. In the F region, on the other hand, due to the chemical reaction between oxygen gas, nitrogen gas and solar UV radiation,  $O^+$  and  $N^+$  ions will dominate the ion composition [Kelley, 2009].

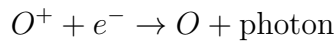
Ionospheric plasma density drops dramatically at night at D region heights while staying nearly the same higher up in the ionosphere in the F-region; this is due to the dramatic difference of the recombination rates of the F- and D-region plasmas as explained in Kelley [2009], where atomic and molecular ions dominate, respectively. In the lower altitude D-region the recombination process may be



and



In F-region, the dominant recombination process goes as



Without the solar radiation at night, the recombination at lower altitude will occur more frequently than at higher altitude. As a result, the plasma



density in D-region will almost disappear.

## 2.2 Incoherent Scatter Theories

According to the incoherent scatter spectral theory [Kudeki and Milla, 2011], ionospheric incoherent scatter is caused by Thomson scattering of radar pulses at radio frequencies from collections of ionospheric free electrons. In this section, we will first describe the Thomson scattering process by single electrons, then study the Thomson scattering effect of multiple electrons.

### 2.2.1 Thomson scattering by a free electron

# CHAPTER 3

## RADAR CONFIGURATION AT ARECIBO OBSERVATORY

## CHAPTER 4

# COMPUTATION OF ARECIBO ISR CODED LONG PULSE IONLINE SPECTROGRAM

## CHAPTER 5

# DERIVATION OF FULL INCOHERENT SCATTER ION-LINE MODEL

## CHAPTER 6

# INVERSION OF ARECIBO ISR CODED LONG PULSE POWER SPECTRA

## CHAPTER 7

### CONCLUSION AND FUTURE WORK