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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TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION 1

CHAPTER 2 THE IONOSPHERE AND THE THEORY OF IONOSPHERIC INCOHERENT SCATTERING 4
- 2.1 Earth's Ionosphere 4
- 2.2 Incoherent Scatter Theories 6

CHAPTER 3 RADAR CONFIGURATION AT ARECIBO OBSERVATORY AND COMPUTATION OF CODED LONG PULSE ION-LINE SPECTROGRAM 7
- 3.1 Arecibo ISR - System Description 7
- 3.2 Arecibo ISR Coded Long Pulse Data Mode 8

CHAPTER 4 (MOVED TO CHAPTER 3) 9

CHAPTER 5 DERIVATION OF FULL INCOHERENT SCATTER ION-LINE MODEL 10

CHAPTER 6 INVERSION OF ARECIBO ISR CODED LONG PULSE POWER SPECTRA 11

CHAPTER 7 CONCLUSION AND FUTURE WORK 12

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 scttering free electrons in the ionospheres fluctuations 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 ω_p/k_B, respectively, where ω_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 broading of eac 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 componentes 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 backscater – 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 Coulumb 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 ionospere:

- 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. About the troposphere the temperature will increase with height throughout a region known as the stratosphere. The region of decreasing temperature about 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 dattime 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-ionozation 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 automic and molecular ions dominate, respectively. In the lower altitude D-region the recombination process may beam

$$NO^+ + e^- \rightarrow N + O$$

and

$$O_2^+ + e^- \rightarrow O + O$$

In F-region, the dominant recombination process goes as

$$O^+ + e^- \rightarrow O + \text{photon}$$

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 scttering effect of multiple electrons.

2.2.1 Thomson scattering by a free electron

CHAPTER 3

RADAR CONFIGURATION AT ARECIBO OBSERVATORY AND COMPUTATION OF CODED LONG PULSE ION-LINE SPECTROGRAM

The Arecibo Observatory is located near the northern coastal town of Arecibo on the island of Puerto Rico in a region populated by natural sinkholes in its terrain. One such sinkhole about 15 km inland from Arecibo houses the largest single dish spherical reflector antenna in the world used for space research. The Arecibo reflector antenna is part of the Arecibo ISR system that was designed and built by William E. Gordon of Cornell University in the mid-1960s and maintained by Cornell University until 2011. Since 2011 the Arecibo Observatory and its ISR system have been operated under cooperative agreements with Ntional Science Foundation. The Arecibo facility supports three major areas of research: radio astronomy, atmospheric science, and radar astronomy. The observatory has radar transmitters with effective isotropic radiated power of 1 MW at 2380 MHz (S-band system) and 2.5 MW at 430 MHz (the ionospheric ISR system). This thesis is focusd on the use of Arecibo ISR system for ionospheric measurements and research, specifically in coded-long-pulse data mode of the system.

3.1 Arecibo ISR - System Description

The Arecibo ISR is a 430 MHz backscatter radar system using a 305 m diameter spherical dish antenna as shown in Figure ??. The radar transmitter generates pulses with peak power of 2.5 MW at the 430 MHz oprerating frequency [Isham et al., 2000]. Given its very large antenna aperture and transmitted power operated within the UHF band, Arecibo ISR achieves an overall sensitivity about 100 times larger than that of other ISR systems currently in existance. The 430 MHz line feed makes an efficient use of the main dish when pointed vertically, as its radiation pattern fills the available aperture. The new Gregorian feed that was added to the system during the

2000 upgrades enables dual beam operations for more efficient determinations of ionospheric plasma drifts [same citation here 2000].

3.2 Arecibo ISR Coded Long Pulse Data Mode

Isham et al. [2000] describes six data acquisition modes for Arecibo ISR operations. One of them, coded long pulse (CLP), is of importance in F-region and topside ionospheric studies. The use of CLP data mode for marrowband ion-line measurements with the main Arecibo ISR receiver will be described below.

In soft target radar measurements, if the correlation times of the scattering density waves are short compared to the inter-pulse period (IPP), then "pulse-to-pulse" correlation methods cannot be used and it becomes necessary to utilize "within pulse" correlation methods with multiple samples taken from the supreposed echos of transmieed pulses whose lengths need to exceed the sampling interval by some substantial margin. Such "within pulse" operations are generally referred to as "long pulse" techniques. The disadvantages of using long pulses is accepting relatively poor radar range resolution, unless the target SNR is so strong that short baud length coding can be applied to the transmitted long pulse to produce a range resolution determined by the baud length rather than the pulse length.

The coded long pulse (CLP) mode utilized at Arecibo implements this idea and works well to probe the lower F-region altitudes of the ionosphere where the electron density is realtively large and the corresponding scatter SNR is sufficient. The mode was developed by Sulzer [1986] for high-resolution ion-line measurements.

CHAPTER 4

(MOVED TO CHAPTER 3)

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