DETECTION OF IONOSPHERIC STRUCTURES WITH L-BAND SYNTHETIC APERTURE RADARS

Paul Bernhardt[1], Tom Ainsworth[1], Keith Groves[2], Ted Beach[2], Ron G. Caton[3], Charles S. Carrano[3], Christian .M. Alcala[3], Dale D. Sponseller[4]

[1]Plasma Physics and Remote Sensing Divisions, NRL, Washington, DC 20375
[2]Space Vehicles Directorate, AFRL, Hanscom AFB, Massachusetts, USA
[3]Atmospheric & Environmental Research, Inc, Lexington, MA, 02421, USA
[4]Kwajalein Range Services LLC, Kwajalein Atoll, Marshall Islands

ABSTRACT

Numerical simulations of low-latitude ionospheric instabilities show the formation of plasma density structures are can be detected by synthetic aperture radar (SAR) radio signals. At L-band, the phase front distortions produced by propagation through plasma "bubbles" should provide measurable changes in both the complex-amplitude and polarization waves from orbiting satellite radars. The diffraction pattern from scattered ground SAR signals can be detected by orbiting receivers. Based on reciprocity, ground radars at Kwajalein Atoll are being used to determine the feasibility of space-based detection of ionospheric density structures. This new measurement technique can provide a global data base of ionospheric data for space-weather models that predict the effects of the ionosphere on radio systems.

***Index Terms*—** Radio Scintillations, Synthetic Aperture Radars, Ionospheric Irregularities

1. INTRODUCTION

Ionospheric irregularities are produced by a wide range of fluid and kinetic instability processes. Understanding of these processes can benefit from images of the phase and polarization changes introduced onto transiting radio waves. L-Band synthetic aperture radar (SAR) signals, such as produced by the Japanese ALOS PALSAR at 1.27 GHz, can be used to study the ionosphere with either phase delays, Faraday Rotations, or, in the case of severe radio scintillations, amplitude and polarization effects. Ionospheric physicists can use the distorted SAR signals to measure natural and artificial ionospheric irregularities. Near the geomagnetic equator, at sunset, the ionosphere often becomes distorted by ionospheric bubbles rising nearly vertically to 600 km or higher. The availability of an orbiting SAR makes the study of such bubbles possible by detecting the distortions of the SAR images for waves passing through the disturbed ionosphere. Such structures may be imaged using space-based SAR.

2. MODEL OF IONOSPHERIC DIFFRACTION EFFECTS ON SAR SIGNALS.

The concept of using SAR data for ionospheric irregularity detection has been tested with simulations of propagation though physics-based models. To detect the usefulness for space borne SAR for measurements of ionospheric structures, a full wave propagation code was coupled with a first-principles model of ionospheric irregularities. Ionospheric bubble irregularities were modeled using the quasi-analytic technique described by Bernhardt [4] and [5] to yield the depleted density structure illustrated by the color density contours in Figure 1. These bubbles are commonly formed in the equatorial ionosphere just after sunset. The SAR radar signal is assumed to have propagated from a satellite at 850 km altitude though the ionosphere where it is scattered by a retro-reflector located on the ground at the origin of the horizontal coordinate axis. The scattered wave from the retro-reflector point source propagates back though the ionosphere where it its phase front is corrugated by the plasma density irregularities in the ionosphere.

For propagation through the ionosphere, this phase perturbation is proportional to the integral of the electron density fluctuations, or the total electron content (TEC) variation along the radar line-of-sight. The complex wave amplitude obtained at a SAR space-based receiver for a spherical wave scattered from a ground point target, results from the calculation of Fresnel diffraction under the assumption of forward scattering [1] and [2]. The advantage of the phase screen technique is that the method applies in both the weak and strong scattering regimes. One limitation of this technique is the assumption of variation in the screen in only one direction, in other words; we are using a 1-D phase screen. This is not an importation limitation at the equator where the horizontal magnetic field lines produce structures that only vary in the zonal (x) and vertical (z) directions. The simulations show that polarization fluctuations are relatively easy to introduce into the SAR signal for ionospheric diagnostics purposes. Amplitude scintillations at L-Band are usually less than 1 dB so they are less useful for ionospheric irregularity detection (Figure 1). Near the equator, the strongest distortions of SAR signals are predicted to come from propagation along the gradients of the ionospheric bubbles.

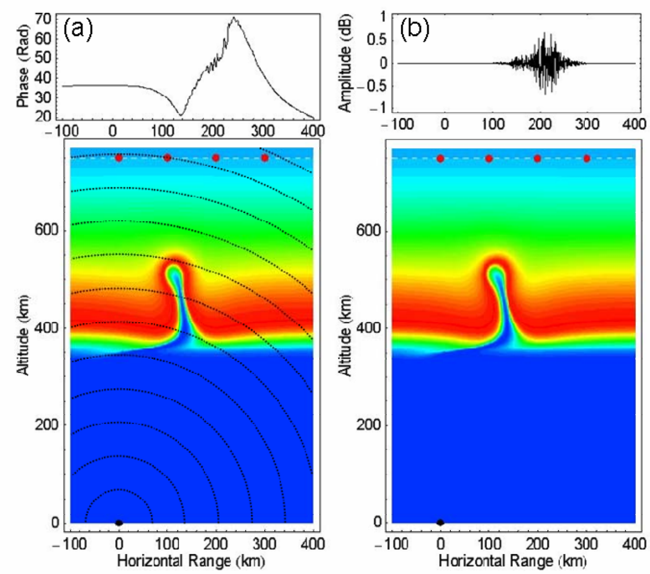

Figure 1. Simulated effects of the equatorial ionosphere on a 1.27 GHz electromagnetic wave scattered from a point on the earth (black dot) and received on a satellite at 750 km altitude (red dots). The simulation represents distortion of SAR backscatter by a single bubble irregularity in the equatorial ionosphere. The electron density layer with a peak density of 10^6 cm^{-3} contains an embedded rising bubble.

3. GROUND OBSERVATIONS OF REPRESENTATIVE IONOSPHERIC DIFFRACTION EFFECTS

Two types of ground measurements have been conducted to represent the diffraction effects of the equatorial ionosphere. First, the VHF/UHF ALTAIR radar located on the Kwajalein Atoll at 4.3o N magnetic dip latitude in the western Pacific tracked along the trajectory of orbiting calibration spheres. Incoherent radar scans made perpendicular to the geomagnetic field provided a characterization of the environment through which the tracking scan occurs. The fully steerable parabolic dish antenna (~46 m diameter) operates in dual frequency mode transmitting signals at 158 and 422 MHz. Raw data collected in tracking mode were reduced by MIT Lincoln Laboratory and provided to the experiment collaborators including full amplitude, phase, and target range information for each frequency.

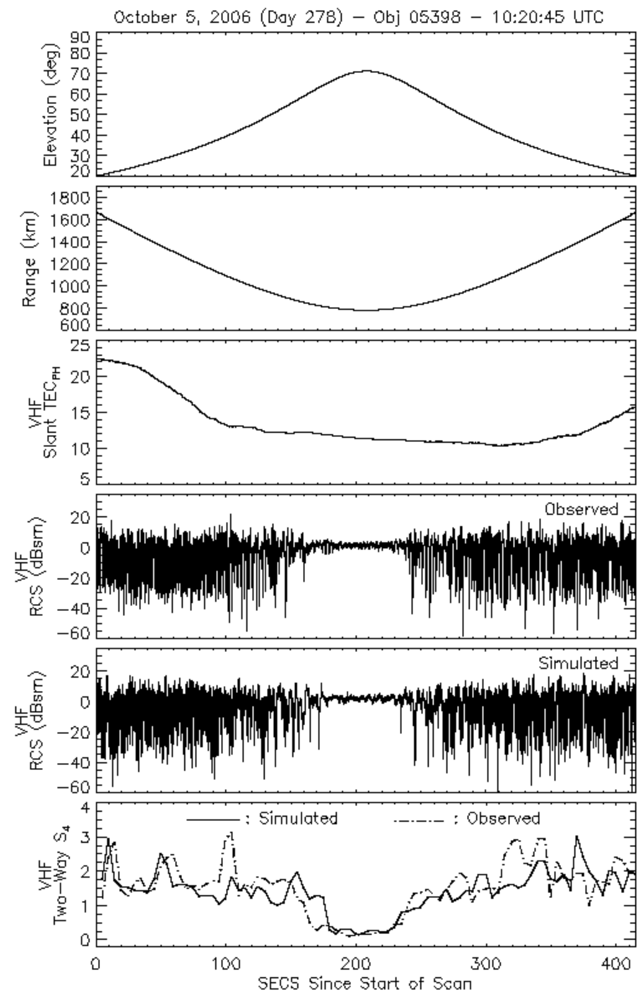

Figure 2. Apparent radar cross section of a spherical target observed through a structured equatorial ionosphere on 5 October 2006.

Sample results are found in Figure 2 with a tracking scan of RIGIDSPHERE-2 (LCS-4, object ID 5398) on Oct. 5, 2006 (Day 278). The top four panels of Figure 4, show the elevation, range, Slant TEC_{PH}, and radar cross section (RCS) from data observed at the VHF frequency on ALTAIR for this scan. Highly structured irregularities over the radar site on this evening resulted in a scan which passed in and out of disturbed regions. The RCS on monostatic paths are enhanced in the presence of scintillation due to backscatter. Evidence of this can be seen in the VHF ALTAIR observations presented in the fourth panel from the top in Figure 2 where the RCS fluctuates significantly near the beginning and end of the tracking scan and is relatively stable as the radio path appears to travel between the discretely spaced irregularities. Simulated RCS from the 1-D phase screen are presented below the observed RCS in Figure 2 with the associated observed and simulated 10-sec scintillation index (S_4) estimates plotted in the bottom panel. Using the relatively smooth TEC_{PH} derived from VHF phase returns at the radar (third panel from the top) and the effective scan velocity across the observed irregularities, the simulated RCS and two-way S_4 values match the observed signatures quite well.

A second point source for electromagnetic radiation is provided by the CERTO VHF/UHF/L-Band radio beacon on the AFRL C/NOFS satellite launched into a 13 degree inclination orbit in April 2008. The characteristics of the CERTO beacon are described by Bernhardt and Siefring [3]. Ground receivers recorded the amplitude fluctuations from the radio beacon transmissions at 600 km altitude. At the same time, 422 MHz scatter was observed when the radar beam was scanned perpendicular to the geomagnetic field lines (Figure 3).

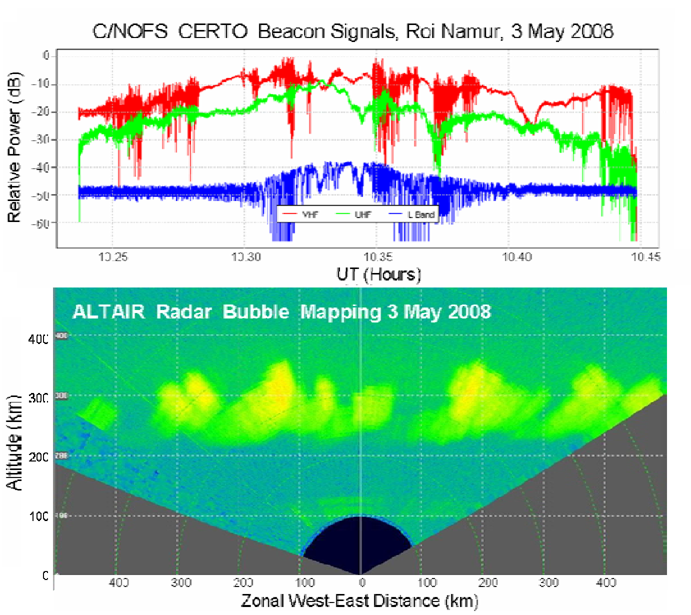

Figure 3. Comparison of radio wave scintillations at 150, 400, and 1067 MHz (top) with radar backscatter from field aligned irregularities (bottom).

4. PLANNED SAR EXPERIMENTS

The computed and measured radio disturbances shown in Figures 1 through 3 are used to plan experiments with ALOS/PALSAR near the equator and at high latitudes. The ALOS PALSAR provides imagery for many repeating orbits. Observations of the natural ionosphere near Kwajalein in the Marshall Islands are planned using incoherent scatter radars and satellite radio beacons to provide ionospheric data complementary to the SAR measurements. The incoherent scatter radar will provide scans of the ionospheric irregularities along a single radar beam. The space-based SAR images are complementary to the radars because they view the full regions of ionospheric disturbance.

4. REFERENCES

[1] Beach, T.L., T. R. Pedersen, and M. J. Starks, Estimating the amplitude scintillation index from sparsely sampled phase screen data**, Radio Sci., 39**, RS5001, doi:10.1029/2002RS002792, 2004.

[2] Bernhardt, PA. and C.L. Siefring, I.J. Galysh, T.F. Rodilosso, D.E. Koch, T.L. MacDonald, M.R. Wilkens, G.P. Landis, Ionospheric Applications of the Scintillation and Tomography Receiver in Space (CITRIS) used with the DORIS Radio Beacon Network, J. Geodesy, 80, 473-485,2006.

[3] Bernhardt, P.A., C.L. Siefring, New Satellite Based Systems for Ionospheric Tomography and Scintillation Region Imaging, Radio Science, 41, RS5S23, 2006.

[4]Bernhardt, P.A., Quasi-Analytic Models for Density Bubbles and Plasma Clouds in the Equatorial Ionosphere: 1. Closed Form Solutions for Electric Fields and Potentials, **J. of Geophys. Res., 112**, A01302, 2007a.

[5]Bernhardt, P.A., Quasi-Analytic Models for Density Bubbles and Plasma Clouds in the Equatorial Ionosphere: 2. A Simple Lagrangian Transport Model, **J. of Geophys. Res., 112**, A11310, 2007b.