Ionospheric Tomography Using Faraday Rotation of Automatic Dependant Surveillance Broadcast (ADS-B) Signals (#A23A-0169)

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“If only three percent of flights were equipped with ADS-B and were able to alter their speed and altitude in a manner to increase efficiency, 2.7 million litres of fuel, and emittance of approximately 7200 tons of greenhouse gases would be saved annually.” - Rudy Kellar, Navigation Canada Vice President of Operations

Abstract

The proposed launch of a satellite carrying the first space-borne ADS-B receiver by the Royal Military College of Canada (RMCC) will create a unique opportunity to study the modification of the 1090 MHz radio waves following propagation through the ionosphere from the transmitting aircraft to the passive satellite receiver(s). Experimental work is described which successfully demonstrated that ADS-B data can be used to reconstruct two dimensional (2D) electron density maps of the ionosphere using techniques from computerized tomography. Ray-tracing techniques are used to determine the characteristics of individual waves, including the wave path and the state of polarization at the satellite receiver. The modelled Faraday rotation (FR) is determined and converted to total electron content (TEC) along the ray-paths. The resulting TEC is used as input for computerized ionospheric tomography (CIT) using algebraic reconstruction technique (ART). This study concentrated on meso-scale structures 100-1000 km in horizontal extent. The primary scientific interest of this thesis was to show the feasibility of a new method to image the ionosphere and obtain a better understanding of magneto-ionic wave propagation.

Introduction

The 1090 MHz ADS-B signal was proposed in support of research conducted in space mission analysis and design at RMCC pioneering the use of ADS-B in space due to its global adoption as the standard mode of ADS-B, especially for larger aircraft [1]. Moreover for this research the ADS-B signal was selected for several other reasons: this frequency allows for robust operational communications yet measurable perturbation due to ionospheric effects, the spatially dense dataset that was estimated by the geometry between multiple transmitting aircraft and the passive satellite receiver(s), and to support the expedition of an operational ADS-B constellation.

As electromagnetic (EM) waves propagate through the electrically charged ionosphere in the near-Earth space environment they are modulated and can provide an exceptional opportunity to model the medium through which they have passed. Modelling the electron density of Earth’s ionosphere (and plasmasphere) in general is essential in determining the state of ionospheric activity. This information can be used to correct for propagation delays in satellite communications, predicting space weather, and ionospheric disturbances due to geomagnetic storms and solar flares [2]. The primary benefit of ADS-B is to improve flight safety and efficiency providing timely, cost-effective wide-area surveillance over the Hudson Bay region, with the eventual expansion to global real-time air-traffic control (ATC). Since the scientific model presented in this thesis cannot be used until the concept demonstrator or the dedicated ADS-B satellite is in orbit, the primary objective is to support the immediate use of ADS-B ATC from space.

The motivation for this study is to investigate the potential exploitation of ADS-B operational data to contribute to current methods of ionospheric electron density mapping, primarily at high latitudes and oceanic regions. In order to characterize the ionospheric electron content under different geophysical, geomagnetic and solar conditions, this research combines knowledge extracted from EM-wave propagation theory, ionospheric electron density and geomagnetic models, to produce independent static data of the wave properties received at the satellite receiver.

Objectives

The primary objective of this research is to investigate the feasibility of 2D ionospheric electron density profile reconstruction using ADS-B signals received aboard a proposed satellite. This research sets out to demonstrate the dual purpose of a single payload for improving air traffic management and for scientific observation of the ionosphere. The topic of ionospheric modelling within the scope of ADS-B has not been explored prior to this work. Previously, ADS-B research was oriented towards the feasibility of the signal for operational communications, not the potential secondary scientific benefits, which is the focus of this investigation.

Methodology

Faraday Rotation: An EM-wave propagating through a magnetised plasma decomposes into two propagation modes which have different indices of refraction and polarizations due to the external magnetic field. The two modes are called the ordinary and extraordinary modes or O-mode and X-mode respectively. The refractive index for each mode, when collisions between neutral and charged particles is neglected, is given by the Appleton-Hartree equation [3] and [4]:

\[
x^2 + 1 - \frac{x}{\sqrt{1 + x^2}} \frac{\omega_p^2}{\omega^2} = 0
\]

where \( x \) is the ratio of square of plasma frequency \( \omega_p \) to radio wave frequency \( \omega \), and \( Y \) is the ratio of gyrofrequency \( \omega_p \) to \( \omega \). The refractive index for the two modes is determined by the positive (O-mode) and negative (X-mode) sign of the denominator. Since the two modes have different refractive indices, the phase velocities will be different for each mode of propagation.

\[
x^2 + 1 - \frac{x}{\sqrt{1 + x^2}} \frac{\omega_p^2}{\omega^2} = 0 \quad (O\text{-mode})
\]

\[
x^2 + 1 - \frac{x}{\sqrt{1 + x^2}} \frac{\omega_p^2}{\omega^2} = 0 \quad (X\text{-mode})
\]

The net imbalance in the phase velocity causes a change in the orientation angle of the polarization ellipse, known as FR. The magnitude of the rotation is the product of the integrated product of the electron density \( ne(\theta) \) in the ray-path or plasma column, the strength of the parallel component of the magnetic field \( B(\theta) \), and the inversely proportional to the square of frequency of the carrier [5].

\[
\Omega = \frac{e}{2c} \int_{\theta_2}^{\theta_1} \frac{1}{\cos \theta} \frac{B(\theta)}{ne(\theta)} \, d\theta
\]

where \( e \) is the charge of an electron, \( c \) is the speed of light in a vacuum, \( m \) is the mass of an electron, and \( \epsilon \) is the vacuum permittivity. The TEC along the path or within the plasma column of unit cross-section is given by:

\[
TEC = \frac{\Omega}{\epsilon \cos \theta}
\]

Ray-tracing has shown that FR measurements of the received signals are detectable and can yield the TEC along the ray-paths [6]. The program was used to generate outputs from rays that passed from given locations, at a given elevation angle through the input 2D ne-profile to a given satellite location. The TEC and ray-path geometry are used to reconstruct the electron density profile through which they propagate. The reconstructed TEC maps are compared to the input profiles to evaluate the capability of the CIT method using ADS-B signal data.

Results

Numerous datasets were analysed in depth. The following illustrates the input electron density profile to the ray-trace program, used to generate FR measurements and TEC along various ray-paths. The data was reconstructed using only the TEC measurements, and the end-points of the path (theoretically obtained from GPS on satellite and aircraft). This reconstruction illustrated the feasibility for CIT using ADS-B data to analyze qualitative phenomena over time, and act as a tool to prioritize other instrument campaigns (eg. Incoherent Scatter Radar). The final reconstruction used a quiet profile a priori guess to refine the altitude distribution of the features.

Conclusion

- CIT with ADS-B data is feasible
- Important ionospheric features of latitudinal scales 25-2000 km detected
- In-situ a priori data required to improve vertical resolution, and calibrate units
- Minimum data density for reconstruction must be greater than 23.4 degrees/latitude.

Future Work

- Extend to 3D
- Parallel processing
- LAUNCH (sensor calibration, noise & filters)
- In-situ a priori data injection from another source
- Methods of interpolation, forming geometry matrix, algorithm optimization
- Automation and GUI
- Constellation (Iridium NEXT)