Volumetric Reconstruction of the Ionospheric Electron Number Density Using Automatic Dependant Surveillance Broadcast (ADS-B) Signals

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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

Numerical modelling has demonstrated that 1090 MHz ADS-B signals can be used to reconstruct two and three dimensional electron density maps of the ionosphere using techniques for computerized tomography (CT). Ray-tracing was used to determine the characteristics of waves, including the path and the state of polarization at the satellite receiver. The modelled Faraday rotation (FR) was computed and converted to total electron content (TEC) along the ray paths. The resulting TEC was used as input for computerized ionospheric tomography (CIT) using algebraic reconstruction technique (ART). This study concentrated on reconstructing meso-scale structures 25-100 km in horizontal extent. **The primary scientific interest of this study was to show that ADS-B signals can be used as a new source of data for CIT to image the ionosphere**.

Introduction

ADS-B is a technology used to track the position and movement of aircraft through intermittent broadcasts of their identity, itinerary and position state vectors to ground based receivers and other aircraft within range. The system is intended to replace radar as the standard for air traffic control (ATC) by providing an enhanced ranging and separation distinction capability with a reduced footprint for ground support infrastructure [1, 2, 3].

ADS-B networks that monitor air traffic have been deployed around the world in high volume air traffic areas, however ground stations cannot be installed mid-ocean and are difficult to maintain in the Arctic. It has been suggested that ADS-B receivers could be deployed on a constellation of satellites to allow for worldwide tracking of aircraft, alleviating the problem of gaps in coverage over oceanic and high latitude airspace [4]. The launch of an ADS-B receiver on a satellite will create an opportunity to study the propagation of the radio waves through the ionosphere from the transmitting aircraft to the passive satellite receiver(s).

The 1090 MHz ADS-B signal was selected for research conducted in space mission analysis and design at the RMCC due to its global adoption as the standard mode of ADS-B, especially for larger aircraft [4, 5]. Moreover, for this study, the signal was selected for several other reasons: the frequency allows for robust operational communications and measurable perturbation due to ionospheric effects; the spatially dense dataset estimated by the geometry between multiple transmitting aircraft and the satellite receiver(s); and to support and expedite the launch of an ADS-B constellation.

When electromagnetic (EM) waves propagate through the electrically charged ionosphere in the near-Earth space environment they are modulated and can provide an 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, as well as ionospheric disturbances due to geomagnetic storms and solar flares [5]. In order to characterize the ionospheric electron content under different aircraft placement scenarios, ray path geometries, geomagnetic and solar conditions, the current study combines knowledge that can be extracted from EM-wave propagation theory and ionospheric electron density and geomagnetic models to produce independent static data of the wave path and polarization state that will be received at the satellite receiver.

Objectives

The scientific purpose of this study is to investigate the potential exploitation of ADS-B operational data and to contribute to current methods of ionospheric electron density mapping, mainly at high latitudes and in oceanic regions. This work sets out to demonstrate the potential dual purpose of a single payload for improving ATC as well as scientific observation of the ionosphere. The topic of ionospheric modelling using ADS-B has not been explored prior to this work [6]. All previous work surrounding ADS-B technologies have focussed on the feasibility of the signal for operational communications and not on their potential scientific benefits. The primary benefit of using ADS-B is to improve flight safety and efficiency by providing timely, cost-effective wide-area surveillance. Since the full potential of the scientific model presented in this study cannot be realized until a constellation of ADS-B receivers are in orbit, an impending objective is to support the use of ADS-B ATC from space.

Methodology

Faraday Rotation: The ionosphere is assumed to be a circular birefringent medium due to the Earth's magnetic field [7, 8]. Any EM-wave propagating through a magnetised plasma decomposes into two propagation modes which have different indices of refraction and polarizations due to the terrestrial magnetic field. Two modes of propagation, called the ordinary and extraordinary modes (or O-mode and X-mode respectively) exist in the ionosphere [9].

When collisions between neutral and charged particles are neglected, the refractive indices of the two modes are given by the Appleton-Hartree equation [10, 11]:

$$n^2 = 1 - \frac{X}{1 - \frac{Y^2 \sin^2\theta}{2(1-X)} \pm \sqrt{\frac{Y^4 \sin^4\theta}{4(1-X)^2} + Y^2\cos^2\theta}}$$

Where θ is the aspect angle in degrees, X is the squared ratio of the plasma frequency ω_p to radio wave frequency ω and Y is the ratio of the gyrofrequency ω_c to ω. 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 (v_ϕ) will be different for each mode of propagation [9,12].

$$n^2 = \frac{c^2}{v^2_{\phi O}} = 1 - \frac{{\omega_p}^2/\omega^2}{1 + {\omega_c}/\omega} \ (\mathrm{O-mode})$$

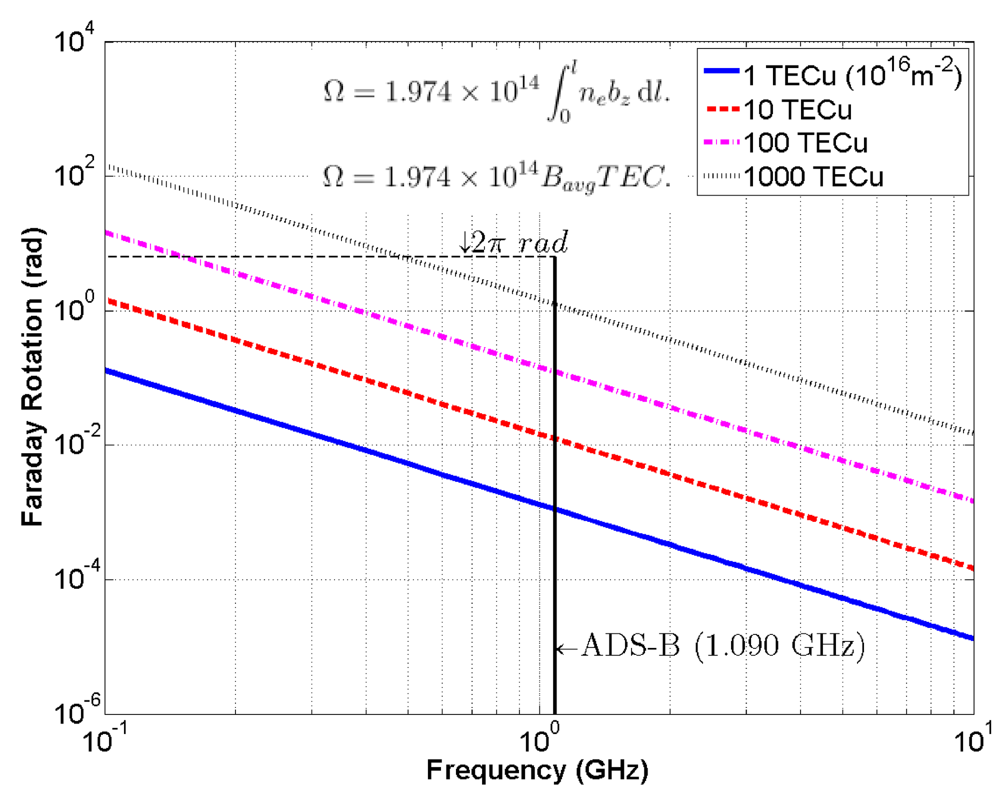
$$n^2 = \frac{c^2}{v^2_{\phi X}} = 1 - \frac{{\omega_p}^2/\omega^2}{1 - {\omega_c}/\omega} \ (\mathrm{X-mode})$$

The resulting imbalance between the phase velocities causes a change in the orientation angle of the polarization ellipse, known as FR. The magnitude of the rotation is dependent on the integrated product of the electron density *ne (l)*, along the ray-path or plasma column and the strength of the parallel component of the magnetic field b_z *(l)*, and inversely proportionate to the square of the frequency [13].

$$\Omega \cong \frac{1}{2c}\frac{e^3}{\varepsilon_0 {m_e}^2 \omega^2}\int_0^l n_e b_z dl$$

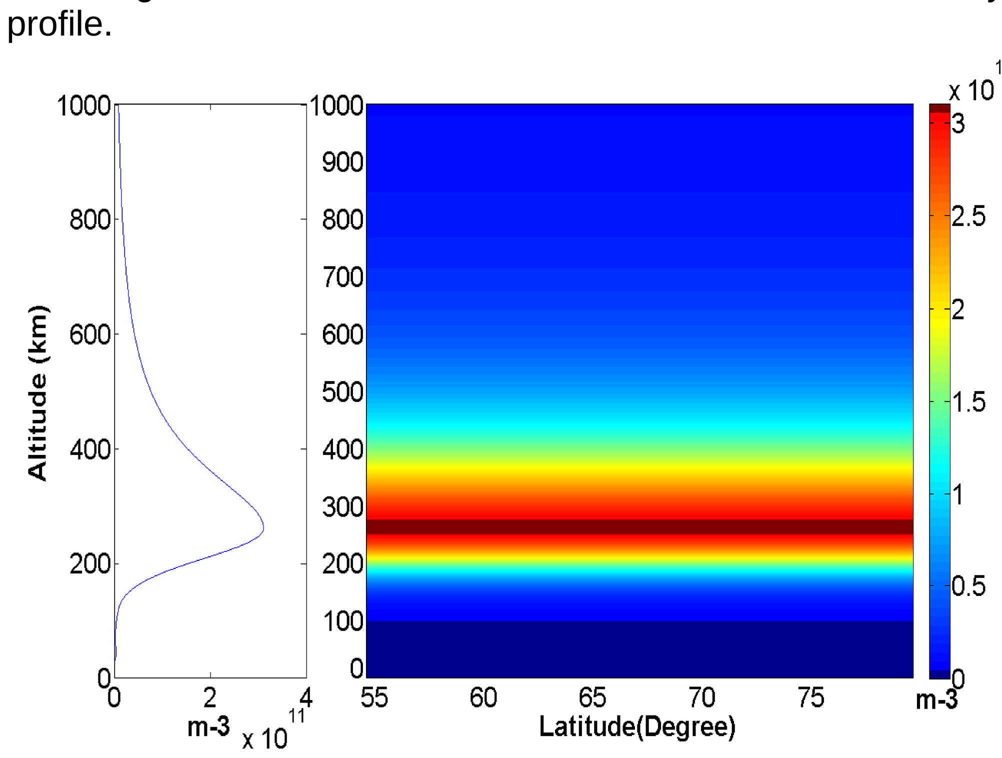
FR (Ω) is in radians, the magnetic field b_z *(l)* is in nT, *e* is the charge of an electron, *c* is the speed of light in a vacuum, m_e is the mass of an electron, and ε_0 is the vacuum permittivity. The TEC along the path or within the plasma column of unit cross-section is given by:

$$TEC = \int_0^l n_e dl$$



FR increases as a function of TEC and carrier frequency and decreases as a function of frequency..

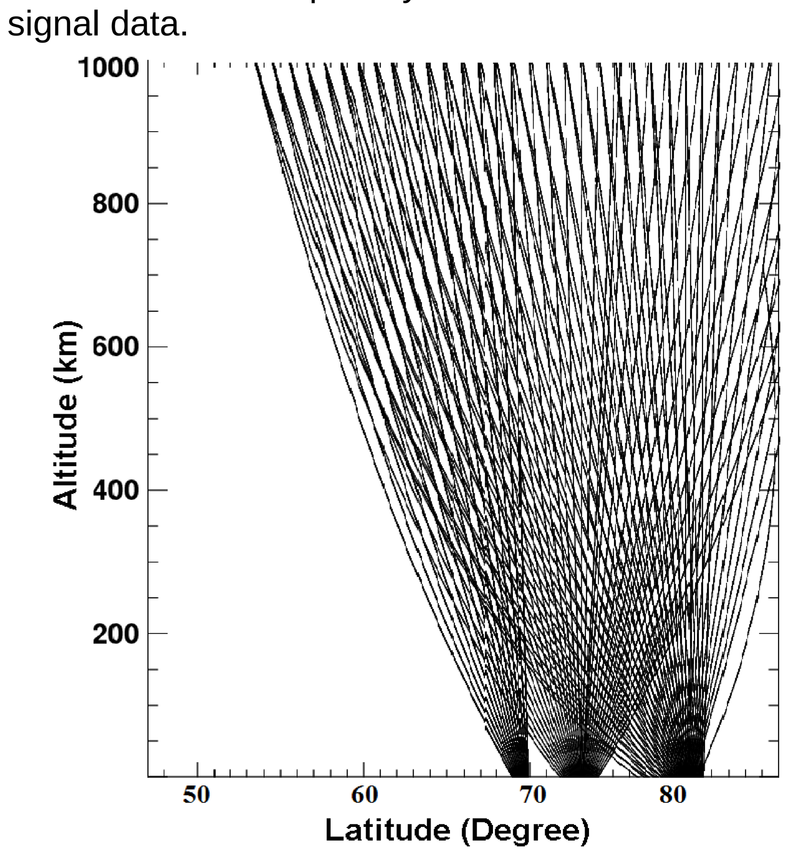
Ray-tracing: An EM-wave ray-tracing model was used to generate simulated ADS-B data to determine the wave path and the polarization state received at the satellite. [13]. For this investigation of ADS-B CIT, the ionospheric electron density profile was generated using IRI. An enhancement of any size and magnitude was added to create a 2D electron density profile.

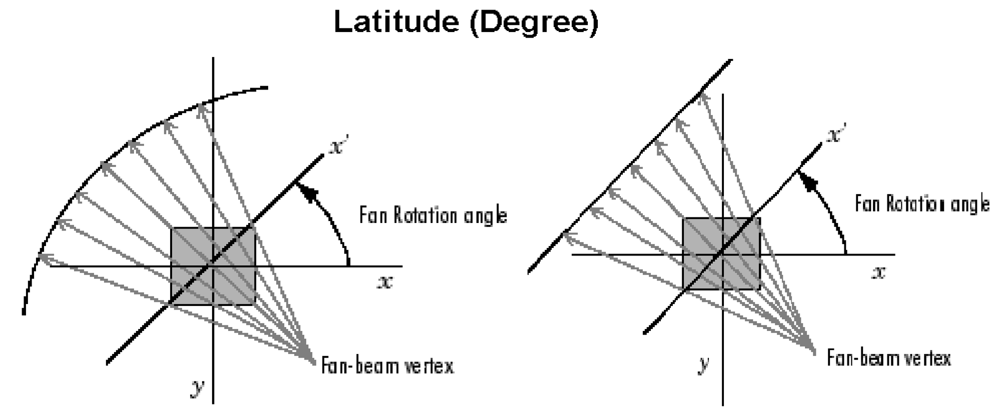


IRI Generated Electron Density Profile . Left: Initial electron density profile for geomagnetic quiet conditions. Right: A contour plot of the initial electron number densities prior to the addition of the enhancement.

Ray-tracing has shown that FR measurements of the received signals are detectable and can yield the TEC along the ray paths [14]. The program was used to generate TEC outputs from rays that passed from given locations, at a given elevation angle through the input 2D electron density 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.





Ray density for modelled output. Top; modelled set-up showing one tenth of the rays for 3-4 minute duration from three aircraft transmitters to a single satellite throughout its pass. Bottom; fan beam sampling for arc (left) or line (right) geometry. Adapted from MATLAB

CIT Reconstruction: Since the possibility of satellite radio tomography was shown, also known as CIT, the study of detailed features of the ionosphere and plasmasphere have become possible by means of tomographic reconstruction [15]. The most noteworthy pixel-based method is ART. Most other pixel-based methods are inferred from the ART algorithm [16].

$$N_e^{k+1} = N_{e^k} + \lambda_k \frac{STEC_i - \sum_{j=1}^{p} d_{ijn_{ej}}{}^k}{\sum_{j=1}^{p} d_{ij}d_{ij}} D_i$$

ART can be viewed as the ill-posed linear algebraic problem;

$$A\vec{x} = \vec{p} \quad \underline{\text{Or}} \quad STEC_{i\,X\,1} = D_{i\,X\,j}\ \mathrm{X}\ Ne_{j\,X\,1} + E_{i\,X\,1}$$

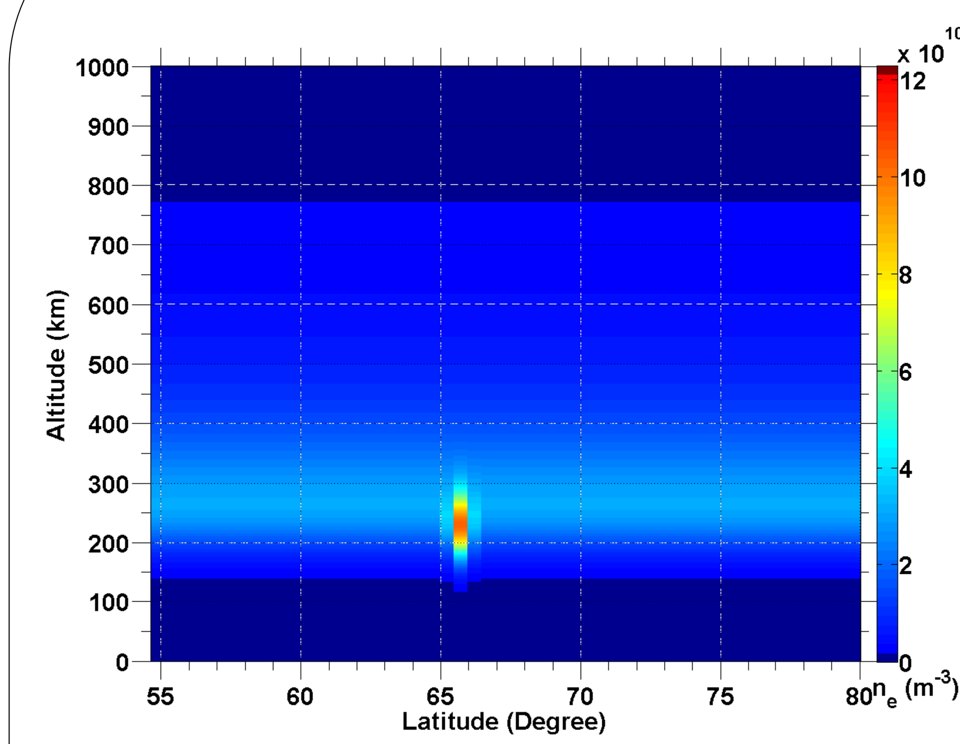
where STEC is a vector of TEC measurements, N is the vector of unknown pixel values, and D is the geometry matrix, which relates the relates the contribution of pixel n_j to the measured value $STEC_i$. Written in expanded form as a system of linear equations for which the unknown n_{ep} must be solved.

$$d_{i1}n_{e1} + d_{i2}n_{e2} + d_{i3}n_{e3} + \cdots + d_{ip}n_{ep} = STEC_i$$

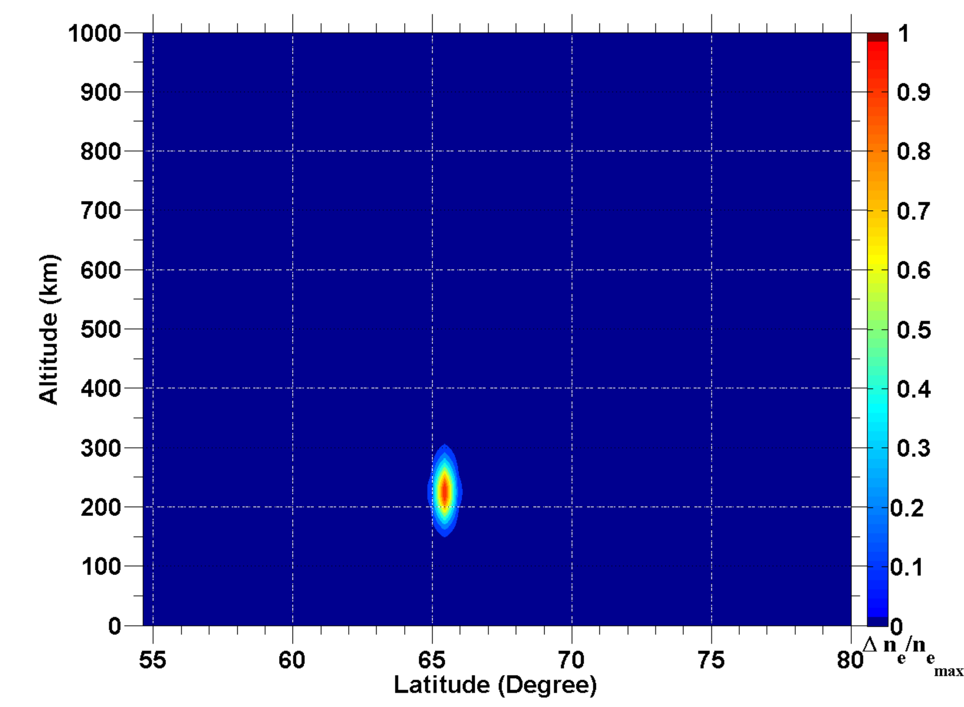
After each iteration, the pixel densities are modified to allow the projection through the pixels (DN) to approach the measured projection (STEC). ART converges relatively quickly, in an iterative fashion, and can use an initial guess or *a priori* estimate.

Results

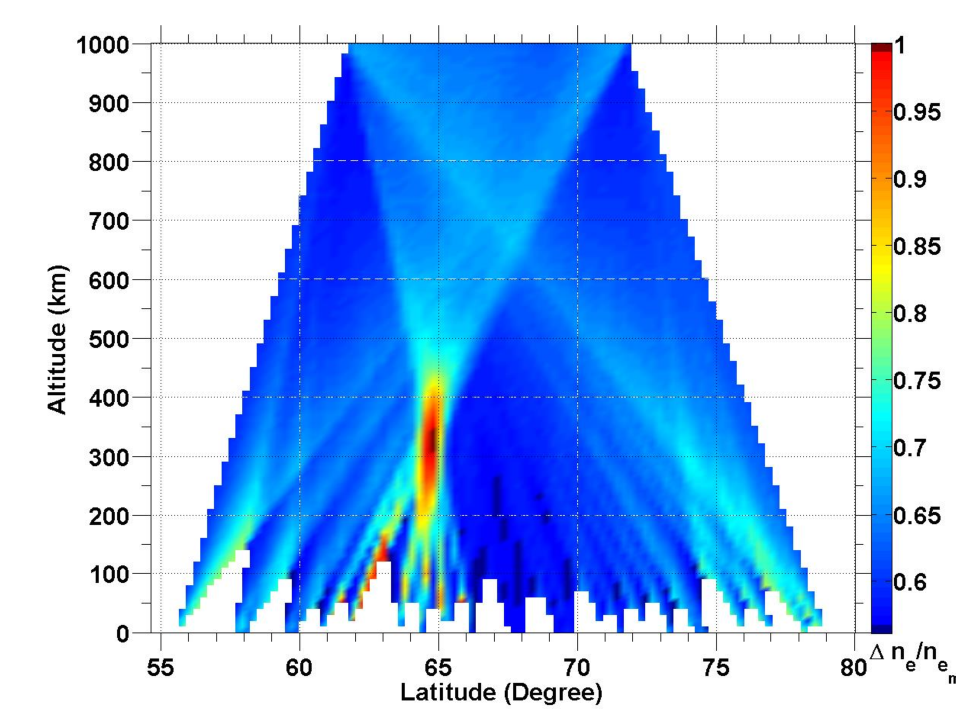
Numerous datasets were analyzed in depth. The following illustrates the input electron density profile to the ray-trace program, used to generate FR measurements and TEC along various ray-paths. The data was reconstructed using only the STEC measurements, and the end-points of the path (theoretically 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.



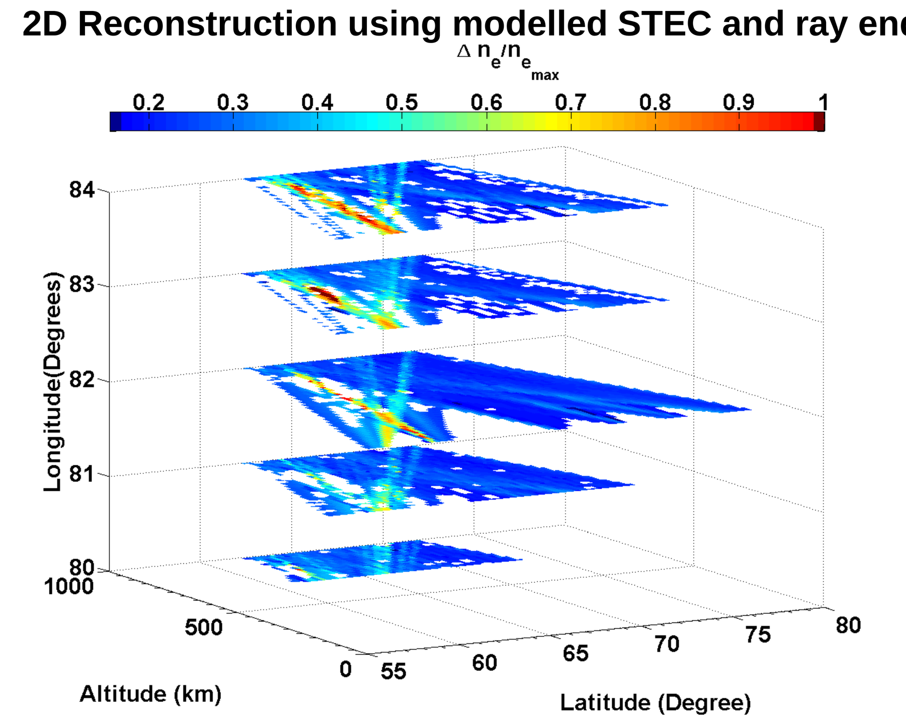
Input electron density profile to ray-trace.



Relative input electron density profile to ray-trace



2D Reconstruction using modelled STEC and ray ends.



3D reconstruction in slices of longitude

Conclusion

- CIT with ADS-B data is feasible
- Important ionospheric features of latitudinal scales 25-100 km detected
- Minimum data density for reconstruction must be greater than 23.4 rays/degree 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)

[1] Marsh, 2006 [2] Brown and Hendricks, 2011 [3] ADS-B Technologies, 2011 [4] Tremblay et al. 2009 [5] Jin et al., 2006 [6] Cushley, 2013 [7] Hartmann and Leitinger , 1984 [8] Orfanidis, 2008
[9] Chen, 1984 [10] Appleton and Builder , 1933 [11] Hartree, 1929 [12] Budden, 1961 [13] Gillies, 2007 [14] Gurnett and Bhattacharjee, 2005 [15] Austen et al. 1986 [16] Choi et al., 2006

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