Volumetric Reconstruction of the Ionospheric Electron Content Using Automatic Dependent Surveillance Broadcast (ADS-B) Signals

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ADS-B

Automatic Dependant Surveillance Broadcast

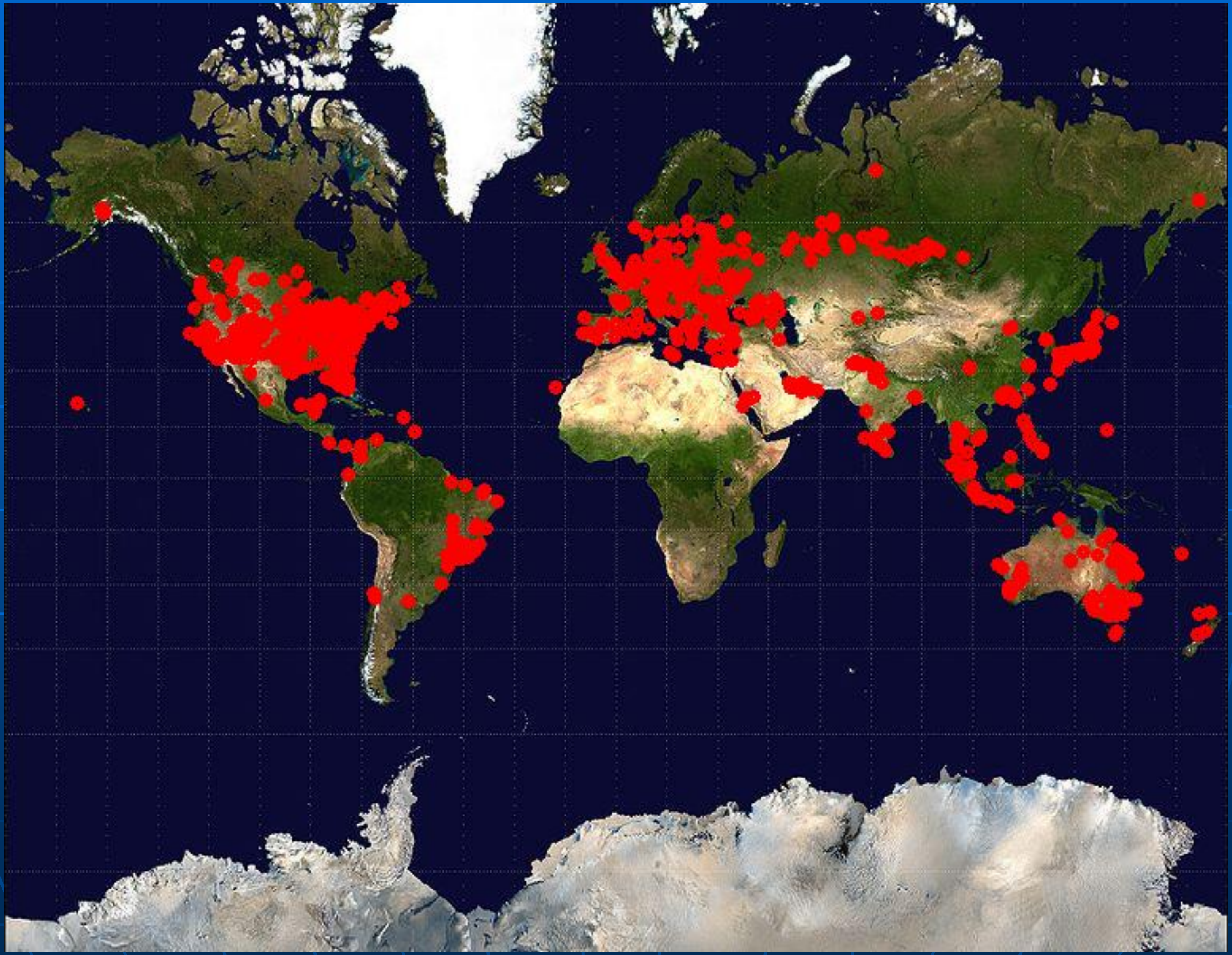
- Radar flight surveillance is insufficient in high latitude and oceanic airspace;

- ADS-B presents an alternative:
  - Aircraft automatically broadcast state vectors
  - Data shared by aircraft and ground stations.

Benefits of ADS-B

- Surveillance to areas lacking radar coverage.
- Real-time air traffic information in the cockpit.
- Improves ETA and departure times.
- Improves separation standard for all classes of airspace; (80 miles → 5 miles along-track).
- Reduces cost of the ground infrastructure.
- Reduces environmental impact.

Free Aircraft Transmitters



Adapted from 1 second of data provided by **Flightradar24**

CubeSat Design Mission

" RMCC will demonstrate a technology which has the potential to vastly improve the management of air traffic and reduce green house emissions produced by inefficient flight routes. In order to do this RMCC proposes a microsatellite mission, equipped with an ADS-B receiver. The primary mission will consist of the collection of ADS-B data and transmission of this data to a ground station."

-CIMON Executive Summary - Mission Requirements, **2003**

ADS-B Research at RMCC

- FLOAT 1
  Launched May 2009: damaged hard-drive.
- FLOAT 2
  Launched 12 June 2009: 2076 messages collected from 3 ADS-B equipped aircraft over 2.5 hour flight. Comparison with NAV Canada yielded 100% detection rate.
- CSDC
  Canadian Satellite Design Competition; two year student design competition with PDR Sept 2011 & CDR Feb 2012.
- FLOAT 3
  Launched 21 March 2012: over 51000 messages from 138 unique aircraft over 2.3 hour flight reaching maximum altitude of 95,500ft (~30km).

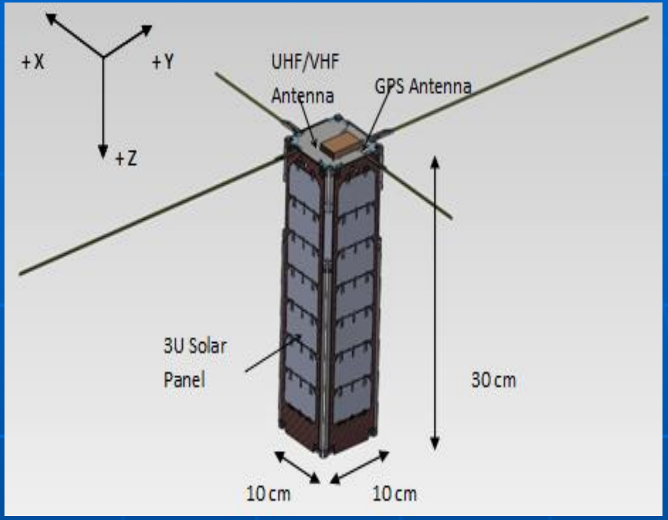
ADS-B Research at RMCC

- MSc Theses:

  -2Lt. Raymond Francis (2009): Detection of ADS-B Using Stratospheric and Orbital Platforms;

  -Maj. Richard Van Der Pryt: Modelling Aircraft ADS-B Signals Received by a Low-Earth–Orbiting Satellite;

  -My work: Tomography using ADS-B



- Can-X 7

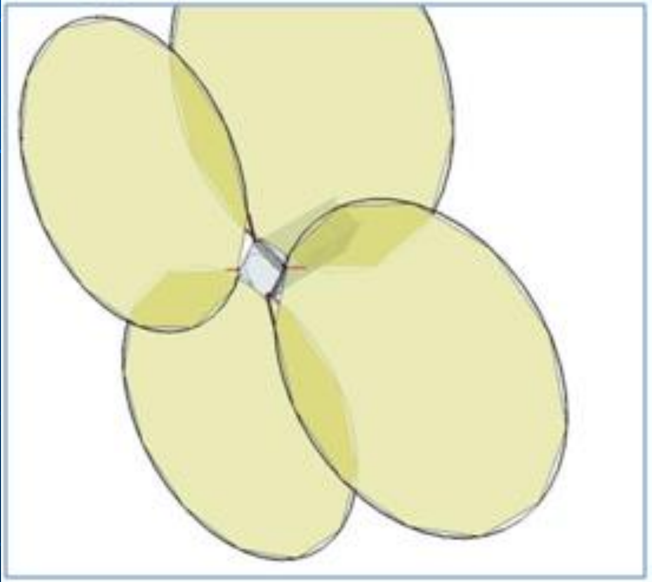
  -Drag sail de-orbit demonstration mission

  -ADS-B receiver as secondary payload;

  -CDR completed Feb 2013;

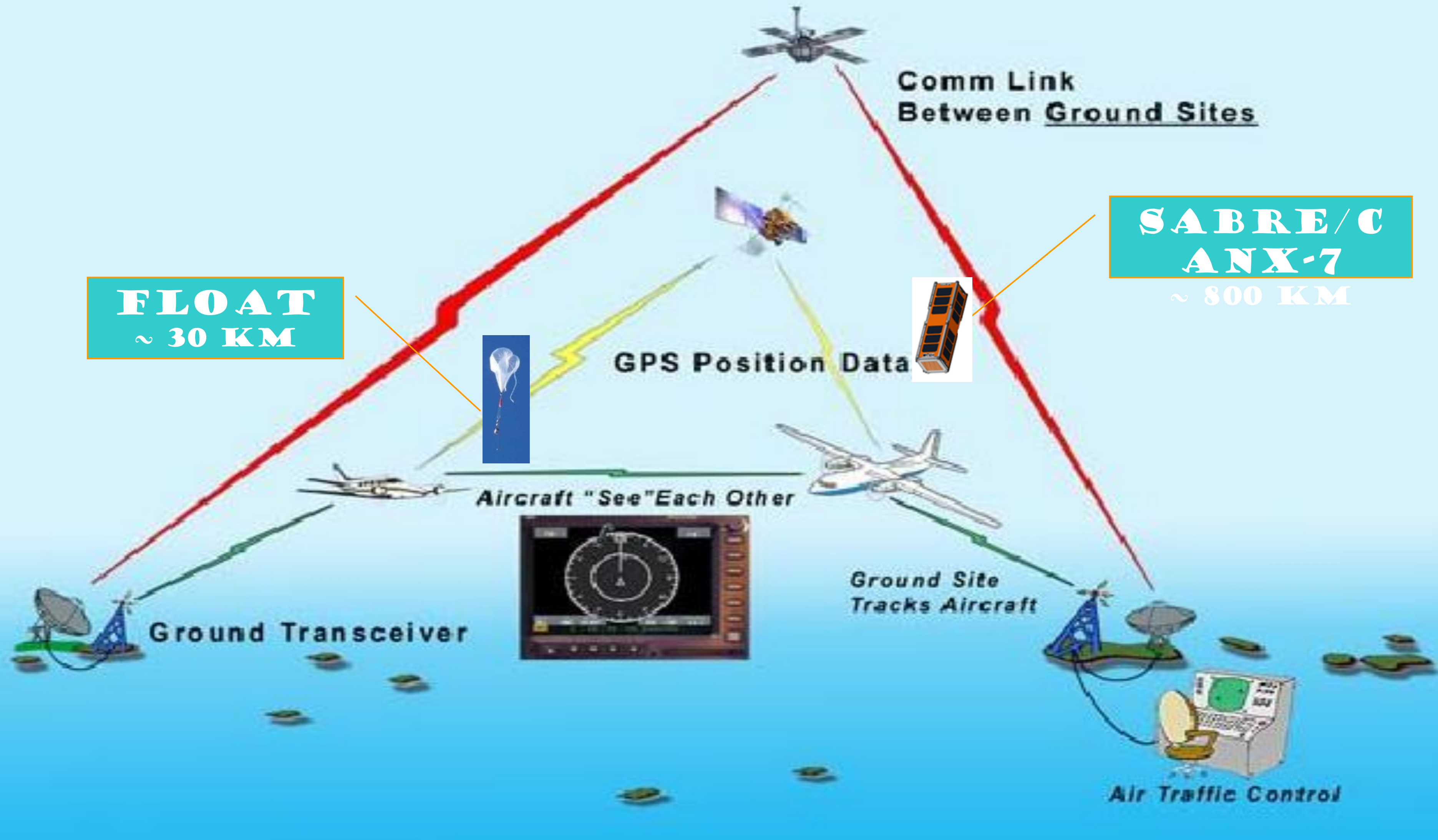
  -Launch yet to be brokered;

  -ADS-B proof of concept demonstrator



CanX-7 Drag Sail Concept

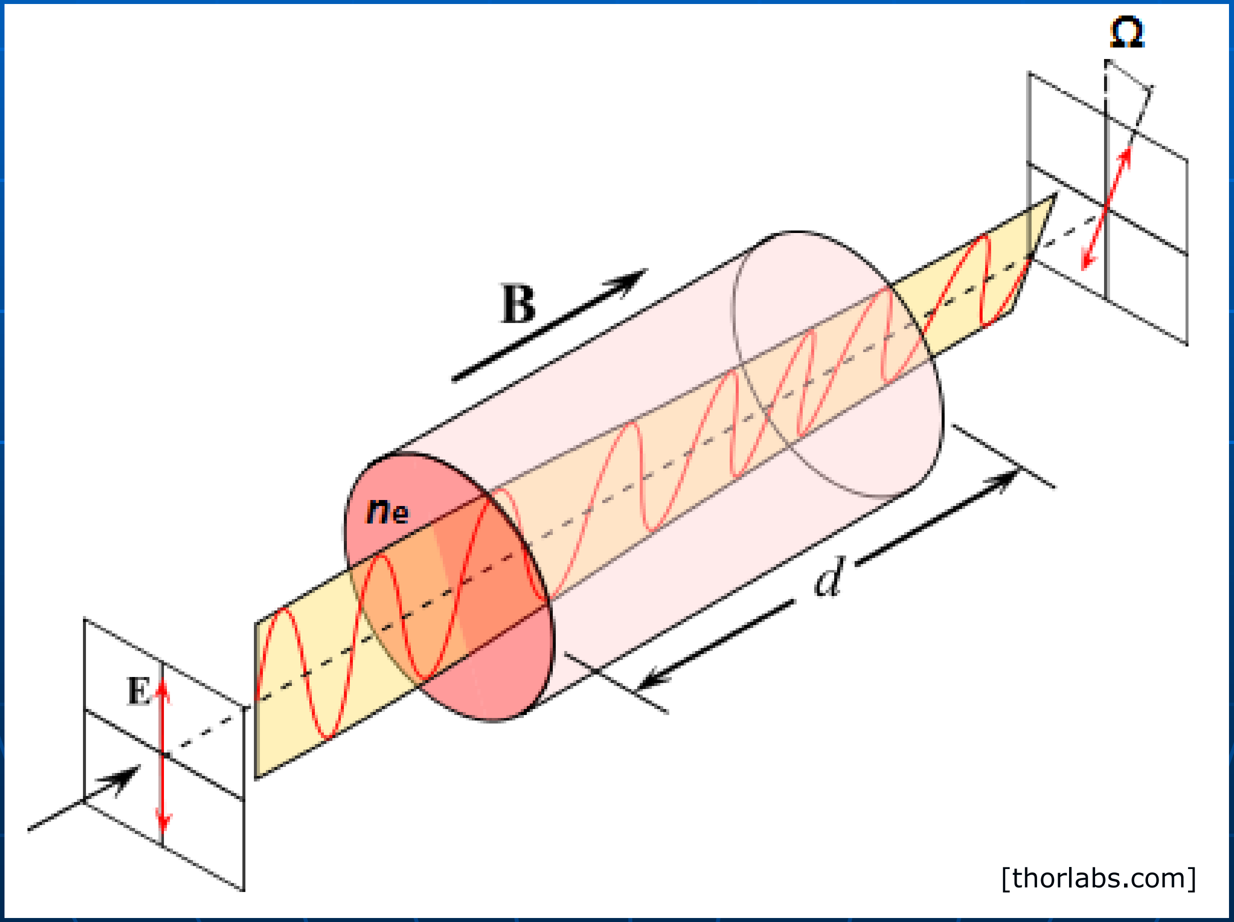
The ADS-B Network



http://www.dynavtech.com/adsb/home.htm

Faraday Rotation of Signals

- A plane polarized wave parallel to a magnetic field in a plasma suffers a rotation of its plane of polarization;



Faraday Rotation of Signals

$$\Omega = 1/2c\,(e^3/e_0 m_e^2)1/\omega^2 \int_0^l n_e b_z dl$$

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

Ω: Faraday rotation (radians)
c : speed of light in vacuum
e: charge of an electron
e_0: vacuum permitivity
m_e: mass of an electron
ω: angular frequency
n_e: electron density
b_z: z-component of magnetic field (nT)
dl: path length

- Measurements of the rotation yield the total electron density (TEC) integrated over the plasma column or ray path.

$$TEC = \frac{\Omega}{2.63e^{-6} B_{avg}}$$

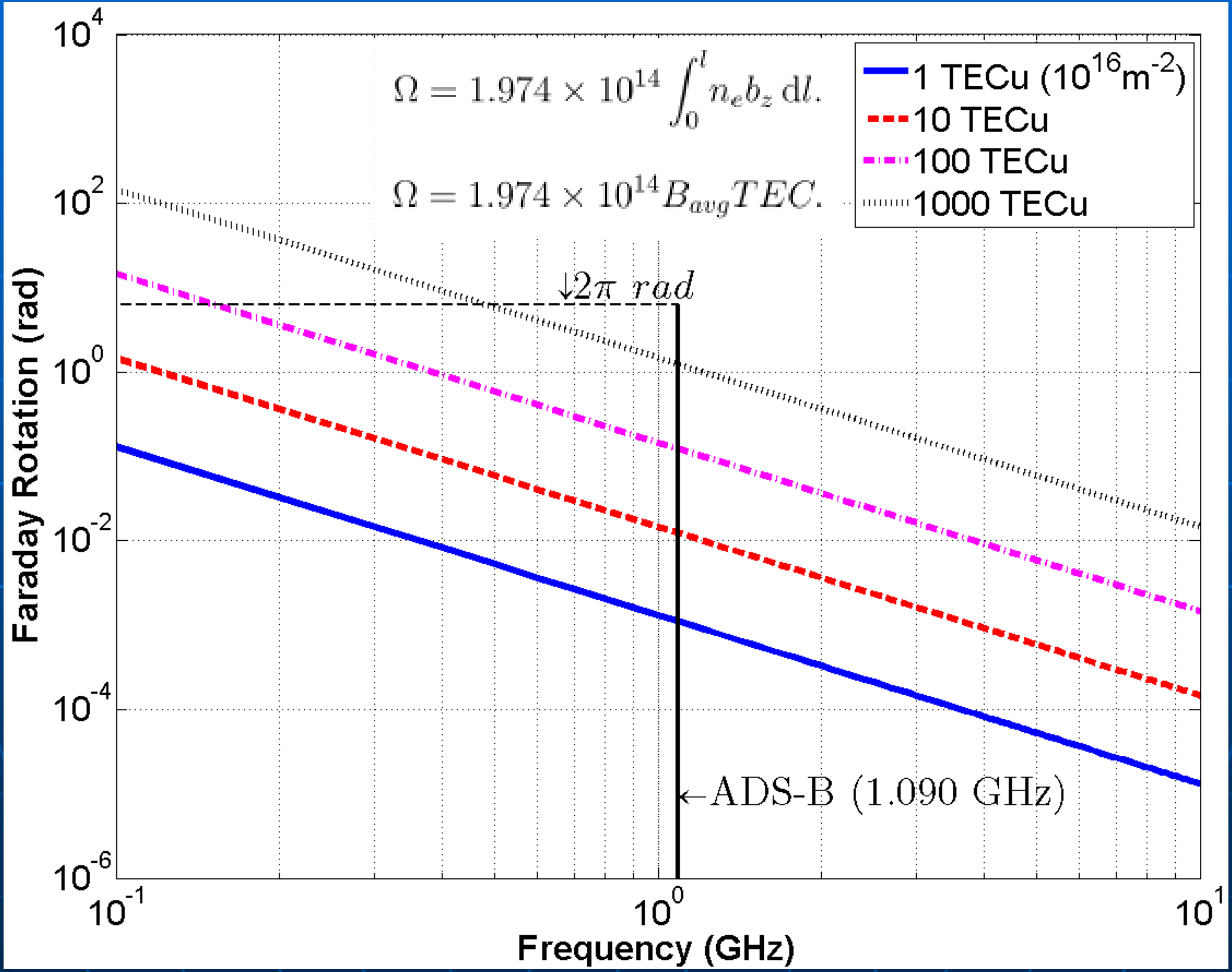
Rotation of ADS-B Signals

- Plane polarized 1090 MHz radio signal;
- Propagation through ionospheric plasma;
- Earth's magnetic field largely parallel at high latitudes (e.g. Hudson Bay and the Arctic)

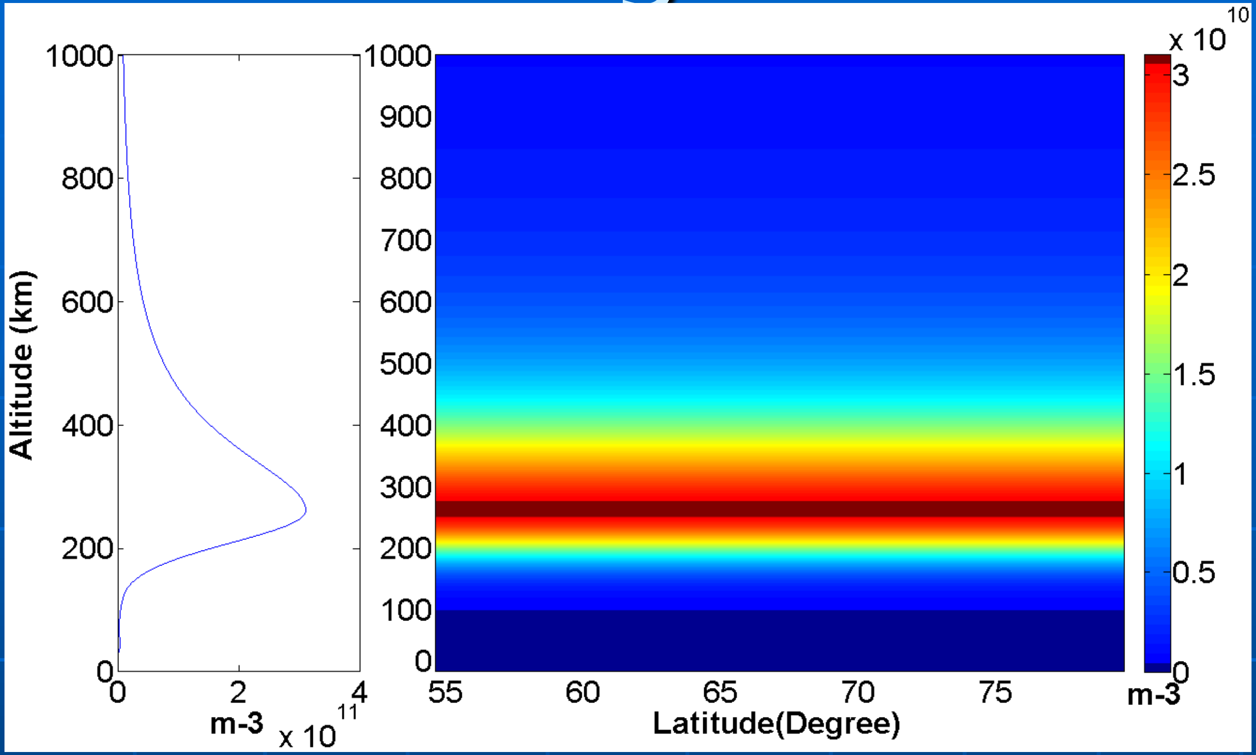
ADS-B Signal rotation is proportionate to the:

- Magnitude of Earth's magnetic field (latitude dependence)
- Total ionization of the medium through which the signal propagates

Unique Frequency Selection

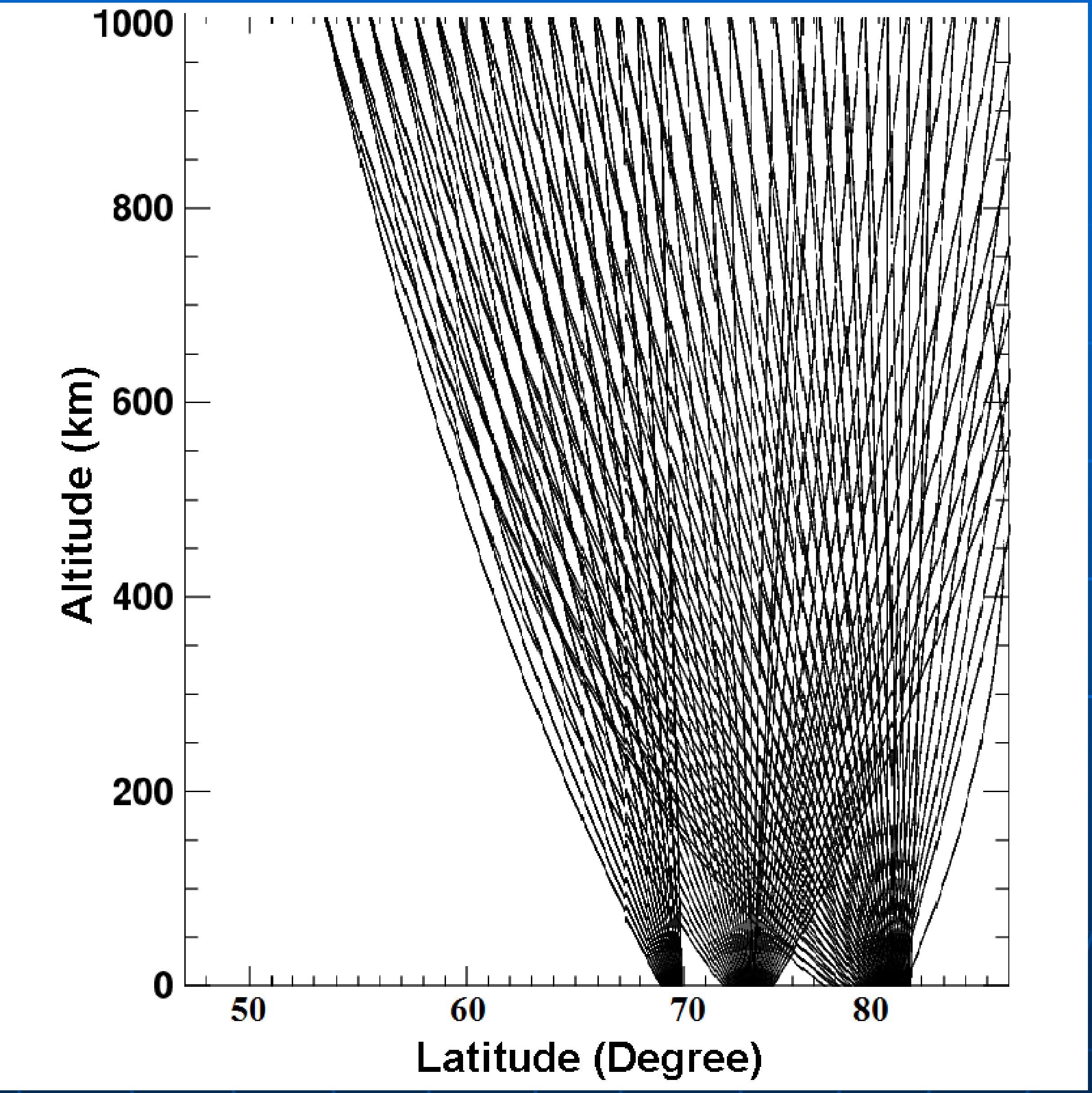


Modelling Data



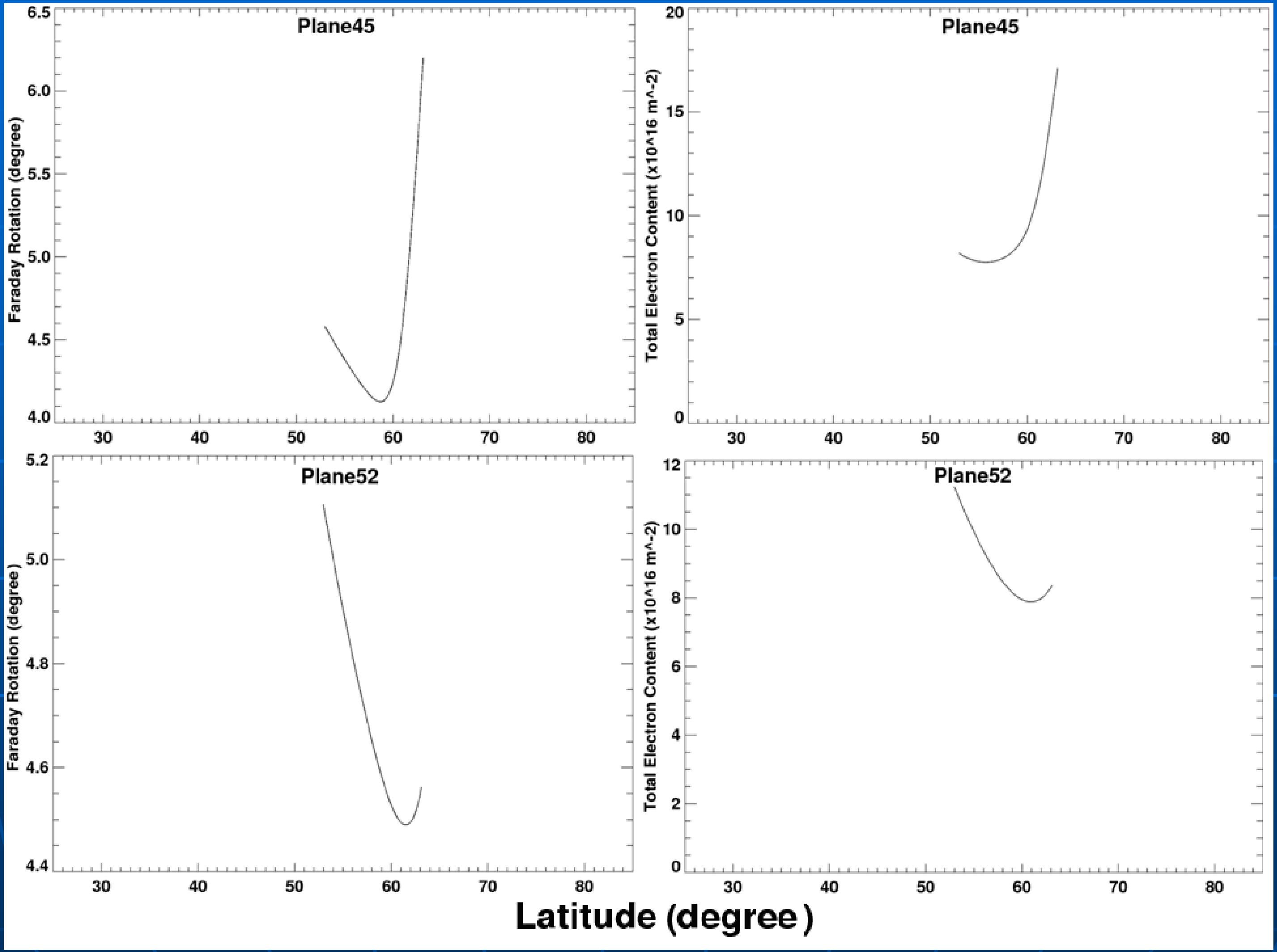
- Raytrace EM-waves in an ionized medium to determine the wave path and polarization state at the satellite receiver;
- Models expected signal received aboard ADS-B equipped satellite.

Ray Density Example



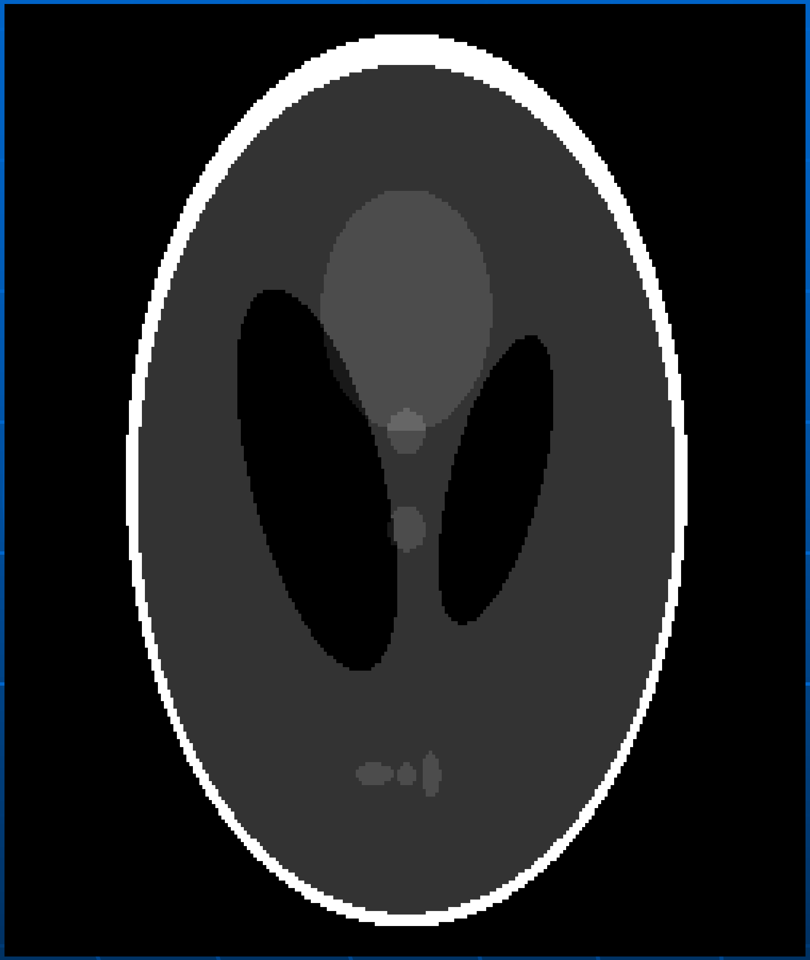
1/10th of ray paths from 3 aircraft to a single satellite

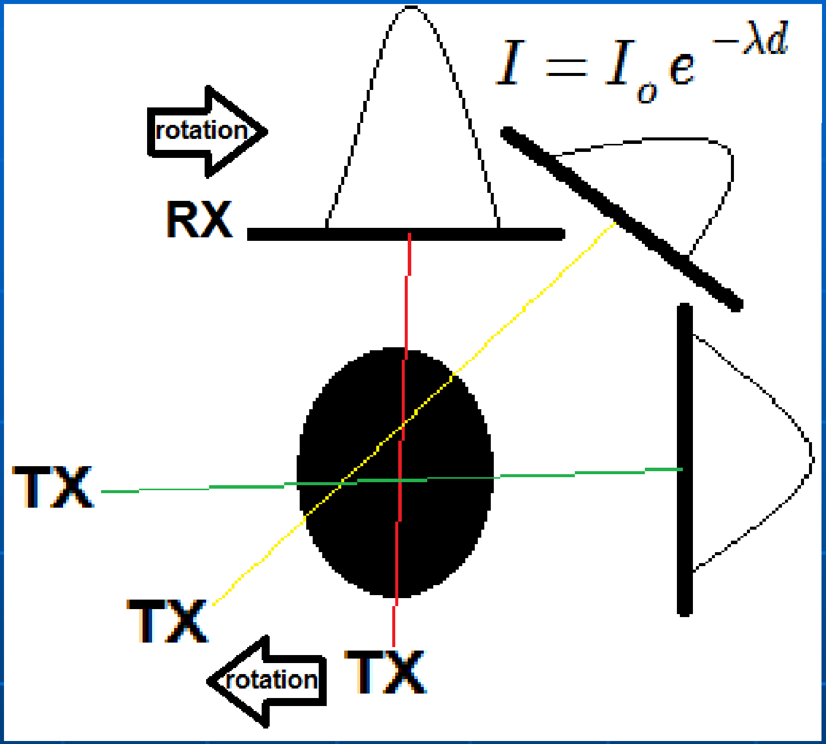
Analysis of Ray Data



Faraday rotation exists and can be converted to slant TEC (STEC)

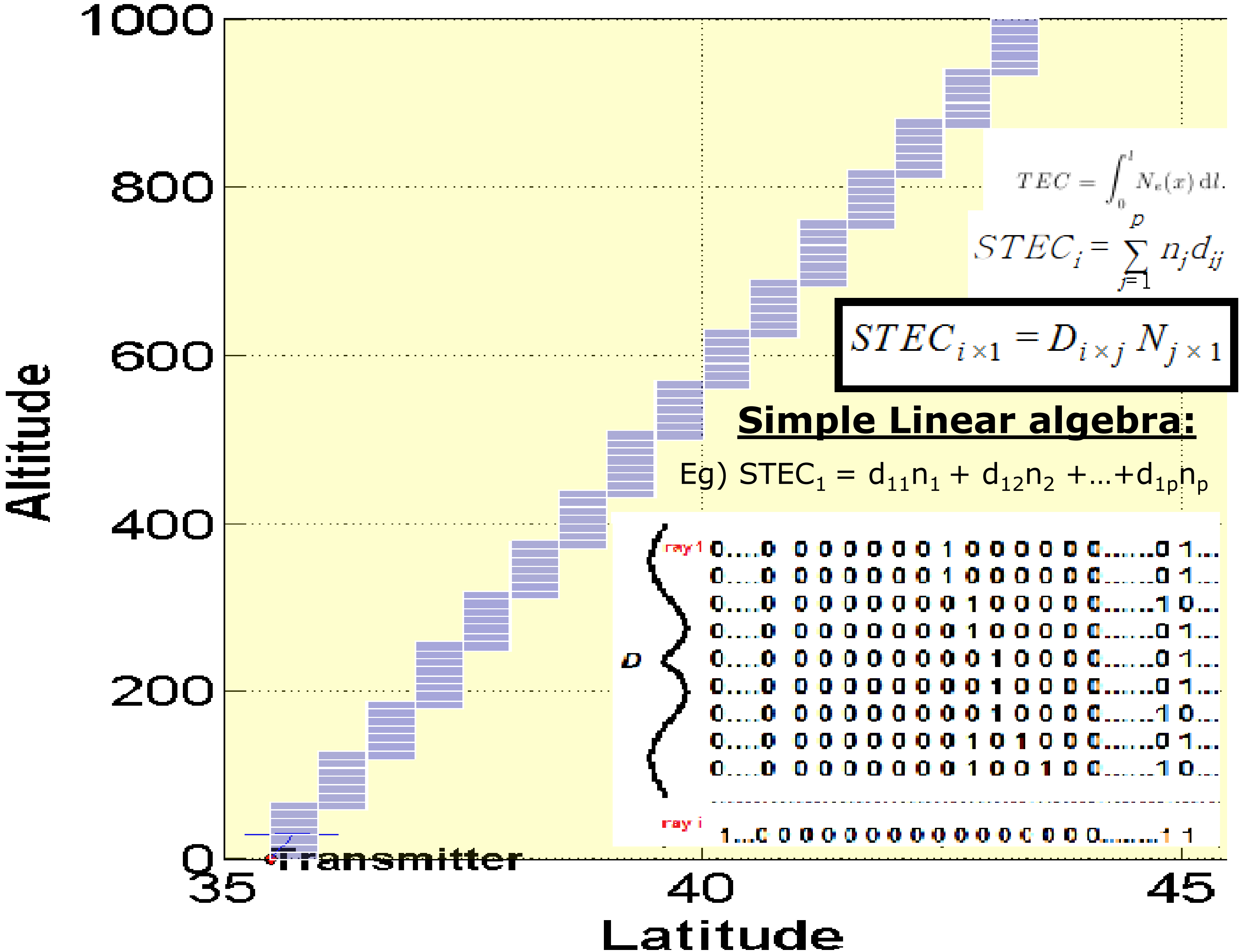
Computerized Tomography (CT)





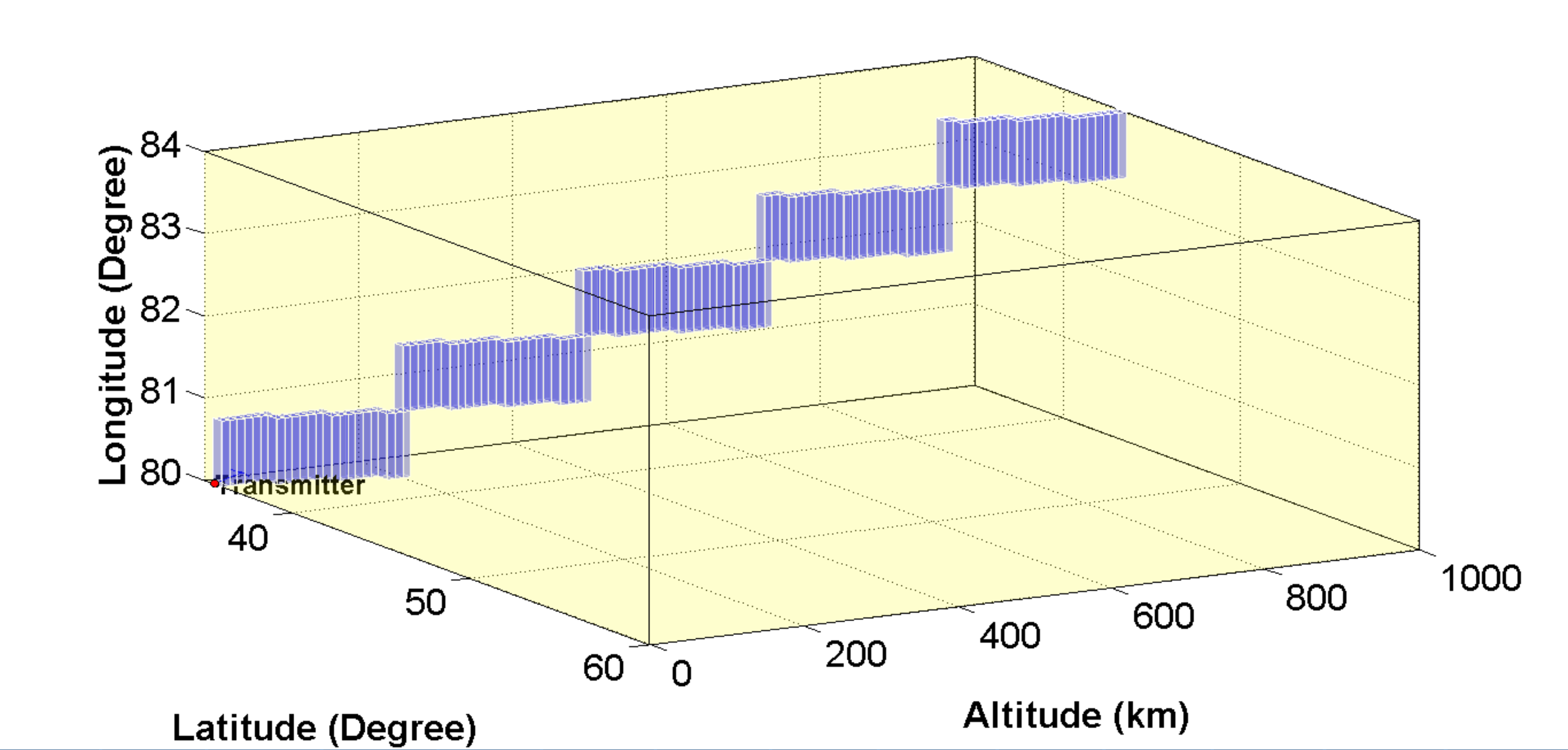
I: Receiver(Rx) intensity
I_o: Transmitter(Tx intensity)
λ: Attenuation co-efficient
d: Distance

- From medical physics: CT scan



$TEC = \int_0^l N_e(x)\,dl.$
$STEC_i = \sum_{j=1}^{p} n_j d_{ij}$
$STEC_{i\times1} = D_{i\times j} N_{j\times1}$
Simple Linear algebra:
Eg) $STEC_1 = d_{11}n_1 + d_{12}n_2 + \ldots + d_{1p}n_p$
D
ray 1
ray i
Transmitter
Altitude
Latitude
1000
800
600
400
200
0
35
40
45

Extension to 3D

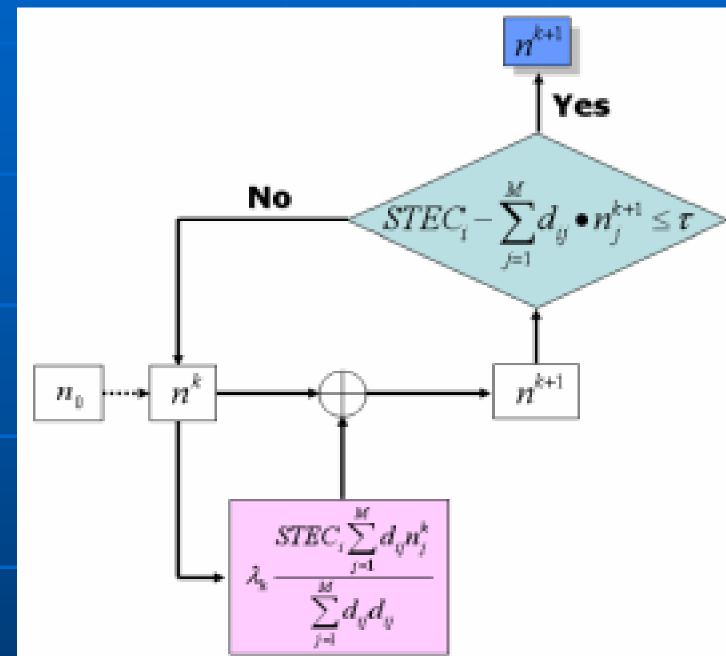


- More sparse (~150/50000 pixels =0)
- Under-determined ill-posed problem

Algebraic Reconstruction Technique (ART)

- The brightness of pixels intersected by rays changes to allow the ray sum to correspond to the projection value.

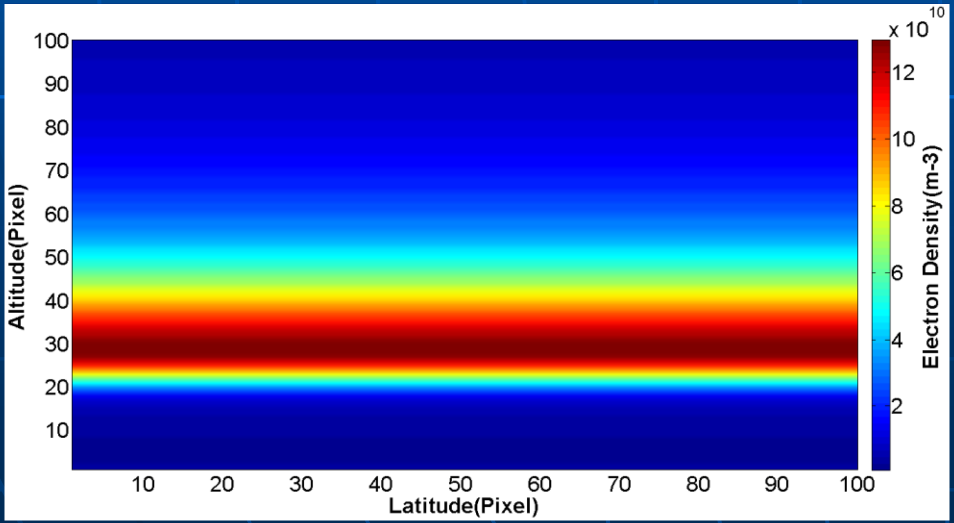
$$N^{k+1} = N^{k} + \lambda_k \frac{STEC_i - \sum_{j=1}^{p} d_{ij} n_j^k}{\sum_{j=1}^{p} d_{ij} d_{ij}} D_i$$

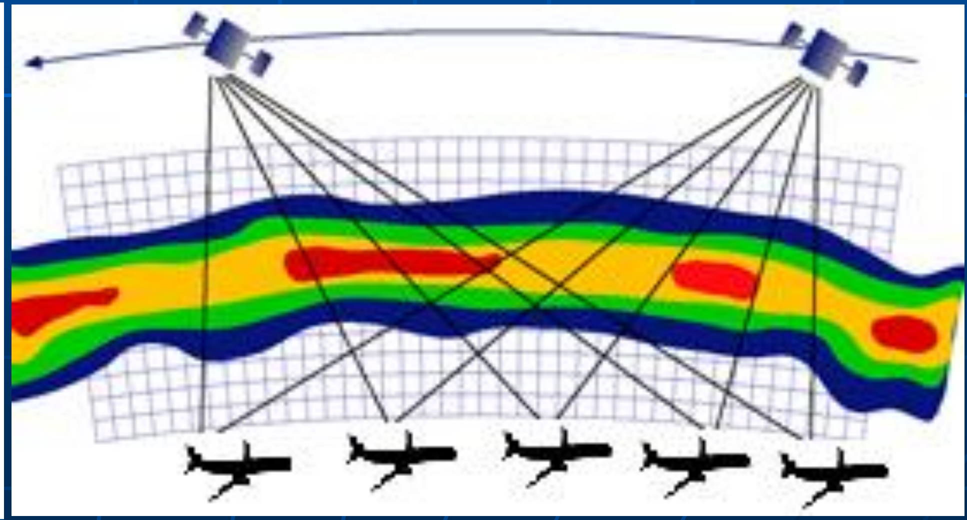


- Each pixel density is modified after each iteration allowing the projection through the pixels (DN) to approach the measured projection (STEC).

ART

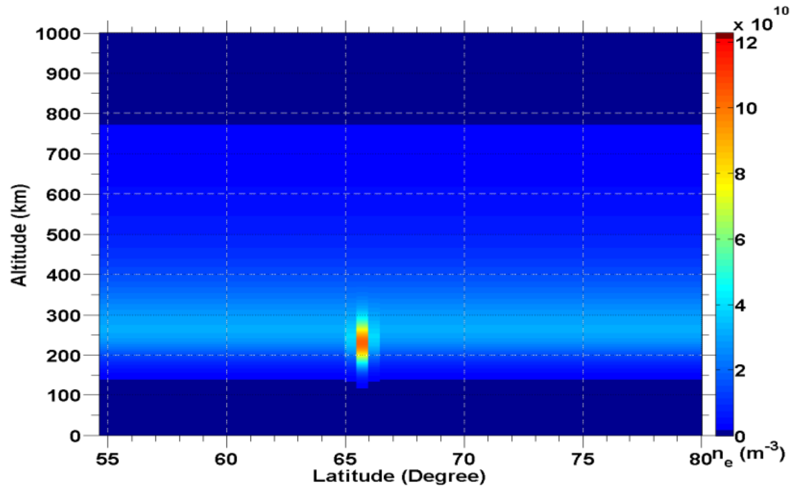
- Converges quickly, improving iteratively on initial *a priori* guess.



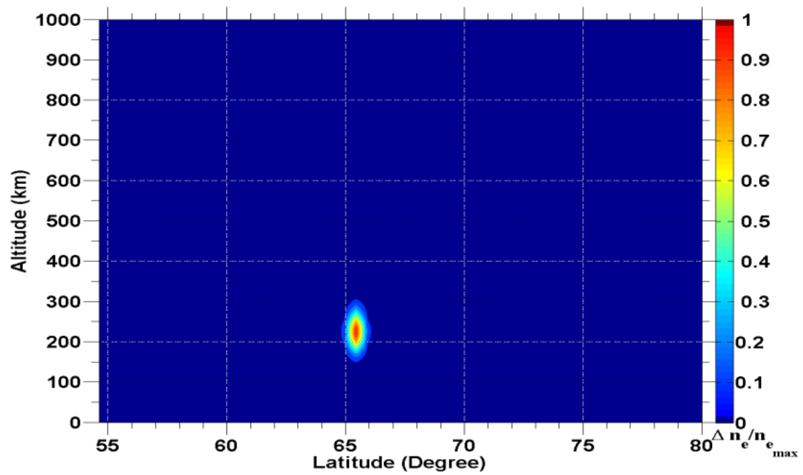


2D CIT Reconstruction

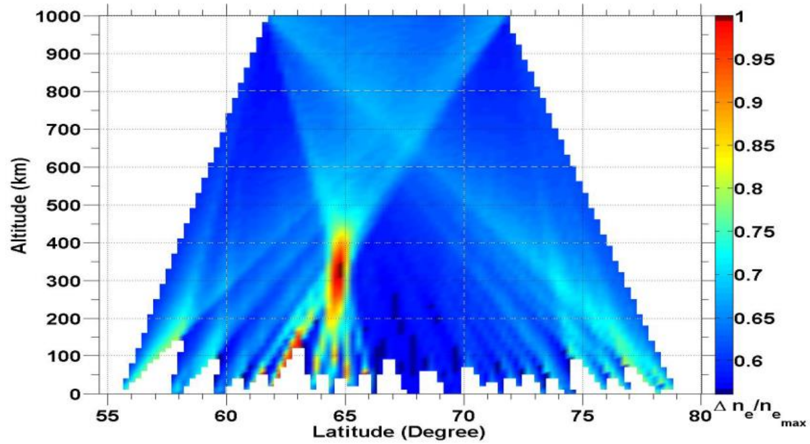
Raytrace Input Profile->



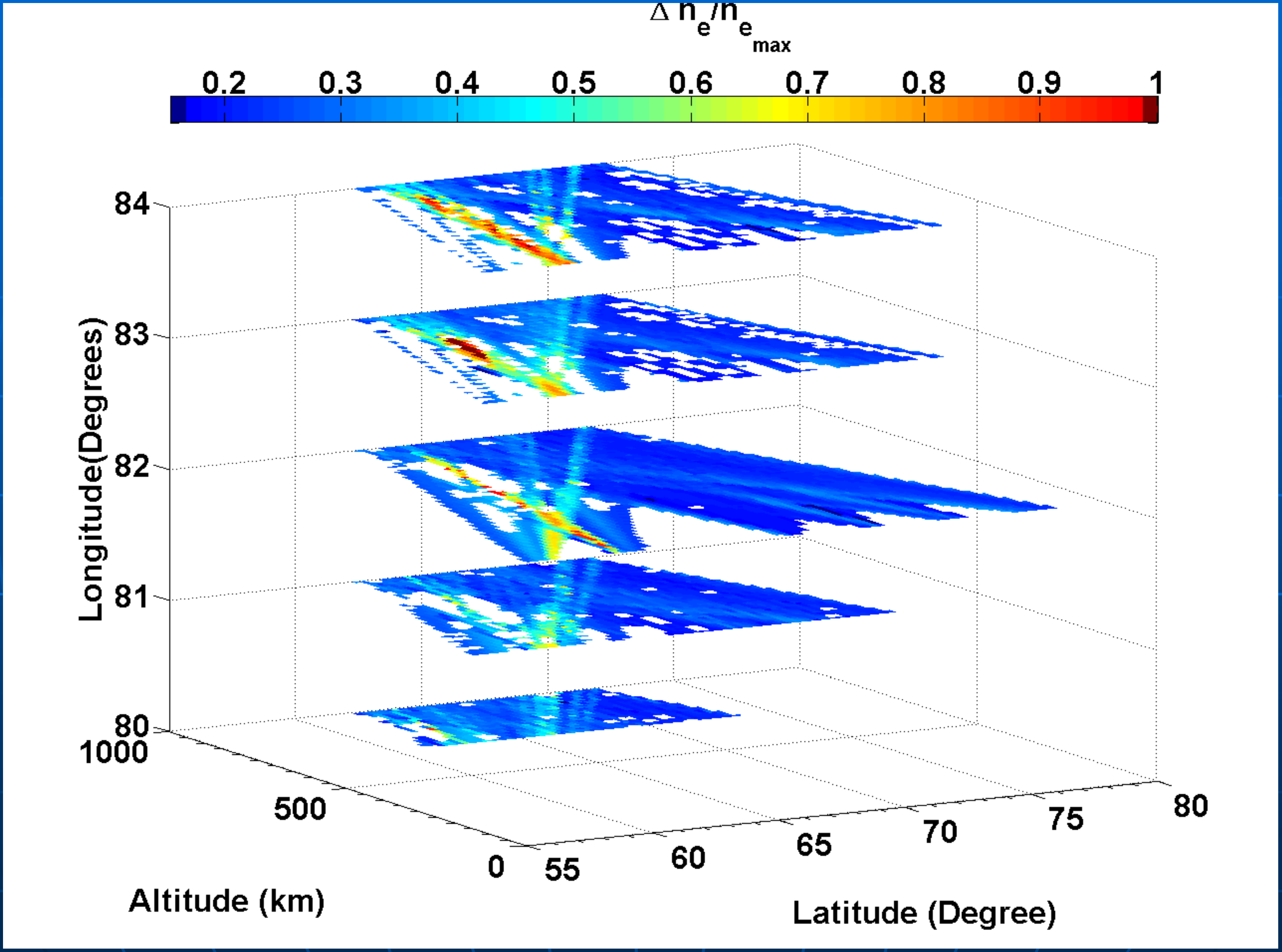
Relative Density->



2D Reconstruction (no *a priori*)->



3D CIT Reconstruction



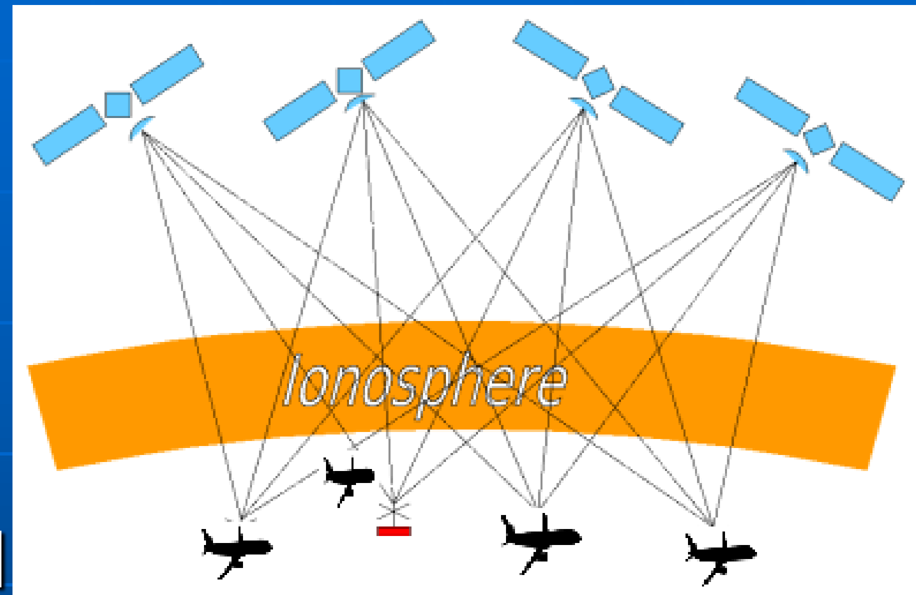
Conclusions

- CIT with ADS-B data is feasible.
- Important ionospheric features of latitudinal scales 25-1000km detected.
- In-situ *a priori* data from another source is required for validation and calibration.
- Minimum data density for reconstruction must be greater than 23.4 rays/degree latitude

Future Work

- Parallel processing;

- LAUNCH!
  - Sensor calibration
  - Noise & filters;
  - Constellation (Irid



- CIT investigations:
  - In-situ a priori data injection from another source (ionosonde-based IRI, radar, etc);
  - Methods of interpolation, filters, forming geometry matrix, algorithm optimization;
  - Automation and GUI.

Questions?¿?

Acknowledgements:

- Dr. Noël: Thesis Supervisor;
- Dr. Robert Gillies: Ray-trace program.

NSERC
CRSNG

Motivation for Current Research

Ionospheric tomography using Faraday Rotation of ADS-B Signals

- Awareness of ADS-B receiver importance in space;
- Potential ADS-B **payload dual-purpose** for **science data**;
- Current limitations of TEC modelling using dual frequency GPS, ionosondes, radar.
- First inverted CIT application ¿

"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

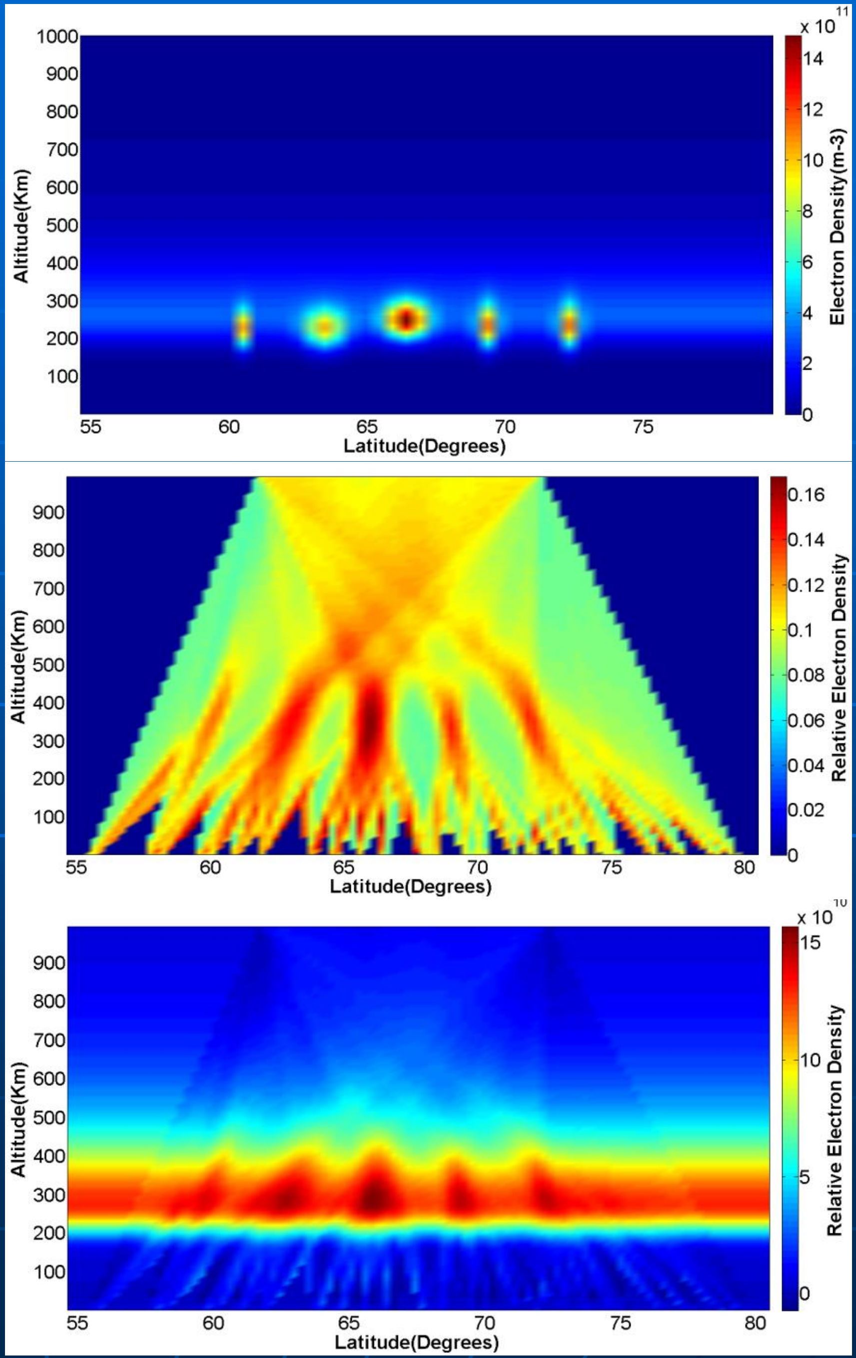
CIT Reconstruction Example

Raytrace Input Profile->

Raw reconstruction

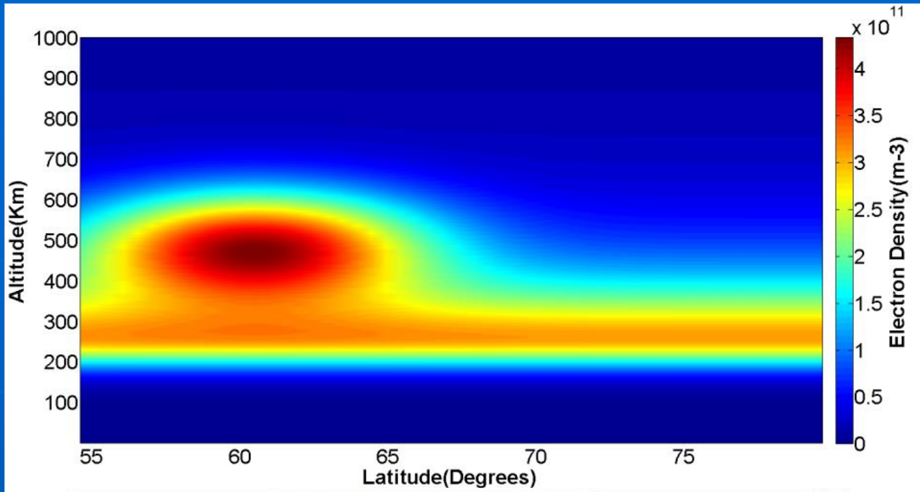
(no *a priori*)->

Reconstruction with *a priori*->



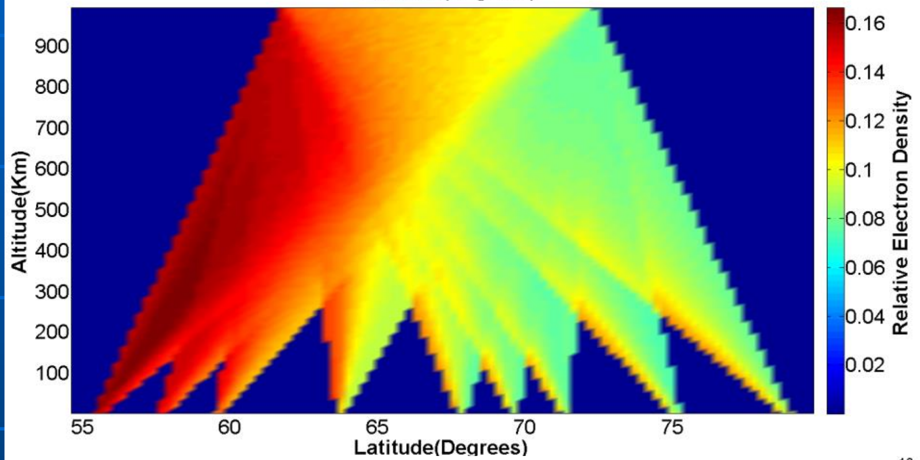
CIT Reconstruction Example 1

Raytrace Input Profile->

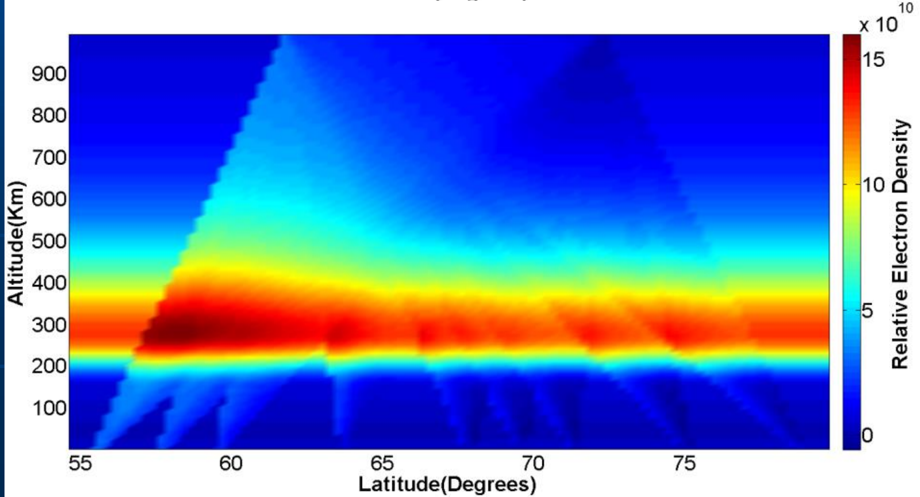


Raw reconstruction

(no *a priori*)->



Reconstruction with *a priori*->



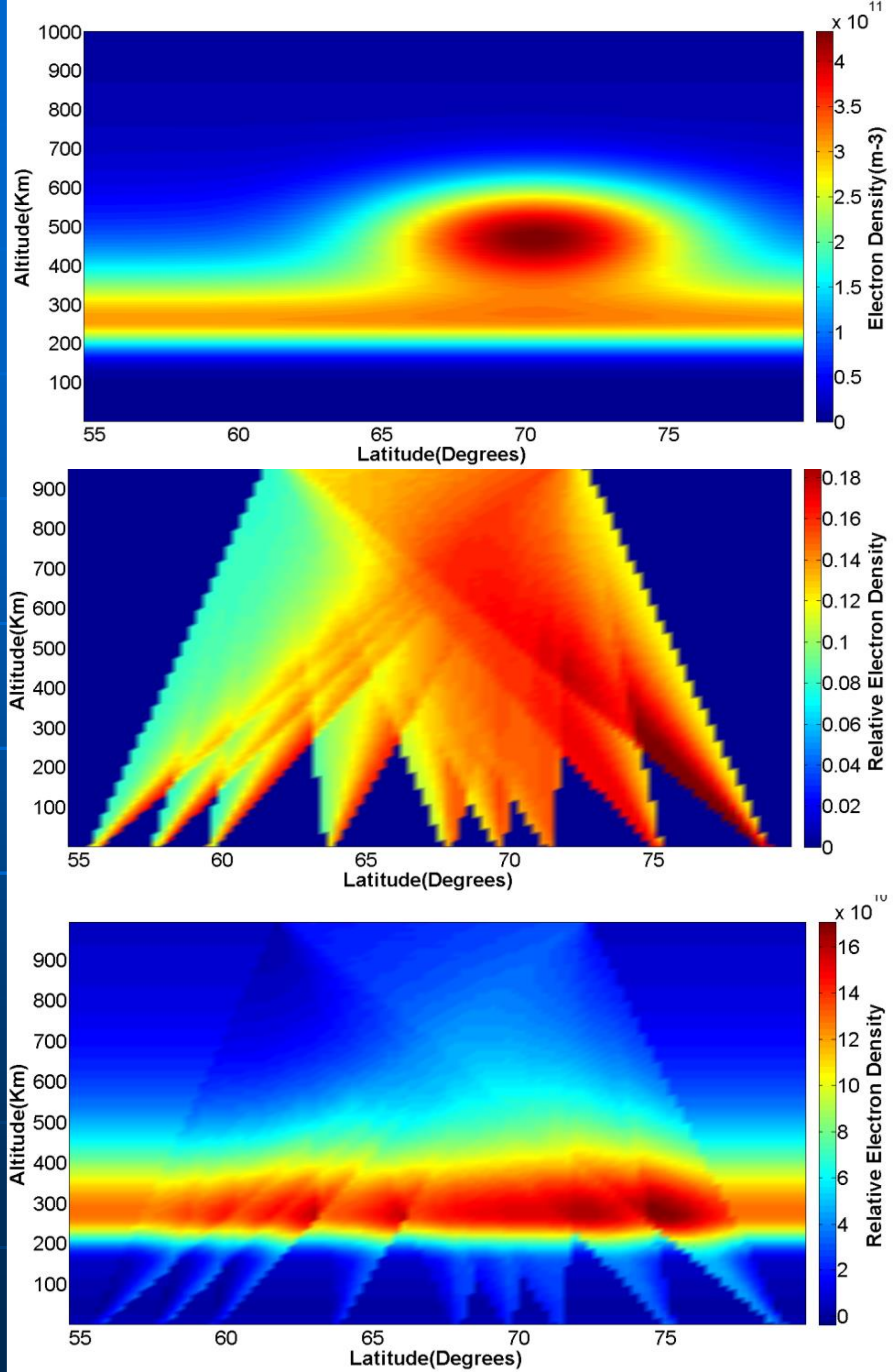
CIT Reconstruction Example 2

Raytrace Input Profile->

Raw reconstruction

(no *a priori*)->

Reconstruction with *a priori*->



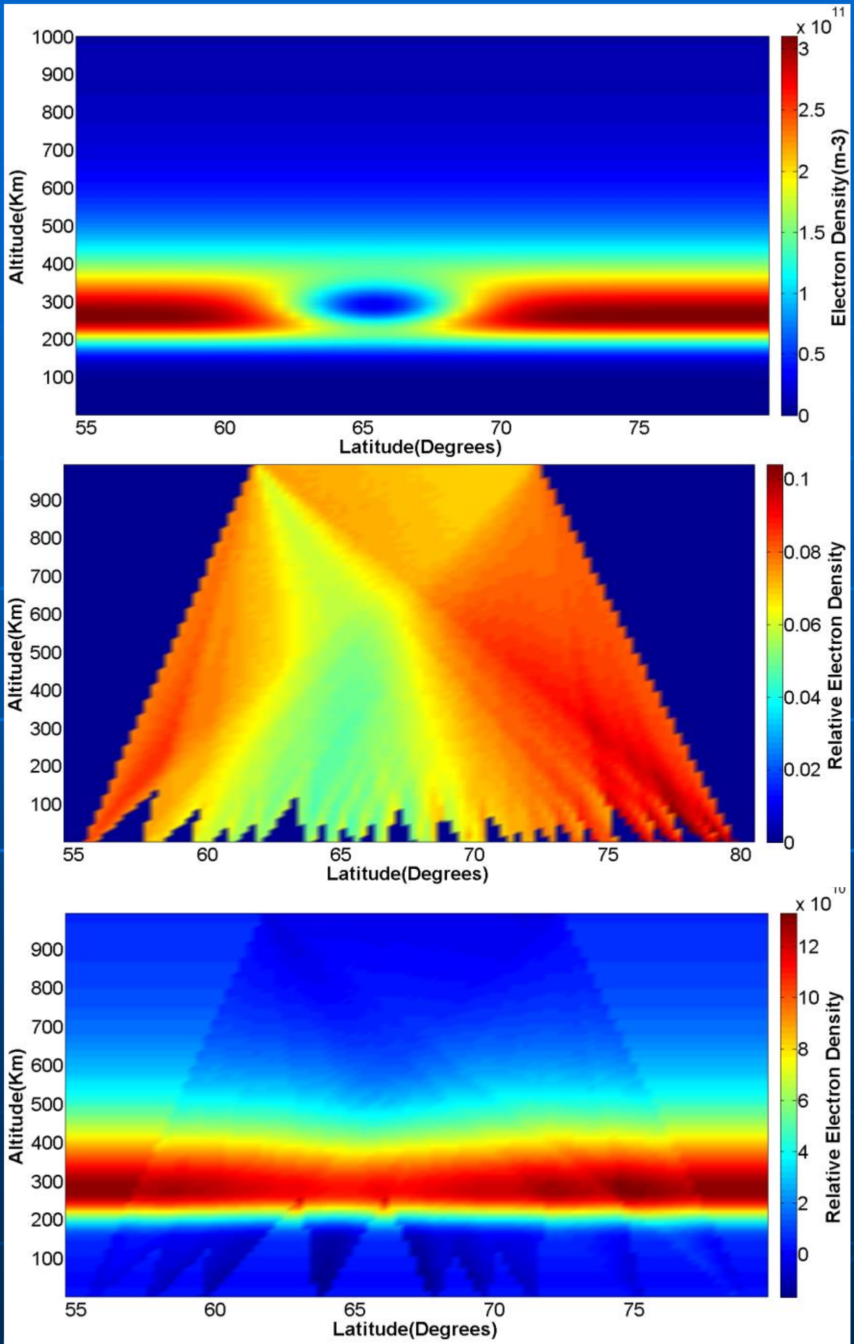
CIT Reconstruction Example 4

Raytrace Input Profile->

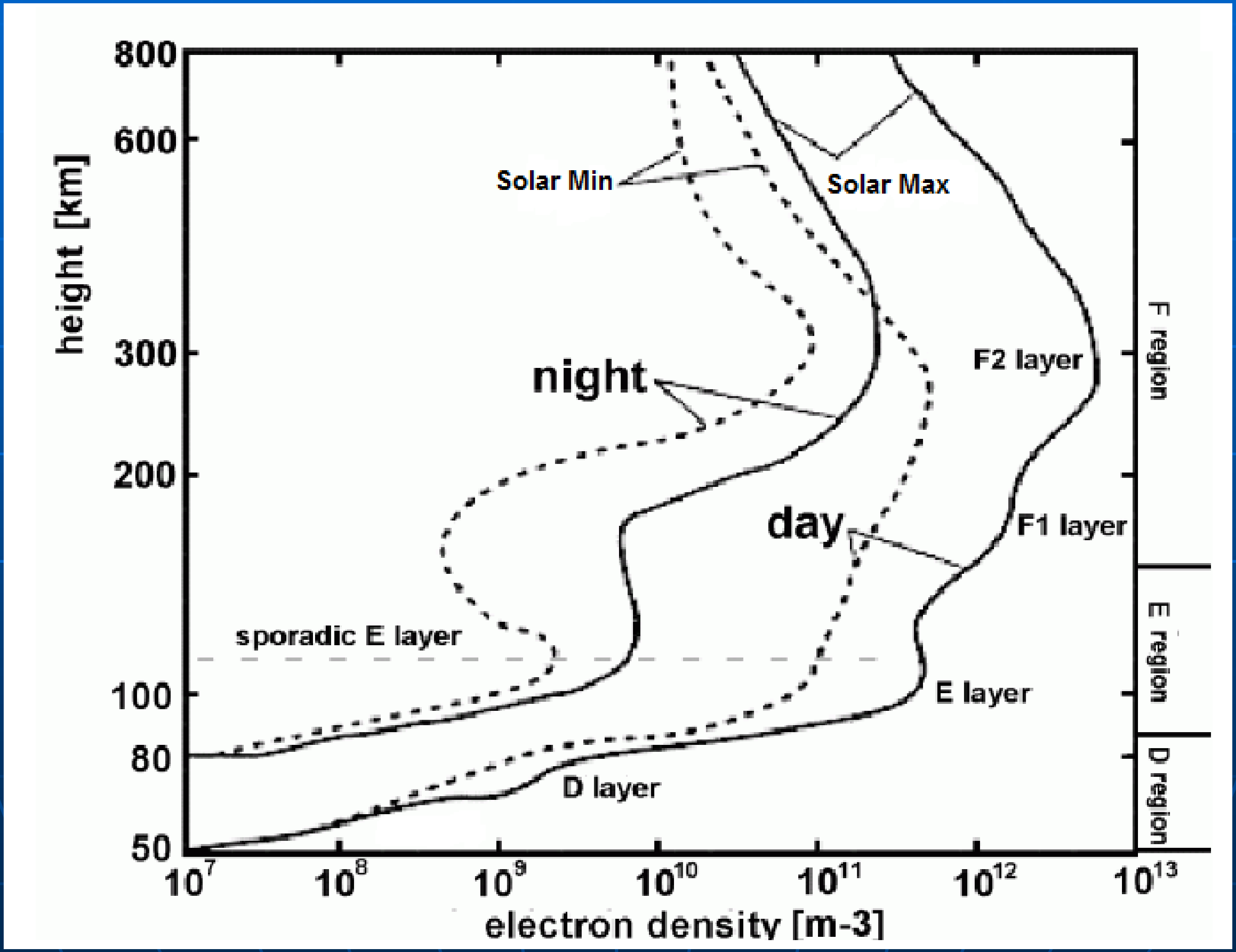
Raw reconstruction

(no *a priori*)->

Reconstruction with *a priori*->



Ionospheric Variation-Unknown Relative Units Problem

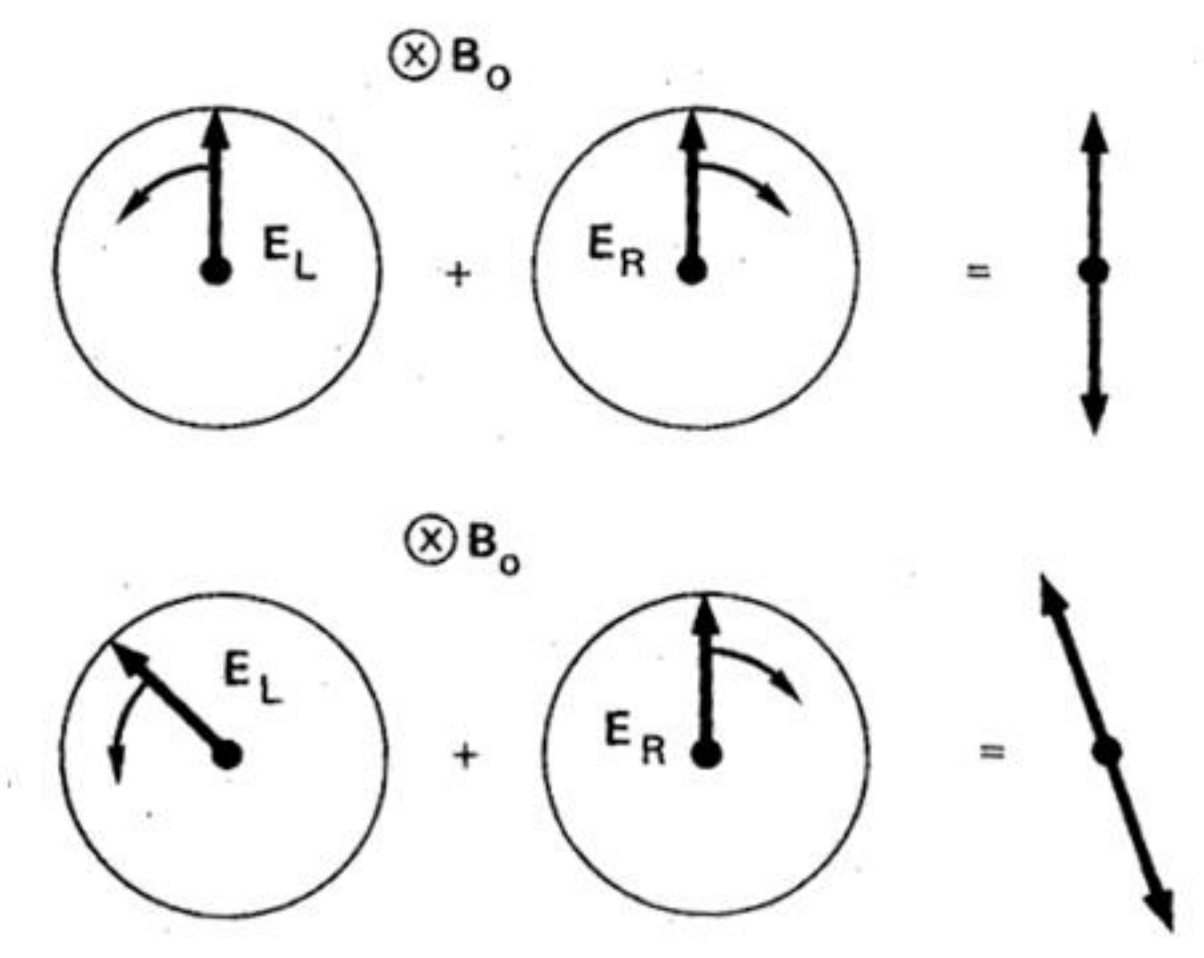


Sample ADS-B Data

Field	Sample
Ground receiver ID aircraft_id - modeS 'hex' latitude longitude track - degrees, 0-359 altitude - feet speed - ground speed in knots squawk - in hex radar_id - internal type - equipment, e.g. B733 registration timestamp - time of sample in seconds since 00:00:00 01/01/1970 UTC / GMT origin - airport code for departure, e.g. KKN destination - airport code flight - flight number e.g. DY311 onground - indication of flight status, 1 for on ground or else 0 vspeed - empty in this sample callsign - e.g. NAX11S eta - empty in this sample	"171e09e" : ["a96c96", 40.593, -73.4894, 10, 4000, 244, 13089, 254, "B752", "N706TW", 1372636803, "SEA", "JFK", "DL1154", 0, 0, "DAL1154", 0],

FLAOT 2 Mission Profile

Faraday Rotation



- **Top:** a linear EM-wave as the superposition of the left-hand circular polarized (LHCP) and right-hand circular polarized (RHCP) waves. **Bottom:** after traversing some distance in the plasma the RHCP has returned to its initial orientation after N-cycles, but the LHCP wave has relatively advanced in phase and the plane of polarization is seen to rotate. Adapted from Chen [2006].

Ω Back of Envelope Calculation

TEC (TECU)	$\Omega_{ADS\text{-}B}$ (°)	$\Omega_{GPS\ L1}$ (°)	$\Omega_{GPS\ L2}$ (°)
1	0.6	0.3	0.5
5	3.1	1.5	2.4
10	6.1	3.0	4.8
20	12.2	6.0	9.6
40	24.4	12.0	19.1

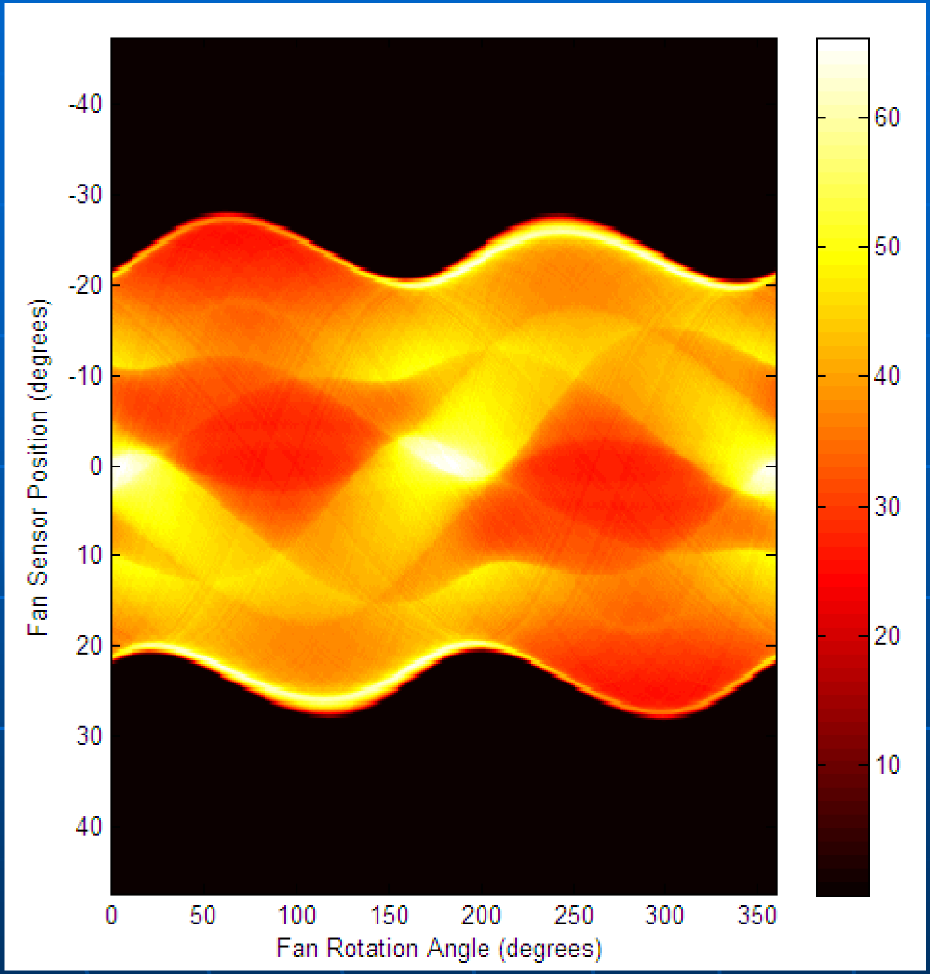
B_{avg}

- ADS-B
  1000km altitude; B_{avg}=55639.51nT
- GPS
  20200km; B_{avg}=55099.88nT

Frequencies:

- ADS-B; λ=0.27m
- GPS L1; λ=0.19m
- GPS L2; λ=0.24m

Sample CT Sinogram

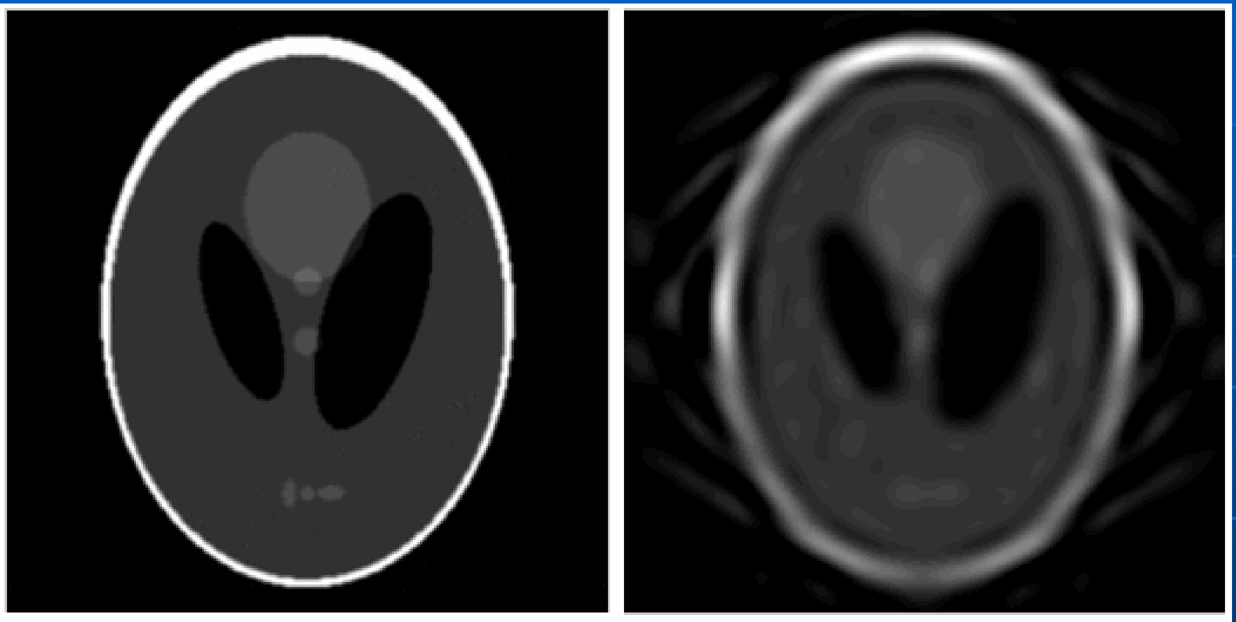


Data amplitude projection as a function of fan rotation angle for Phantom Image

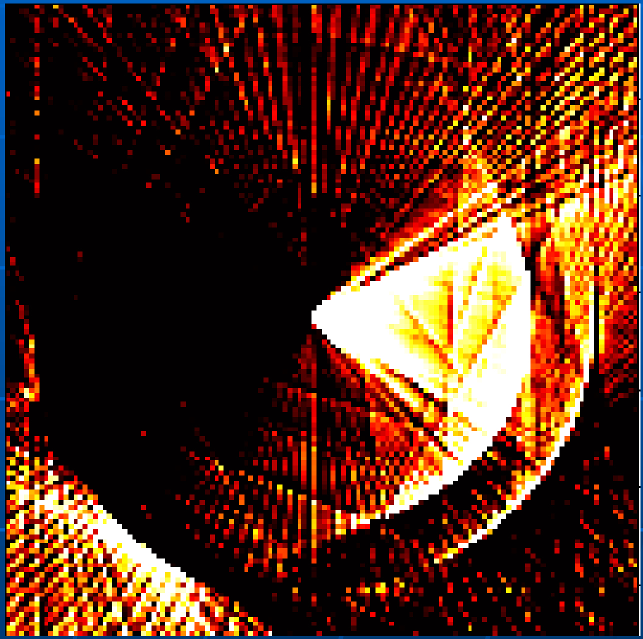
Projection Theorem:

The Fourier Transform of the projection at angle φ is the Fourier transform of the attenuation function along φ in transform space.

Reconstruction by Back-projection

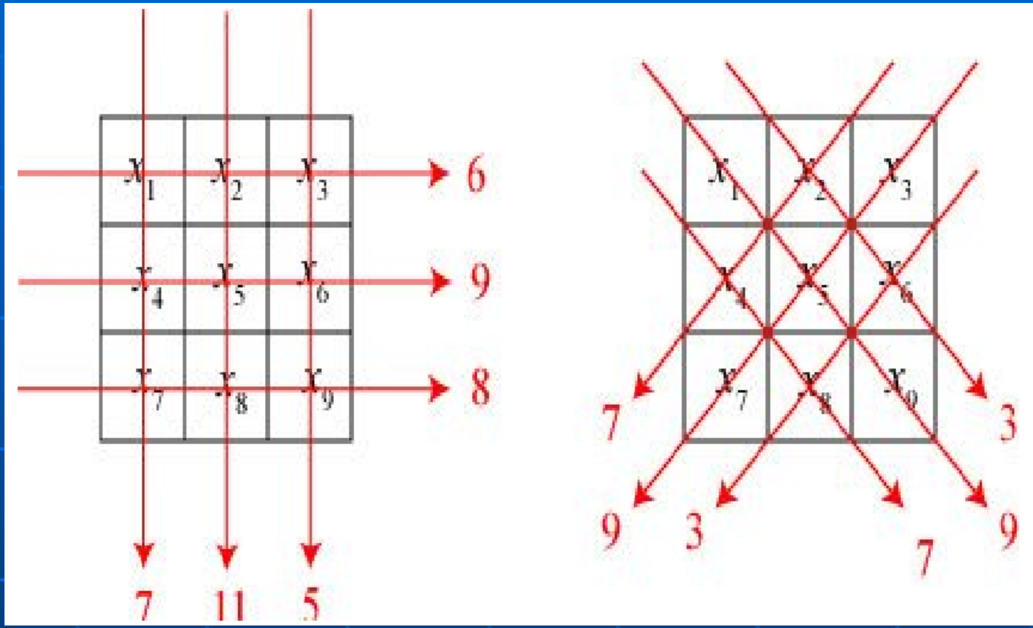


Fan Sensor Spacing
0.25° vs. 2°



Raytrace
Output

Simple Numerical Example



Imaging the grid in four directions gives 12 equations (eg. x1+x2+x3=6);

- Simple algebra requires 9 independent equations to solve 9 unknowns;
- Equations not independent, 11 used.
- Hence “computer” in CT