Imaging the global vertical electron density structure from the ground and space

Brett A. Carter[1,2], Endawoke Yizengaw[2] and Kefei Zhang[1]

[1]SPACE Research Centre, RMIT University, Australia, www.rmit.edu.au/space
[2]Institute for Scientific Research, Boston College, USA, http://www.bc.edu/research/isr/

Outline

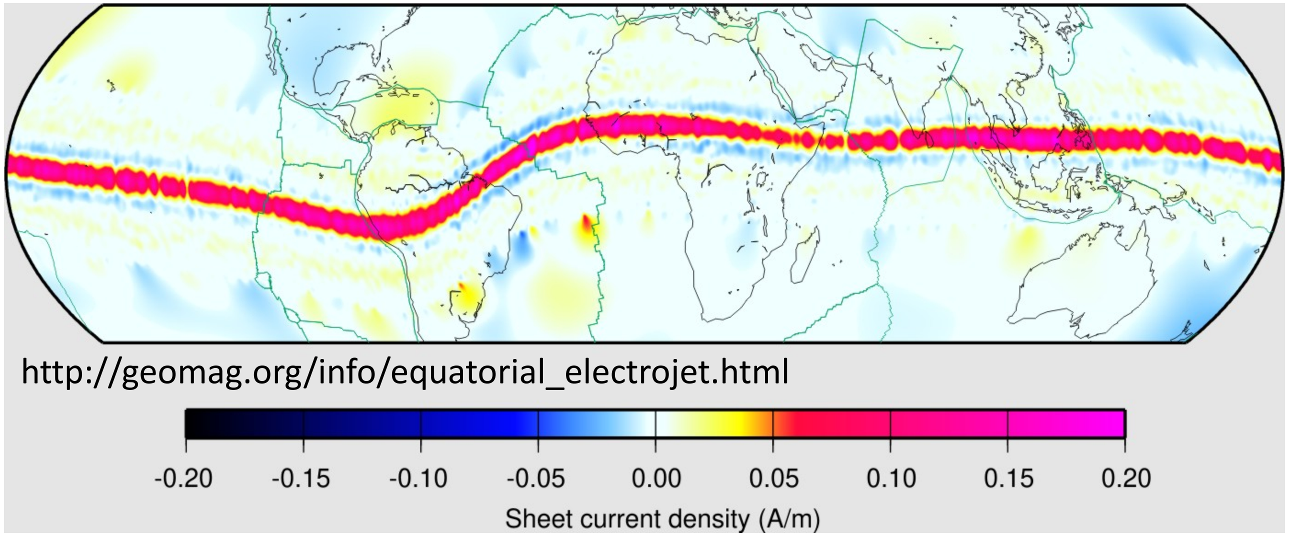
- **Large-scale ionospheric structures:**
  - Ground- and space-based infrastructure to study the ionosphere
  - Equatorial ionosphere structure and the formation of Equatorial Plasma Bubbles
- **GPS Radio Occultation for "bottom-side" ionosphere**
  - Longitudinal variability
  - Solar cycle variability
- **Low-Earth Orbit satellite data for "top-side" ionosphere**
- **Summary and conclusions**

Ionospheric plasma distribution

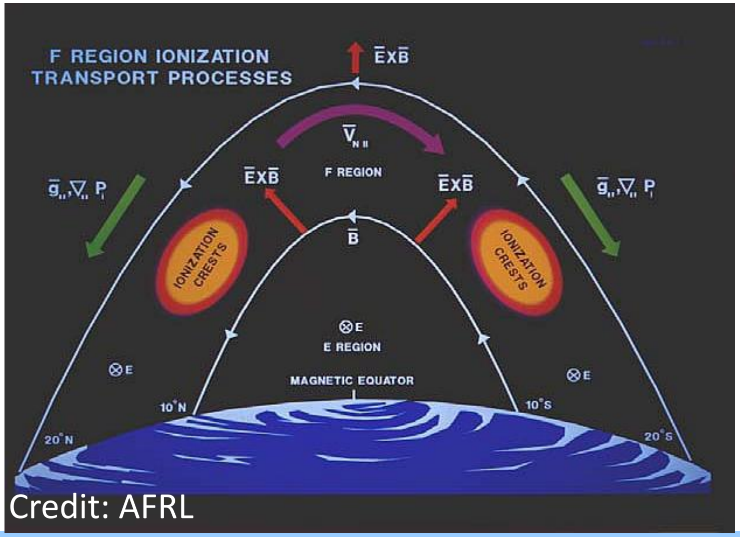
RMIT UNIVERSITY
SPACE Research Centre

- Equatorial Electrojet electric field controls low-latitude ionospheric plasma distribution

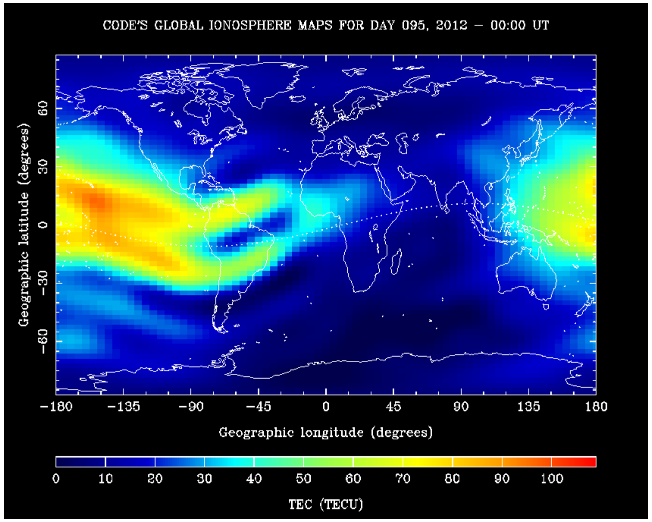
~3° MLAT
(or ~ 300 km) wide



http://geomag.org/info/equatorial_electrojet.html

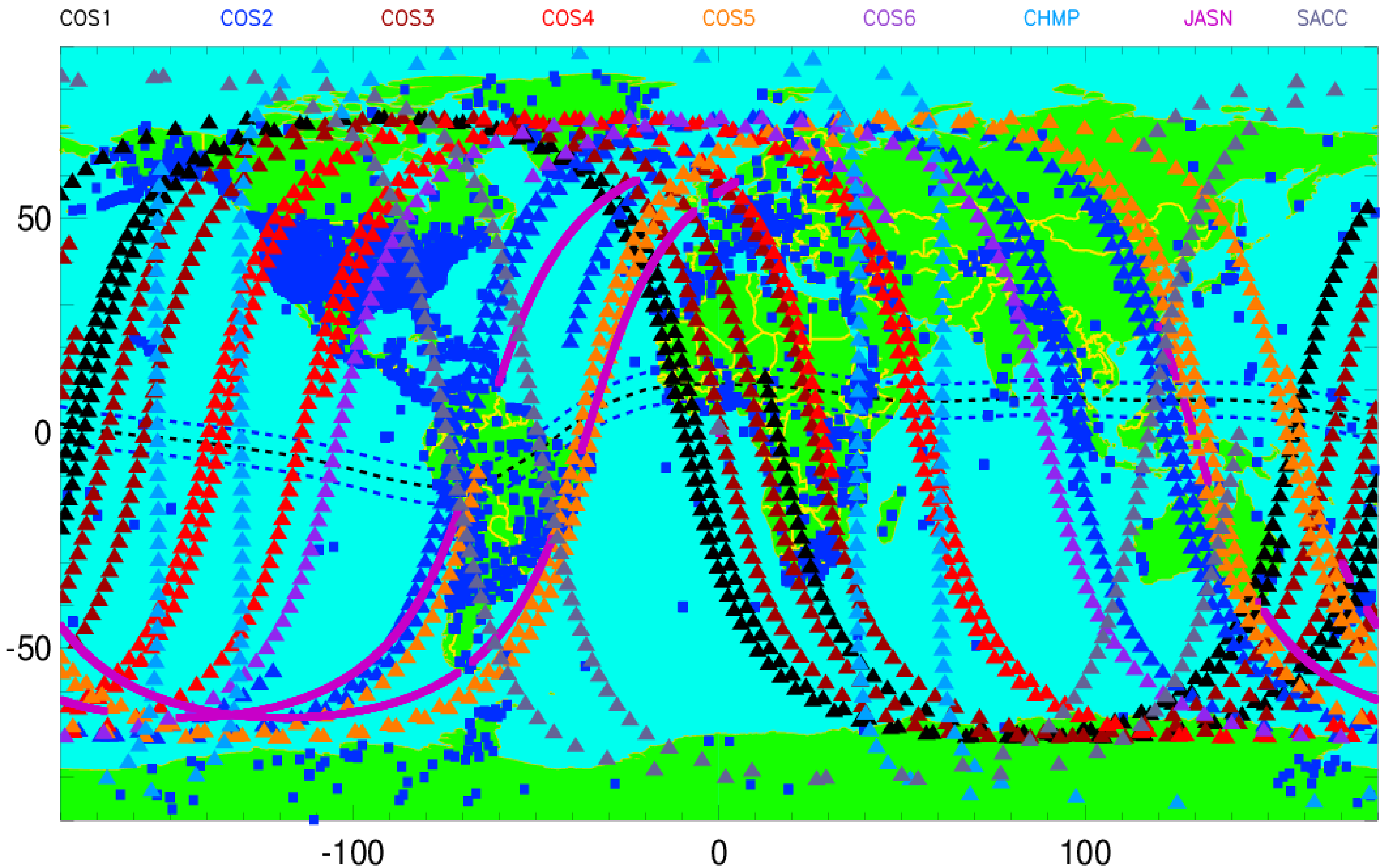


Credit: AFRL

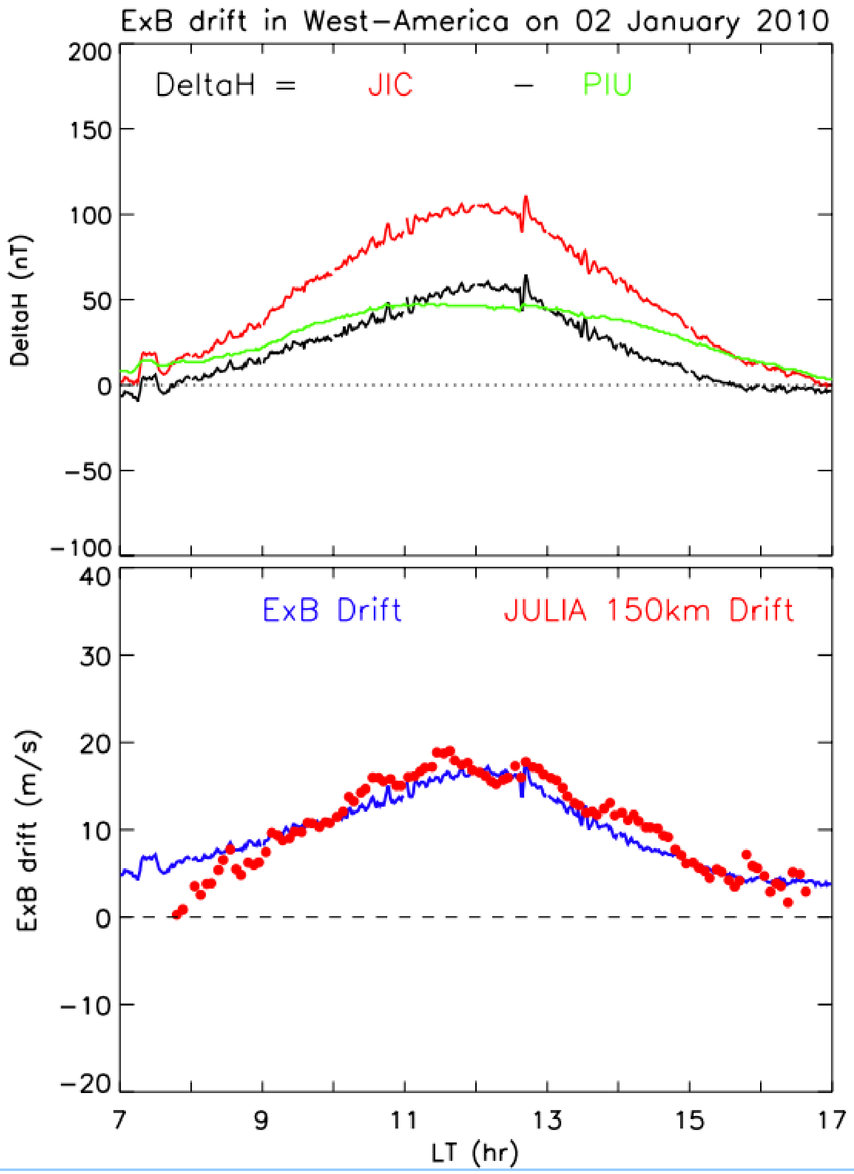


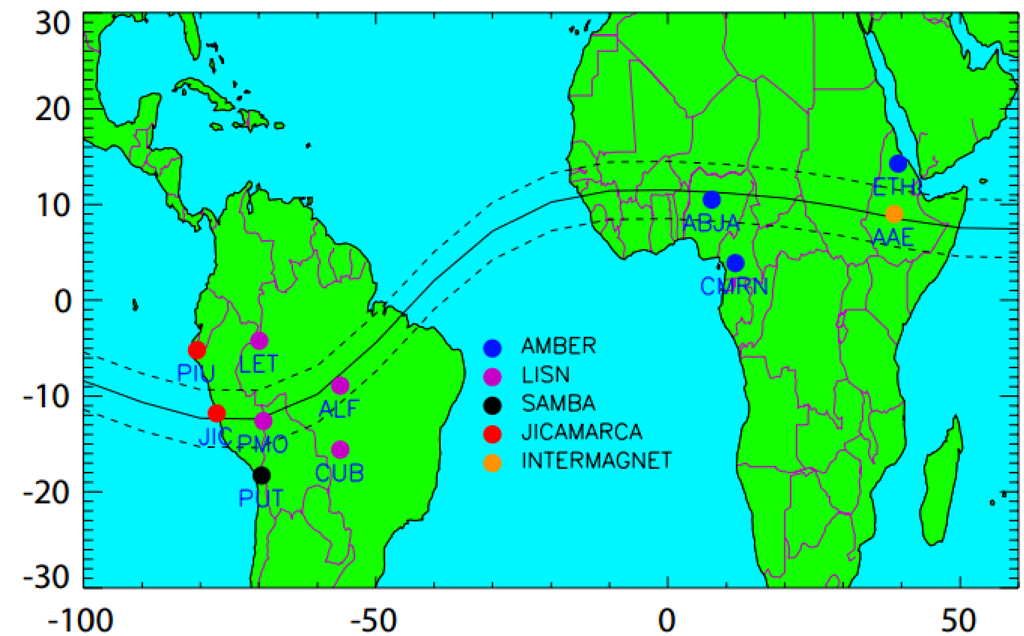
GPS TEC Coverage

RMIT UNIVERSITY
SPACE Research Centre



EEJ from the ground





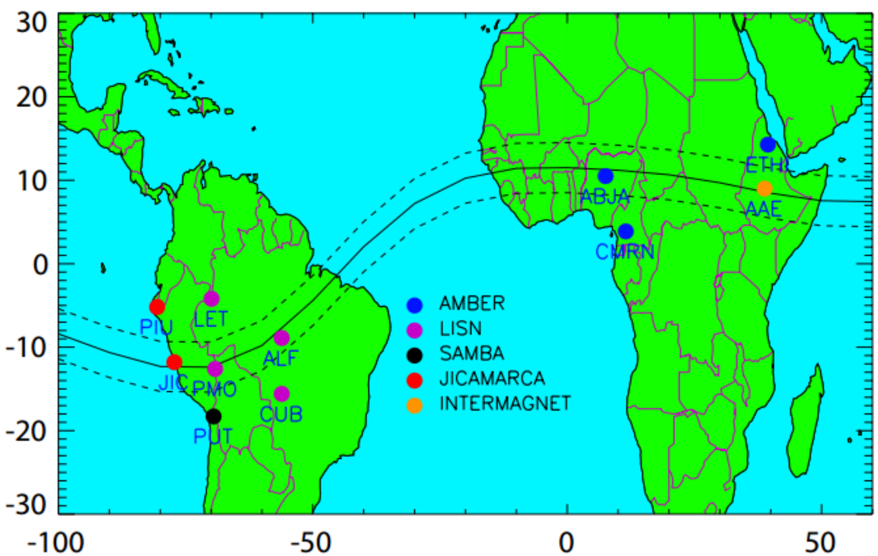
EEJ strength from magnetometer pairs compares well with direct radar observations

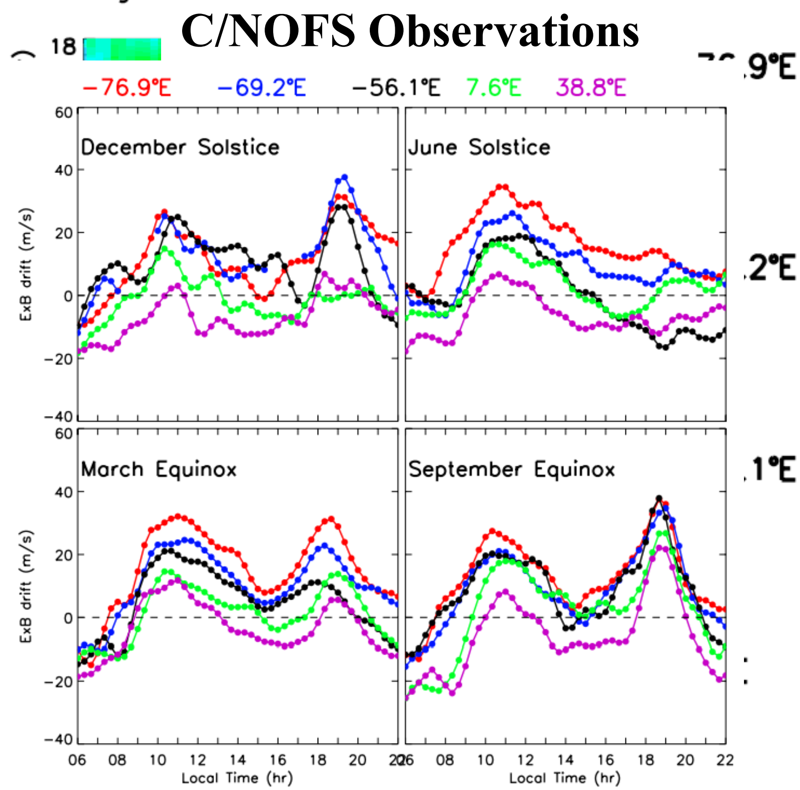
Yizengaw et al. (2014)

Longitudinal variability

RMIT UNIVERSITY
SPACE Research Centre

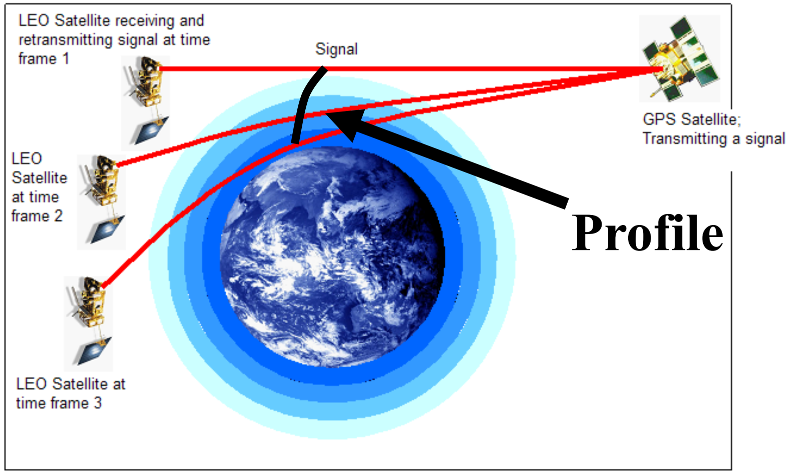
- Equatorial Electrojet shows strong variability between the American and African sectors
- These EEJ differences translate into longitudinal differences in the large-scale plasma distribution (i.e., anomaly structure)
- It is clear that more data is required in order to better understand these longitudinal variations





- Satellite data also reveals a strong longitudinal dependence in the upward plasma drift
- Note the differences in the strength of the PRE in particular

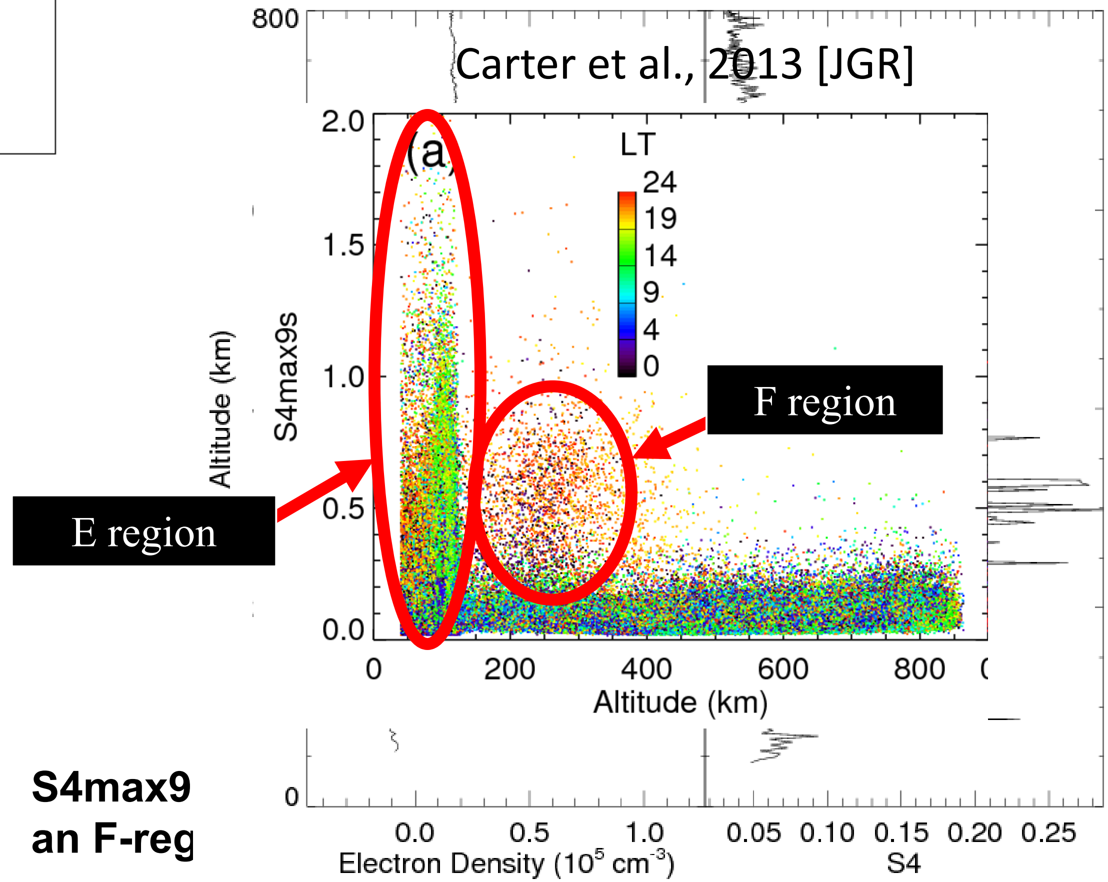
Radio Occultation – GPS Scintillation



The Low Earth Orbit (LEO) satellites measure the GPS signals that are occulted by the Earth's atmosphere. These occulted signals are used to infer atmospheric properties such as wet temperature (troposphere) and electron density (ionosphere).

<u>Dataset:</u> ~ 5 years (2007-2011) of RO data collected by the COSMIC satellites.

The 's4max9s' is used for each event instead of the 's4max' parameter to avoid the use of spurious S4 measurements.

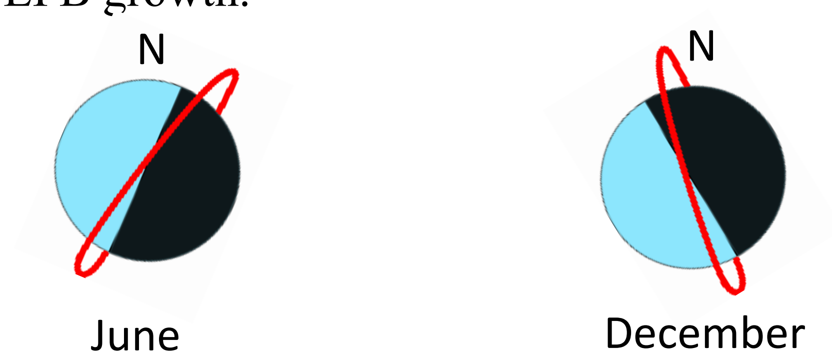


EPB Climatology: GPS RO data

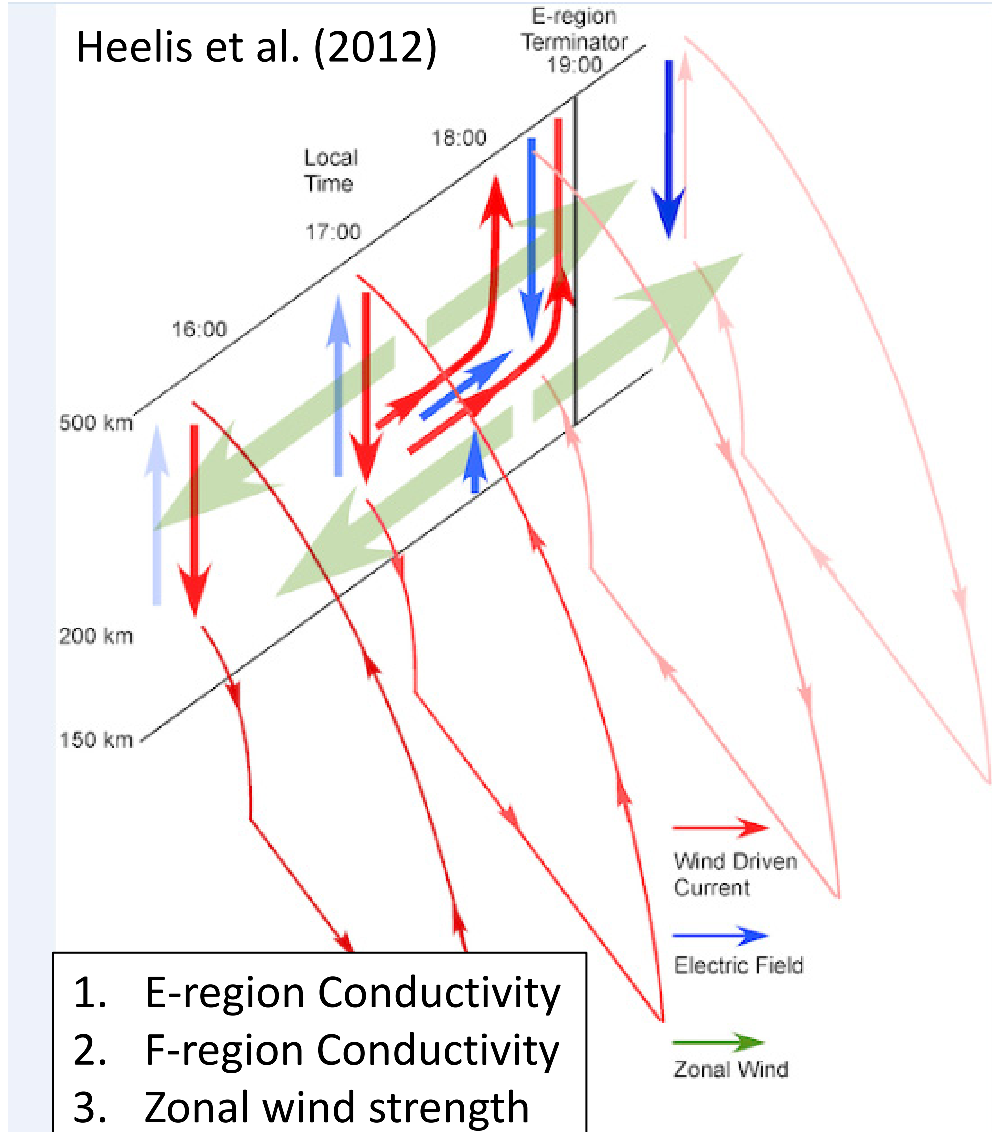
RMIT UNIVERSITY
SPACE Research Centre

On a map, the EPB occurrence climatology, and its dependence on the magnetic declination angle during the solstices, become clearer.

During the June solstice (MJJ), positive declinations provide favourable EPB growth conditions, whereas during the December solstice (NDJ), negative declinations favour EPB growth.



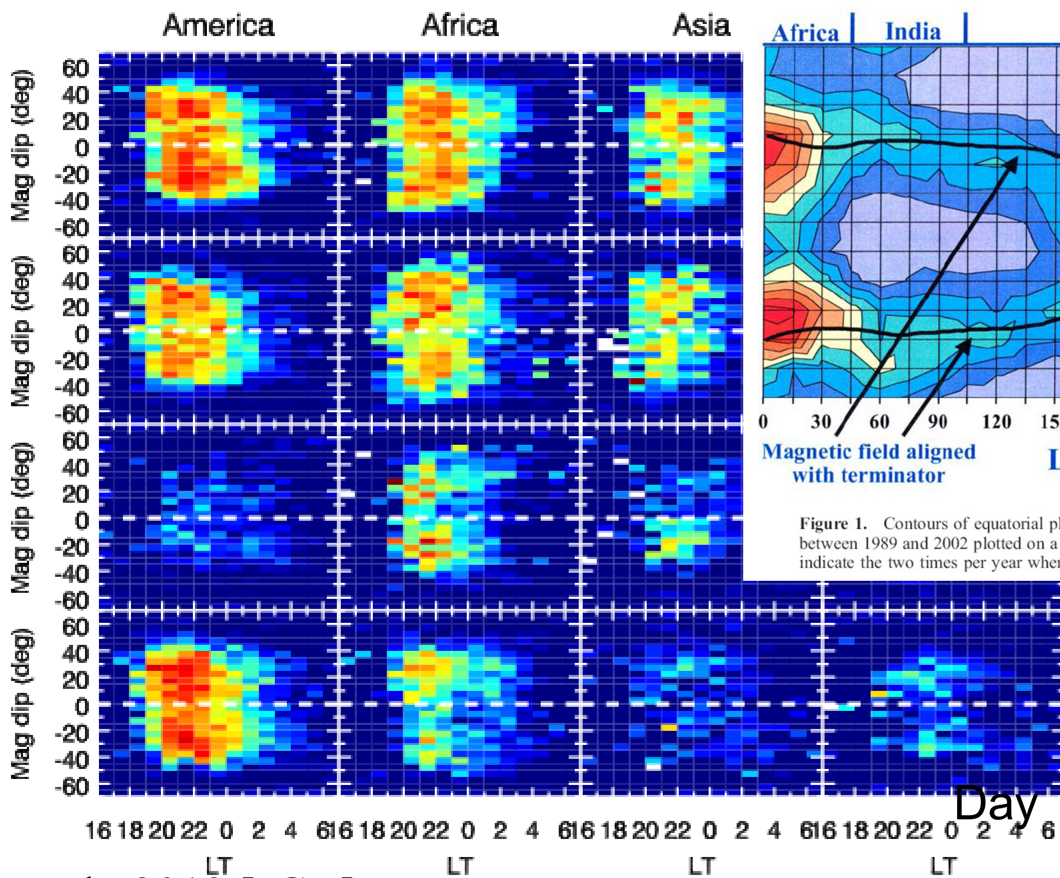
A strong longitudinal E-region conductivity gradient creates stronger polarisation E field that drives vertical plasma drift after sunset.



1. E-region Conductivity
2. F-region Conductivity
3. Zonal wind strength

EPB Climatology: GPS RO Results

RMIT UNIVERSITY
SPACE Research Centre



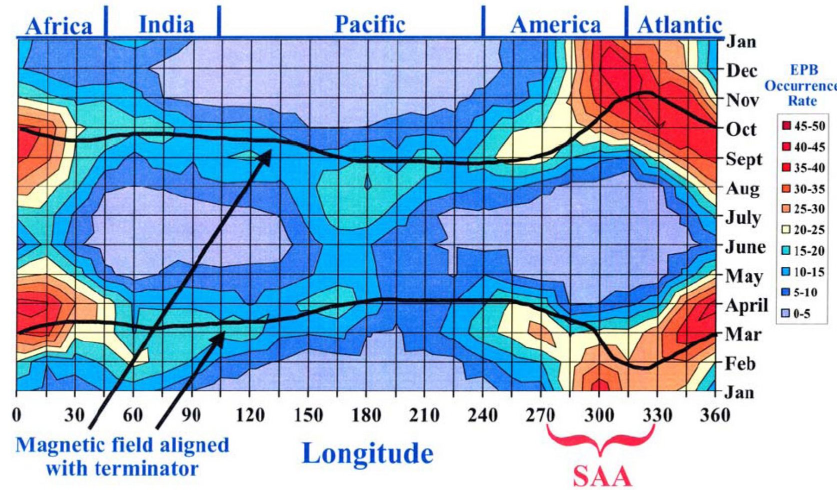
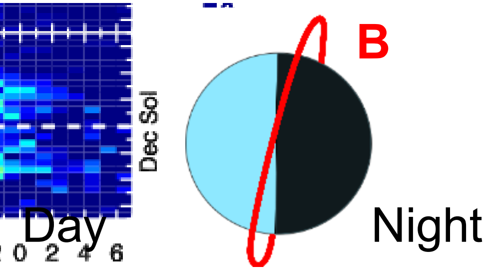


Figure 1. Contours of equatorial plasma bubble (EPB) occurrence rates measured by DMSP satellites between 1989 and 2002 plotted on a month versus longitude grid in nine 5% increments. The solid lines indicate the two times per year when $\alpha = 0°$ at given longitudes.

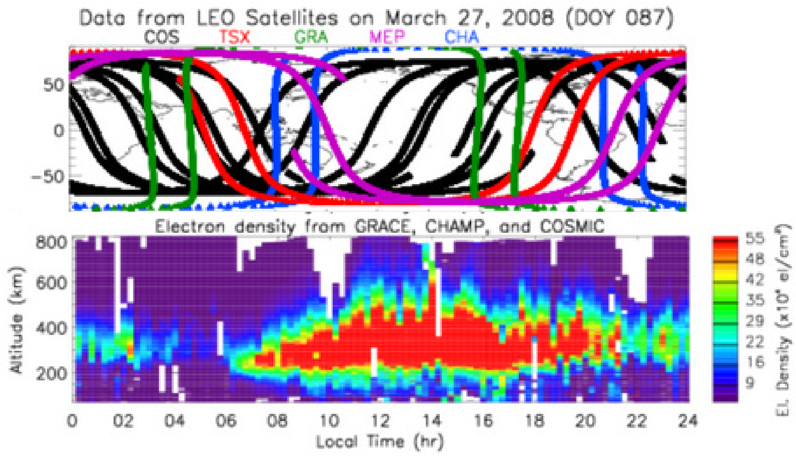


Carter et al., 2013 [JGR]

- Sorting the data according to season and longitude sector show strong differences in EFI occurrence.
- These trends match those found in previous studies of EPB occurrence; e.g. Burke *et al.* (2004)
- Occurrence of F-region irregularities is strongly controlled by the magnitude of the angle between the magnetic field and the direction of the day-night terminator (Abdu et al., 1981; Tsunoda, 1985)

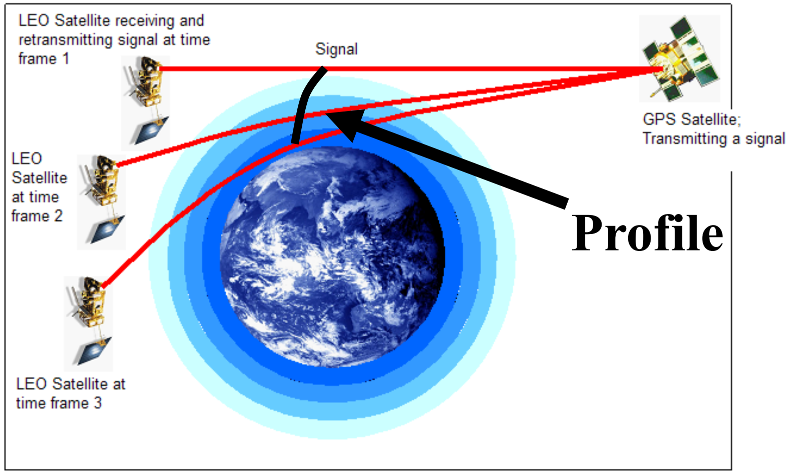
Radio Occultation

RMIT UNIVERSITY
SPACE Research Centre



- LEO satellite ground tracks over 2 hrs
- Ionospheric density profiles from +/- 25° LAT

- Combining the RO profiles in this way reveals the diurnal variation of low-latitude plasma distribution
  - The lull in ionisation prior to dawn, and the increase afterwards
  - The slow increase in altitude of the plasma above the F layer peak

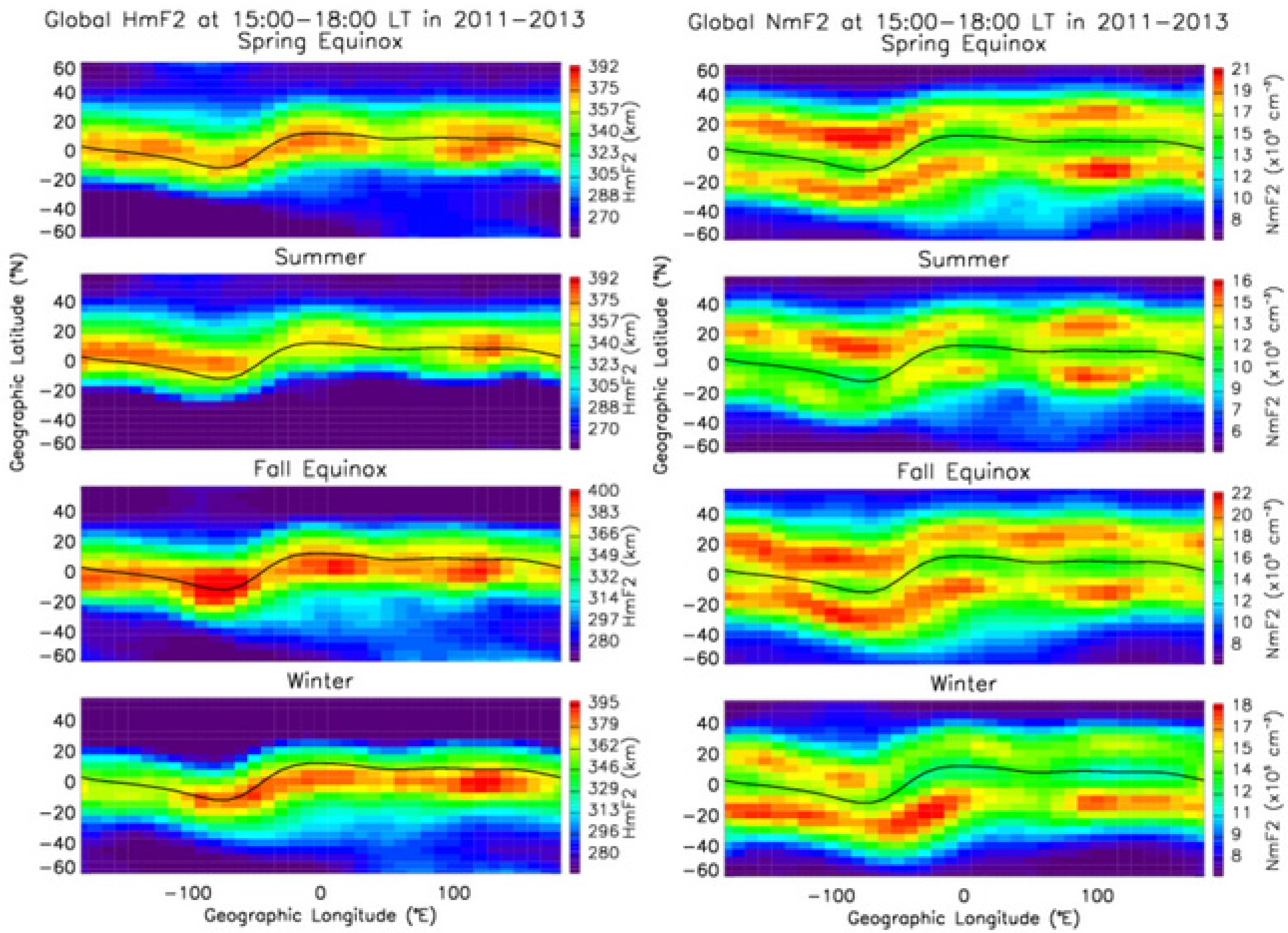


Seasonal dependence

- Wave-4 structure (due to non-migrating tides) evident in both HmF2 and NmF2 distributions

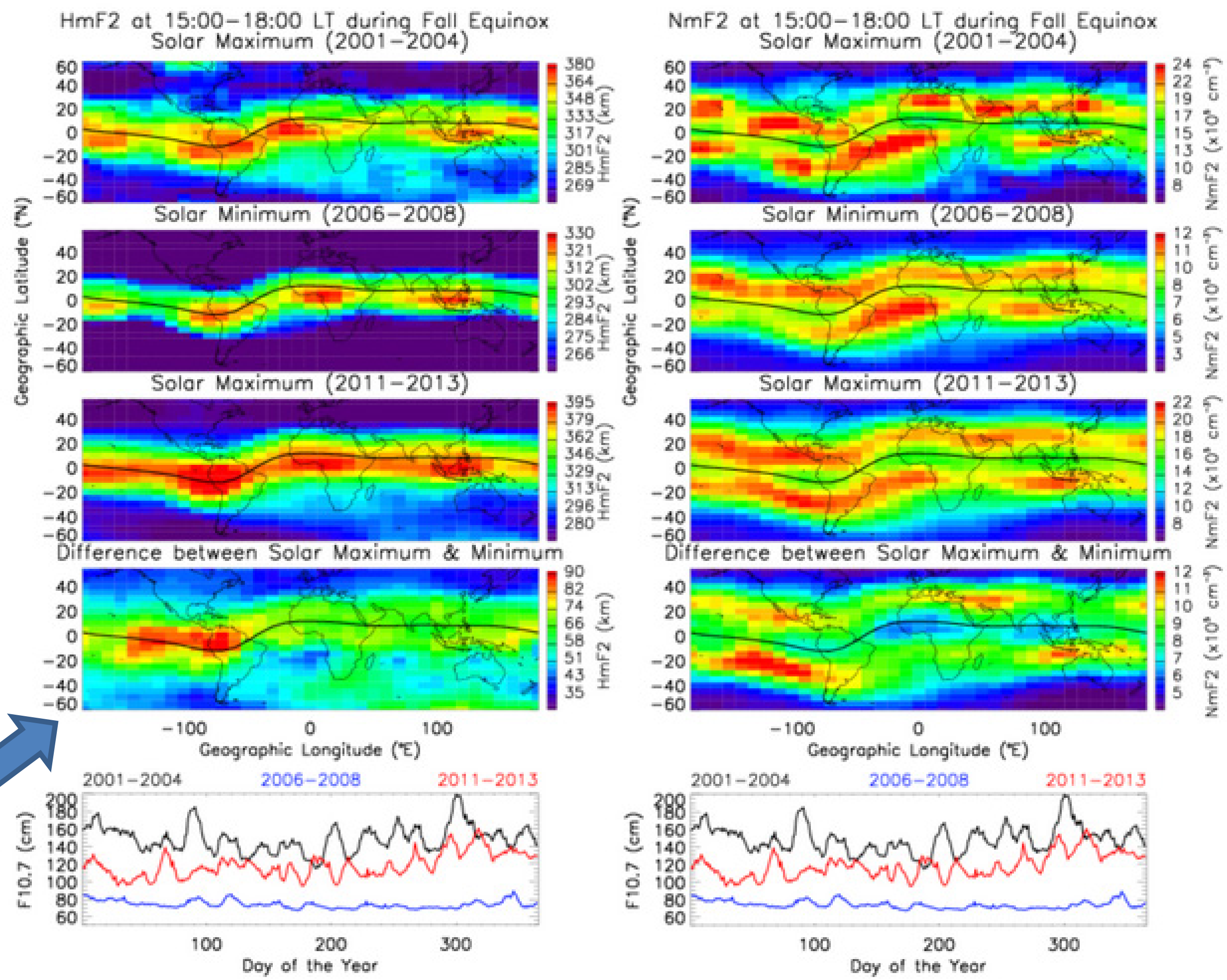
- Higher altitude equatorial plasma corresponds to stronger anomaly densities at off-equatorial locations

- Strong seasonal dependence

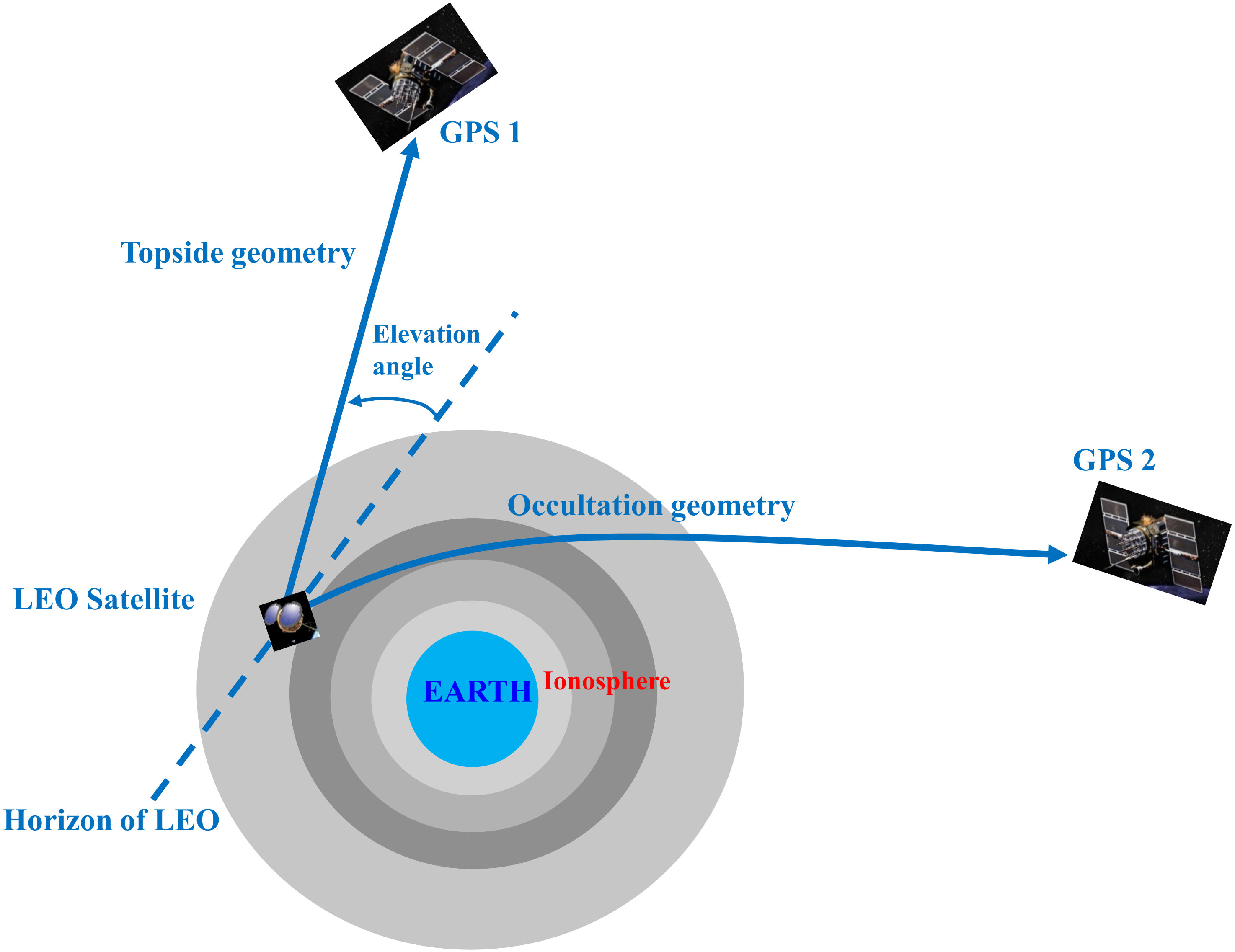


Solar cycle variations

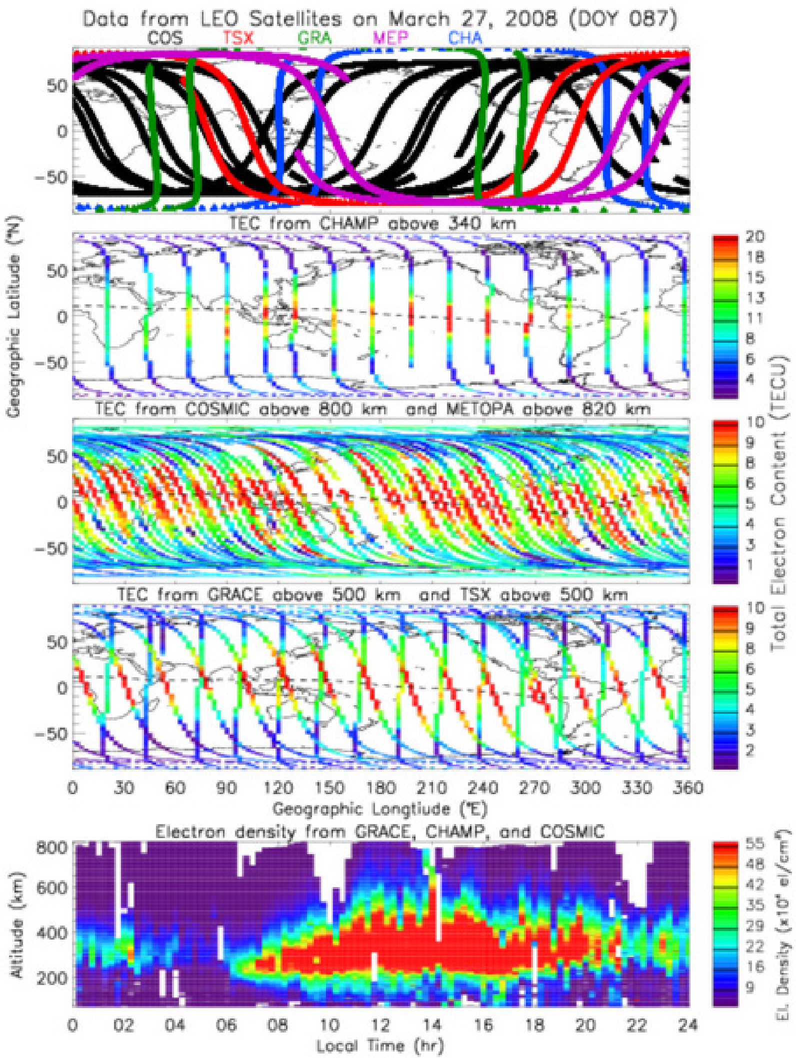
- Sorting data according to solar cycle reveals differences in wave-4 structures (clearest during solar minimum)
- Interestingly, plasma resided almost 100 km higher over South America during solar max compared to solar min
- Not clear what drives these longitudinal differences



“Topside” soundings



“Topside” soundings



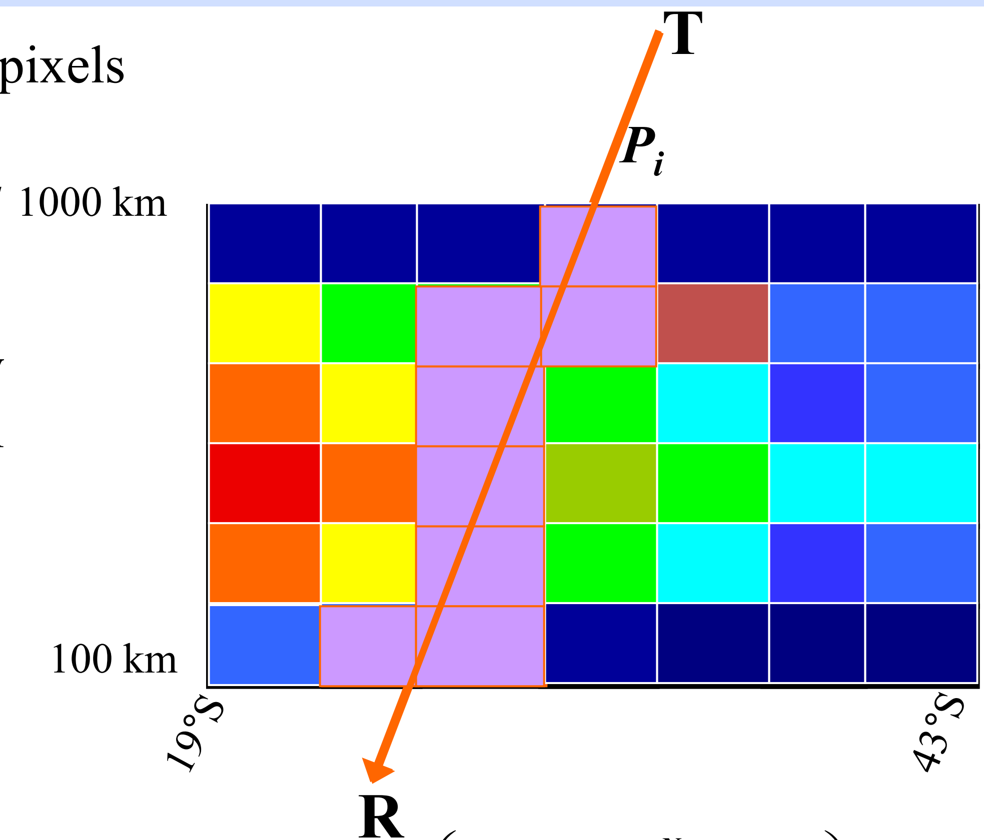
- Descending satellite passes, coloured according to the TEC above satellites
- CHAMP above 340 km
- COSMIC above 800 km and Metop A above 820 km
- GRACE and TerraSAR-X above 500 km
- GPS information from altitudes above LEO orbit provide a complete picture of the ionosphere

Tomography Inversion technique

RMIT UNIVERSITY
SPACE Research Centre

Divide the imaging region into number of pixels

$$TEC_i = \int_{p_i} N_e ds = \sum_{j=1}^{N} d_{ij} n_j + E$$



Fill each pixel with initial electron density guess, which can be obtained from model profiles.

$$TEC_{guess} = \sum_{j=1}^{N} d_{ij} (n_{gs})_j$$

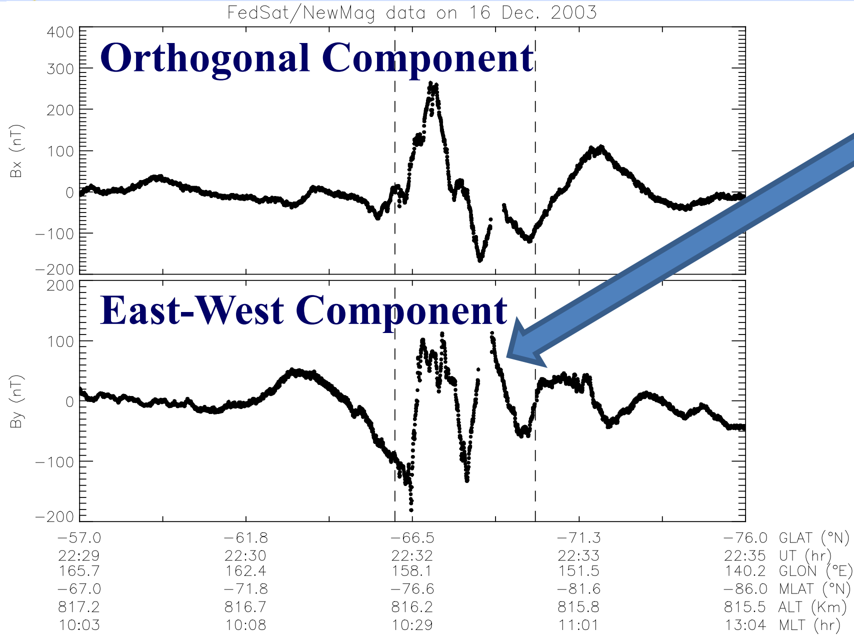
Calculate TEC for the current raypaths through initial guess.

Using an iterative fashion, the vertical electron density profile then can be calculated as:

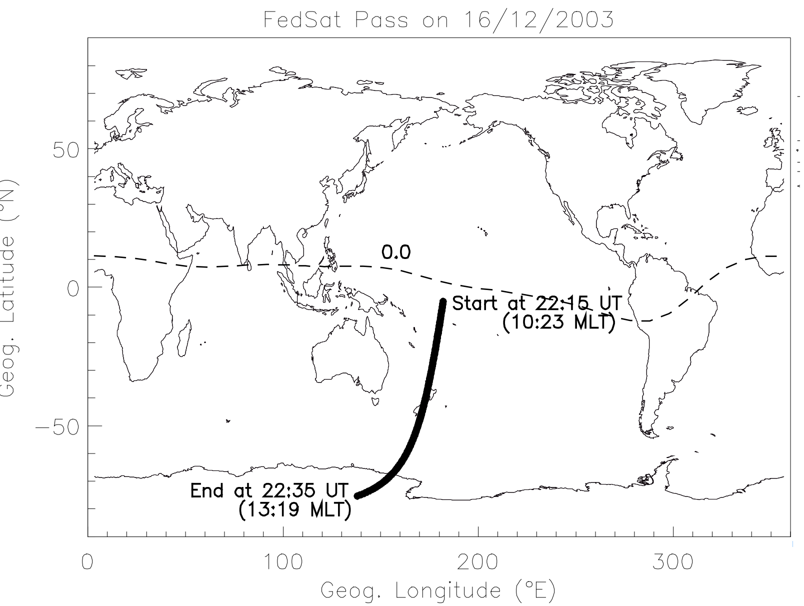
$$N_e^{k+1} = N_e^k + \lambda_k \left(\frac{TEC_i - \sum_{j=1}^{N} d_{ij} n_j^k}{\sum_{j=1}^{N} d_{ij} d_{ij}} \right) D_i$$

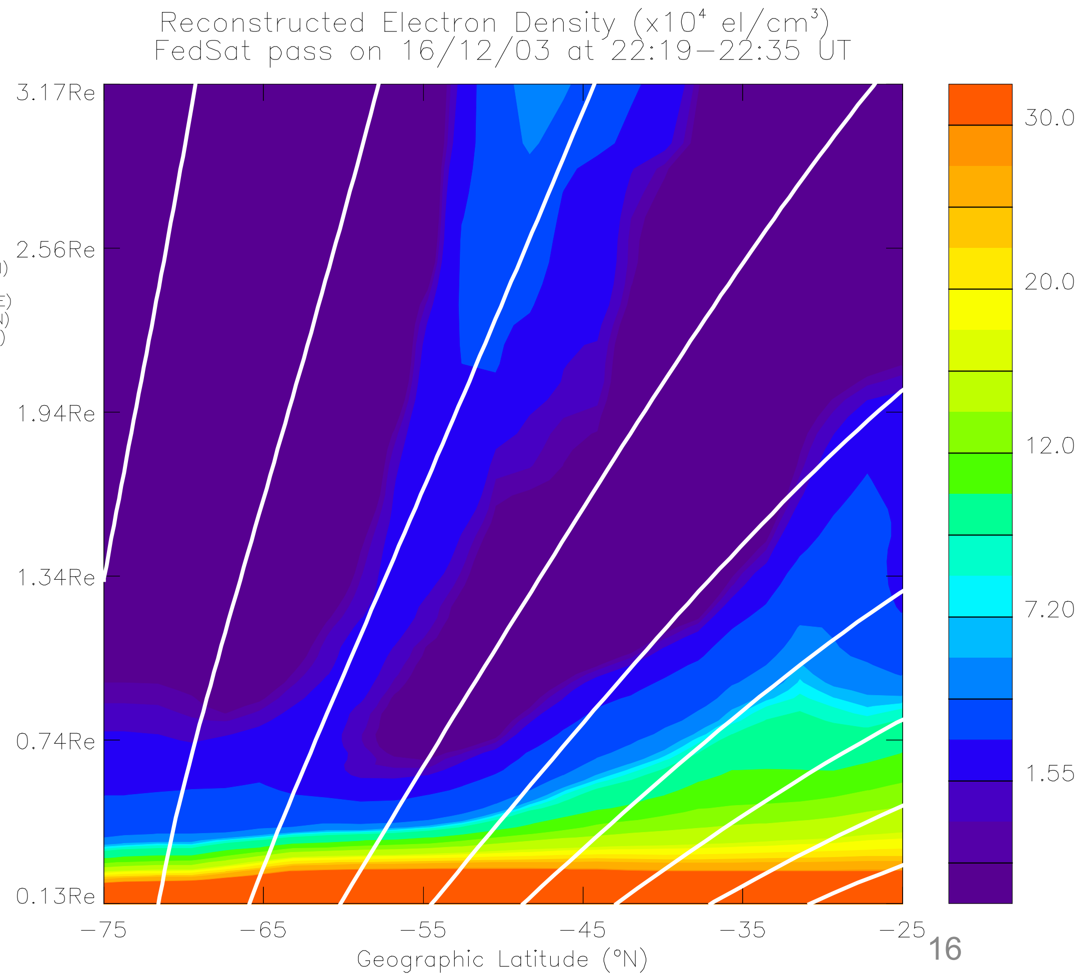
Topside tomography: FedSat

RMIT UNIVERSITY
SPACE Research Centre



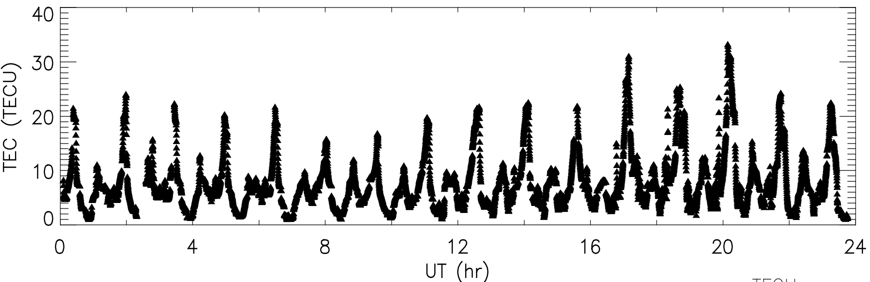
East-west magnetic field component shows presence of FAC sheets, which indicates the existence of precipitated electrons in the cusp region where ion outflows occur.

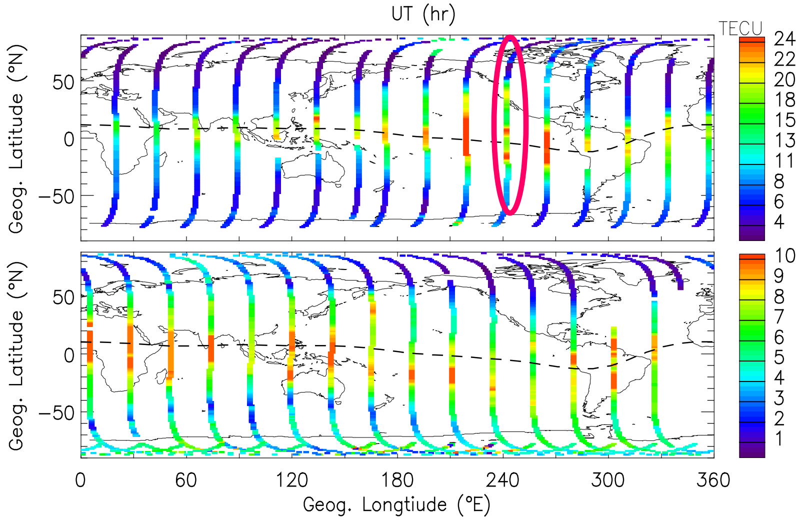


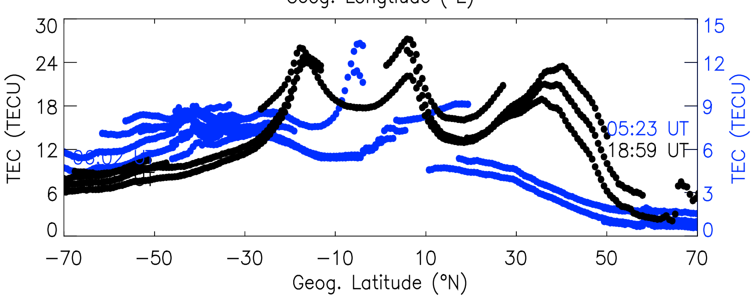


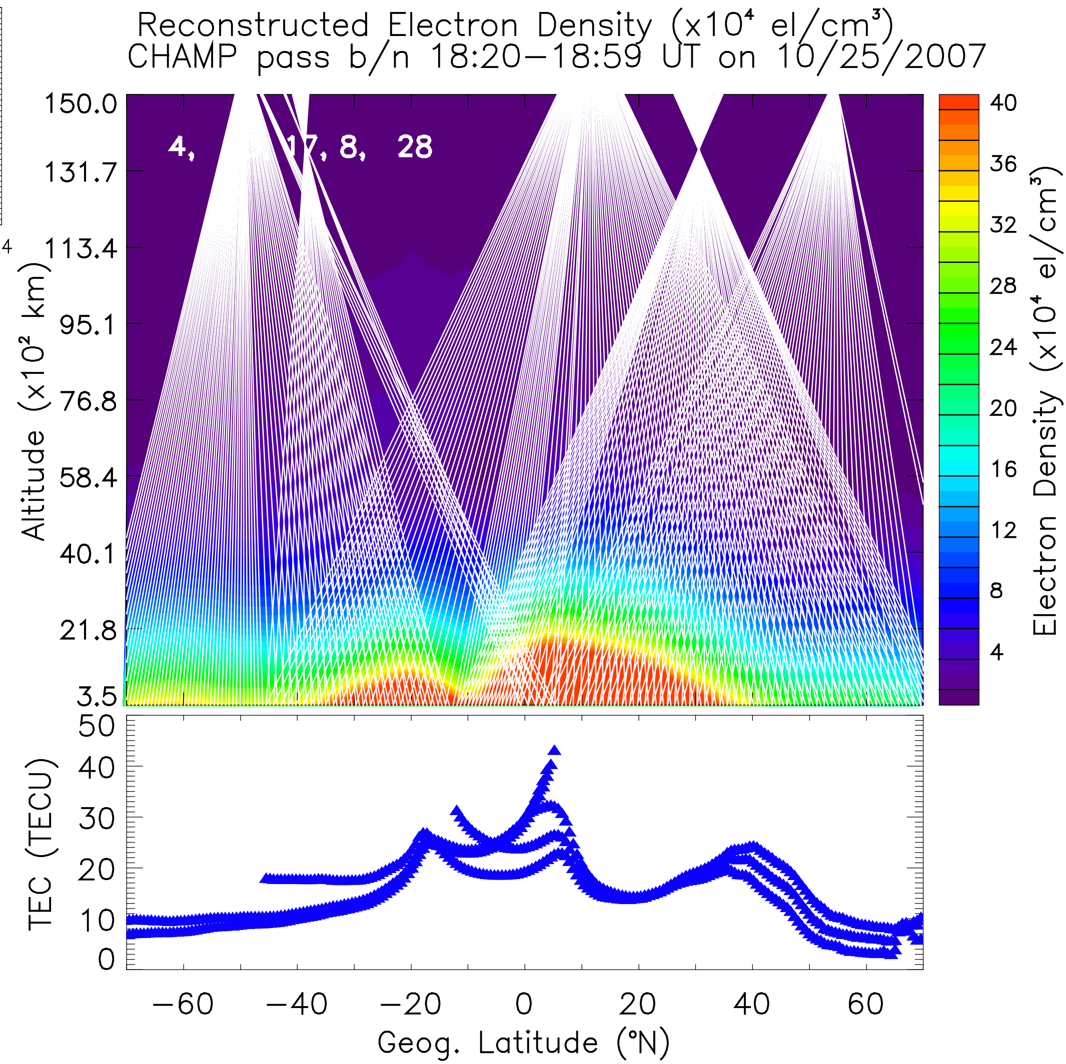
Tomography using CHAMP GPS data

RMIT UNIVERSITY
SPACE Research Centre





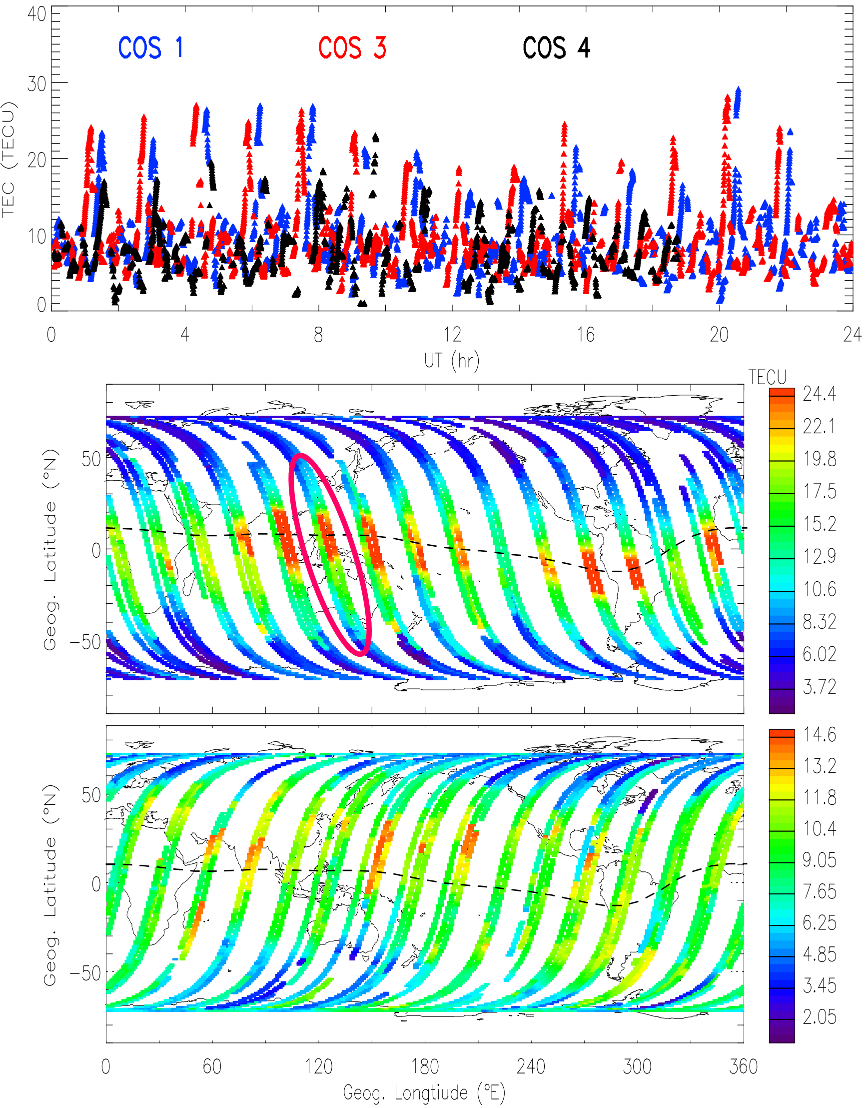


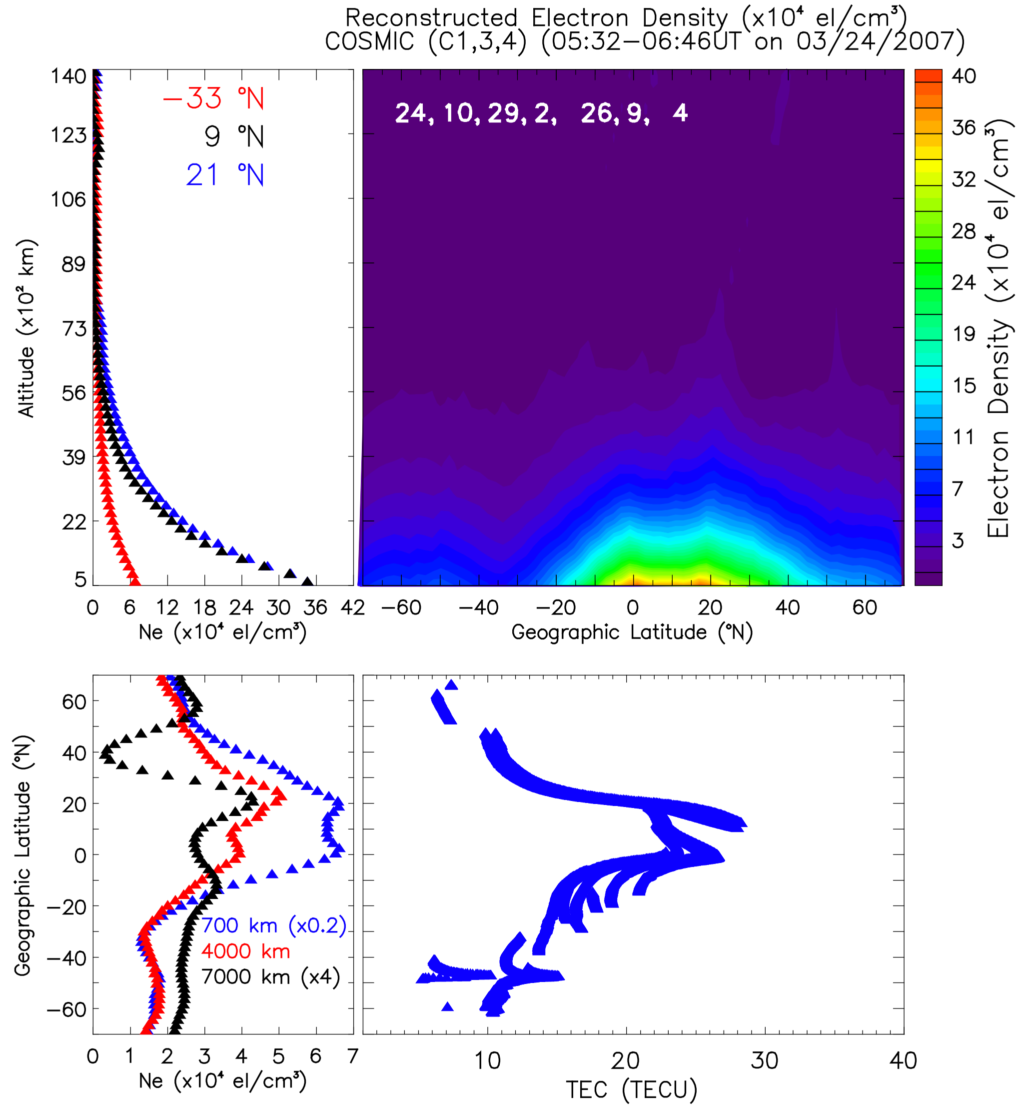


Tomography using COSMIC GPS data

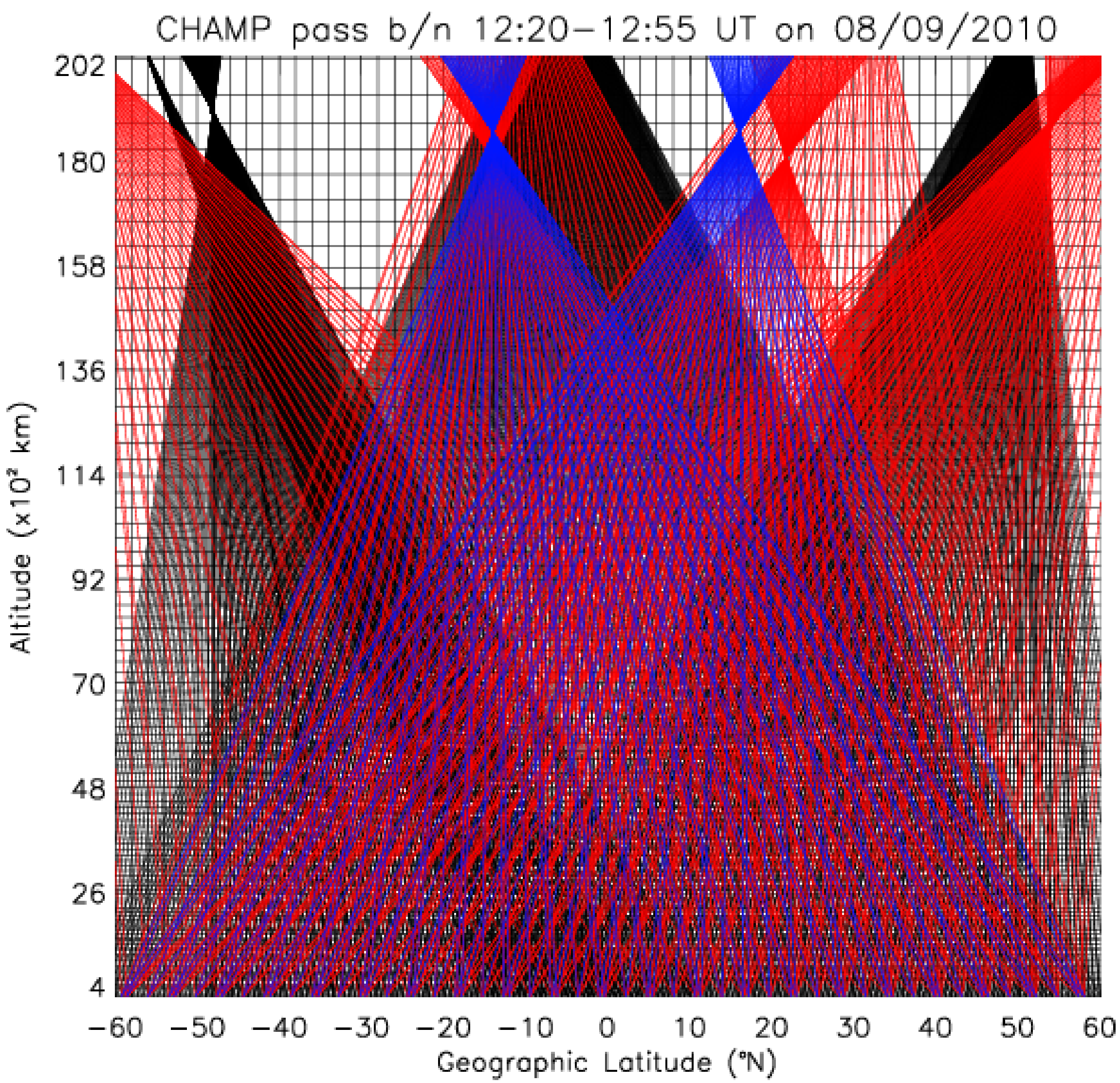
RMIT UNIVERSITY

SPACE Research Centre





Potential Topside Ray Paths



GPS

GPS+GLON

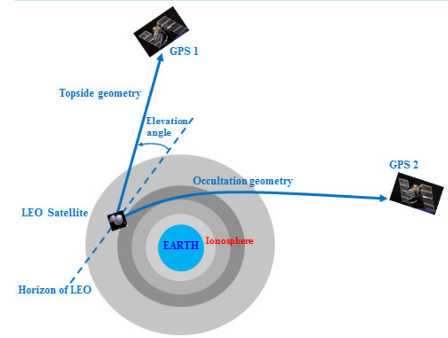
GPS+GLON +GAL

Summary and conclusions

RMIT UNIVERSITY
SPACE Research Centre

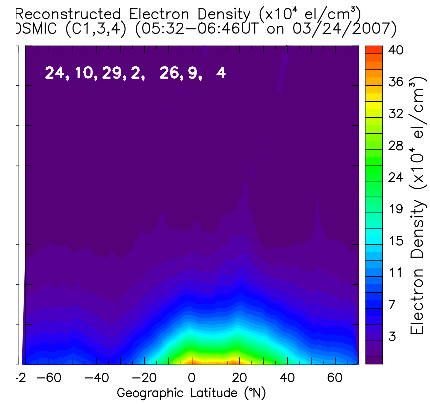
Large-scale ionospheric structure is driven by various phenomena:

- Low-latitude electric fields drive plasma fountain, which ultimately controls the large-scale plasma distribution
- Ionospheric monitoring capabilities have significantly increased over recent years – particularly GPS TEC monitoring



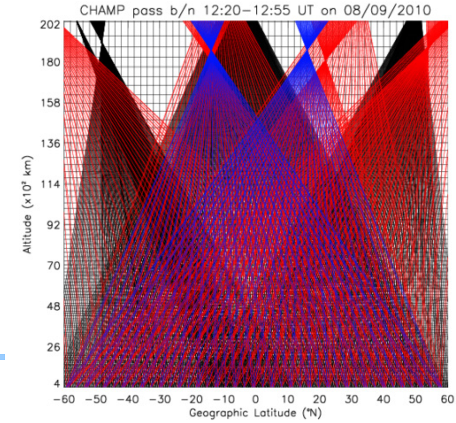
Ground-based measurements only give us so much :

- Low-Earth orbiting satellite data has proved extremely useful in studying the longitudinal variability in the ionosphere – including EPB occurrence and plasma flow strength
- GPS RO data, when grouped together, provide a global perspective that reveals that diurnal, seasonal and solar cycle variability controls the large-scale ionospheric plasma



GPS RO data is not the only useful dataset:

- TEC information above the LEO satellite orbits up to the GPS satellites provides additional insights into the high-altitude plasma dynamics, enabling detailed investigations of the ionosphere/plasmasphere
- The upcoming COSMIC-II is highly anticipated, and is expected to provide an extremely beneficial dataset for “topside” ionosphere studies



Ionospheric structures: What are we dealing with?

RMIT UNIVERSITY
SPACE Research Centre