Space geodetic techniques for remote sensing the ionosphere

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Outline

- Modeling VTEC from VLBI (TU Wien – VLBIonos)
- Integration of GNSS, satellite altimetry, and Formosat/Cosmic measurements for combined GIM (TU Wien – COMBION)
- Multi-dimensional modeling of the ionosphere (TU Wien, TU Berlin – MDION)
- Sporadic E-layer from Radio Occultation measurements (GFZ)

Parameters from different techniques

Parameter Type	VLBI	GNSS	DORIS	SLR	LLR	Altimetry
ICRF (Quasars)	X					
Nutation	X	(X)		(X)	X	
Polar Motion	X	X	X	X	X	
UT1	X					
Length of Day	(X)	X	X	X	X	
ITRF (Stations)	X	X	X	X	X	(X)
Geocenter		X	X	X		X
Gravity Field		X	X	X	(X)	X
Orbits		X	X	X	X	X
LEO Orbits		X	X	X		X
Ionosphere	X	X	X			X
Troposphere	X	X	X			X
Time Freq./Clocks	(X)	X		(X)		

Table 1 – Parameters estimated by different space geodetic techniques

VLBIonos

TU Wien (2003 – 2006)

Very Long Baseline Interferometry

- Unique technique for
  - CRF (Celestial Reference Frame)
  - Celestial pole
  - UT1-UTC
- Primary technique for
  - EOP (complete set of parameters)
  - TRF (most precise technique for long baselines)
- Observations at X- and S- band
  - Possibility to determine ionosphere delay

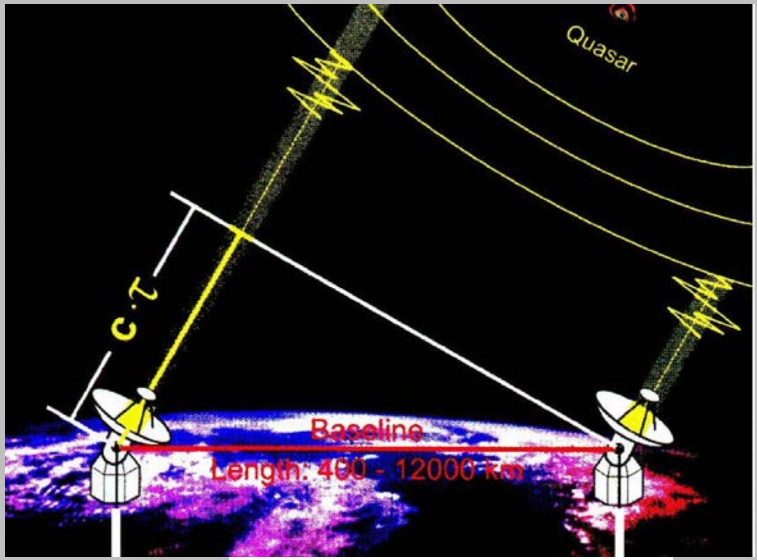


Figure 1 – VLBI concept

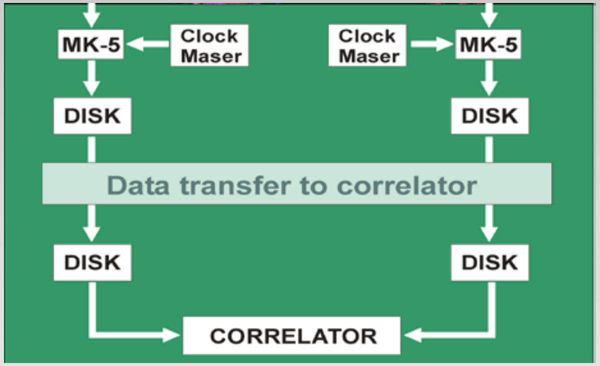


Figure 2 – VLBI procedure

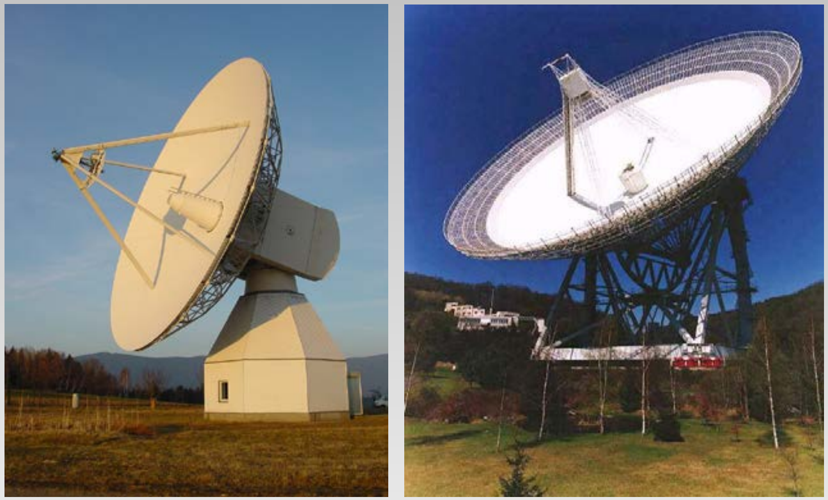


Figure 3 – VLBI antenna, Wettzell (left), Effelsberg (right)

VLBIonos: Procedure

Modeling VTEC from VLBI

- VLBI observations are performed at two different frequencies (X- and S-band) in order to determine the ionospheric delay. This information can be used to model the ionosphere above each station (eq. 1).
- The ionospheric delay at X-band over station *i* can be modeled in the form of equation 2 with an appropriate mapping function (eq. 3).

$$\tau_{model}(t) = \tau_{ion,1}(t) - \tau_{ion,2}(t) + \tau_{offset,1} - \tau_{offset,2} \qquad (1)$$

$$\tau_{ion,i}(t) = \frac{1.34 \cdot 10^{-7}}{f_x^2} \cdot M_f(\varepsilon_i) \cdot VTEC_i(t) \qquad (2)$$

$$M_f(\varepsilon_i) = \frac{1}{\cos\left\{\arcsin\left[\frac{R\cos\varepsilon_i}{R+h}\right]\right\}} \qquad (3)$$

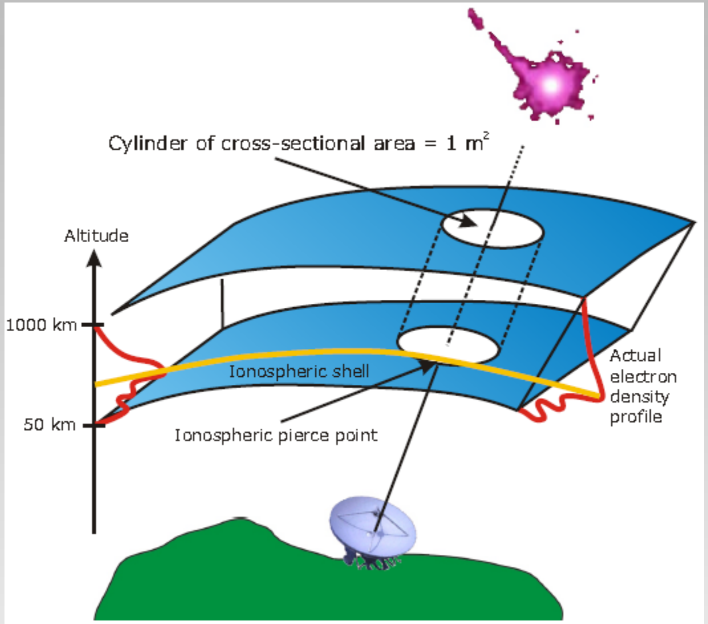


Figure 4 – Modeling VTEC from VLBI

VLBIonos: Sample Results *(Hobiger et al. 2006)*

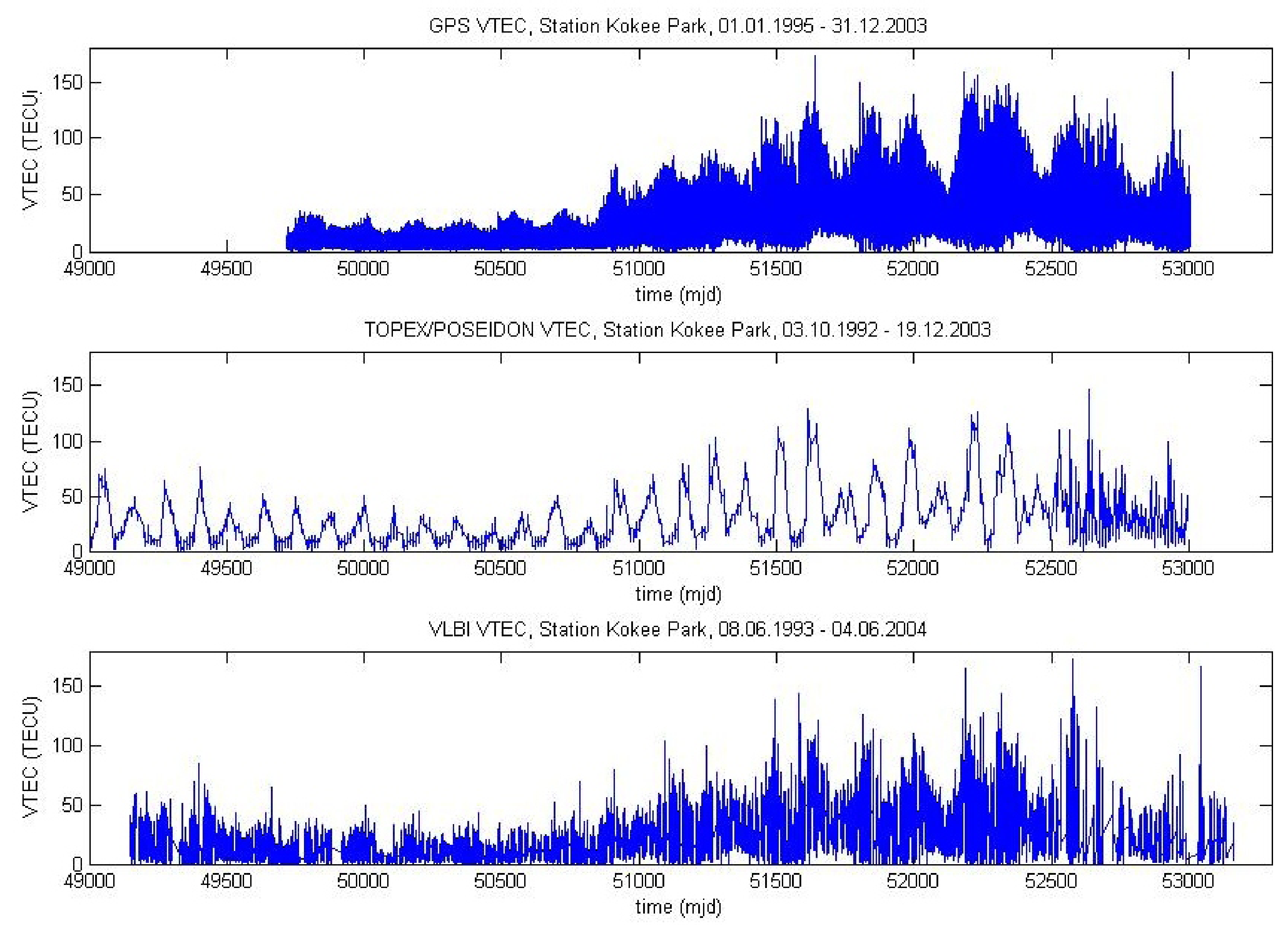


Figure 7 – Long time series of station specific VTEC values for station Kokee Park, Hawaii, derived from GPS (International GNSS Service - IGS), TOPEX/Poseidon, and VLBI

COMBION

TU Wien (2007 – 2010)

COMBION: Motivations

- GNSS has turned into a classical tool for developing Global Ionosphere Maps.
- IGS stations are in-homogeneously distributed around the globe, with large gaps over the oceans, which reduces the accuracy and reliability of the GIMs.
- The low precision and unreliability of ionospheric maps over the ocean can be improved by combining GNSS data with data from other techniques, such as satellite altimetry or Low Earth Orbiting (LEO) satellites.

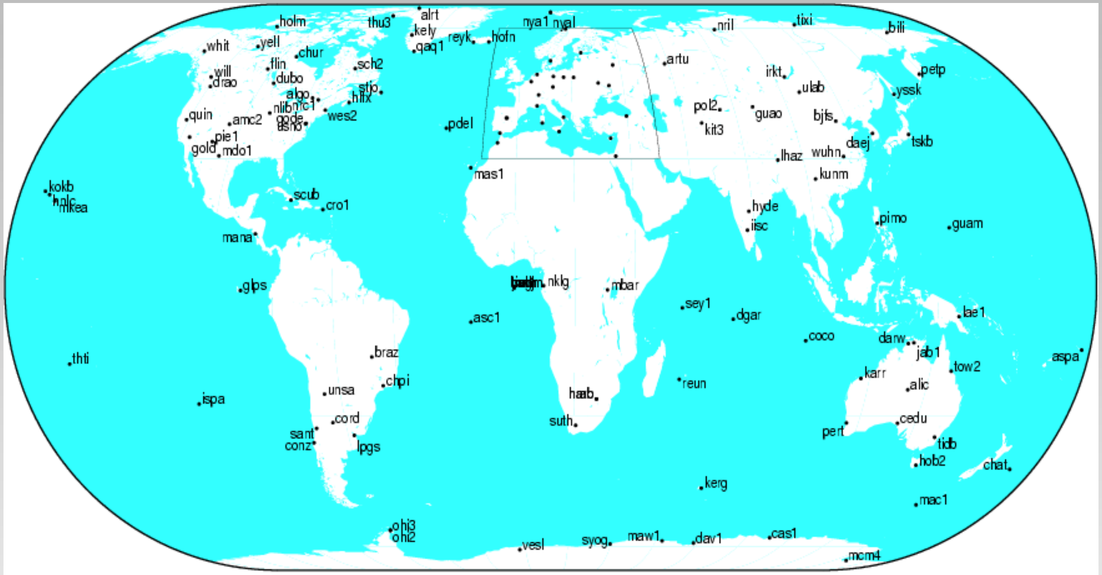


Figure 8 – IGS station map – in-homogeneous global coverage

COMBION: Input data

- GNSS
  - Geometry-free linear combination of smoothed code (TEC observable)
- Satellite Altimetry
  - Obs.: direct VTEC over the oceans
  - bias w.r.t GNSS
- Formosat-3/COSMIC
  - Obs.: RO measurements (transformed into electron density profiles and then VTEC calculated),
  - systematic bias w.r.t GNSS

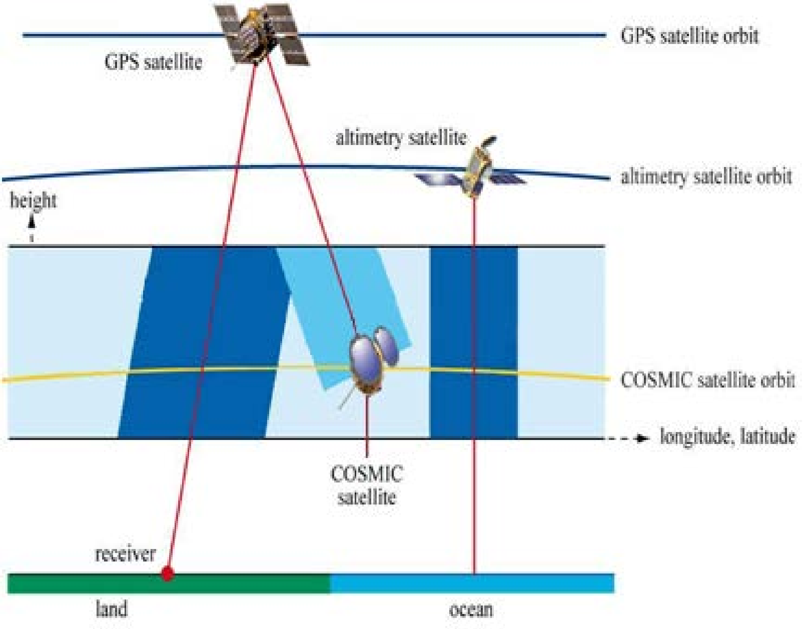


Figure 9 – Different input data for monitoring the ionosphere

VTEC is modeled using spherical harmonics expansion up to degree and order 15.

COMBION: Inter-technique combination

Observation equations from each technique are combined at the normal equation level:

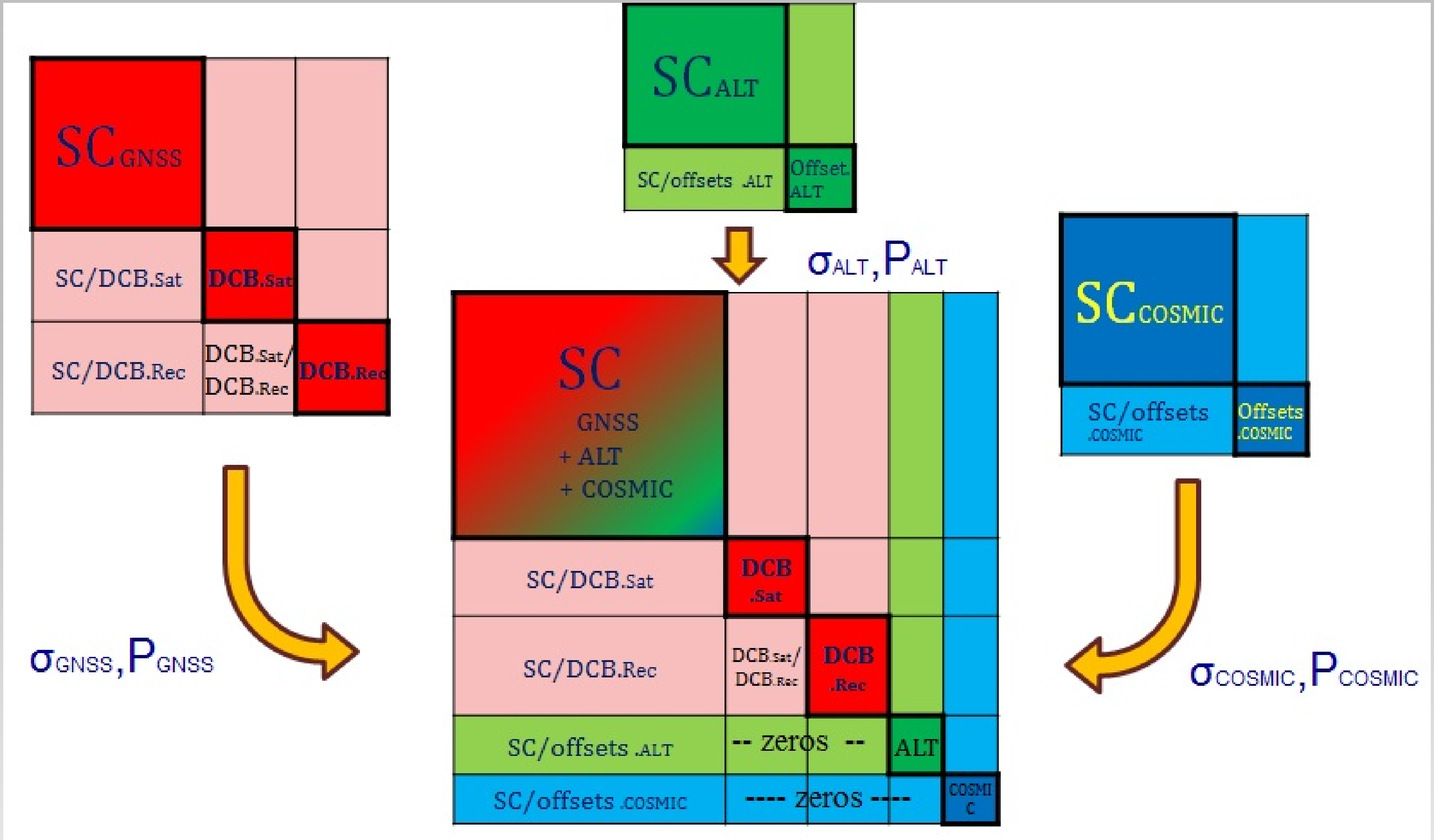


Figure 10 – GNSS and satellite altimetry combination scheme

COMBION: Sample Results *(Todorova et al., 2007)*

GNSS, satellite altimetry combined GIM

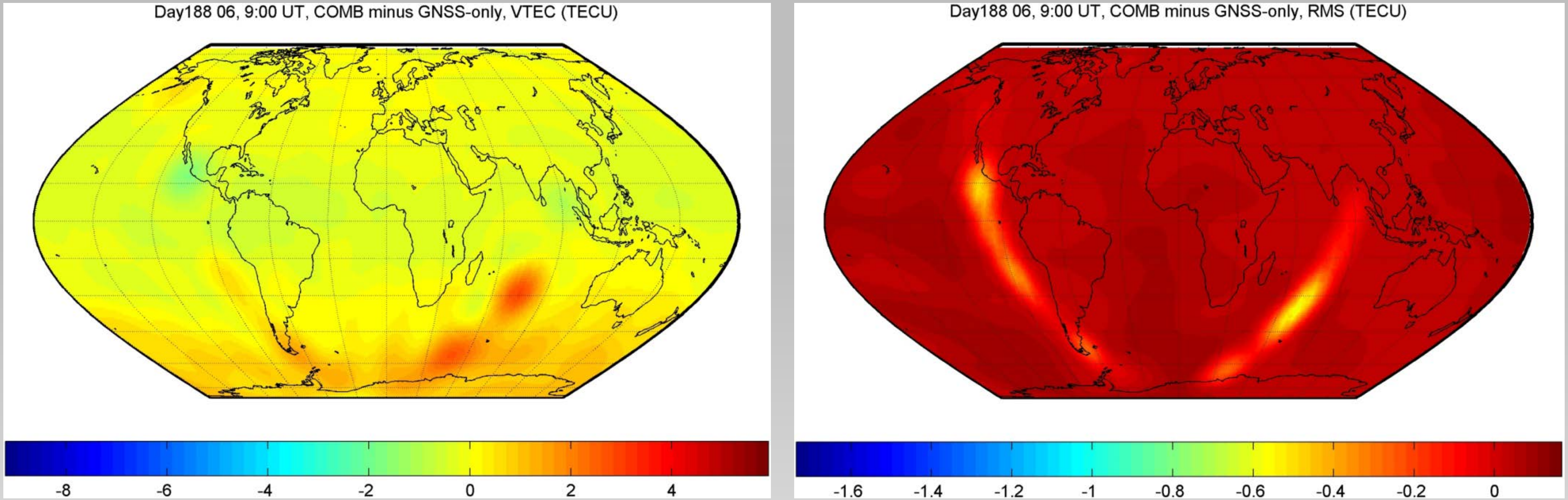


Figure 11 – (a) VTEC map (b) RMS map of GNSS and satellite altimetry combined <minus> GNSS-only solution, day 188, 2006, 9:00 UT.

COMBION: Sample Results *(Alizadeh et al. 2011)*

GNSS, satellite altimetry, and Formosat3/Cosmic combined GIM

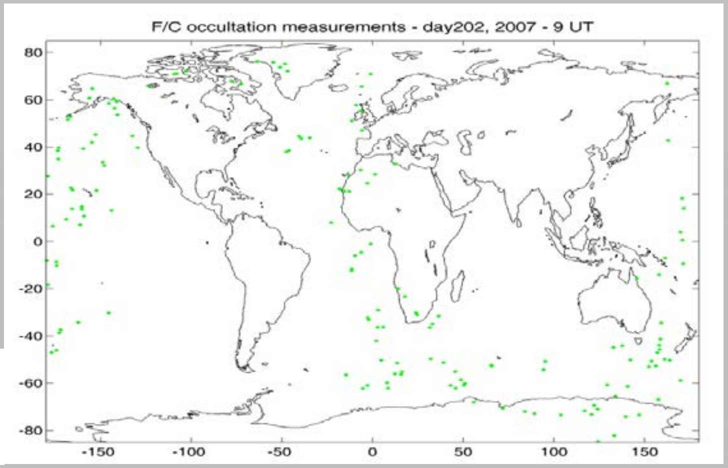


Figure 12 - footprints of F/C occultation measurements, day 202, 2007.

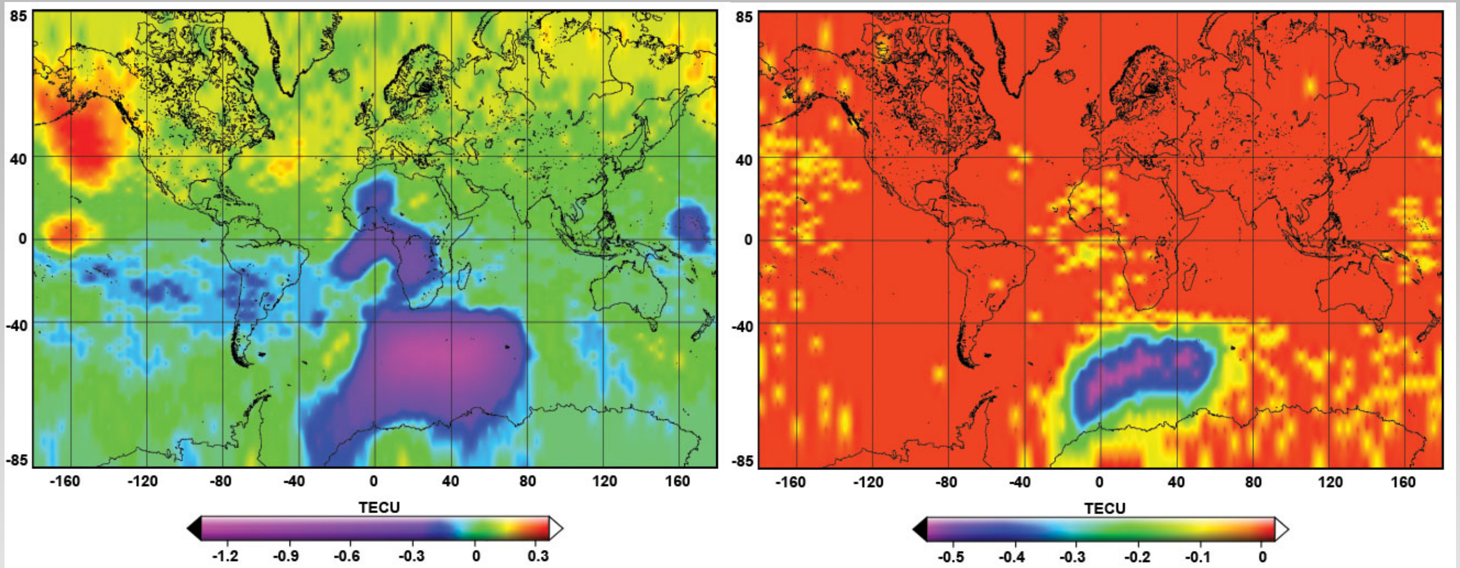


Figure 13 - (a) VTEC and (b) RMS map of GNSS, satellite altimetry and COSMIC combined <minus> GNSS, satellite altimetry solution, day 202, 2007 – 9:00UT

MDION

TU Wien, TU Berlin (2010 – 2015)

MDION: Motivation

- Up to now 2D (and 2D+time) models of VTEC have been widely developed and used in geodetic community,
- these models provide information about the integral of the whole electron content along the vertical or slant ray-path,
- when information about the ionosphere at different altitude is needed, these maps are not useful; e.g. when satellite to satellite observation is being performed,
- in such cases a 3D (or 4D) model of the electron density is required.

MDION: TEC observable and Electron density

GNSS TEC observable is related to electron density $N_e(h)$ using combination of two models:

- Multi-layer Chapman function $\xrightarrow{\textit{for}}$ Bottom side ionosphere
- TIP model $\xrightarrow{\textit{for}}$ Topside ionosphere / Plasmasphere

$$N_e(h) = \overbrace{NmF2.e^{\alpha(1-z-e^{-z})}}^{\text{Bottom side ionosphere}} + \overbrace{NmF2.e^{\beta(1-z-e^{-z})}}^{\text{topside ionosphere}} + \overbrace{N_{P_0}.e^{-h/H_P}}^{\text{plasmasphere}} \qquad (4)$$

Ionospheric F2-peak electron density

Plasmasphere basis density

Plasmasphere scale height

where

$$z(h, hmF2) = \frac{h - hmF2}{H_{TS}} \qquad (5)$$

Ionospheric F2-peak height

Ionospheric scale height

GNSS TEC observable P_4 and electron density model:

$$\tilde{P}_4 = \xi \int_R^S N_e(h) ds + c(\Delta b^S - \Delta b_R) + \varepsilon \qquad (6)$$

MDION: Ray-tracing & simulation

- Ray-tracing:
  - describes the estimation of a ray through a medium
  - the integration in Eq(6) is turned into a simple summation
- Simulating input data
  - Using true positions of satellites
  - Extracting VTEC values from IGS GIM
  - Using simulated input data, satellite and receiver DCB are eliminated

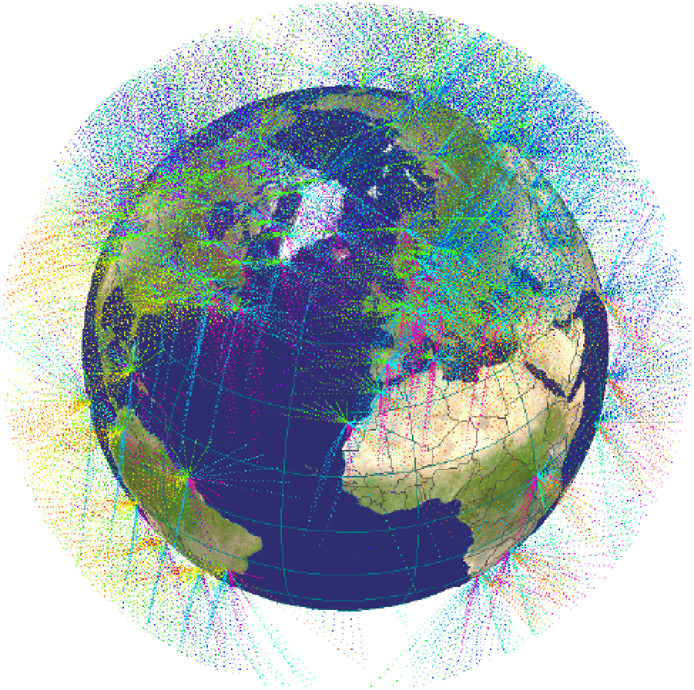


Figure 14 – Sample input data with true GNSS ray-path, but values from IGS GIM

- ➢ The final model:

$$F(z')VTEC = \sum_{i=1}^{k} NmF2_i . e^{\alpha(1-z(h_i,hmF2_i)-e^{-z(h_i,hmF2_i)})} ds_i \qquad (7)$$

- ➢ NmF2 and hmF2 are modeled using two sets of spherical harmonic expansions (both with degree and oder 15)

MDION: Sample Results *(Alizadeh et al. 2014, 2015)*

Estimated F2-peak parameters

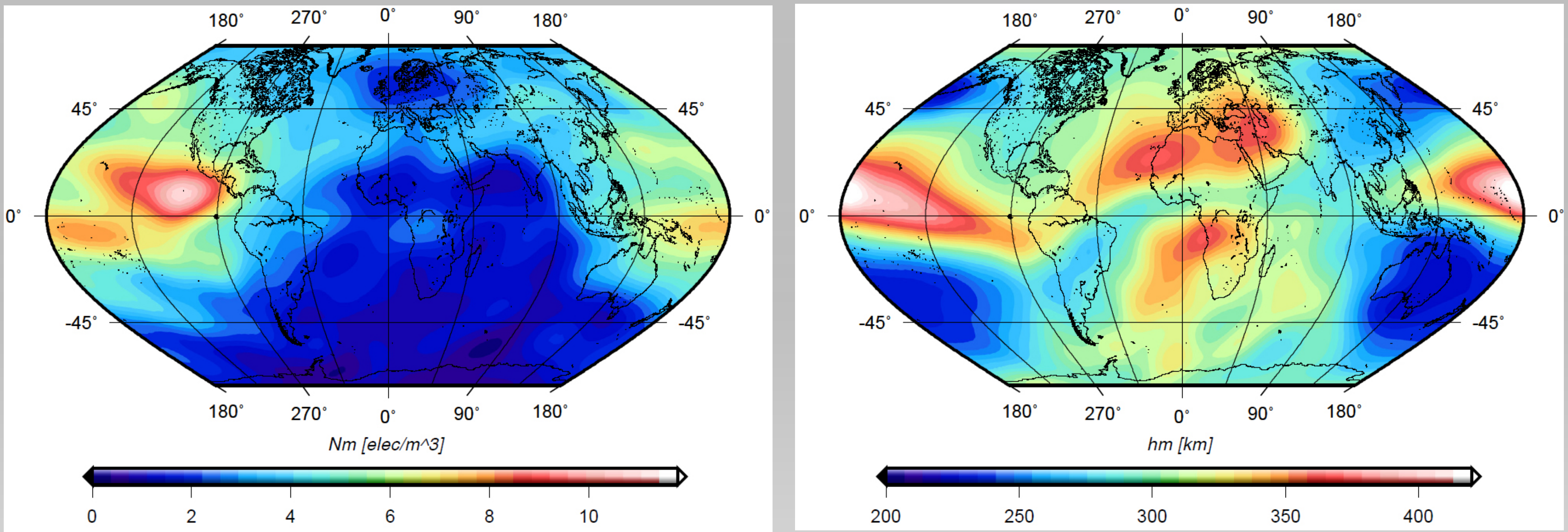


Figure 15 – (a) Estimated maximum electron density NmF2($\times 10^{11}$ *elec/m*^{3}) and (b) estimated maximum electron density height hmF2 (*km*) GNSS estimated model, doy 182, 2010 – [0,2]UT

MDION: Sample Results *(Alizadeh et al. 2014, 2015)*

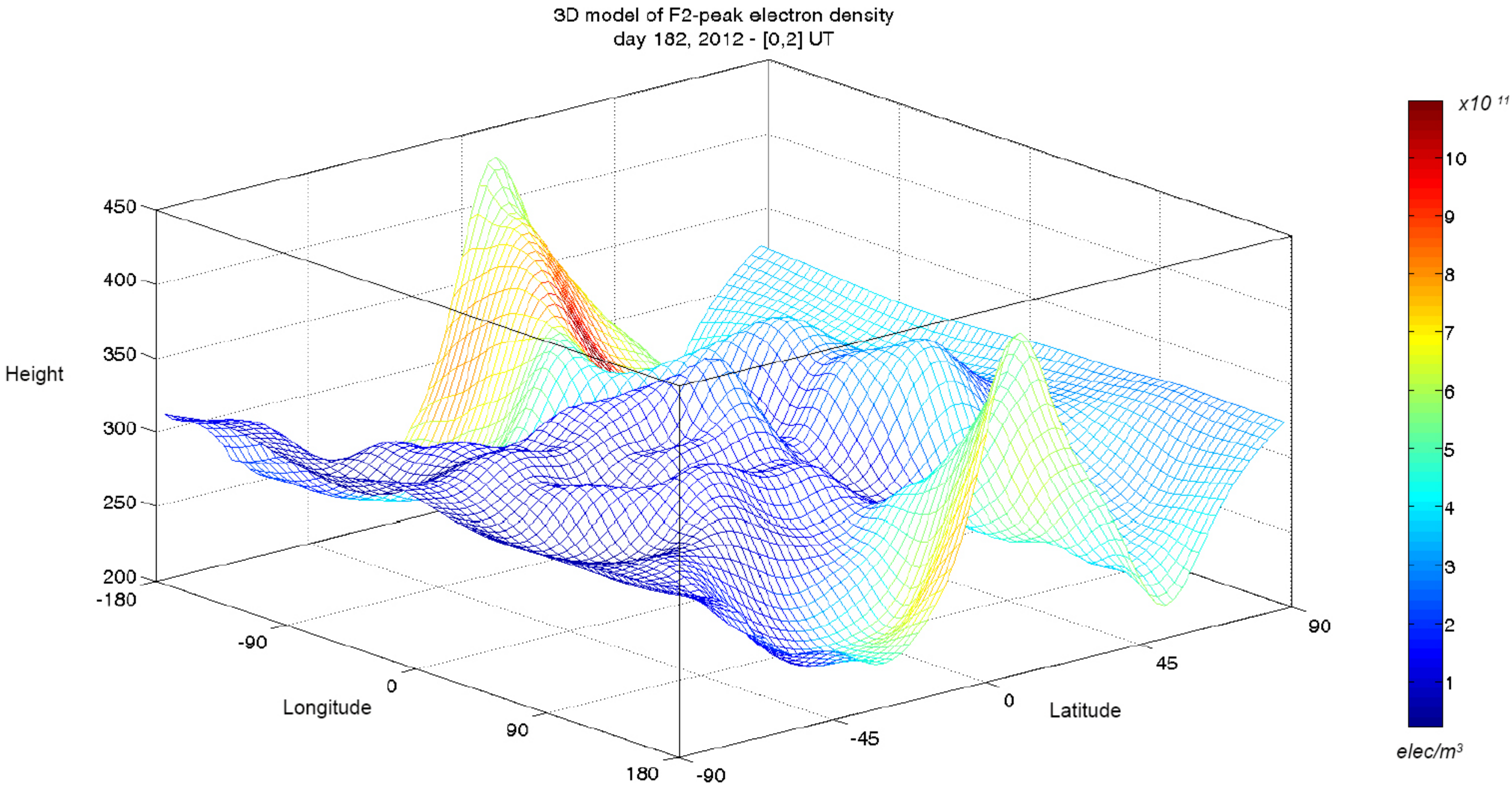
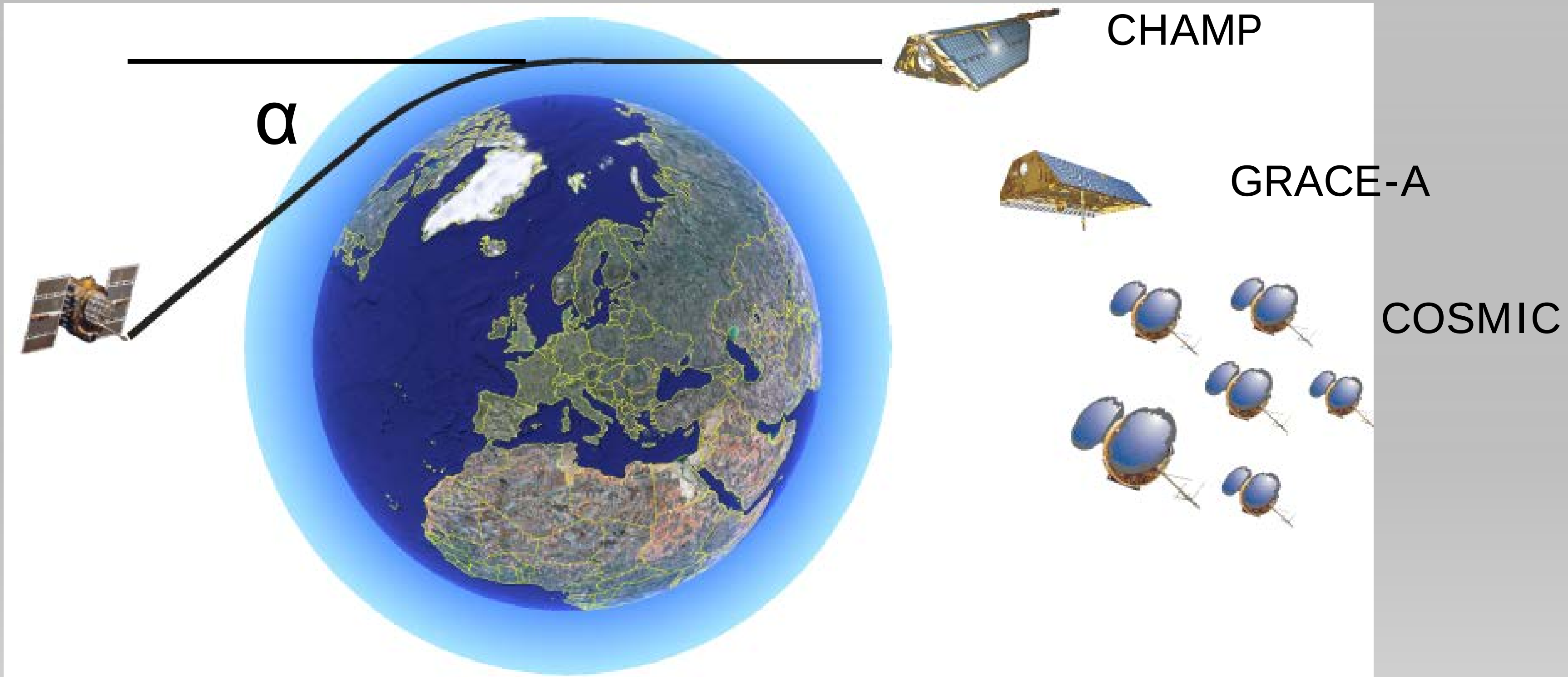


Figure 16 – 3D model of F2-peak electron density for day 182, 2010 - [0,2]UT; color bar indicates the maximum electron density (x10^{11} elec/m3) and the Z-axis indicates maximum electron density height in km

Sporadic E layer from Radio Occultation

(GFZ, 2002 - 2015)

GNSS Radio Occultation principle



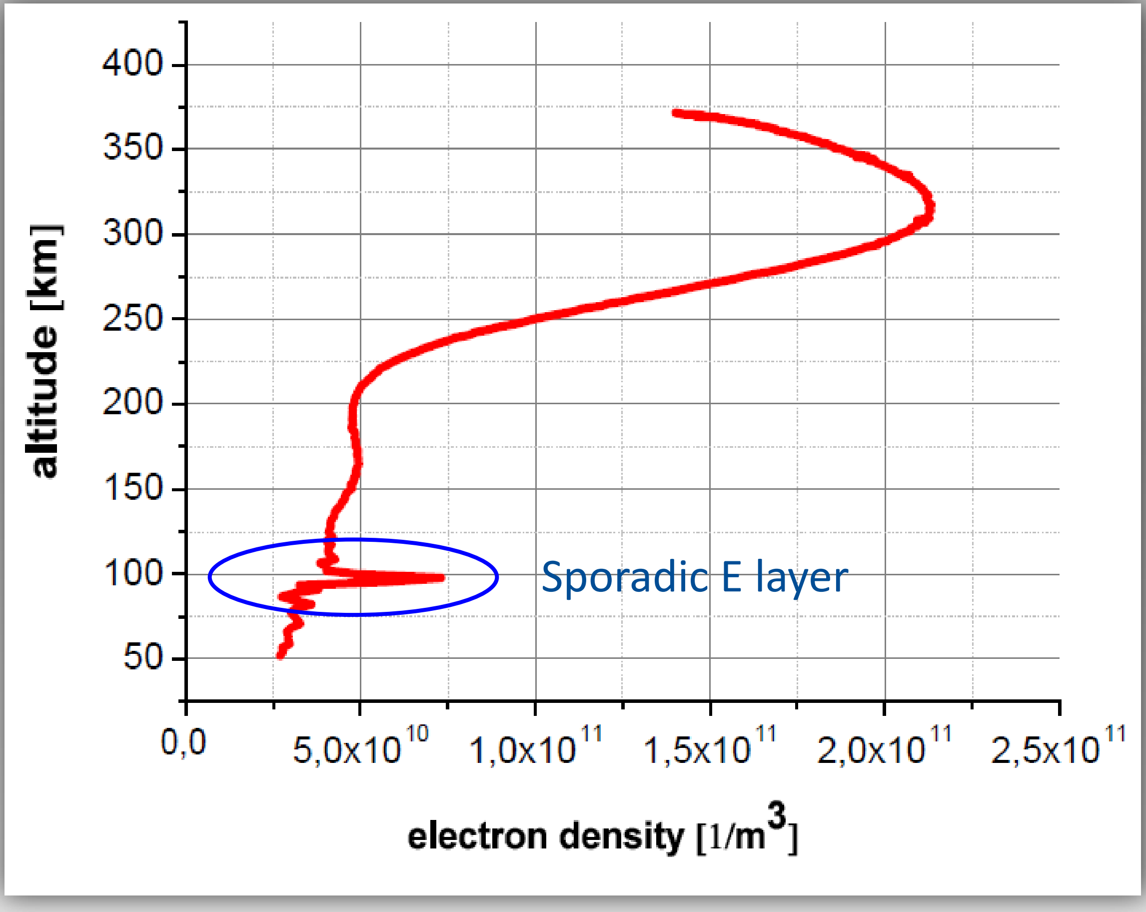
GNSS signals received on LEOs

profiles of : - T, p, ρ, water vapour in troposphere, stratosphere
- electron density in ionosphere

Advantages of RO: - global data coverage
- high vertical resolution of RO profiles

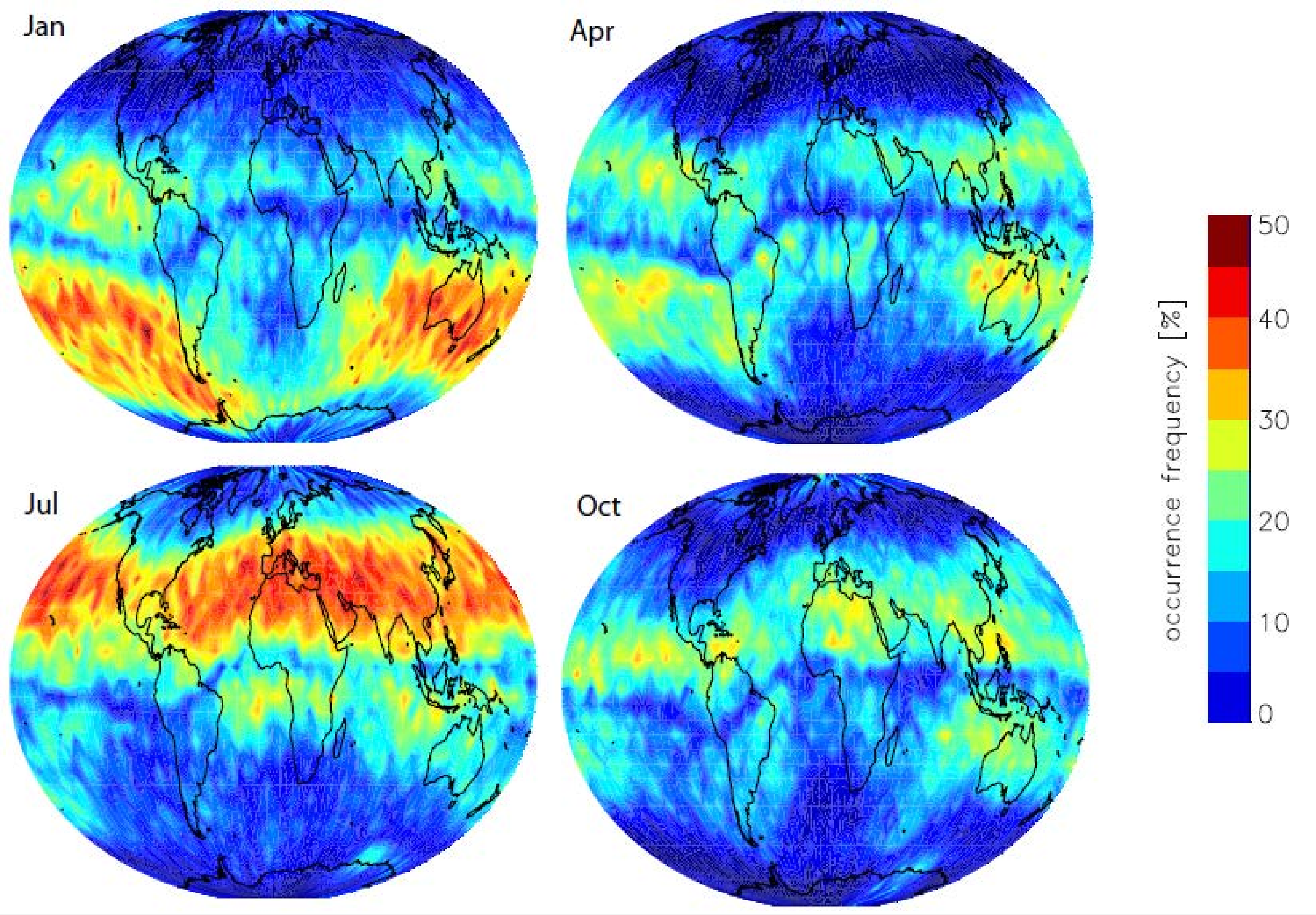
profiles

Sporadic E layer characteristics



- regions of enhanced electron density
- altitude range: between 90 and 120 km
- thickness: ~1 bis 5 km
- horizontal extent: max. 1000 km
- lifetime: several minutes to several hours
- Es formation: depends on ionization rates , **zonal wind shears**

Global sporadic E layer distribution

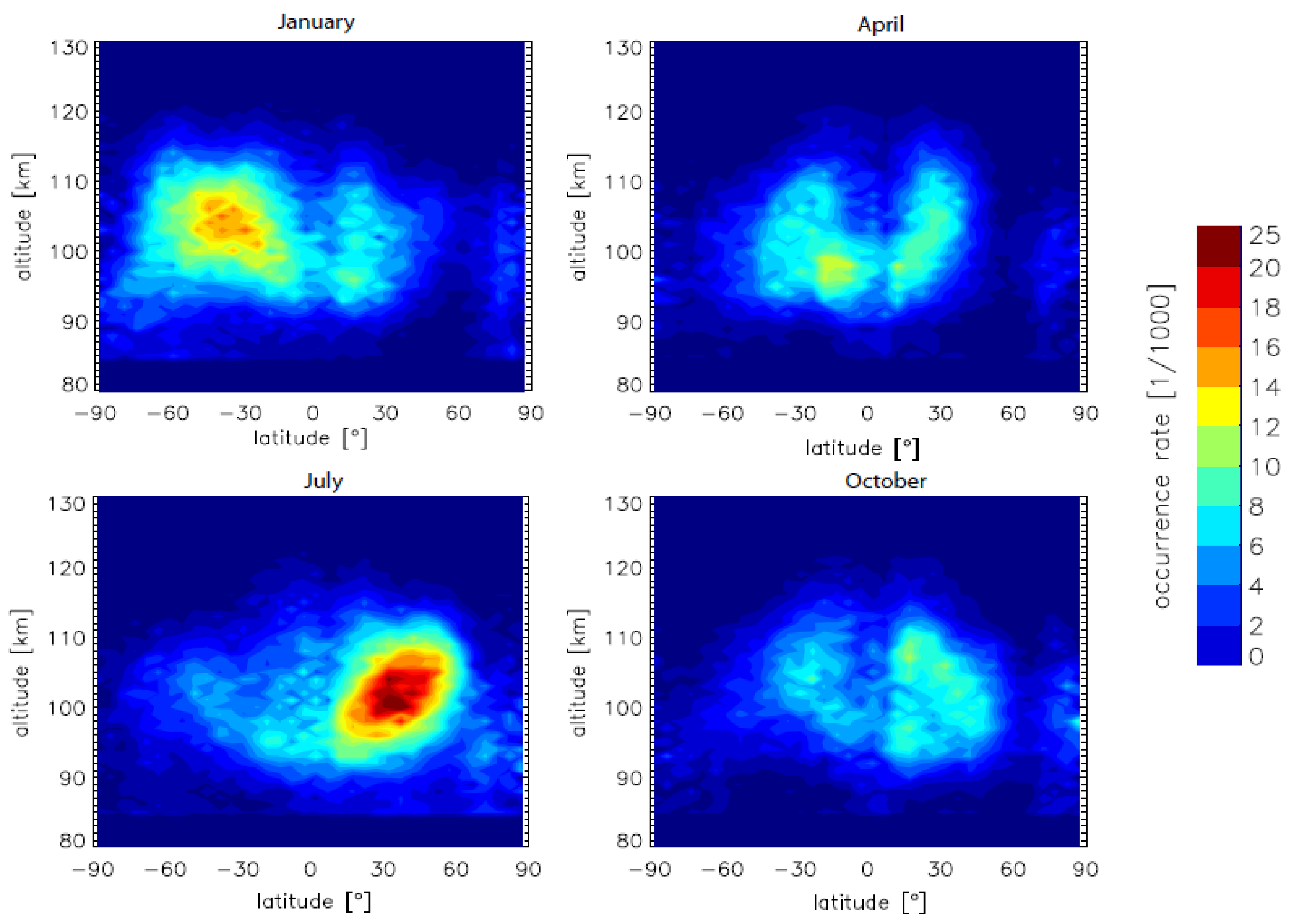


Arras et al. 2013

- Es is a summer phenomenon
- clear footprint of Earth‘s magnetic field
- no Es along magnetic equator

Global sporadic E layer distribution

Latitude/altitude cross-sections:

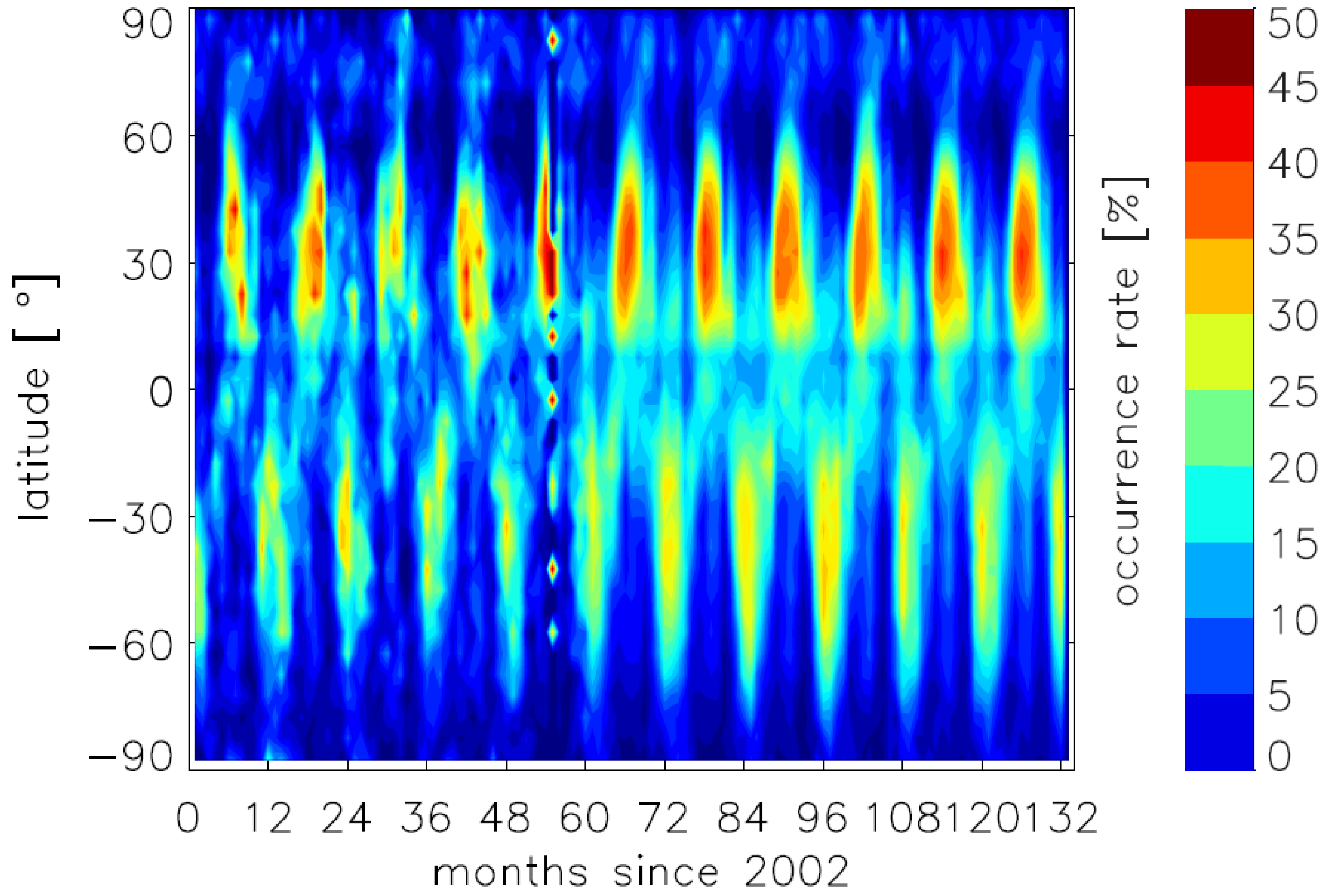


Arras et al. 2013

- Es appear mainly at altitudes around 100-110km
- higher Es in northern summer but in slightly lower altitudes than in southern summer
- low Es in equatorial regions

Temporal variability in Es

Interannual sporadic Es occurrence (2002 - 2012)



Variations:

- Intensity
- Duration
- Extension (North-/ Southward)

Conclusions

- During the last decade space geodesy has turned into a promising tool to probe the ionosphere.
- VLBI can contribute to long term studies of the ionosphere as it covers almost three complete solar cycles *(Hobiger et al., 2006).*
- Integrating data from different space geodetic techniques improves the reliability and accuracy of GIM *(Todorova et al., 2007) and (Alizadeh et al. 2011).*
- *3D modeling of electron density using space geodetic techniques* provides information about geophysical parameters, i.e. F2-peak electron density and its corresponding height *(Alizadeh et al. 2014, 2015).*
- GNSS radio occultation measurements provide an excellent data base to investigate the lower ionosphere, especially sporadic E layers, on a global scale *(Arras et al. 2013).*

Thank you for your attention

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[2003 – 2015]

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BackUp slides

VLBIonos: Conclusions

Within project VLBIonos it was concluded that:

- It is possible to derive ionospheric parameters in terms of VTEC, exclusively from VLBI data, i.e. without any external information. *(Hobiger, 2005)*
- VLBI measurements can be used for regional modeling of the ionosphere over the area where VLBI stations are available. *(Hobiger et al., 2006)*
- VLBI can contribute to long term studies of the ionosphere as it covers two complete solar cycles. *(Hobiger et al., 2006)*

COMBION: Conclusions

Within project COMBION (TU Wien) it was concluded that:

- The combined GIM from GNSS and satellite altimetry increases the precision of GIM from GNSS data over the oceans, which is the worst case for GNSS. *(Todorova et al., 2008)*
- The combined GIMs from GNSS, satellite altimetry, and F/C have a great potential to improve the accuracy and reliability of the GIMs, especially when a high number of occultation measurements is available *(Alizadeh et al., 2011)*
- The oscillations related to the insufficient data and the limitations of the spherical harmonics interpolation for modeling the ionosphere, is considerably compensated applying the combination procedure. *(Alizadeh et al., 2011)*

MDION: Ionospheric observable & electron density

Considering GNSS ionospheric observable:

$$\tilde{P}_4 = \tilde{P}_1 - \tilde{P}_2 = \xi STEC(\beta, s) + c(\Delta b^S - \Delta b_R) + \varepsilon \qquad (1)$$

STEC is the integral of ionospheric electron density N_e along the signal path:

$$STEC = \int_R^S N_e(s)\,ds\ , \qquad (2)$$

Electron density can be represented by means of different models,
in this study we combine two models:

- Multi-layer Chapman function *for* → bottomside ionosphere
- TIP model *for* → topside ionosphere /plasmasphere

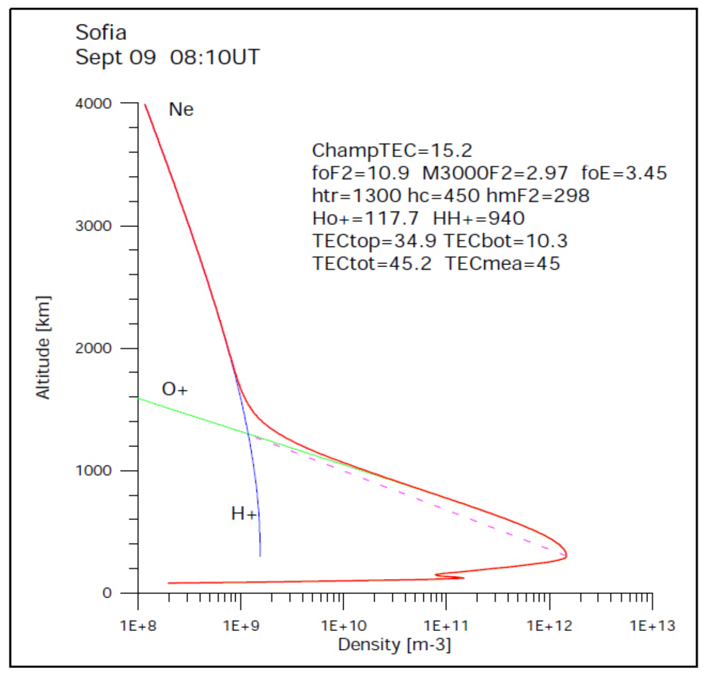


Figure 1 –Topside Ionosphere/Plasmasphere (TIP) model (courtesy of *Jakowski et.al 2011*)

MDION: Electron density representation

$$N_e(h) = \underline{NmF2}.e^{\alpha(1-z-e^{-z})} + \underline{NmF2}.e^{\beta(1-z-e^{-z})} + \underline{N_{P_0}}.e^{-h/\underline{H_P}} \quad (3)$$

Ionospheric F2-peak electron density

Plasmasphere basis density

Plasmasphere scale height

where

$$z(h, hmF2) = \frac{h - \underline{hmF2}}{\underline{H_{TS}}} \quad (4)$$

Ionospheric F2-peak height

Ionospheric scale height

Substituting Eq. (3) into Eq.(1):

$$\tilde{P}_4 = \xi \int_R^S N_e(h)ds + c(\Delta b^S - \Delta b_R) + \varepsilon$$

- Analytical integration is sophisticated,
- several approximating assumptions are required

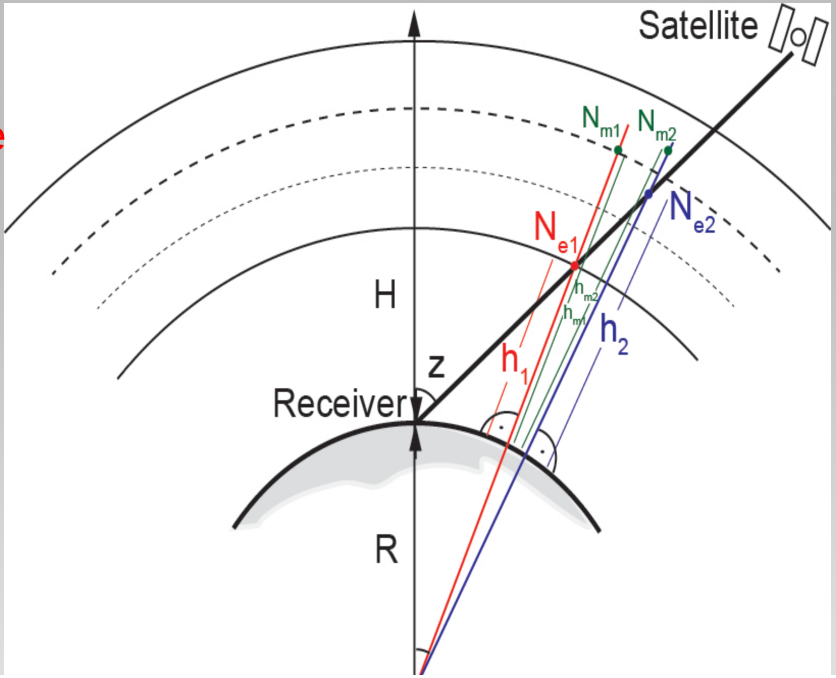


Figure 2 – signal path and multi-layer Chapman function

MDION: Ray-tracing technique

- describes the estimation of a ray through a medium
- provides
  - satellite zenith angle (z_i)
  - solar zenith angle (χ_i)
  - increment at each layer (ds_i)
  - height of each layer above Earth's surface (dh_i)

The integral in Eq. (5) would turn into a simple summation:

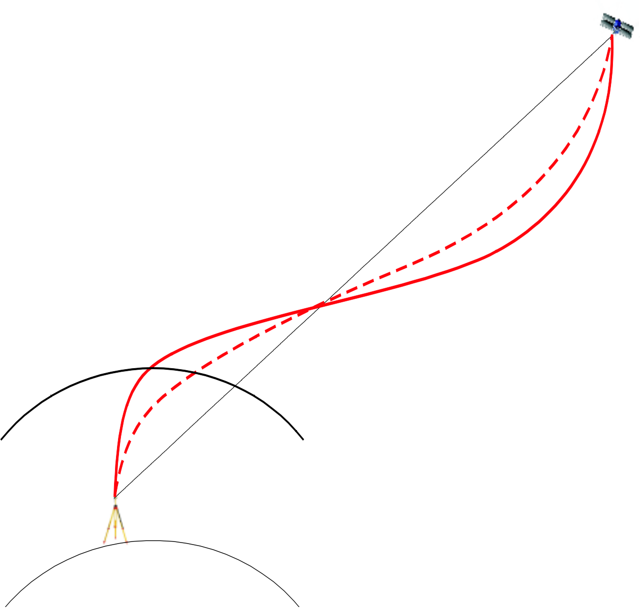


Figure 3 – Curved and straight ray-path

$$\tilde{P}_4 = \xi \sum_{i=1}^{k} N_e(h_i) ds_i + c(\Delta b^S - \Delta b_R) + \varepsilon \qquad (6)$$

The plasmasphere contribution is assumed to be known, so

$$\tilde{P}_4 = \xi \sum_{i=1}^{k} NmF2_i . e^{\alpha(1-z(h_i,hmF2_i)-e^{-z(h_i,hmF2_i)})} ds_i + c(\Delta b^S - \Delta b_R) + \varepsilon \qquad (7)$$

MDION: Conclusions

This study

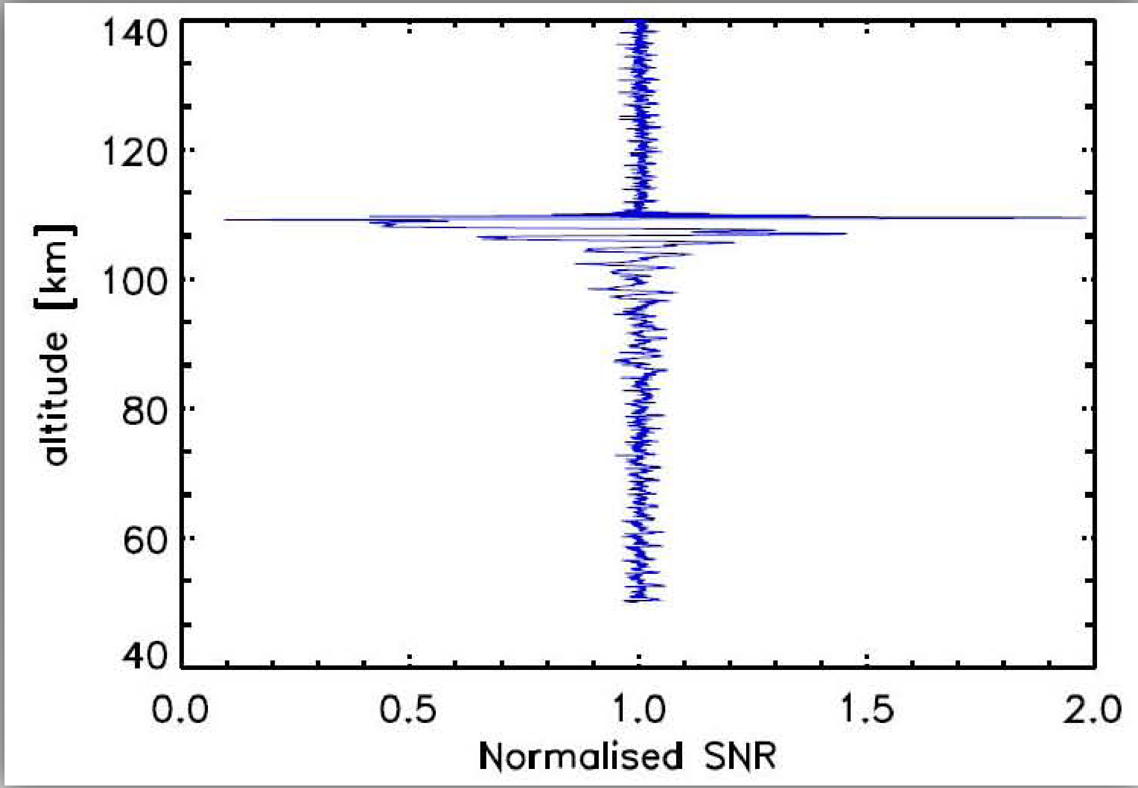
- aims at global 3D modeling of the ionospheric parameters, by applying ray-tracing technique to the upper atmosphere,
- includes modeling of geophysical parameters, i.e. F2-peak electron density and its corresponding height,
- provides information about the ionosphere at different altitudes.
- Comparisons with IRI and NeQuick model as well as F/C derived parameters prove the great potential of this modeling approach.

MDION: Outlook

- Applying real GNSS observations,
- Integrating data from different space geodetic techniques,
- Estimating plasmaspheric parameters as well as characteristic parameters of other layers as individual unknowns,
- 4D modeling of electron density by applying Fourier series expansion.

Data analysis

- SNR profiles (50 Hz) of GPS L1 signal (high vertical resolution)
- Normalise profiles
- Identify vertically thin structures by applying a band pass filter



Information on:

1. altitude
2. geographic latitude/longitude
3. local time