NRFP-3 Final Presentation
Radio Occultation Inversion Methods

Thomas Sievert
Vinícius Ludwig Barbosa

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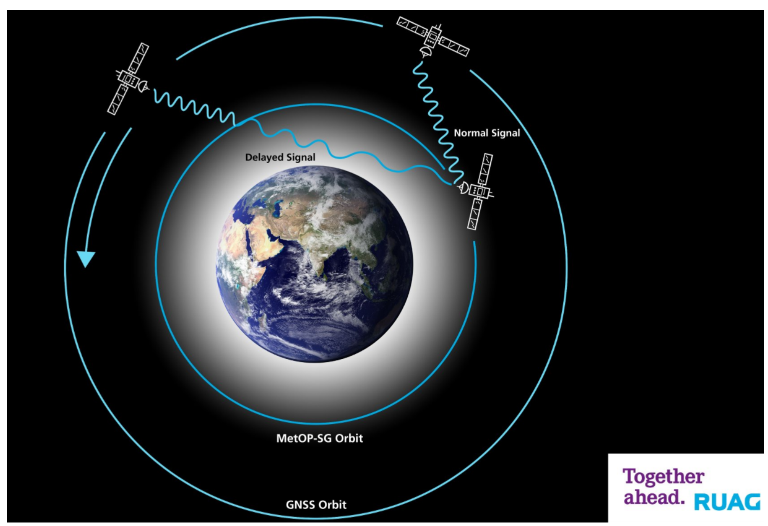
Outline

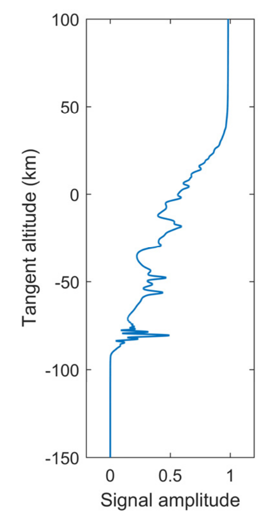
- GNSS Radio Occultation
    - Concepts
    - Features and Applications
    - Background
- RUAG Space products
- Our project: Simulation tool
    - Troposphere
    - Ionosphere
- Conclusions & Contributions

GNSS Radio Occultation

Concept

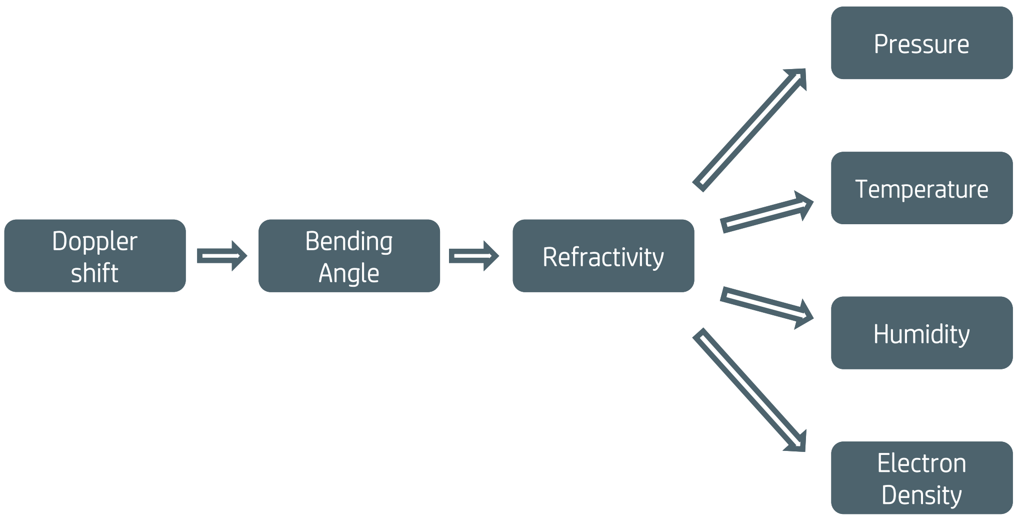
- Origin: Scanning planets' atmosphere;
- Occultation event;
- Sensing the Earth…
  - 80's: GPS and GLONASS
  - Source: GNSS satellite
  - Bending: signal refracts in the atmosphere;
  - Receiving: LEO satellite;

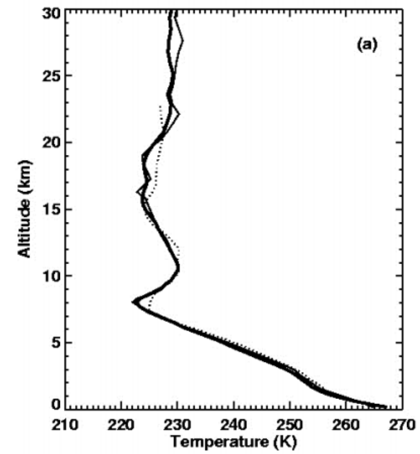




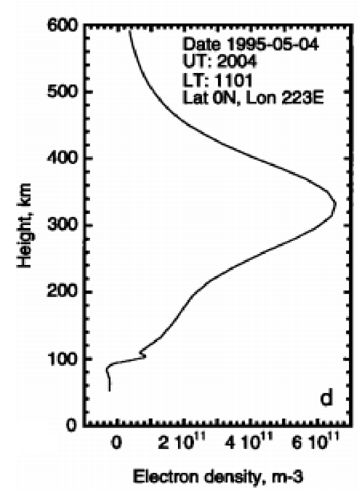
GNSS Radio Occultation

Features and Applications





Temperature profile. Kursinski et al (1996), Science, vol. 271, pp.1107-1110.



Electron density profile. Hajj, G. A. et al (1998), *Radio Sci.*, vol. 33(1), pp- 175–190.

GNSS Radio Occultation

Features and Applications

- High precision and vertical resolution;
  - Resolve small structures;
- Low sensitivity to clouds or precipitation;
- Global coverage (oceans, continents)
- Assimilation of RO data in Numerical Weather Prediction (NWP);
  - Top 5 technique in forecast error reduction (source: ECMWF);
- Investigation of atmospheric phenomena and space weather
  - Tornado;
  - Hurricanes;
  - Ionospheric scintillations;
- Climate change monitoring enabled by long term temperature accuracy;

GNSS Radio Occultation

History

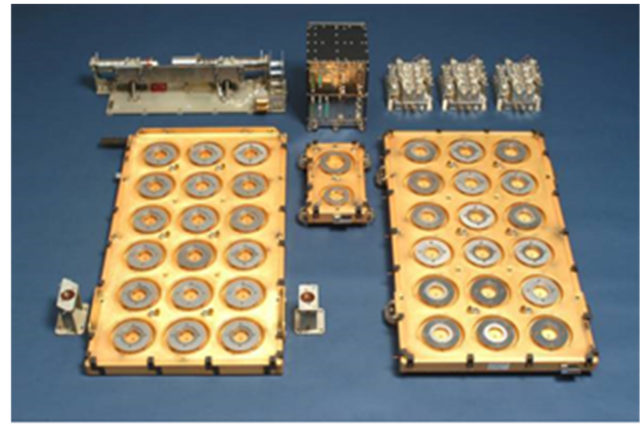
- 1995-1997: GPS/MET (UCAR)
- 2000-2010: CHAMP
- 2000-2013: SAC-C
- 2003-2011: GRACE
- 2006: COSMIC
- 2007: TerraSAR-X
- 2008-2015: C/NOFS
- 2010: TanDEM-X
- 2006/2012: MetOp A/B
- 2017: COSMIC-2
- 2018: MetOp C (launched on Nov 7th)
- 2021/28/35: MetOp-SG A
- 2022/29/36: MetOp-SG B

RUAG Space products

Together ahead. RUAG

- GRAS on MetOp
  - 700 occultation measurements per day (GPS);
  - Bending angle accuracy: <0.6 µrad;
  - Altitude coverage: 0 to 85 km;
  - MetOp-A Launch: Oct 2006;
  - MetOp-B Launch: Sep 2012;
  - MetOp-C Launch: Nov 2018;

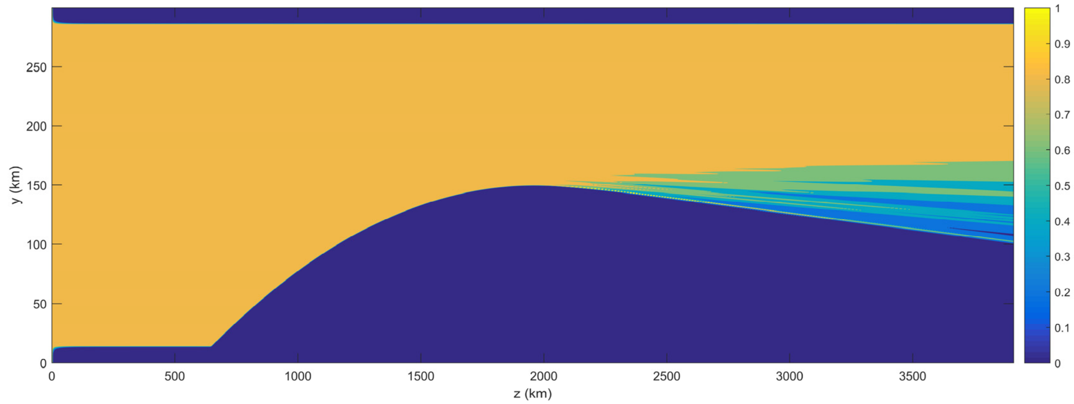
- GRAS-2 on MetOp-SG
  - 2800 occultations per day
    - GPS, Galileo, Beidou, QZSS;
  - Bending angle accuracy <0.5 µrad;
  - Altitude coverage: 0 to 500 km;
  - Full open loop tracking for lower troposphere;
  - Includes redundant modules;
  - 6 flight models ordered;
  - First launch in 2021;



Our project

Simulation tool

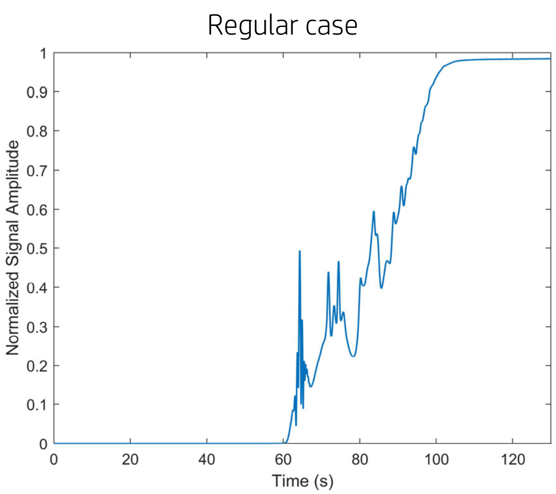
- Multiple Phase Screen (MPS);
- Simulation of occultations;
- Compare to real data and improve inversion methods;
- Verification tool for bending angle measurement errors;
- Two focus
  - Troposphere;
  - Ionosphere

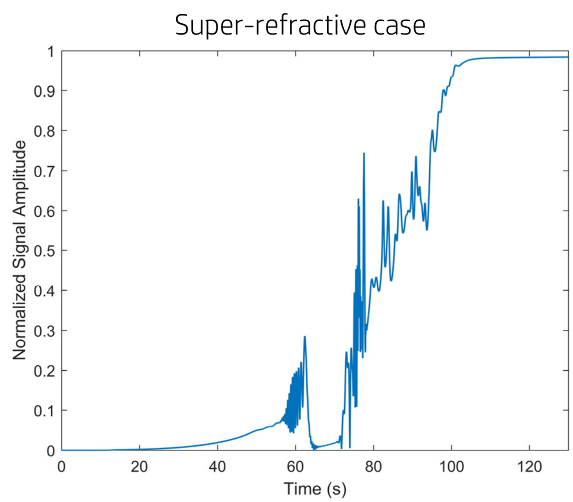


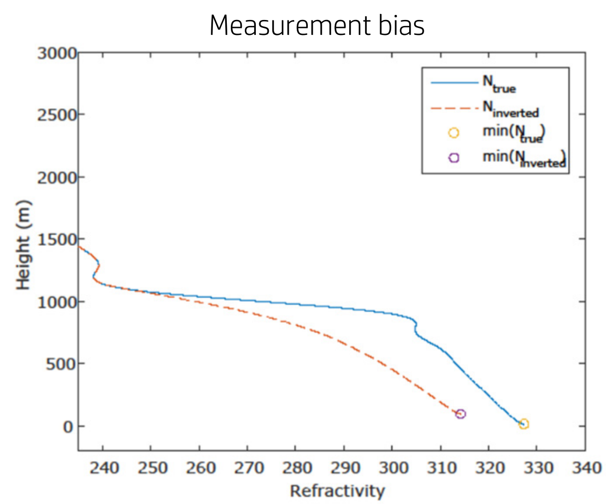
Our project

Troposphere

- Problem area:
  - Super-refractive regions measurement bias;
- Research approach:
  - Develop methods to detect signal components reflected in the Earth's surface;
  - Use reflected components to retrieve additional data;
  - Use the additional data to correct the bias;

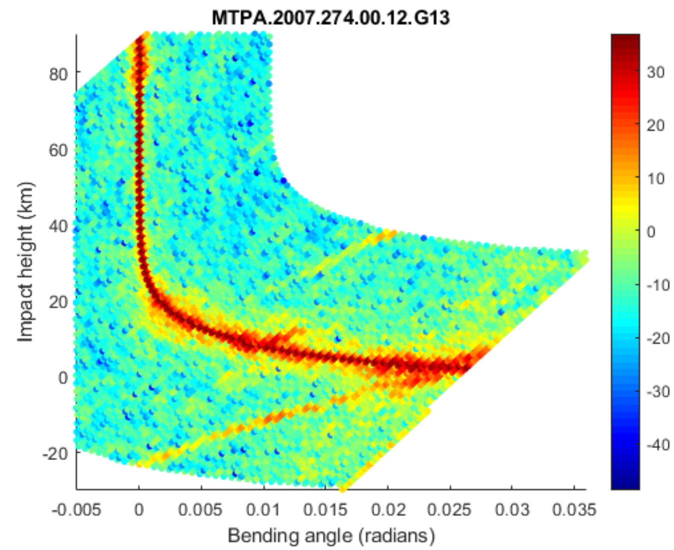


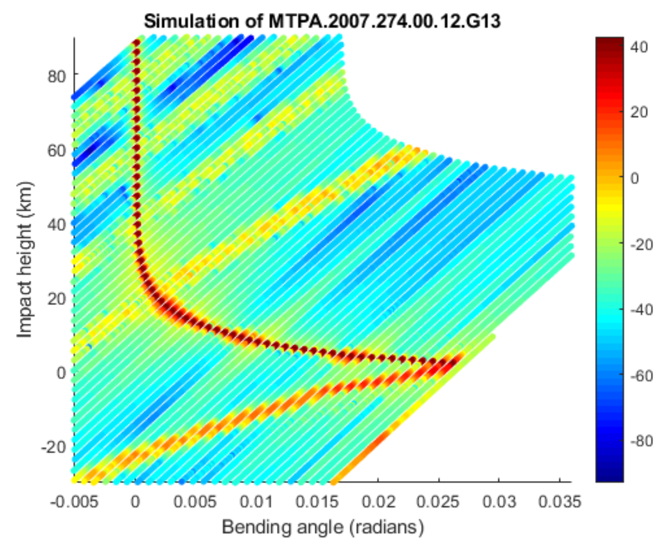




Our project
Troposphere

- Surface reflections;
  - Normally detected with time-frequency analysis;
  - Mapped to bending angle spectrum;
- My approach;
  - Detect reflections using inversion algorithms;
  - Attempt to extract information about conditions at Earth's surface from reflected components;
  - Simulation tool is useful for modeling real measurements;





Our project

Ionosphere

- Problem area:
  - Residual Ionospheric Error;
- Presence of ionosphere adds extra bending to the phase in lower altitudes;
- Majority of the bias is removed by an linear combination of L1 and L2 bands;
- Scintillation in the ionosphere contributes to the measurement noise;
- Modelling ionosphere into simulations;
  - Analytical model for electron density;
  - Fluctuations: gaussian model;
- Simulation tool is used for solving scenarios such as:
  - Silent ionosphere;
  - Disturbed ionosphere;
- Capability to model and reproduce occultation measurements;

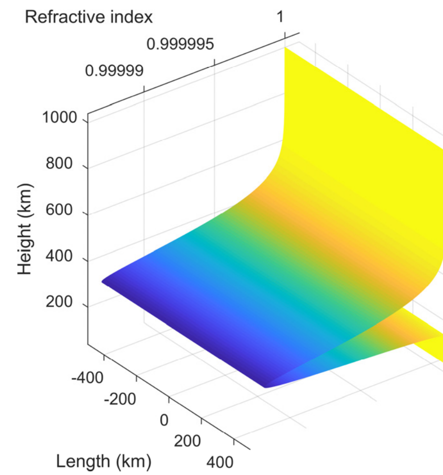


Figure (a) Refractive index without ionospheric scintillation

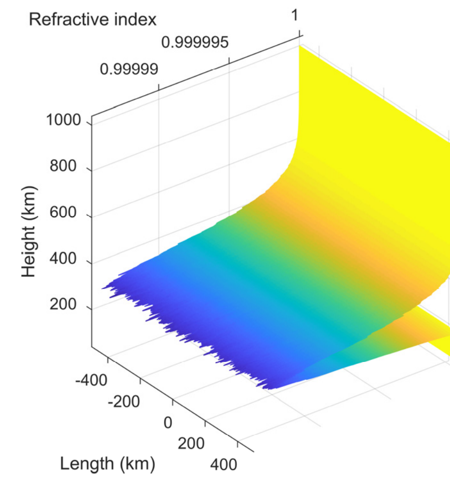
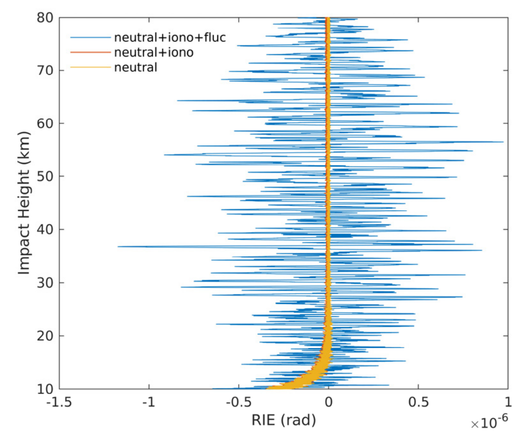


Figure (b) Refractive index with ionospheric scintillation

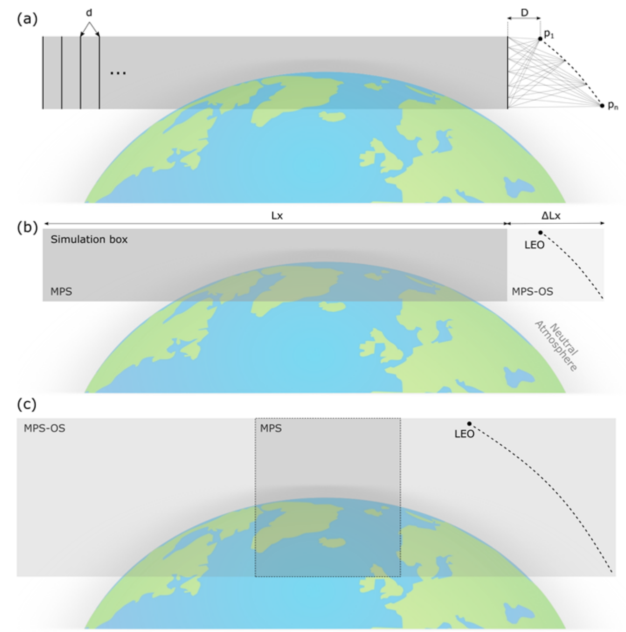


Residual ionospheric error. Comparison between neutral atmosphere combined to ionosphere (neutral + iono) without fluctuation and with fluctuation (neutral+iono+fluc).

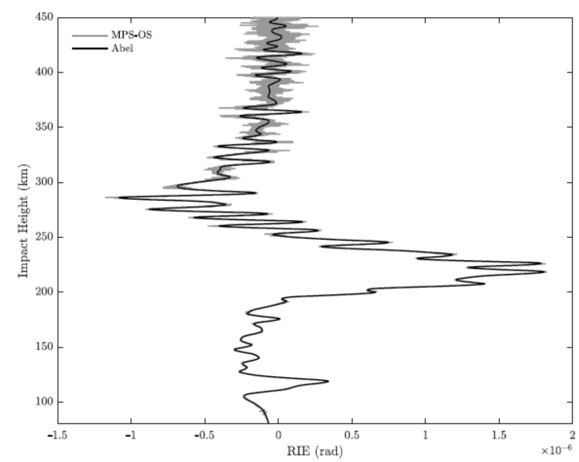
Our project

Ionosphere

- Improvements on the simulation tool
- Multiple Phase Screen (MPS) method is combined with a diffraction propagation from the last screen to LEO orbit, Figure (a);
- Diffraction propagation integral is only valid when performed in vacuum;
- Depending on the simulated orbit and on ionospheric contribution, diffraction propagation yields misleading results;
- An potential alternative is using MPS screens to sample the radio signal in LEO orbit, Figure (b);
- The proposed method, MPS Orbit Sampling (MPS-OS), has been evaluated and validated during the project for short and long orbit segments;
- Results for short orbit segments are equivalent between MPS with diffraction propagation and MPS-OS;
- However, only MPS-OS can handle simulations of long orbit segments such the ones to be featured by METOP-SG, Figure (c);
- It allows to investigate the influence of the ionosphere on higher layers of the atmosphere (stratosphere and mesosphere) in long observation time;



MPS geometry. Figure (a) depicts the MPS set-up for a short orbit segment simulation with diffraction propagation from the last screen to LEO orbit, Figure (b) shows the modification in the simulation box to sample the radio signal in orbit, MPS-OS, and Figure (c) shows the limitation of MPS combined with diffraction propagation for simulation of long orbit segments.



Ionosphere evaluation on higher atmospheric layers. MPS-OS yields accurate results on simulations of short and long orbit segments including the ionosphere.

Conclusion & Contributions

- Better understanding of how RO inversion methods treat reflected signal components in simulated and real measurements;
- Steps toward improving inversion by using the information content of reflected components;
- Better understanding of residual ionospheric error and the influence of different error sources;
- Development of the simulation tool, which will help to evaluate new methods of residual ionospheric error mitigation;
- RUAG Space has obtained a good verification method for performance requirements on bending angle measurement errors where small-scale atmospheric irregularities play a major role;
- Output from the project
  - Simulation tool for Troposphere;
  - Simulation tool for Ionosphere

Publications

T. Sievert, J. Rasch, A. Carlström, M. I. Pettersson, ”Analysis of reflections in GNSS radio occultation measurements using the phase matching amplitude”, Atmospheric Measurement Techniques, vol. 11, no. 1, pp. 569–580,December 2017;

T. Sievert, J. Rasch, A. Carlström, M. I. Pettersson, V. Vu, ”Determining the refractivity at the bottom of the atmosphere using radio occultation”, IGARSS, Fort Worth, TX, USA, July 23-28 2017;

V. L. Barbosa, J. Rasch, A. Carlström, M. I. Pettersson, V. T. Vu, “A Simulation Study of the Effect of Ionospheric Vertical Gradients on the Neutral Bending Angle Error for GNSS Radio Occultation”, 2017 Progress in Electromagnetics Research Symposium - Fall (PIERS - FALL), Singapore, November 19-22th 2017;

T. Sievert, J. Rasch, A. Carlström, M. I. Pettersson, V. Vu, ” Comparing reflection signatures in radio occultation measurements using the full spectrum inversion and phase matching methods”, SPIE Remote Sensing Conference, Berlin, Germany, September 10-13th 2017;

V. L. Barbosa, J. Rasch, A. Carlström, M. I. Pettersson, V. T. Vu, ”Analysis of reflections in GNSS radio occultation measurements using the phase matching amplitude”, submitted to IEEE Geoscience and Remote Sensing Letters, October 2018;

* At least one upcoming journal manuscript (ionospheric fluctuations modelling)

Thank you!
Q&A

Contact Information:

Thomas Sievert (ths@bth.se)
Vinícius Ludwig Barbosa (vlb@bth.se)