

Improved Abel transform inversion: application to **COSMIC/FORMOSAT-3** ionospheric occultations

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Introduction

During a GPS occultation event, a LEO receiver 'sees' the GPS transmitter rise or set behind the Earth's limb.

The signal travels through the atmosphere below the LEO orbit, being very sensitive to the vertical refractivity gradient.

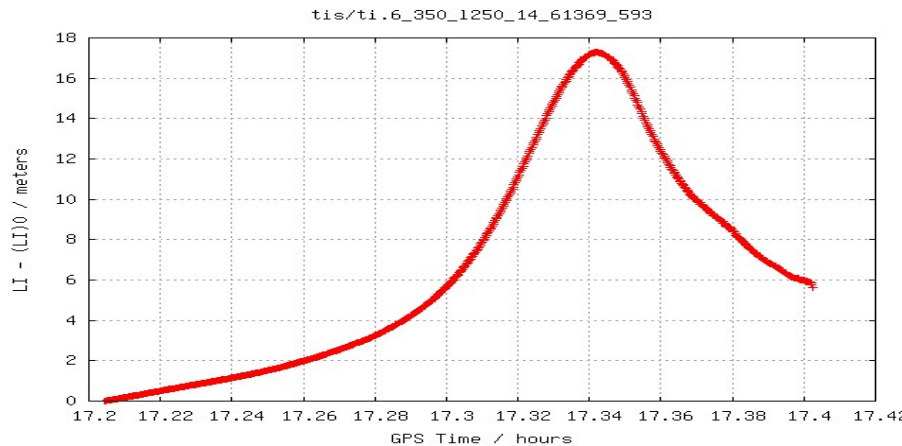
At ionospheric heights this means sensitive to vertical electron density profiles.

— GPS signal
■ Portion of atmosphere

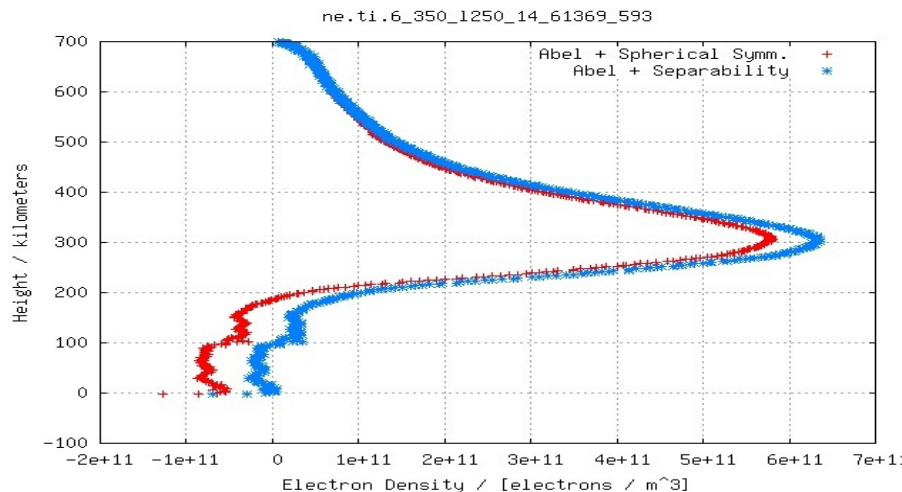
LEO height range:
300-2000km

Introduction

Occultation example: COSMIC STEC vs. time

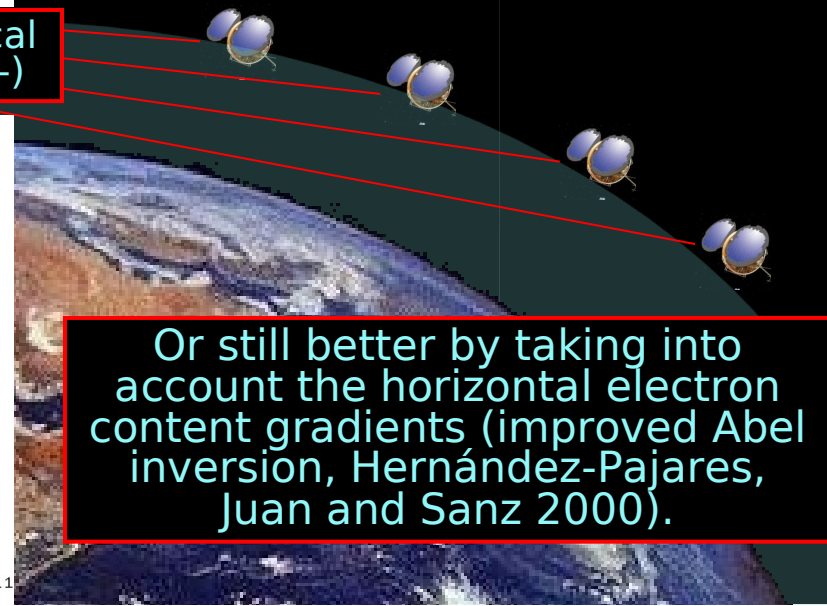


Corresponding electron density profile (Classical Abel inversion -red-, improved inversion -blue-)



As a result of this very good geometry the electron density profile on the occultation region can be easily computed by the Abel transform inversion: by making simplifications such as neglecting the horizontal gradients: Classical Abel inversion assuming electron density spherical symmetry

Or still better by taking into account the horizontal electron content gradients (improved Abel inversion, Hernández-Pajares, Juan and Sanz 2000).



Main goals of this work

- To show the **equivalence between deriving electron density profiles from bending, or from observed STEC assuming straight line propagation**, also working with the Improved Abel Inversion (applied in Hernandez-Pajares et al. 2000, Garcia-Fernandez et al. 2003 on GPS/MET, SAC/C, CHAMP data, pointed out in Tsai et al. 2001).
- This has been done **processing in the two ways**, on a representative subset of FORMOSAT-3/COSMIC data.
- FORMOSAT-3/COSMIC has offered an excellent dataset to do this, thanks to the **simultaneous Constellation observations**.
- Indeed: in particular when working with bending we have been able to **compare the clocks drift** for solving the bending angles derived from GNSS Doppler L1 phase excess in two ways from (i) subtracting the ionospheric-free combination of carrier phases, or (ii) by working in double-differences regarding to a second LEO.

Classical Abel transform applied to L_1

The basic measurement is the **phase path**:

$$L = \int_{GPS}^{LEO} n ds$$

From it, the **phase excess** is defined:

$$\Delta L = L - |r_{LEO} - r_{GPS}|$$

The change rate of the excess phase, called **Doppler shift excess** (or phase rate excess), is what is going to become our input observable:

$$\Delta D = \frac{d(\Delta L)}{dt}$$

The projection of satellite orbital motion along signal ray-path produces a Doppler shift at both the transmitter and the receiver. The fundamental observable is the **Doppler shift excess, which is different than expected from only velocities due to the satellite and receiver clock drifts and the atmospheric bending of the signal (ionosphere and troposphere).**

Classical Abel transform applied to L_1

The signal path is curved due to the changes in the refractive indexes along the ray trajectory according to **Snell's law**

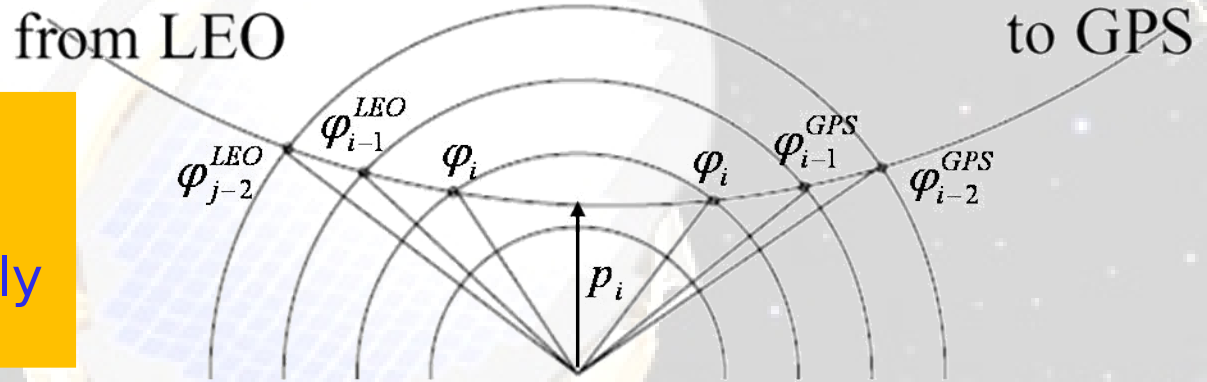
Locally, in a spherical symmetric medium, Snell's law is replaced by **Bouguer's law** imposing an extra constraint.

- Satellite positions and velocities known (both GPS and LEO) from navigation messages.
- Clock drifts required (for instance double differencing).
- Excess Doppler known derived from observations.
- With local spherical symmetry assumption, the bending angle will be determined associated to each impact parameter. An extra assumption needed: refractive index equal to 1 at LEO and GPS starting occultation positions i.e. void, with a negligible error [Hajj and Romans, 1998].
- **Using inversion techniques, the refractive index will be derived from the knowledge of bending angles.**

Classical Abel transform applied to bending angles

Signal excess
Doppler
shift

Each GPS
occultation
event is
independently
solved



The classical spherical symmetry hypothesis can be expressed as:

Unknown to be
solved is N_e

$$N_e(LT, LAT, H) = \Phi(H)$$

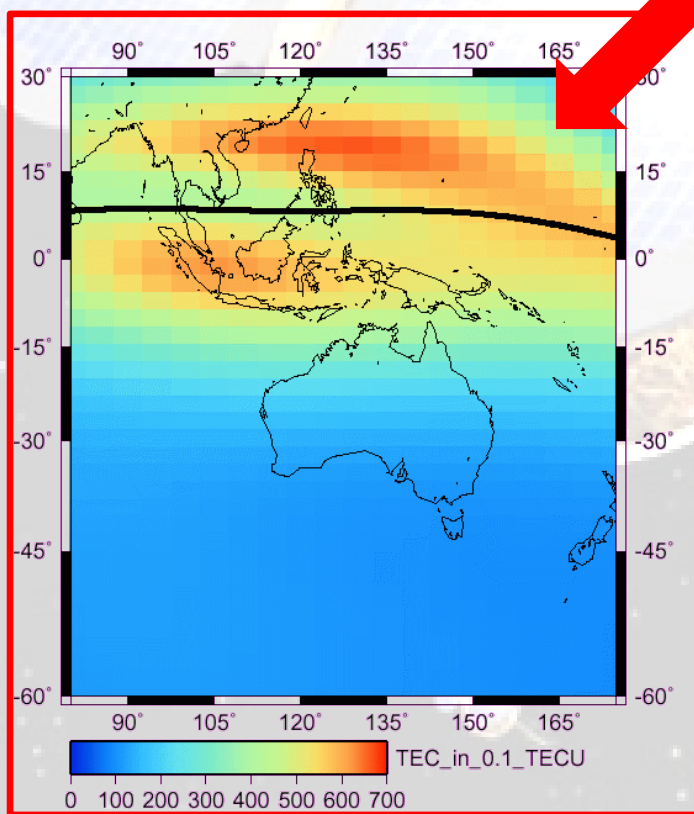
- Recursive solution starting from the outer ray.
- i corresponds to the bending angle of the ray with impact parameter p_i .

Improved Abel transform

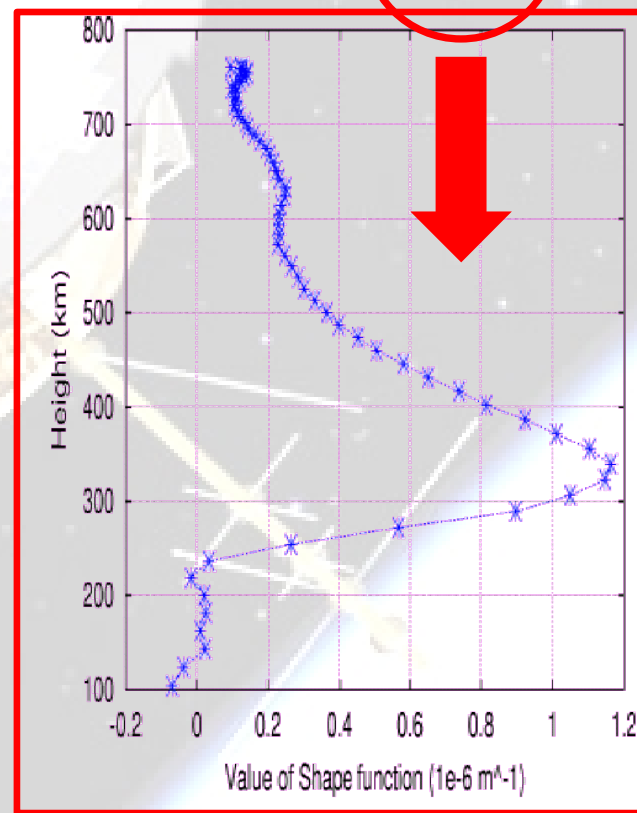
A more general approximation than the spherical symmetry is assumed:

$$N_e(LT, LAT, H) = VTEC(LT, LAT) \cdot F(H)$$

New unknown instead of N_e



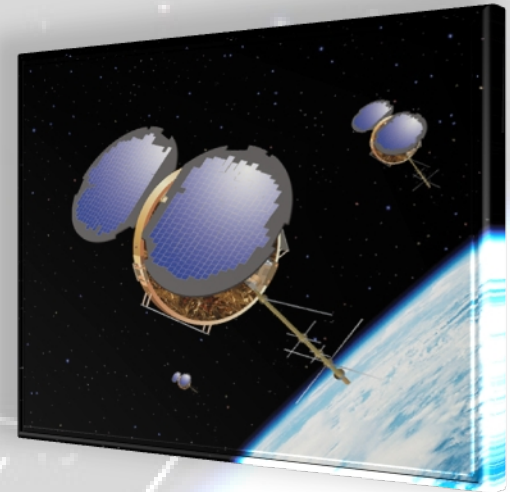
VTEC information externally provided



Shape function

FORMOSAT-3/COSMIC mission

- ✓ Constellation Observing System for Meteorology Ionosphere and Climate (ROCSAT-3)
- ✓ **6 Satellites** launched in Apr.'06 **bringing 2-freq GPS rec.**
- ✓ **Orbits: alt=800km, Inc=72deg, ecc=0**
- ✓ Weather + Space Weather data
- ✓ Global observations of:
 - Pressure, Temperature, Humidity
 - Refractivity
 - TEC, Ionospheric Electron Density
 - Ionospheric Scintillation
- ✓ Demonstrate quasioperational GPS limb sounding with global coverage in near-real time
- ✓ Climate Monitoring
- ✓ Geodetic Research

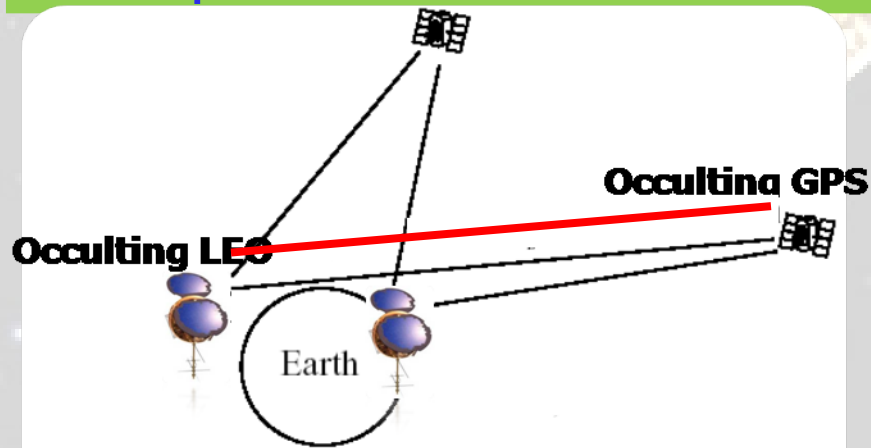


Information available at
www.nspo.org.tw
www.cosmic.ucar.edu

Bending angle: Calibration of phase rate excess

To compute accurate radio occultation inversion, it is necessary to **remove the drifts of the GPS transmitter and receiver clocks** from the raw phase data.

Classically, the clock drift has been removed by double differencing using a fiducial (ground) site, but it can be affected by phase multipath.



With a LEO constellation deployed (such as FORMOSAT-3/COSMIC), complete double differencing coverage can be better provided.

Bending angle: Calibration of phase rate excess

Alternative approach

The ionospheric-free linear combination of observables, L_c , has been used to remove the clock drift.

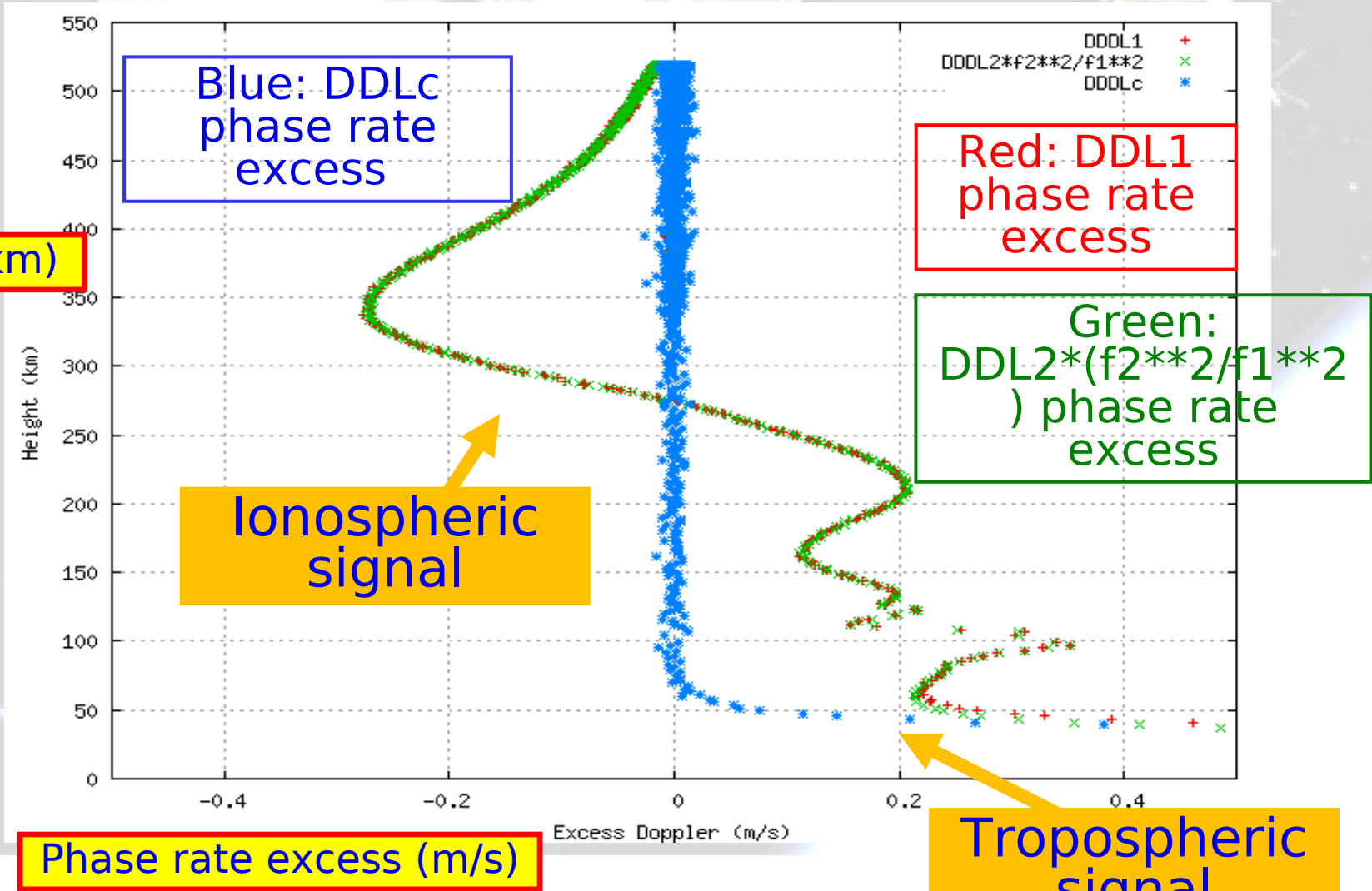
Basically, the excess Doppler of L_c has been subtracted from the excess Doppler of L_1 .

Implicit hypothesis: L_1 & L_2 same path

Common clocks will be canceled.

$$\frac{d}{dt}(\Delta L_c) = \frac{dT}{dt}$$

Example of equivalence of L1 and L2 phase rate excess

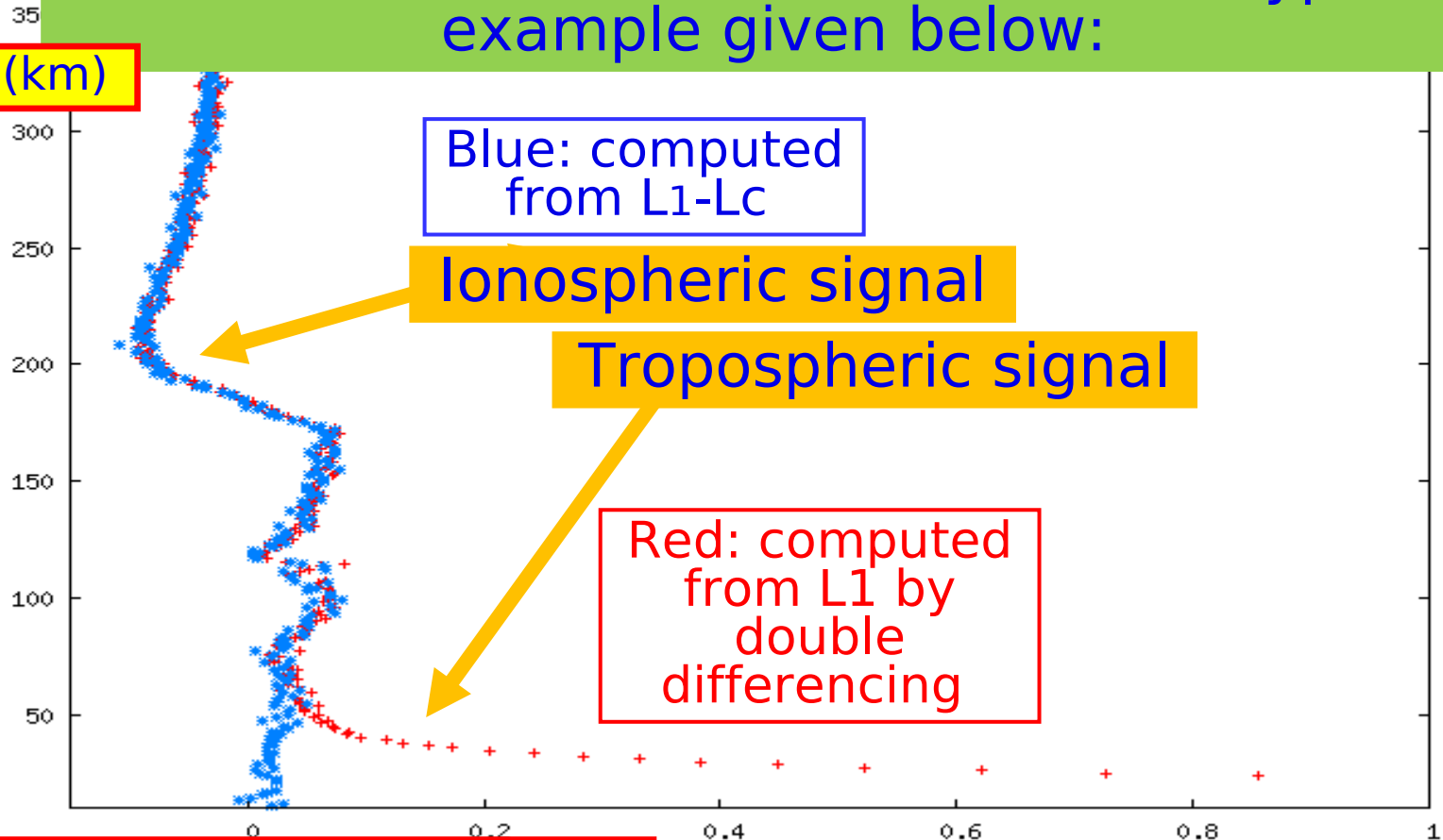


Bending angle: Calibration of excess phase delay

Alternative approach

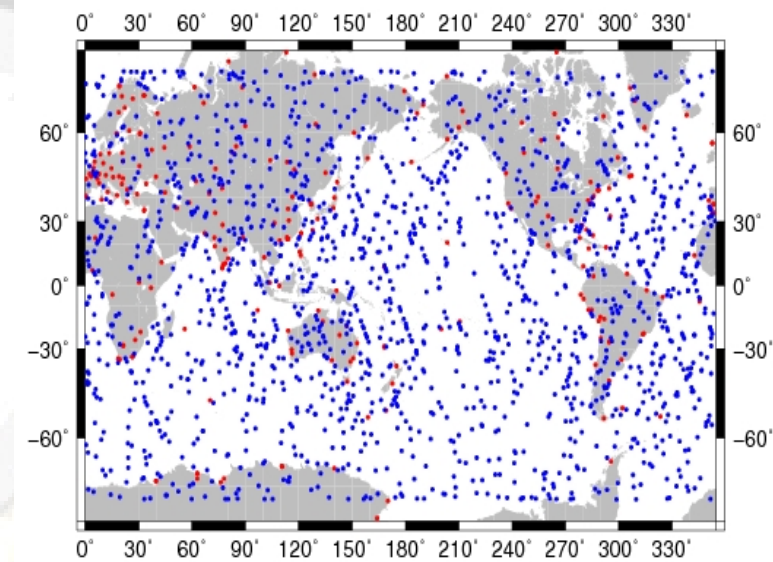
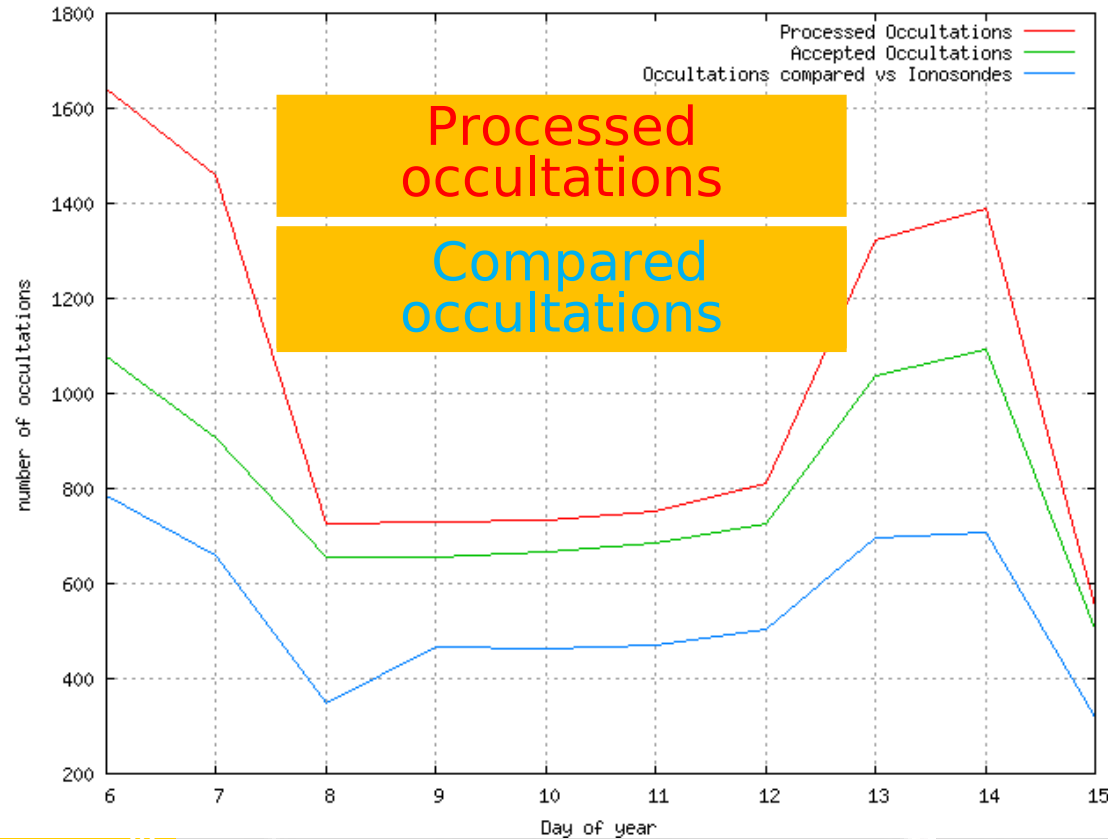
The linear combination of observables, L_c , has been used to remove the clock drift. Typical example given below:

Height (km)



Phase rate excess (m/s)

Scenario: Jan 6th to 15th, 2007

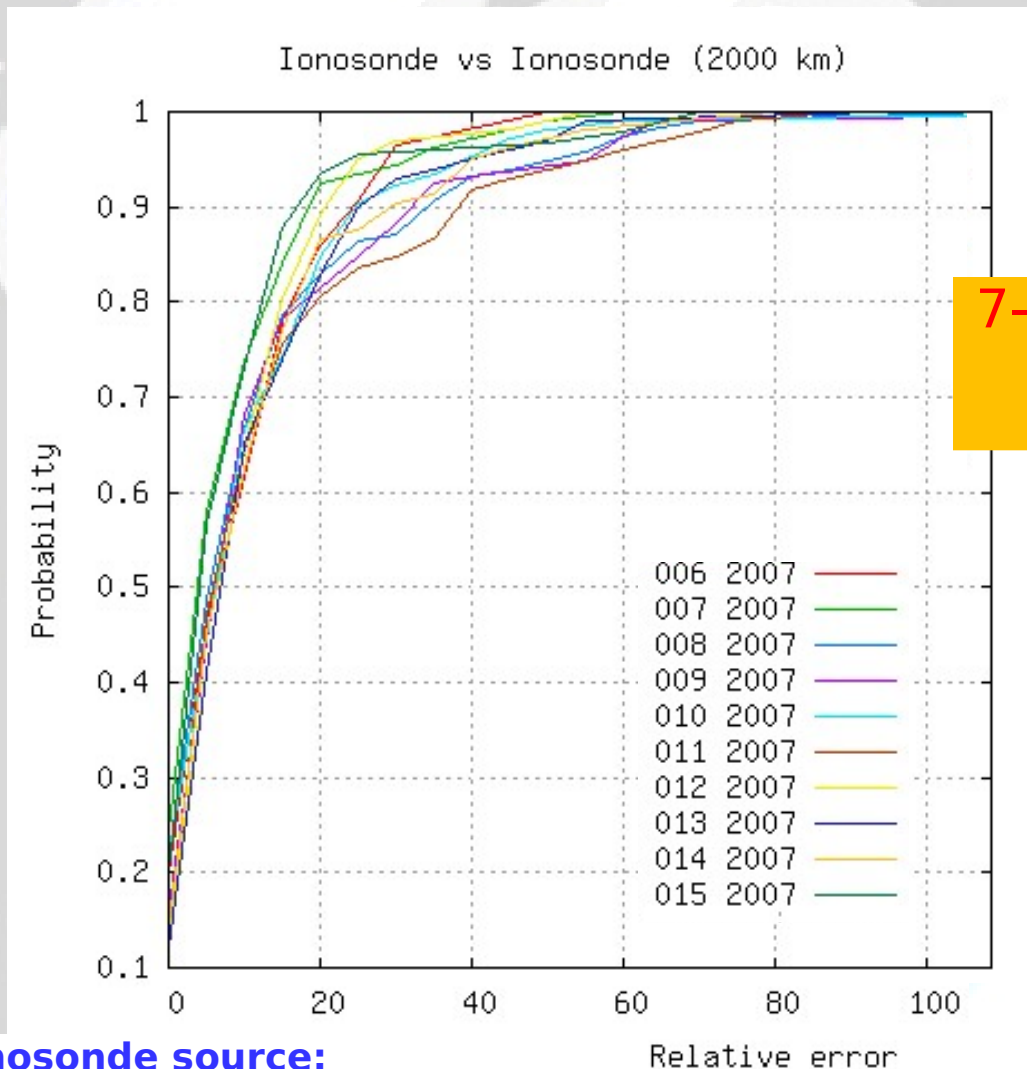


FORMOSAT-3/COSMIC Occultation's starting points / Ionosondes

- Reasons to rule out derived profiles:
 - Occultation starts too low in height
 - Occultation ends too high in height
 - Minimal duration
 - Occultation fails cycle slip check
 - No co-located ionosonde



Assessment of reference values: Ionosonde reliability



7-11% foF2 relative error for 67% percentile

Maximum co-location distance set to 2000km and 1 hour LT time span

Ionosonde source:

SPIDR web

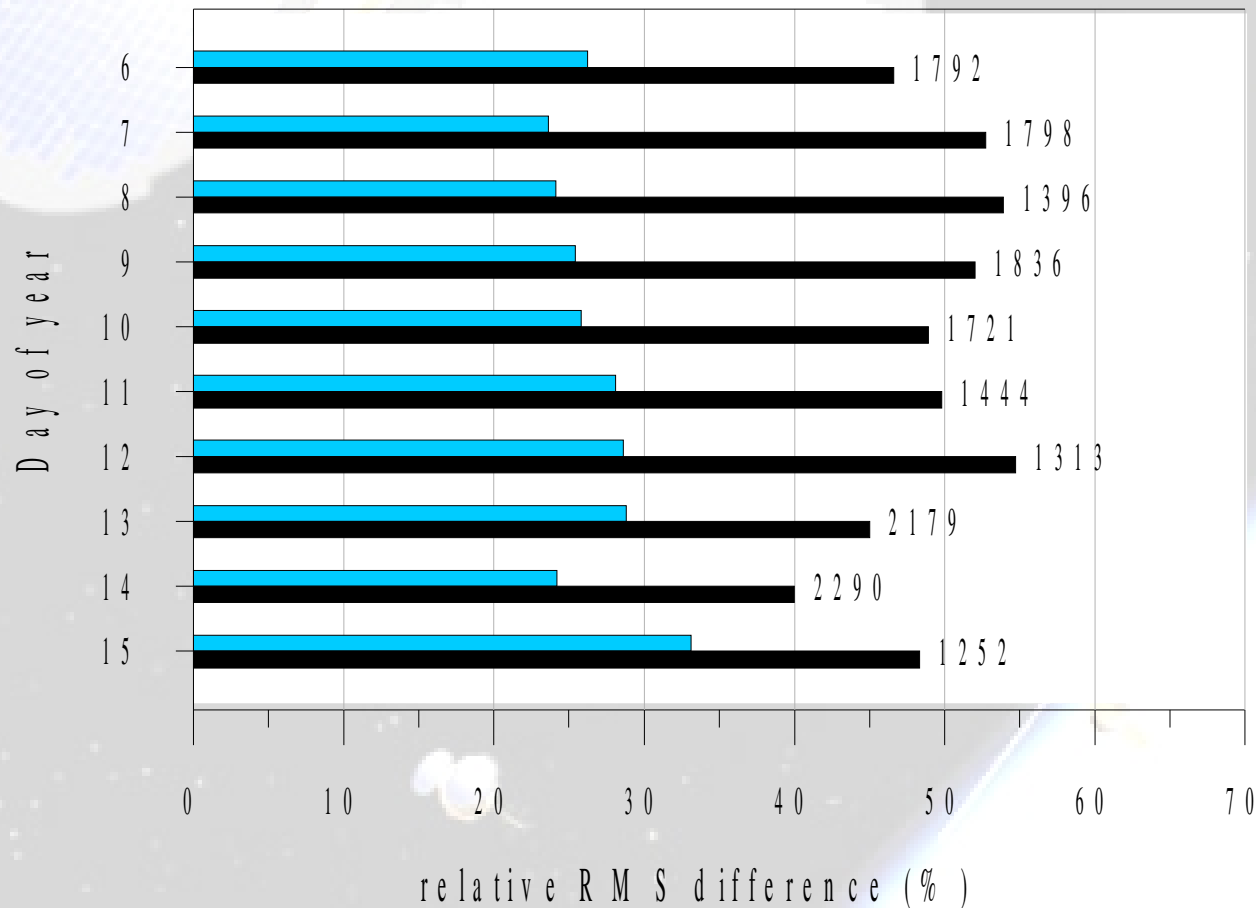
Results: foF2 from bending angle

Co-location ≤ 2000 km

separability

spherical sym.

Separability
45% better



F2 layer critical frequency foF2 comparisons with collocated ionosonde data

Conclusions

The results from this study using FORMOSAT-3/COSMIC occultation data show:

- Usefulness of **Separability technique** for the retrieval of electron densities from **bending angles**.
- For ionospheric sounding, **the equivalence of using LI and L₁ bending angle** as main input has been shown on the analyzed data set → This confirms previous results in which the different path between L₁ & L₂ cannot be considered a drawback when inverting profiles [Tsai et al., 2001].
- The **Improved Abel transform** provides more accurate determination of foF2 (**~45% better**) regardless of the chosen observable, either LI or L₁ bending angle.
- When working with bending angles, **clocks can be calibrated by means of the ionospheric-free combination** of carrier phases avoiding double differencing strategies (**valid for ionospheric heights**).
- **Future work:** Study of potential extension of **Improved Abel approach to tropospheric profiling.**

References

- Garcia-Fernandez, M., M. Hernandez-Pajares, J. M. Juan, J. Sanz, "Improvement of ionospheric electron density estimation with GPSMET occultations using Abel inversion and VTEC information", Journal of Geophysical Research, vol. 108, nr. A9, 1338, doi:10.1029/2003JA009952, 2003.
- Hernandez-Pajares, M., J. M. Juan, J. Sanz, "Improving the Abel inversion by adding ground data LEO radio occultations in the ionospheric sounding", Geophysical Research Letters , 27 (16) : 2743-2746. ISSN: 0094-8276, 2000.
- Tsai, L.C., W. H. Tsai, W. S. Schreiner, F. T. Berkey, J. Y. Liu, "Comparisons of GPS/MET retrieved ionospheric electron density and ground based ionosonde data", Earth Planets Space, 53, 193-205, 2001.