

Context

Radio signals used by geodesy techniques such as GNSS, DORIS and VLBI cross the Earth’s ionosphere, resulting in a time delay for the modulation codes and a phase advance for the carrier waves. The magnitude of this effect can reach several dozens of meters, but is hopefully mitigated using frequency combination or appropriate models. However, millimeter-level precision required for precise positioning applications and geodesy implies that the ionospheric error would be mitigated or estimated with a similar precision as well. Besides the first-order term of the ionospheric error, which represents more than 99% of the total error, the high-order terms, including the bending terms, have an amplitude than can reach several centimeters under adverse conditions, for instance low elevation, solar maximum, equatorial region, etc. In this study, we investigate the added value of computing the ionospheric error with a ray-tracing algorithm evolving in a 3D model of the ionosphere. The numerical integration of the electron density and other geophysical parameters provide a precise estimation of the high-order terms, and in a near future, the bending terms needed to achieve the mm-level precision.

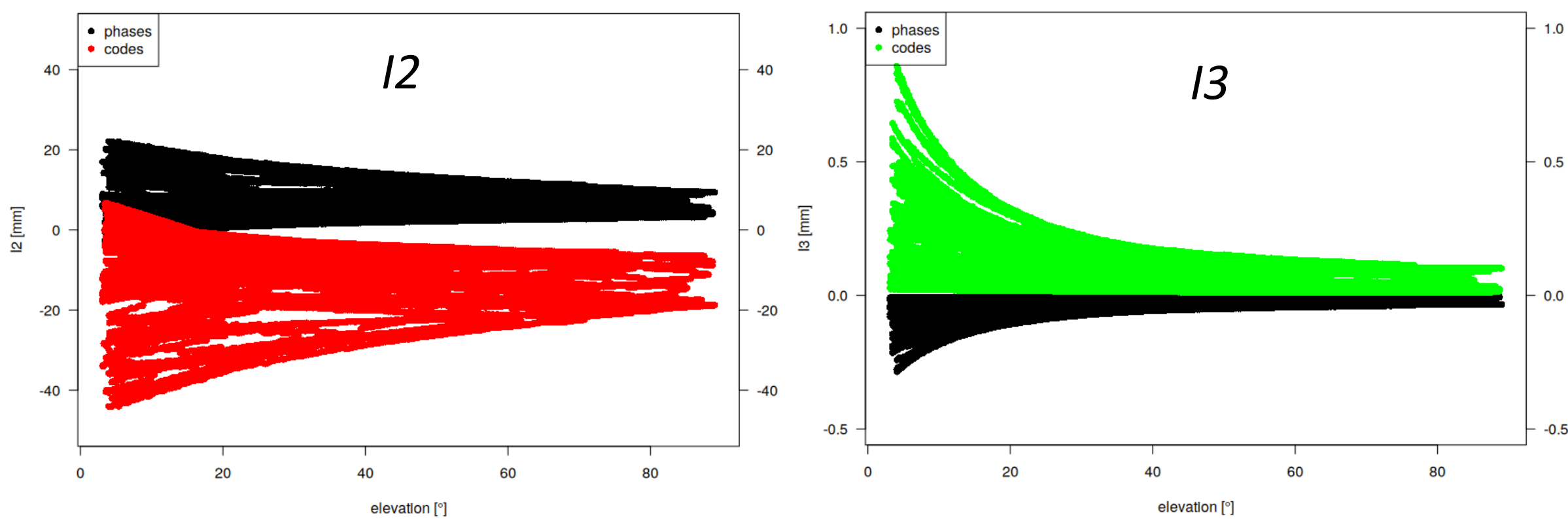
3D ionospheric tool: methodology and data

3-D ionospheric model: ray-tracing

- Voxel size (lat/lon/h) : 1° / 1° / 20km (altitude range : 80 to 2000 km)
- Ionospheric model: IRI 2020, time resolution of 15 min
- Geomagnetic model: IGRF14 computed for a single day → same **B** value during the whole day
- Ray path geometry: straight line approximation; intersection computation using simple geometry
- Input : GNSS observation files, pre-processed by CNES/GINS software (arcs, cycle slip detection, etc.)
- Principle: using GNSS observations from a given ground station, we compute:
 - Slant TEC and the first-order ionospheric term *I1*
 - High-order ionospheric terms *I2* and *I3*
- Computation for two frequencies and for the iono-free combination (IF)
- Note** : A single observation file = 30,000 ray paths (at 30s sampling rate), leading to computational time that strongly depends on the model resolution and IRI time resolution

$$\Phi_1 = \rho + N_1 \lambda_e - \frac{40.3}{f_1^2} \int N_e dL - \frac{1.1284 \times 10^{12}}{f_1^3} \int N_e B \cos \theta dL - \frac{812.0}{f_1^4} \int N_e^2 dL$$
$$P_1 = \rho + \frac{40.3}{f_1^2} \int N_e dL - 2 \frac{1.1284 \times 10^{12}}{f_1^3} \int N_e B \cos \theta dL + 3 \frac{812.47}{f_1^4} \int N_e^2 dL$$

I1 *I2* *I3*



Example of *I2* (left) and *I3* (right) terms for the GPS L2 carrier (black) and pseudorange (red and green) at BRUX station during high solar activity period (15 April 2024)

Data set

Stations : - low-latitude : CHPG00BRA (Brazil, -14° MLAT)
- mid-latitude : BRUX00BEL (Belgium, 52° MLAT)
- high-latitude : YEL200CAN (Canada, 68° MLAT)

Case study : - solar minimum, quiet-time : 15 December 2019 (F10.7 = 68 s.f.u.)
- solar maximum, quiet-time : 15 April 2024 (F10.7 = 180 s.f.u.)

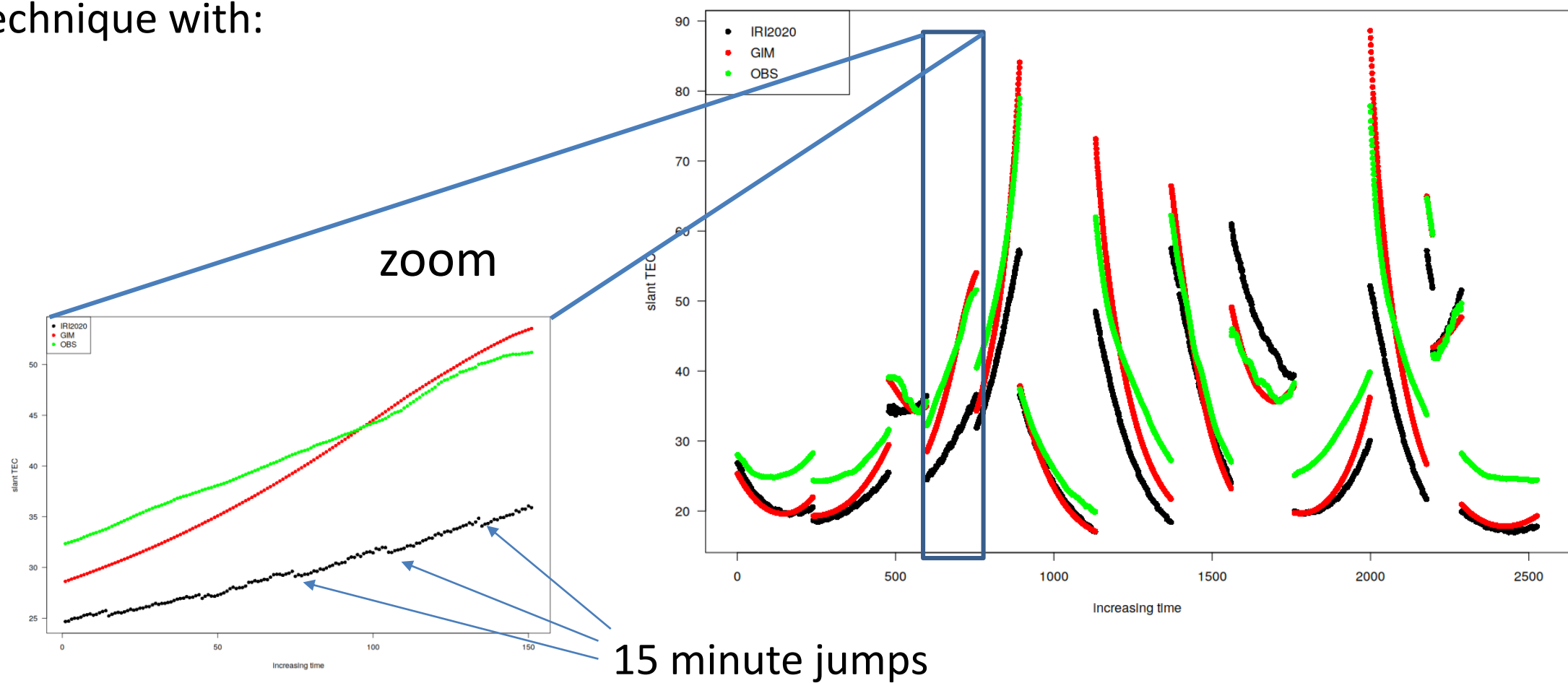
STEC comparison: first results

As a matter of validation, we compare the slant TEC (STEC) values computed by the ray-tracing technique with:

- slant TEC derived from IGS final **Global Ionospheric Maps** (using mapping function)
 - slant TEC directly computed based on **Geometry-Free combination of GNSS observations**
- Ambiguities and biases are computed using GIM levelling with a 2-3 TECU accuracy

Observations:

- difference between ray-tracing and observations are the same order than that between GIMs and observations
- GIMs provide really smoothed values while ray-tracing is characterized by small jumps, due to the discretization of time between consecutive IRI runs.
→ Do we need to increase time resolution in IRI to ensure smooth curves?



Magnitude of high-order ionospheric terms

On GPS phase L_2

I2

I3

	low-lat	mid-lat	high-lat
e < 15°	-5.5 (-26.5)	7.0 (22.1)	7.5 (16.3)
40° < e < 60°	-2.9 (-12.4)	6.1 (14.4)	7.3 (12.7)
e > 75°	-2.4 (-5.8)	6.7 (10.5)	7.7 (10.4)

	low-lat	mid-lat	high-lat
e < 15°	-0.1 (-0.6)	-0.05 (-0.3)	-0.03 (-0.1)
40° < e < 60°	-0.07 (-0.2)	-0.02 (-0.06)	-0.01 (-0.03)
e > 75°	-0.04 (-0.2)	-0.02 (-0.04)	-0.01 (-0.02)

SOL. MAX
(106/2024)

	low-lat	mid-lat	high-lat
e < 15°	-1.8 (-8.6)	0.7 (3.7)	0.6 (3.2)
40° < e < 60°	-0.9 (-4.4)	0.6 (2.1)	0.7 (1.9)
e > 75°	-1.1 (-2.1)	0.5 (1.5)	0.5 (1.5)

	low-lat	mid-lat	high-lat
e < 15°	-0.02 (-0.06)	< -0.01	< -0.01
40° < e < 60°	< -0.01 (-0.03)	< -0.01	< -0.01
e > 75°	-0.01 (-0.02)	< -0.01	< -0.01

SOL. MIN
(349/2019)

Mean and extremum (in brackets) values of ionospheric terms *I2* and *I3*, expressed in mm

On GPS ionosphere-free phase (L_1/L_2)

I2

I3

	low-lat	mid-lat	high-lat
e < 15°	1.9 (9.0)	-2.4 (-7.5)	-2.6 (-5.6)
40° < e < 60°	1.0 (4.2)	-2.1 (-4.9)	-2.5 (-4.3)
e > 75°	0.8 (2.0)	-2.3 (-3.6)	-2.6 (-3.6)

	low-lat	mid-lat	high-lat
e < 15°	-0.15 (-0.6)	-0.06 (-0.3)	-0.03 (-0.1)
40° < e < 60°	-0.07 (-0.2)	-0.02 (-0.06)	-0.01 (-0.03)
e > 75°	-0.04 (-0.1)	-0.02 (-0.04)	-0.01 (-0.02)

	low-lat	mid-lat	high-lat
e < 15°	0.6 (2.9)	-0.2 (-1.2)	-0.2 (-1.1)
40° < e < 60°	0.3 (1.5)	-0.2 (-0.7)	-0.2 (-0.6)
e > 75°	0.4 (0.7)	-0.2 (-0.5)	-0.2 (-0.5)

	low-lat	mid-lat	high-lat
e < 15°	-0.02 (0.06)	< -0.01	< -0.01
40° < e < 60°	< -0.01 (-0.03)	< -0.01	< -0.01
e > 75°	-0.01 (-0.02)	< -0.01	< -0.01

Mean and extremum (in brackets) values of ionospheric terms *I2* and *I3*, expressed in mm

Summary and upcoming developments

This paper presents the very first **results** of the implementation of a ray-tracing algorithm used in the frame of GNSS satellite-to-station link, which can be summarized as follows:

- High-order terms and TEC values are on the same order of magnitude as those published in the literature, which serves as a first validation of the algorithm
- High-order terms are larger at low elevation, but their absolute value is far from being negligible at high elevation
- High-order terms are larger for undifferenced measurements (i.e. raw phase or code observations) than in the iono-free combination

The ray-path algorithm is intended to deliver a simulated dataset that can be considered as “super truth”, as each system variable such as Ne, B and geometrical configuration of the ray path are known over a discretized system evolving in full 4D. This “super truth” will provide the baseline to develop and validate new algorithms providing the mm accuracy needed for future geodetic challenges. Indeed, the total contribution (*I2* + *I3* + *geometric bending* + *dSTEC bending*) must remain < 1 mm for any ray path, included under low elevation conditions (< 10°)

Future development and considerations therefore include but are not limited to:

- Increase the IRI time resolution to get STEC time series as smooth as those computed from observations
- Refraction computation → ray tracing and bending in 3D environment : geometric bending + dSTEC bending
- Include plasmaspheric model different to the OTSR2012 included in IRI2020
- Include the possibility to simulate radio-occultation measurements
- Compare our “super truth” higher order terms with classical implementations based on ionospheric pierce point values
- Include physical models like TIEGCM instead of IRI2020 as well as real observations coming from the ICON mission, which has the advantage of providing full electronic density profiles in the equatorial and mid-latitude regions from 200 to 600 km altitude. TIEGCM model will also allow to benchmark our model during active geomagnetic conditions.

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