Sounding the Atmosphere: Improvement of the Ray Geometry using Dense European GNSS Networks and Multi-GNSS Signals

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1. Introduction

Tomography based on GPS data is presently largely used for a better understanding of atmospheric physics. In that frame, previous studies on ionospheric and tropospheric tomography conclude that it is necessary to improve the spatial resolutions of atmospheric parameters estimated from GPS data in order to improve the utility of the tomography imaging (Bender and Raabe, 2007; Bust and Mitchell, 2008).

Presently, GPS observations allow deriving 4-D atmospheric (tropospheric or ionospheric) models using tomography. For that, the GPS data are used to estimate the Slant Tropospheric Delay (STD) for the troposphere (e.g. Pottiaux, 2010) and the Slant Total Electron Content (STEC) for the ionosphere (e.g. Bergeot et al., 2010). The tomographic approach consists in discretising those quantities through voxels (a voxel is a 3D pixel, Figure 1) representing the troposphere or ionosphere. This allows getting information on the distribution variations of those parameters at the resolution of the tomographic grid (Mitchell and Spencer, 2003). In the near future, the use of GLONASS and the future Galileo system as well as increased ground GNSS networks increase of the observations of STD and STEC and will imply less reliance on a priori information, finally resulting in atmospheric tomography mainly based on the data (Bust and Mitchell, 2008; Bender and Raabe, 2007).

In Europe, an important number of ground stations tracking signals from GPS satellites is available thanks to: (1) the EUREF Permanent Network (EPN, Bruyninx, 1994) and (2) national dense networks. Moreover, the EPN tends to be fully developed for tracking different Global Navigation Satellite Systems (i.e. GPS, GLONASS, future Galileo). Consequently, this increasing number of GNSS satellites and ground receivers will induce a steady growth of the number of radio navigation signals sounding the Earth’s atmosphere. From these multiple observations, it is expected that a better modelling of the ionosphere and the troposphere will be possible. In order to evaluate the current and future potential of these multiple GNSS observations for atmospheric imaging, it is thus of interest to investigate their distribution within the atmosphere. In this study, we quantify the added value of the use of multi-GNSS satellites and dense ground networks in terms of ray distribution sounding the atmosphere over Europe in the frame of a tomographic approach. First, we estimate the number of GPS signals traversing the ionosphere and the troposhere using the EPN only. Then the benefit of GNSS constellations such as GLONASS and Galileo in addition to GPS-only is assessed. Finally, stations from national dense networks are added to the EPN to obtain a first evaluation of the expected improvements of the atmospheric sounding from an EPN densification or enlargement.

2. Methodology and Data

2.1 Method

As tomography relies on the distribution of the data, we quantify the GNSS signal distribution into the troposphere and the ionosphere using a purely geometric approach. In order to estimate the distribution of GNSS signals gathered by a set of GNSS tracking stations during a given time span, GNSS signal ray paths are traced for each satellite/receiver pair, assuming a straight-line propagation. The tropospheric and ionospheric layers located in a zone extending from -10° to 40° in longitude, from 25° to 70° in latitude are discretized into two grids of voxels (Figure 1): the grids extend in altitude from 0 to 10 km for the troposphere and from 80 to 850 km for the ionosphere. Only signals traversing the whole voxelized atmosphere are taken into account (Figure 1), similarly to what is done in tomography (Bender and Raabe, 2007). Then the intersections of the rays with the voxels of the grids are determined and we analyse the distribution of the rays into the voxels. Tests are performed for different spatial resolutions of the grid and for different time spans of observations.

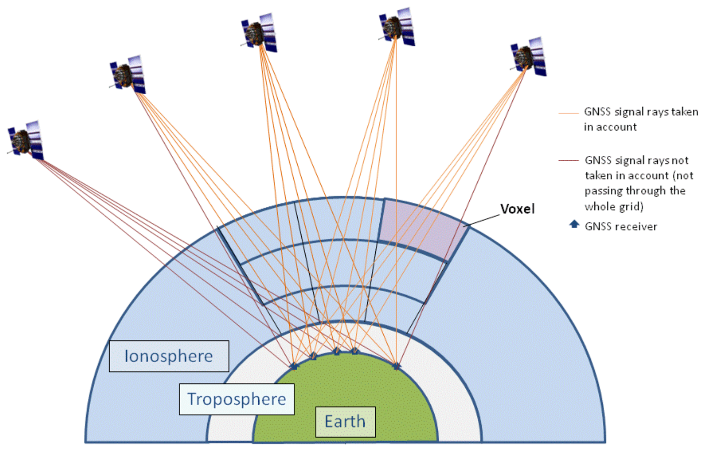


Figure 1: Schema of the GNSS signal gathered by a set of GNSS station through a grid of voxel constituting the ionosphere

2.2 GNSS orbits

Signal rays are computed for the 1st February 2010. At this date, 32 GPS satellites and 19 GLONASS satellites were in orbit. Real GPS and GLONASS orbits are used in these tests and are provided by the International GNSS Service (IGS) (Dow et al., 2009). Concerning Galileo, only two satellites, GIOVE-A and GIOVE-B, were in orbit at this epoch. In order to anticipate the future Full Operational Capability (FOC) Galileo constellation, the orbits of its 27 planned operational satellites are simulated for the Feb. 1st 2010 (Table 1).

	# of satellites in orbit / # of satellites in FOC	# of satellites and orbits used in this study (Feb. 1st, 2010)	Full Operational Capability (FOC)
GPS	32/32	32 (IGS products)	1995
GLONASS	19/24	19 (IGS products)	2011
Galileo	2/30	27 (simulated orbits)	2018

Table 1: Characteristics of the GNSS constellation used in the study

2.3 GNSS ground networks

First tests are performed using only the EPN stations (227 stations in February 2010). Despite the fact that on Feb 1st 2010, only 51% of the EPN stations tracked GLONASS signals, it is assumed that the entire EPN has already the capability of tracking GPS, GLONASS and Galileo.

In a second step, stations belonging to national GNSS networks located in Belgium, France, Germany, Sweden and United Kingdom (total number of 409 stations, see Table 2) are added in order to densify and enlarge the EPN (Figure 2). Signal rays are traced each 30 seconds (corresponding to the typical sampling rate used by GNSS receivers within the EPN) with a cut off angle fixed to 10°.

Network		# stations
EPN		227
National densifications	Belgium	61
	France	39
	Germany	15
	Sweden	164
	U.K	130

Table 2: Station number of the GNNS ground networks used in this study

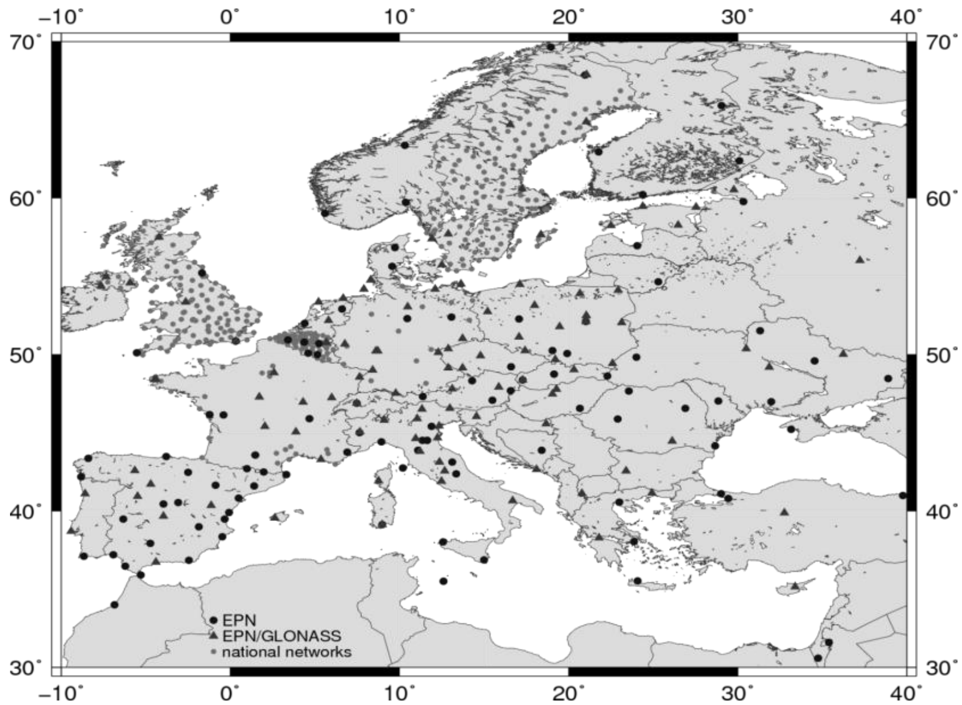


Figure 2: GNSS ground receiver network

3. Results

In this section, the results of the GNSS signal distribution above Europe are presented in paragraphs 3.1 for the ionosphere and 3.2 for the troposphere. In these two atmospheric layers, GNSS signals are traced for different configurations of GNSS ground networks and GNSS satellites: 1) with GPS satellites and EPN receivers, 2) with multi-GNSS and EPN, and finally 3) with GPS-only and the national networks in addition to the EPN.

For a better understanding and visualization, the scale of the following plots are set with a maximum of 200 rays per voxel for the ionosphere (Figure 3a, Figure 4a, Figure 6a, Figure 9a, Figure 10) and 40 rays per voxel for the troposphere (Figure 11a, 11c and Figure 12). One voxel might contain more rays in both cases, however above this number it is assumed that a sufficient number of observations are gathered.

3.1 Ionospheric layer

The F-layer (120-800 km) of the ionosphere is subject to most of electron concentration variations, especially around 300 km height corresponding to the maximum of ionization. Therefore all following results are displayed at a height of 300 km. To investigate the distribution of GNSS rays with the EPN, three different types of tests are carried out.

The first step consists in investigating the spatial and temporal resolution of GPS-only observations, for that purpose we have used different voxel sizes and time spans. In a second step, the EPN is assessed for multi-GNSS applications with the hypothesis of an EPN fully capable of tracking Galileo and GLONASS in addition to GPS (see 2.2). Finally, the potential of a densified EPN network, thanks to stations belonging to national dense networks, is evaluated.

3.1.1 Spatial and Temporal Resolution

The use of different voxel sizes as well as different time spans directly affects the number of GNSS signals crossing the voxels. The results demonstrate that:

- reducing the voxel size from 0.5° x 0.5° x 30 km to 0.25° x 0.25° x 10 km increases the number of empty voxels by 25% (Figure 3 and Figure 4),
- decreasing the span time from 20 minutes to 5 minutes increases the number of empty voxels by 10% (Figure 5),

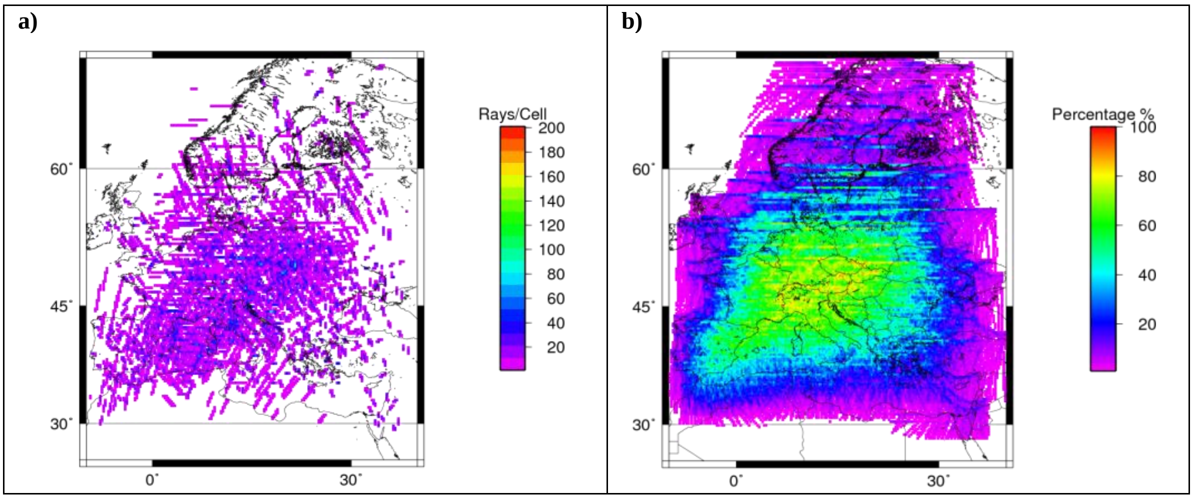


Figure 3: GPS signal distribution at a height of 300 km in a grid of 0.25°x0.25°x10km, and using the EPN: a) number of GPS rays per voxel during a time span of 20 min, from 10h00 to 10h20, b) percentage of epochs during one day for which the voxel is traversed by at least 5 rays

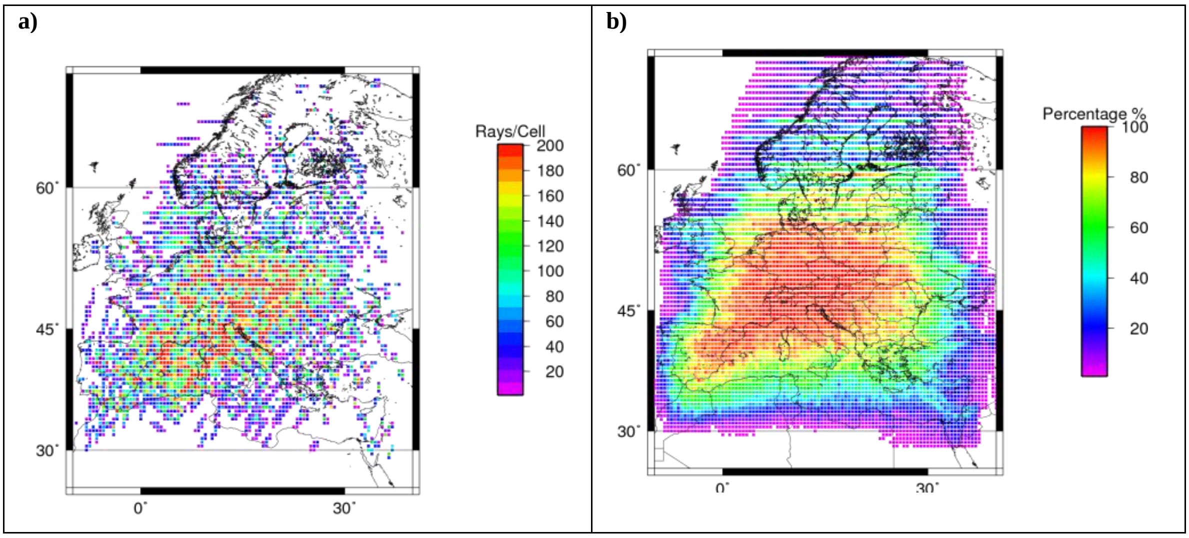


Figure 4: GPS signal distribution at a height of 300 km in a grid of 0.5°x0.5°x30km, and using the EPN: a) number of GPS rays per voxel during a time span of 20 min, from 10h00 to 10h20, b) percentage of epochs during one day for which voxels are traversed by at least 5 rays.

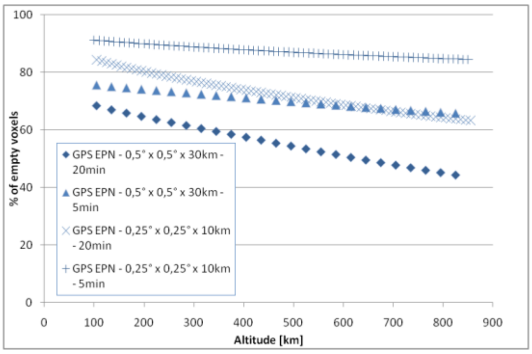


Figure 5: Percentage of empty voxels (averaged over the day)

Results show that gathering GNSS observations in a grid of 0.5° x 0.5° x 30 km with a 20min time span provides suitable coverage while the resolution remains suitable for most of ionospheric applications. Therefore, in the following, we will use the 0.5° x 0.5° x 30 km grid with a time span of 20 min.

3.1.2 GPS-only vs. Multi-GNSS

To assess the added value of multi-GNSS, we compared the GPS-only signal distribution gathered by the EPN with the GPS+GLONASS and GPS+GLONASS+Galileo signal distributions gathered by an EPN supposed to be fully capable of observing Galileo and GLONASS in addition to GPS. Using a grid of 0.5° x 0.5° x 30 km, we observe that using multi-GNSS (Figure 6) in comparison to GPS-only (Figure 4):

- the mean number of rays per voxel is increased homogeneously by a factor of 1.6 for GPS+GLONASS, and by 2.5 for GPS+GLONASS+Galileo (Figure 7),
- the percentage of empty voxels decreases by a factor of about 0.7 (depending on the altitude) (Figure 8).
- the coverage in terms of percentage of voxels traversed by at least 5 rays GNSS signals is improved (Figure 6b):
    - during 80% of the day, it is improved by a factor of 2 (19% for GPS-only and 38% for multi GNSS),

- during the full day, it is only 1% in the case of GPS only, while it is 15% in the case of multi-GNSS (Table 3)

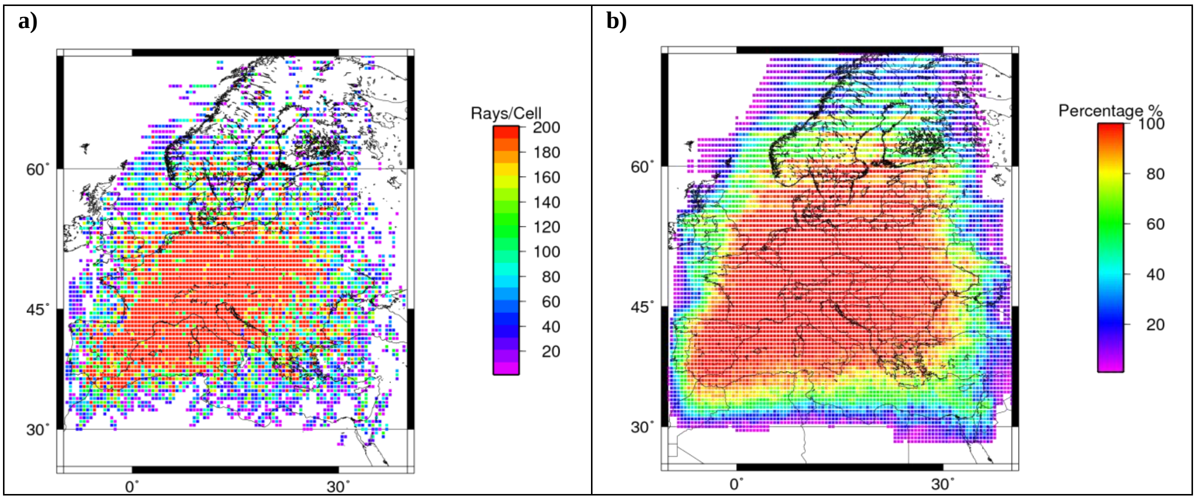


Figure 6: Multi-GNSS (GPS+Galileo+GLONASS) signal distribution at a height of 300 km in a grid of 0.5°x0.5°x30km and using the EPN: a) number of GNSS rays per voxel during a time span of 20 min, from 10h00 to 10h20, b) percentage of epochs during one day for which voxels are traversed by at least 5 rays

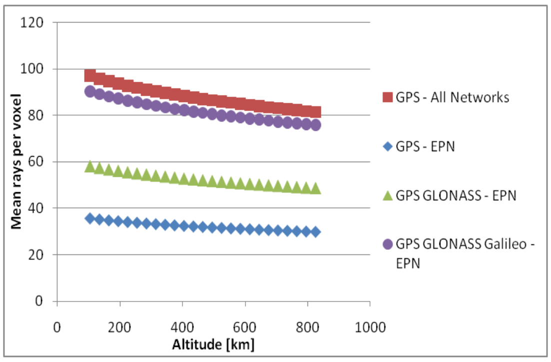


Figure 7 : Mean rays per voxel as function of the altitude

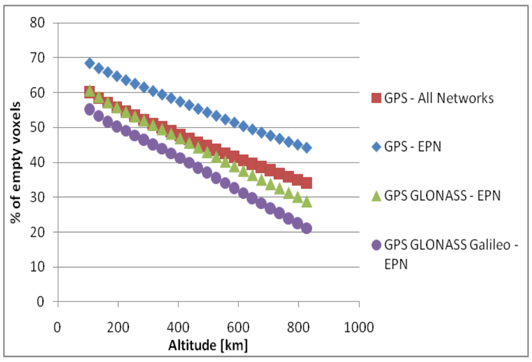


Figure 8 : Percentage of empty voxels as function of the altitude (averaged over the day)

	% of voxels traversed by at least 5 rays	
	GPS-only	**Multi-GNSS**
80% of the full day	19	38
Full day	1	15

Table 3: Percentage of voxels traversed by a minimum of 5 rays

3.1.3 EPN Densification with National Networks

As the EPN tends to extend and densify in the next future, it is of interest to evaluate where new stations could be installed to improve significantly the potential of the EPN data when reconstructing ionosphere. For that purpose, the stations belonging to several national GNSS networks are added to the EPN.

By comparing the EPN+national networks with the present-day EPN in the case of GPS observations, it could be shown that:

- The percentage of empty voxels decreases by 17% (Figure 8) thanks to the contribution of the UK and Swedish networks (Figure 9) which provide more stations in the North than the EPN alone (Figure 4).
- The mean number of rays traversing the voxels is increased by a factor of 2.7 compared to EPN-only (Figure 7). However this increase occurs only in tiny zones whose locations depend on the geometry of the satellite constellation during the considered time span. For example, by using only the Belgium network (Figure 10), ~5000 rays per voxel at a given epoch (the maximum is ~1000 for the EPN only) are gathered. However, this ray concentration occurs only into localized voxels and affects the homogeneity of the ray distribution without bringing new information.

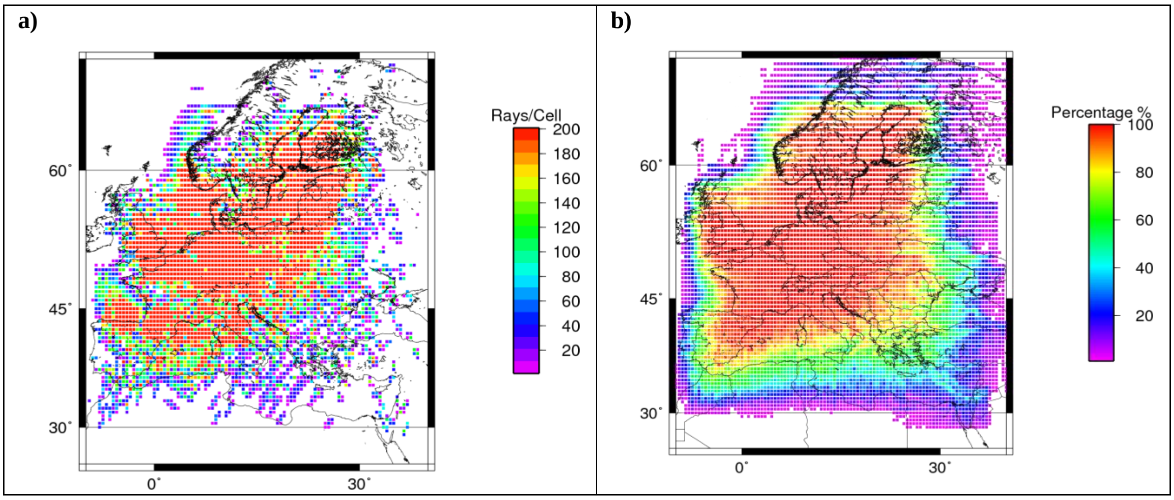


Figure 9 : GPS signal distribution at a height of 300 km in a grid of 0.5°x0.5°x30km, using the EPN and national networks: a) number of GNSS rays per voxel during a time span, from 10h00 to 10h20, b) percentage of epochs during one day for which voxels are traversed by at least 5 rays.

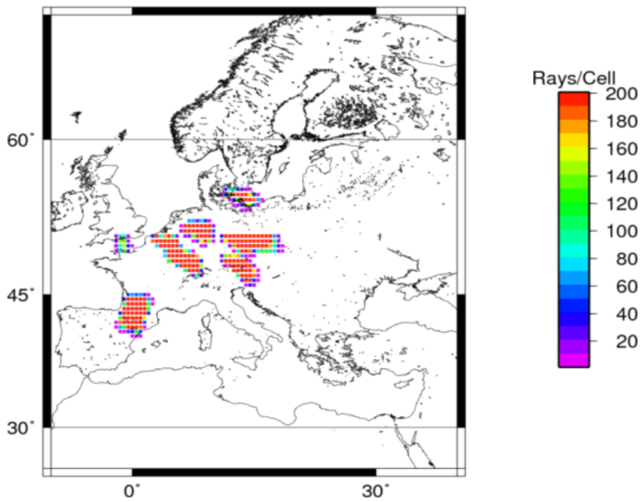


Figure 10 : GPS signal distribution at a height of 300 km in a grid of 0.5°x0.5°x30 km, and only using Belgian dense network for a time span of 20 min

3.2 Tropospheric layer

The same kind of investigations was conducted in the case of troposphere. Tropospheric tomography targets reconstruction of water vapour structures. These structures are located between 0-10 km of altitude, therefore our figures point out the GNSS signal distribution in the troposphere at 9 km of altitude. In addition, today, tropospheric physics look for small scale water vapour structures (Barlag et al. 2004). Therefore the typical voxel size used here is: 0.10° in longitude, 0.05° in latitude and 1 km in height, this corresponds to a size of 6 km x 5km x 1 km above Belgium. We used a time span of 20 min (typical time spans used in tropospheric tomography range from 5 to 20 minutes).

3.2.1 GPS-only Observations with the EPN and the Belgian Network

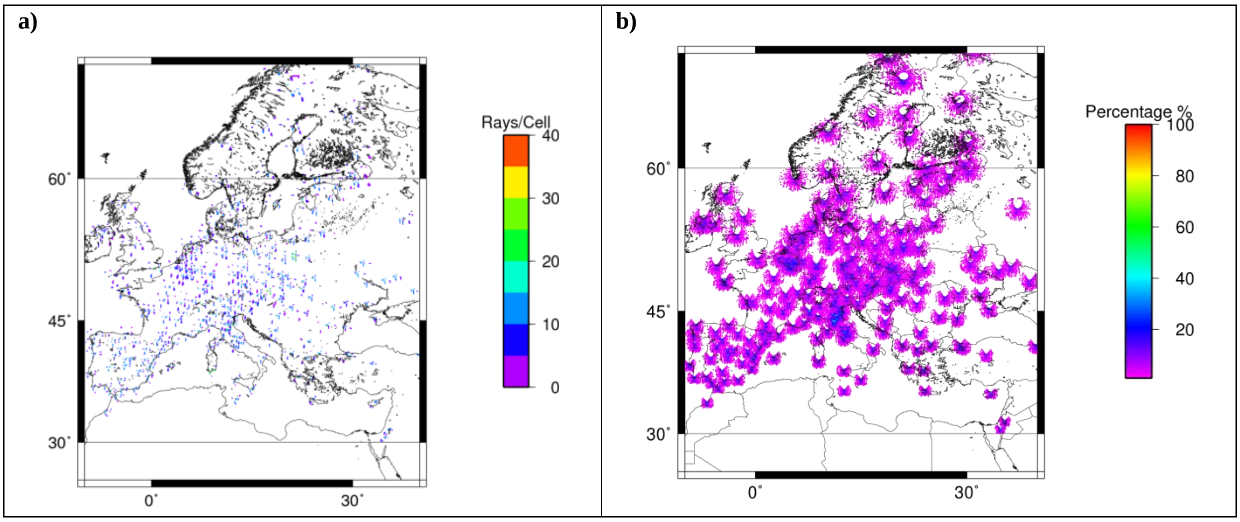
As shown in Figure 11a and 11b, spots of signals are observed above the stations of the EPN; it indicates that GNSS signal rays from different satellite/receiver rays do not intersect between them in the troposphere which is not optimal for tomography. Therefore, the EPN with mean inter-station distances of ~225km is not dense enough to provide a good coverage of signals in the troposphere above Europe.

To highlight the added value of a densification of the EPN with national networks, we investigate the effect of a network having lower inter-stations distances. To do so, we focus on Belgium only and compare the Belgian dense network having mean inter-station distances of ~30km, with the EPN-only.

For this comparison, only intersections above Belgium are taken in account. In the case of the EPN, the GNSS signals are sparse over the Belgium (Figure 11c and 11d) and are concentrated above the stations. With the Belgian network (Figure 12a and 12b), the signals are well distributed and provide a quasi-full coverage of the troposphere.

Indeed, with the Belgian network (resp. the EPN), 73% (resp. 14%) of the voxels above Belgium are traversed by GPS signals with a mean of 9.3 (resp. 1) rays per voxel. Moreover, on average, voxels are traversed by at least 5 rays for 63% (resp. 10%) of the epochs of the day (Figure 12).

The use of the dense Belgium network over Belgium improves the rays concentration by a factor of 5 compared to the EPN only. The use of a dense network is thus necessary to significantly improve the distribution of the data and consequently tropospheric imaging.



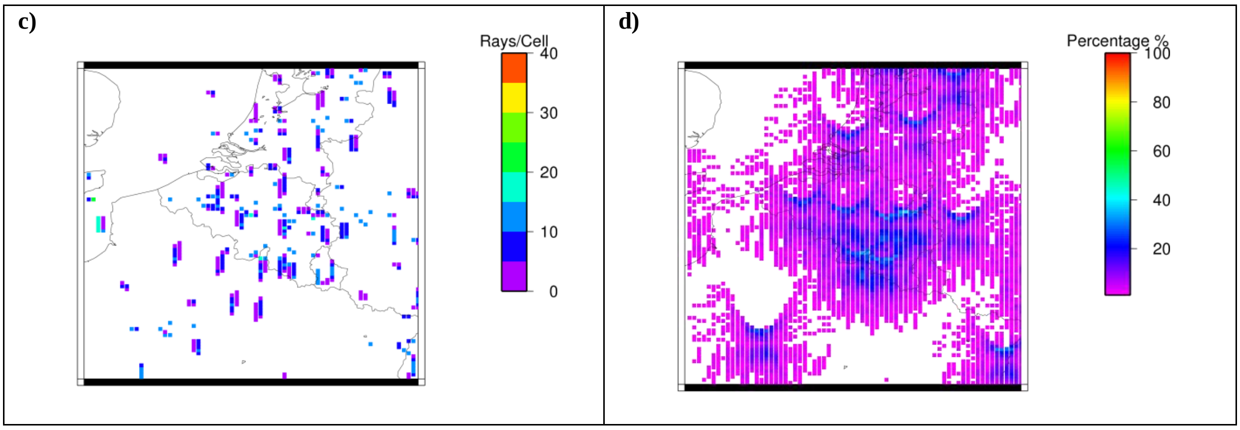


Figure 11 : GPS signal distribution at an altitude of 9 km in a grid of 0.1° in longitude, 0.05° in latitude and 1 km in height, and using the EPN : a) number of GPS rays per voxel for a time span of 20 min from 10h00 to 10h20, b) percentage of epochs during one day for which voxels are traversed by at least 5 rays, c) zoom of a) over Belgium, d) zoom of b) over Belgium

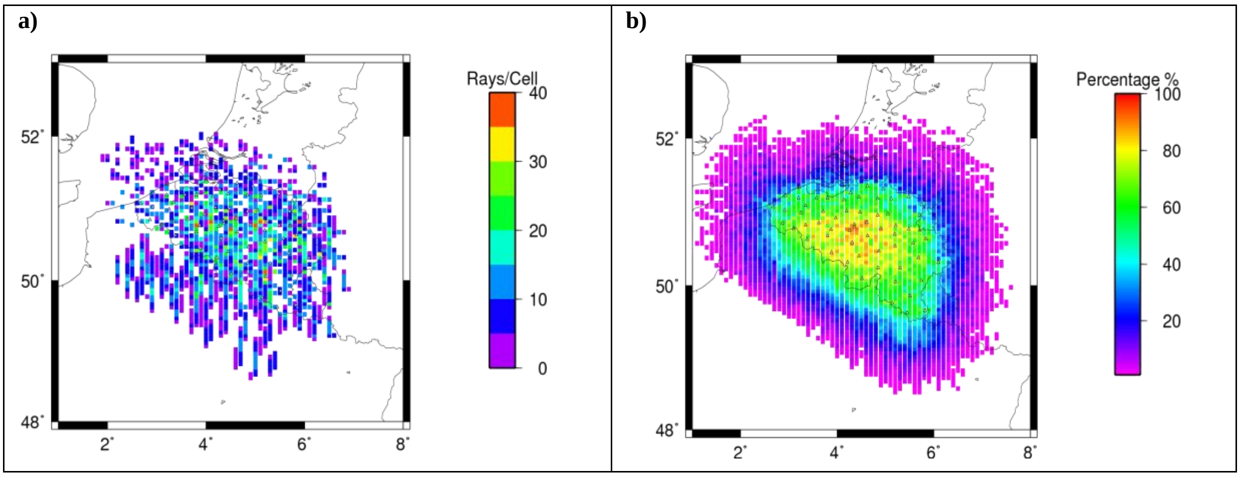


Figure 12 : GPS signal distribution at an altitude of 9 km in a grid of 0.1° in longitude, 0.05° in latitude and 1 km in height, and using the Belgian dense network : a) number of GPS rays per voxel for a time span of 20 min, from 10h00 to 10h20 , b) percentage of epochs during one day for which voxels are traversed by at least 5 rays

	GPS – EPN	GPS – Belgium network	GPS+GLONASS +Galileo – EPN	GPS+GLONASS +Galileo – Belgium Network
Percentage of coverage	13.5	72.5	28.5	94
Mean # of rays per voxel w.r.t. the total number of voxel above Belgium	1	9.5	2.5	22.5
Percentage of epochs during the day for which voxels are traversed by at least 5 rays	10	63	21.5%	89%

Table 4: Statistics of the GNSS signal in the troposphere above Belgium

3.2.2 Added value of the multi-GNSS

In the case of the EPN only, the use of GLONASS and Galileo data in addition to GPS, improves the GNSS signal distribution by a factor of 2 above Belgium. Despite this improvement, the percentage of coverage remains low (28%) and not sufficient enough to expect a reliable atmospheric imaging.

In the case of the dense Belgian network, the use of multi-GNSS improves the tropospheric coverage by factor of 1.4. 94% of the voxels are traversed by GNSS signals with a mean of 22.5 rays per voxel. Moreover, on average, voxels are traversed by at least 5 rays for 89% of the epochs of the day (Table 4).

Therefore when studying the troposphere, it is essential to use dense GNSS networks having inter-stations distances of at least 30 km and this even if multi-GNSS is used.

4. Conclusions

By investigating the GNSS signal distribution in the troposphere and ionosphere, we pointed out the clear interest of using the EPN for ionospheric tomography, while its potential for tropospheric tomography is less evident.

For performing tropospheric tomography, inter-station distances within the EPN do not insure a sufficient coverage of the troposphere. Dense networks with inter-station distance of 30 km are more appropriate to fulfil the requirements of tropospheric imaging.

In the case of the ionosphere, the GNSS signals from the well-distributed and wide EPN ensure a homogeneous coverage of the ionosphere over the full day. The integration of national networks in addition to the EPN reduces the number of empty voxels and increases the coverage of the ionosphere particularly thanks to stations located in the North. Unfortunately, inhomogeneities are induced into the GNSS signal distribution, due to the inhomogeneous distribution of the stations. A wise densification of the EPN by adding a selection of uniformly distributed stations could take advantage of the available GNSS data in Europe, while avoiding any in-homogeneity.

The use of multi-GNSS signals definitely demonstrates a clear added-value in terms of GNSS signal distribution for both ionospheric and tropospheric layers. The wise densification together with the future Galileo and GLONASS observations will allow increasing the spatial and temporal resolution of atmospheric tomography over Europe.

5. Acknowledgements

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