

Tomography of the troposphere using dense GPS networks

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Introduction

The troposphere is the lower part of the atmosphere and covers the region between the Earth's surface to a height of about 15 km. Its strong spatial inhomogeneity and temporal variability continues to be a source of random and systematic errors in geodetic techniques. The major limitation is attributed to mismodeling of the water vapor component.

Tropospheric path delay is a serious error in GPS measurements both through ray path bending and the modification of the electromagnetic velocity, and is especially critical for the GPS accuracy of the height component. Accurate estimation of atmospheric path delay in GPS signals is necessary for high-accuracy positioning (e.g., tectonics and sea-level change) and meteorological applications (climatology and weather forecasting).

Due to their non-dispersive nature and smaller magnitude, the estimation of tropospheric delay is very hazardous and require a refinement in the processing techniques of GPS data. Furthermore, the high spatial and temporal variability of the troposphere demands a sufficient number of ground GPS receivers to be used.

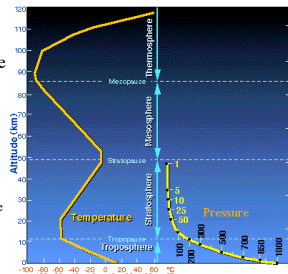
Dense GPS continuous networks provide therefore an opportunity to estimate the 3-dimensional state of the troposphere with a appropriate spatial and temporal resolution. Tomographic techniques are applied to obtain 3D images of the tropospheric refractive index using dense networks of GPS receivers in Japan (GEONET). We show how GPS data are processed to obtain the tropospheric delays and discuss the validity of the processing providing evidence that these techniques can yield horizontal and vertical structure of the atmospheric refractivity.

The tomography can be used for the calibration of the other remote-sensing techniques (e.g. SAR) and in numerical weather prediction models as additional data.

The troposphere

The troposphere is the lower part of the atmosphere extending from the Earth's surface to a height of approximately 15 km. This is an electrically neutral and non-dispersive medium for frequencies as high as about 30 GHz. Within this medium, group and phase velocities of the GPS signal on both L₁ and L₂ frequencies are equal.

Variation of the temperature and the pressure in atmosphere vs. altitude



Troposphere path delay

An electromagnetic signal propagating through the neutral atmosphere is affected by the constituent gases. The effect of the troposphere on GPS signals appears as an extra delay in the measurement of travel time from the transmitter to the receiver.

The troposphere propagation delay is defined as the difference between the electromagnetic path and the geometric path, neglecting the ray bending :

$$\Delta L_{trop} = \int n(s) ds - \int ds = 10^6 \int (n(s) - 1) ds$$

n is the refractive index of air and N the refractivity.

The resulting tropospheric delay is a function of atmospheric temperature, pressure, and moisture component. Without appropriate compensation, tropospheric delay will induce pseudo-range and carrier-phase errors from about 2 m for a satellite at zenith to more than 20 m for a low-elevation satellite.

The refractivity can be divided into hydrostatic and wet components. These 2 components have different effects on the propagation of the GPS signal. The hydrostatic component accounts for approximately 90% of the total tropospheric affect, and can be modeled to a large degree. The wet component, however varies considerably with time and location, and is notoriously difficult to model effectively. As most of the water vapor in the atmosphere occurs at heights less than 4 km, signals from low elevation satellites, which have a long propagation path length through the troposphere, are most affected.

Dense GPS networks

The high spatial and temporal variability of the troposphere demands dense ground network of GPS receivers to be used, in order to better estimate the 3-D structure of the troposphere, and therefore the induced path delay.

GPS observables and error sources

To achieve millimeter precision using GPS, it is necessary to analyze GPS pseudo-range or carrier phase measurements and eliminate or significantly reduce the biases and errors influencing the measurements. The major error sources of the GPS measurements are atmospheric refraction in the ionosphere and the troposphere, satellite orbit errors, clock biases, measurement errors (multipath bias and receiver noise), as well as reference station coordinates errors. Many of these errors can be eliminated (ionospheric refraction) or reduced (precise orbits and station coordinates). However, GPS measurement are still affected by several errors and the extraction of tropospheric delay is very difficult, even impossible to separate from satellite and station clocks biases.

Formulation of 3-D tropospheric tomography

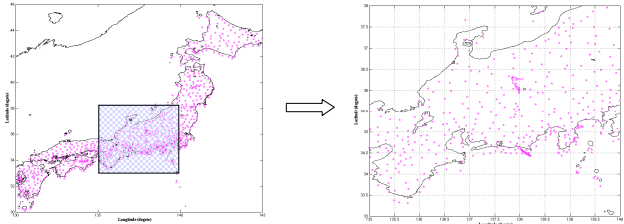
Our method consists in a joint least-square inversion of refractive index and satellites and receivers clock biases. The observable is expressed by

$$d_{sat,rec} = \Delta L_{trop} + c \cdot dt + c \cdot dT = \int n(s) ds + c \cdot dt + c \cdot dT = G \cdot m$$

where, dt and dT are clock error terms, ΔL_{trop} the tropospheric delay and n the refractive index. G is the path length from the receiver to the model space m.

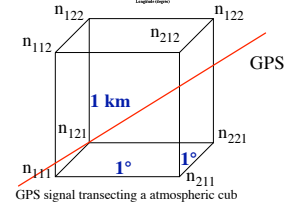
The Japanese GPS Earth Observation Network (GEONET)

The Japanese GPS permanent network consists of about 1000 dual-frequency receivers, collecting data with a 30 s sampling interval and with approximately 25-km mean distance between receivers.



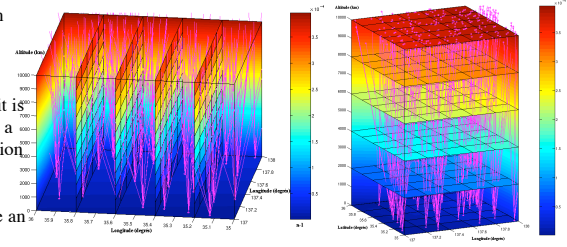
Tropospheric tomography

The atmosphere is divided into 11 layers whose thickness is one km. The atmosphere of interest is hence divided into 396 cubes (6*6*11). The resolution of each cub is 1°(longitude)* 1°(latitude)*1km (altitude).



Resolution test

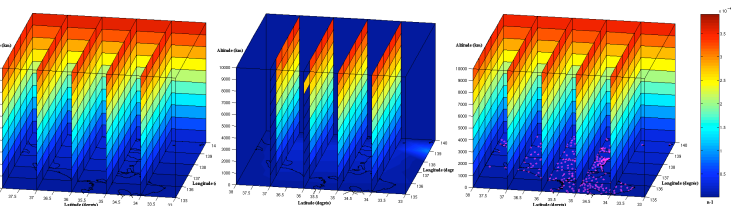
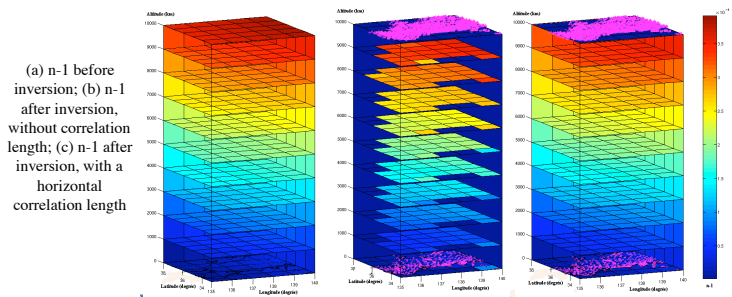
With 25-km mean distance between receivers and for elevation angles greater than 10°, it is possible to obtain a horizontal resolution of 25 km and to characterize the atmosphere above an altitude of 2 km.



Model of refractive index (n-1) used for this study. GPS rays transecting the atmosphere at a given time (March 28, 2000).

Model simulation results

The model of the refractive index used for our study is represented below (a). We estimated the excess path delay induced by this atmosphere for different receiver-satellites pairs at a given time. Then, we used the previous estimations of excess path delays as tomographic input data.



The reconstructed refractive index is very good. The retrieved atmospheric refractive index appears to be less accurate above oceans because of lack of GPS measurements.

Conclusion and perspectives

We present a formulation of GPS tropospheric tomography and a way to produce the slant excess path delay as tomographic data using processed GPS data.

Our study shows that dense GPS networks enable the recording of the 3-dimensional structure of the troposphere with a sufficient resolution to detect and estimate the short scale variability.

Realization of the proposed tropospheric tomography could improve atmospheric forecasting through assimilating the retrieved refractive index into numerical weather prediction models and the accuracy of geodetic techniques providing thus the estimation of the induced tropospheric delay.