Weather and Climate: Signal and Noise for Geodesy

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Abstract

The impact of the atmosphere on space geodetic techniques, like GNSS and VLBI, is reviewed. It is described how the atmospheric delays can be modelled in the data analysis of the space geodetic observations, and the limits of this modelling due to atmospheric turbulence are discussed. Furthermore, the possibility to use GNSS and VLBI can be used for atmospheric studies, e.g. for meteorology or in climate research are described.

Keywords: GNSS, VLBI, tropospheric delay, meteorology

Kurzfassung

Dieser Artikel gibt einen Überblick über die Einflüsse der Erdatmosphäre auf die Signale der geodätischen Weltraumverfahren wie GNSS und VLBI. Es wird erklärt und diskutiert, wie die Laufzeitverzögerung in der Auswertung von weltraumgeodätischen Beobachtungen modelliert wird, und wie die atmosphärische Turbulenz Grenzen für diese Modellierung setzt. Zusätzlich wird die Möglichkeit beschrieben, wie GNSS und VLBI für atmosphärische Studien verwendet werden können, z.B. in der Meteorologie oder in der Klimaforschung.

Schlüsselwörter: GNSS, VLBI, troposphärische Laufzeitverzögerung, Meteorologie

1. Introduction

The Earth's atmosphere is one of the most important error sources for space geodetic techniques like geodetic Very Long Baseline Interferometry (VLBI) and Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS). In order to obtain accurate results using these techniques, e.g. for the station coordinates, it is important that the atmospheric effects are modelled as good as possible. Since the atmospheric properties are highly variable – especially the water vapour content – this is a challenging task. On the other hand, the fact that the space geodetic observations are affected by the atmosphere also makes it possible to use space geodetic techniques to study the atmosphere. For example, GNSS and VLBI have turned out to be good techniques for measuring the amount of water vapour in the atmosphere, a quantity which is of great interest for meteorology and climatology.

This paper discusses how the atmosphere can be modelled in the data analysis of space geodetic observations (Section 2). The description concentrates on the microwave techniques such as GNSS and VLBI. For optical techniques such as Satellite Laser Ranging (SLR) the situation is slightly different (no ionospheric delay, less impact of water vapour), see e.g. [1] for more information about atmospheric modelling in SLR. The paper also describes some applications of GNSS and VLBI for atmospheric studies (Section 3).

2. Atmospheric delays

As the signals of space geodetic techniques propagate through the Earth's atmosphere, they are affected by it. In the atmosphere, the signals are propagating slower than in vacuum, their paths are refracted, and they are attenuated. Since space geodetic techniques observe the travel time of the signals, the attenuation is not very important as long as the signals can be detected without problem. On the other hand, refraction and the decrease of the propagation velocity both affect the travel time (see Figure 1), causing a delay of the signals compared to if there would have been no atmosphere. These delays need to be considered when analysing space geodetic observations.

The atmospheric delay, ℓ_{atm}, of a signal can be expressed as:

$$\ell_{atm} = 10^{-6} \int_S N(s)\,ds + \left[S - G\right] \qquad (1)$$

where N is the so-called refractivity of the atmosphere, S is the (bended) propagation path of the signal, and G is the geometric path length of the signal (the path the signal would have taken in vacuum). When considering the atmospheric delays of space geodetic signals the atmosphere is commonly divided into two parts: the ionosphere and the troposphere.

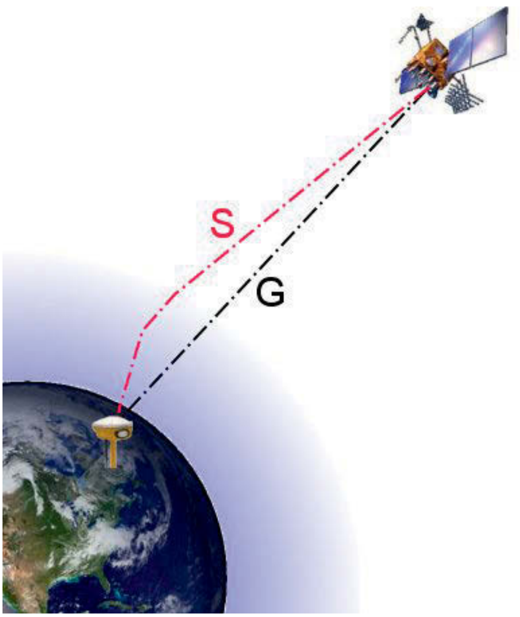

Fig. 1: The signals used by space geodetic techniques are delayed in the Earth's atmosphere because (i) the propagation speed in the atmosphere is lower than in vacuum, and (ii) the propagation path S is longer than the geometric path G.

2.1 Ionospheric delays

The upper part of the atmosphere consists of free electrons and ions and is called the ionosphere. The ionosphere is a dispersive medium meaning that the refractivity – and thus also the ionospheric delay – is frequency dependent. Approximately the ionospheric delay is proportional to f^2, where f is the frequency. Hence, measurements at two different frequencies (f_1 and f_2) can be combined into an ionospheric free combination:

$$\ell_{if} = \frac{f_1^2\,\ell_{atm}(f_1) - f_2^2\,\ell_{atm}(f_2)}{f_1^2 - f_2^2} \quad (2)$$

Since both GNSS and VLBI use (at least) two frequencies, this combination can usually be applied to get rid of the ionospheric effects. For conditions with high ionospheric activity it may be necessary also to consider higher order terms (f^3 etc.) [2], at least for techniques using relatively low frequencies (<2 GHz) such as GNSS.

2.2 Tropospheric delays

The lower part of the atmosphere is neutral and is called the neutral atmosphere or the troposphere. The troposphere is non-dispersive for microwaves, thus the refractivity is frequency independent and thus it is not possible to remove the tropospheric delay using measurements at several different frequencies. Hence it needs to be modelled in the data analysis. The refractivity in the troposphere is a function of the atmospheric density ρ, the partial pressure of water vapour p_w, and the temperature T [3]:

$$N = k_1 \rho R_d + k'_2 \frac{p_w}{T} + k_3 \frac{p_w}{T^2} \quad (3)$$

where R_d is the specific gas constant of dry air and k_1, k'_2, and k_3 are constants. Normally the refractivity is divided into a hydrostatic part N_h and a wet part N_w ($N=N_h+N_w$), where N_h depends only on ρ (first term in eq. (3)) while N_w only depends on p_w and T (second and third term of eq. 3). Subsequently the atmospheric delay are also divided into a hydrostatic part ℓ_h and a wet part ℓ_w.

Since the horizontal variations in the refractive index and the bending are relatively small, the atmospheric delay is approximately proportional to the geometrical distance travelled by the signal through the atmosphere. Thus, for elevation angles ε above 20° (were the curvature of the atmosphere can be ignored) ℓ_{atm} is proportional to 1/ sin(ε). Since the partial derivative of the travel time w.r.t. the vertical coordinate of the receiving antenna is proportional to sin(ε), it is obvious that there will be errors in the especially vertical coordinate estimates if the atmospheric delay is not corrected for.

2.3 Modelling of atmospheric delays in space geodesy

There are basically two ways of correcting for the atmospheric delays in the data analysis of space geodetic observations: The first method is to use external information about the tropospheric delay. External tropospheric delays can be obtained from ray-tracing through numerical weather prediction models (see e.g. [4] and references therein) or measured by other instruments such as water vapour radiometers [5]. A problem is that neither numerical weather prediction models nor other instruments are free from errors, and these errors will degrade the accuracy of the coordinates and the parameters estimated with the space geodetic techniques. Furthermore, external instruments for measuring tropospheric delays can be expensive and may not be able to operate under all weather conditions. For example, water vapour radiometers do not give reliable results during rain.

The other method is to estimate the tropospheric delays in the space geodetic data analysis. For high accuracy applications, this is the commonly used approach. To do this the atmospheric delays need to be parameterised as functions of the observation direction. The most common parameterisation is to model the tropospheric delay as function of the zenith hydrostatic delay ℓ^z_h, the zenith wet delays (ZWD) ℓ^z_w, and horizontal north and east gradients (G_n and G_e):

$$\begin{aligned}\ell_{atm} &= m_h(\epsilon)\,\ell^z_h + m_w(\epsilon)\,\ell^z_w \\ &+ m_h(\epsilon)\cot(\epsilon)\left[G_n\cos(\alpha) + G_e\sin(\alpha)\right]\end{aligned} \quad (4)$$

where α and ε are the azimuth and the elevation angles, respectively, and m_h and m_w are the hydrostatic and wet mapping functions (see e.g. [6]). The zenith hydrostatic delay can accurately be estimated from surface pressure measurements [7], while the zenith wet delay and the gradients need to be estimated in the data analysis. The temporal variations of these quantities are normally modelled using piece-wise linear functions (or as a random walk process if a Kalman filter is used for the estimation). The problem in this approach is that there are more unknown parameters to be estimated in the data analysis, i.e. the degree of freedom is increased and thus the formal uncertainties of the estimates will be higher. Hence it gets even more important to have many observation with a good coverage of the sky above the station.

2.4 Atmospheric turbulence

The model for the tropospheric delay presented in eq. (4) is only an approximation because it assumes that the horizontal variations in the refractivity are linear. However there are non-linear small-scale variations in the refractivity caused by atmospheric turbulence. These variations are in principle impossible to model exactly, thus atmospheric turbulence will limit the accuracy that can be achieved by space geodesy. One way to investigate the impact of atmospheric turbulence on the space geodetic results is to use simulations. A method for simulating tropospheric delays of a turbulent atmosphere was presented by [8]. This method assumes that the atmospheric turbulence can be described using the theory of Kolmogorov turbulence [9], i.e. the structure function for the variations in the refractivity between r and $\mathrm{r} + \mathrm{R}$ is given by:

$$\left\langle \left[N(\mathrm{r}) - N(\mathrm{r}-\mathrm{R})\right]^2 \right\rangle = 10^{12} C_n^2 \,|\,\mathrm{R}\,|^{2/3} \quad (5)$$

where C^2_n is called the refractive index structure constant and $\langle\cdot\rangle$ denotes expectation value. Temporal variations can be modelled by assuming these are caused by the air moving with the wind. Examples of simulated wet tropospheric delays are shown in Figure 2. In these simulated delays small scale variations which cannot be modelled by eq. (4) can be seen.

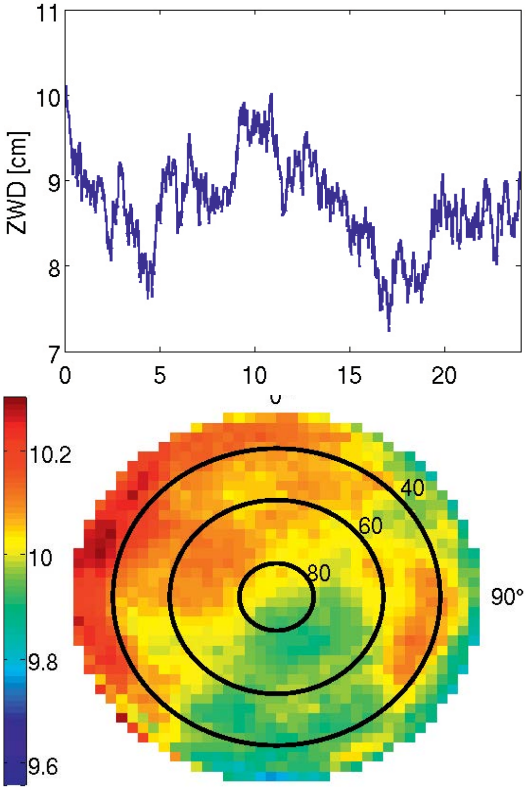

Fig. 2: Top figure shows simulated zenith wet delays for a 24 h long period. The bottom figure shows simulated equivalent zenith wet delays (slant wet delays divided by a mapping function) as function of direction. The delays were simulated using the method presented in [8], with $C^2n = 1\cdot 10^{-14}\ m^{-2/3}$, effective tropospheric height H=2 km, and wind velocity 8 m/s.

In [8] VLBI observations were simulated considering the three most important random error sources for geodetic VLBI: tropospheric turbulence, clock errors, and observation noise. Tropospheric turbulence was found to be the most important error source for the current VLBI system. Similar simulations was performed in [10], aimed at evaluating the performance of the future VLBI system, VLBI2010. It was found that atmospheric turbulence will still be the major error source and the limiting factor for the accuracy of station coordinates estimated using this system. If the goal of VLBI2010 (1 mm station position accuracy) are to be reached the modelling of the atmospheric delays needs to be improved.

3. Using space geodetic techniques for atmospheric studies

As mentioned in section 2.3 the normal way of handling the tropospheric delays in the data analysis is to estimate them as functions of ZWD and gradients. Although these parameters are normally considered as nuisance parameters by geodesist, they contain interesting information about the atmosphere. Most importantly, the ZWD are strongly related to the integrated water vapour content (IWV) above the observing station [11]. Several studies have been performed to evaluate the accuracy of the ZWD (or IWV) estimated from space geodetic techniques [12, 13]. In general it has been found that the ZWD obtained from GNSS and VLBI are at least as accurate as those obtained from other techniques (e.g. water vapour radiometers, radiosondes, numerical weather prediction models). Thus there is a big interest of using the tropospheric parameters estimated from space geodetic techniques e.g. in meteorology or for climate studies.

3.1 GNSS meteorology

In meteorology water vapour is a very important parameter, and good knowledge of its distribution in the atmosphere is needed for weather forecasts. Since the water vapour content is highly variable, continuous monitoring with high spatial resolution is needed. However, typical meteorological instruments for measuring the IWV – such as radiosondes – are relatively expensive to operate. Hence there exists a big interest from the meteorological community to use IWV estimated from the dense national networks of GNSS stations that have been established in the last decades (see Figure 3 for a map of some of the permanent GNSS stations in Europe). Several studies have been performed investigating how to best assimilate the GNSS results in the numerical weather prediction models and evaluating the impact on the weather forecasts (see e.g. [14, 15]). It has been shown that GNSS IWV improves the weather forecasts, especially for extreme weather conditions.

There are also attempts to use GNSS to also estimate the 3D structure of the tropospheric water vapour, so-called GNSS tomography. This is done by applying tomographic methods to the

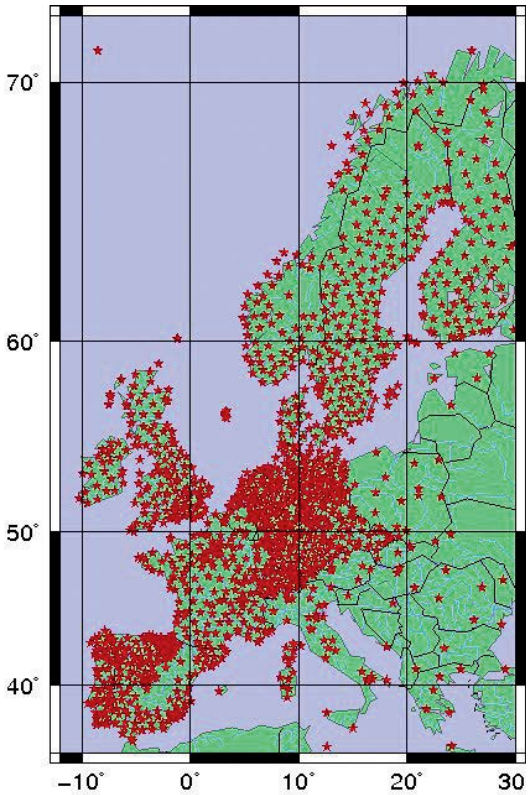

Fig. 3: Some of GNSS stations in Europe. The stations shown are those used in the E-GVAP project (http://egvap.dmi.dk/).

slant wet delays observed at several GNSS stations in a very dense (< 10 km baselines) network. Several implementations of this technique have been presented (e.g. [16, 17]). However, several problems still need to be resolved, like how to estimate the slant wet delays or how to handle the normally weak geometry of the observations (all stations are on the surface of the Earth and all satellites are above the top of the troposphere).

3.2 Climate studies

Water vapour is also an important parameter for climate research. It is the most important greenhouse gas, and the water vapour content in the atmosphere is (over longer time-scales) strongly correlated with the temperature. Thus water vapour will amplify warming caused by e.g. other greenhouse gases, and in order to predict the future climate this feedback mechanism needs to be well understood. Furthermore, this also means that a long-term increase of water vapour content is an indication of an increase in the temperature. Thus the atmospheric water vapour

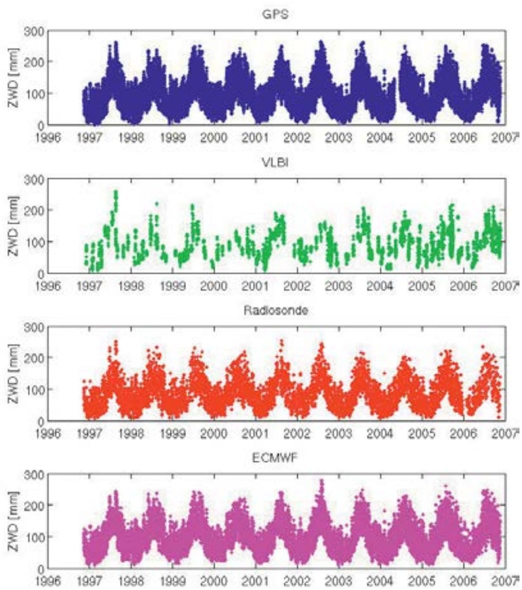

Fig. 4: Time series of ZWD estimated from various instruments at the Onsala Space Observatory, Sweden: GPS, VLBI, radiosondes, and ECMWF data.

content needs to be monitored with a high long-term stability, which is difficult to achieve. Space geodetic techniques could potentially provide the needed stability.

Several investigations on measuring long-term ZWD/IWV trends using GNSS and VLBI have been performed (see [18] and references therein). Figure 4 shows the ZWD measured over a 10 year long period using four techniques – measured by GPS, VLBI, and radiosondes, and calculated from ECMWF numerical weather analysis data – at the Onsala Space Observatory on the Swedish west coast. The ZWD trends calculated from these time series are shown in Table 1. The trends calculated using all data for each technique do not agree with each other. This is because of the short time period (in climatology normally only time periods of 40 years and longer are considered), making the estimated trends very sensitive to the exact time epochs with ZWD measurements. The different techniques have different temporal resolutions which have varied over the time intervals, e.g. in 1996 there were sometimes four radiosonde launches per day, in 2006 normally only one. If the trends of two techniques calculated using only data from time epochs where both techniques observe, the agreement improves (except for ECMWF).

Technique	Trend [mm/yr]
GPS	0.38
VLBI	1.06
Radiosonde	0.27
ECMWF	0.00
Common epochs GPS and VLBI	
GPS	1.12
VLBI	1.09
Common epochs GPS and Radiosonde	
GPS	0.42
Radiosonde	0.32
Common epochs GPS and ECMWF	
GPS	0.31
ECMWF	0.01

Tab. 1: ZWD trends 1996-2006 calculated from the time series shown in Figure 4

4. Conclusions

As discussed in this paper, the signals used by space geodetic techniques are delayed in the troposphere. This delay needs to be accurately modelled in the data analysis in order to avoid large errors in the results (e.g. the coordinate estimates). Nevertheless, since the accuracy that the tropospheric delay can be modelled with is limited (e.g. small-scale fluctuations due to turbulence cannot be modelled), the troposphere will in the end limit the precision that can be achieved. This is true for the current space geodetic systems, and will most likely be even more true for future systems. If future goals of 1 mm position accuracy are to be reached it is important to improve the modelling of the tropospheric delays.

However, the tropospheric delays are not only causing problems, they also open up new applications of space geodesy. The tropospheric delay estimates obtained from the analysis of GNSS and VLBI data have turned out to be useful for example in meteorology. Hence the troposphere can be considered both as signal and as noise for the space geodetic techniques, depending on the application.

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