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Sounding the Earth's Atmospheric Water Vapour Using Signals Emitted by Global Navigation Satellite Systems



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Biography

Biography

In 1998, the author received a Master's degree in Mathematics from the Université Catholique de Louvain (UCL), Belgium, for studying images of the Sun taken by the Extreme ultraviolet Imaging Telescope (EIT) on board of SOHO, using wavelet analysis. Since then, he worked on the interaction between the Earth's atmosphere and the GNSS signal propagation within the GNSS research group of the Royal Observatory of Belgium [ROB GNSS Web Site].

From 1999 onwards, the author has taken part in European actions and programs (COST-716, TOUGH, E-GVAP) targeting the exploitation of ground-based GNSS observations for meteorological and climate applications. Today, in the framework of the Solar-Terrestrial Centre of Excellence, he acts as Belgian delegate in the geodetic expert team of the *EUMETNET EIG GNSS Water Vapour Program II* (E-GVAP II) and he is responsible for the Belgian geodetic contribution to this project [E-GVAP Web Site].

The work presented in this dissertation led to several communications and publications in international peer-review journals. In 2008, the author's work on "Detecting small-scale tropospheric phenomena using GNSS observations from dense national networks" was awarded with the "Best student poster award" during the EUREF Symposium 2008.

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*Demain ne sera pas comme hier. Il sera nouveau
et il dépendra de nous. Il est moins à découvrir
qu'à inventer.*



Phénoménologie du temps et prospective
Gaston Berger

*If we knew what it was we were doing, it
would not be called research, would it?*

Albert Einstein (1879-1955)

1

Preface

1.1 Atmospheric Delay: Noise or Signal?

Advances in *Global Navigation Satellite System* (GNSS) technologies and state-of-the-art analysis techniques allow us today to reach from millimetre to centimetre precision in position determination, depending on the type of application (near real-time, rapid or post-processing). To reach this level of precision, the effect of all error sources affecting GNSS signals must be removed, or at least properly mitigated. Among them, the Earth's atmosphere remains the main error source limiting GNSS precise positioning. Indeed, as they are propagated from outer space towards the Earth's surface, the GNSS signals traverse different atmospheric layers and interact with them. The atmospheric refraction bends the signal path and alters the propagation speed of the signals. It induces errors of the order of several metres in positioning. The atmospheric refraction effect on GNSS signals is bound, on one hand, to the influence of the ionised part of the atmosphere (the *ionosphere*) and, on the other hand, to the influence of the neutral atmosphere (usually referred to as the *troposphere*).

Ionospheric Refraction

The *ionosphere* is the region of the atmosphere that extends from about 70km above the ground surface to more than 1000km (Figure 1.1). It is a shell of electrons and electrically charged atoms and molecules that surrounds the Earth. It is a dispersive medium in the GNSS-frequency band and consequently, GNSS signals (carrier-waves and modulations) propagate in it at different speeds, depending on their frequencies. As it will be shown in Chapter 2, the ionospheric refraction effect is mitigated at first-order during the processing of the GNSS observations by using dual frequency GNSS signals.

Tropospheric Refraction

The *troposphere* is the lowest region of the Earth's atmosphere and extends from the ground surface up to about 8km at the poles and up to about 17km at the Equator [Houghton, 1986]. This layer is thin compared to the height of the entire atmosphere but it is also the densest region: it contains about 75 % of the total atmospheric mass and 99 % of its water vapour and aerosols. Therefore, the neutral atmosphere (which extends from the ground surface up to about 50km) is usually referred to as the troposphere. In this work, we will often use the word “troposphere“ to refer to the entire neutral atmosphere. The composition of the latter consists of a mixture of gases, solid particles (aerosols) and liquid particles, in which nitrogen and oxygen account for more than 90 % at sea level. The nature of tropospheric components is such that this region of the atmosphere is non dispersive for electromagnetic waves with a frequency lower than 15 GHz [Baueršima, 1983]. As a consequence, the tropospheric refraction effect cannot be mitigated by a linear frequency combination, as it is the case

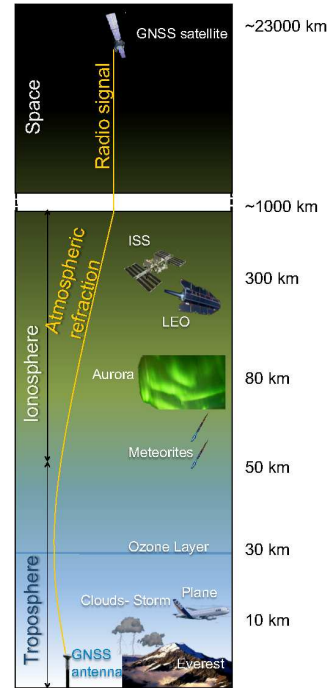


Figure 1.1: Vertical structure of the Earth's atmosphere

for ionospheric refraction and must be modelled or estimated during GNSS observation analysis.

As it will be shown in Chapter 3, the tropospheric refraction is commonly separated into two components. The first component, the *hydrostatic* or *dry component*, mainly depends on the profile of the atmospheric pressure along the signal propagation path. At the present time, the dry component of the tropospheric refraction error can be modelled with sufficient accuracy based on surface meteorological measurements. The second component, the *non-hydrostatic* or *wet component*, depends on the partial pressure profile of water vapour along the signal propagation path. The atmospheric water vapour is a physical quantity that rapidly and strongly varies in both space and time. Moreover, its spatial distribution and its time evolution do not follow simple physical laws. Therefore, the wet component of the tropospheric error cannot be properly modelled based on surface meteorological measurements: the effect of the wet tropospheric refraction on GNSS signal propagation must be parametrised during the processing of the GNSS observations.

The Inverse Problem

“One man’s noise is another man’s data”

While in high-accuracy positioning applications, atmospheric refraction is a disturbance that needs to be removed or at least properly mitigated, one can consider the inverse problem: when using stations with (accurately) known positions, the effect of atmospheric refraction on GNSS signal propagation can be retrieved and thereby, becomes a source of valuable information for studying the atmosphere. This is the basis of ground-based GNSS atmospheric remote sensing.

1.2 GNSS-Meteorology

Atmospheric Water Vapour

In the case of the wet tropospheric delay, the key physical parameter is atmospheric water vapour. As the major greenhouse gas present in the Earth's atmosphere, water vapour plays an important role in climate models and in the global warming process [Desbois and Roca, 2000; Elgered *et al.*, 2007]. It is also one of the driving forces of convection and obviously plays a crucial role in several atmospheric processes such as the development of clouds and precipitation. The water vapour content is highly variable due to temperature changes, micro-physical processes (such as cloud formation) and atmospheric circulation [de Haan, 2008]. Water vapour is thus a key parameter in *Numerical Weather Prediction* (NWP) models and in *nowcasting*¹ applications. In these models, the humidity field information is usually provided by surface and radiosonde observations. The spatial and temporal resolutions of these two techniques are not good enough to properly observe the high variability of water vapour distribution in space and time. Ground-based GNSS is a low-cost tool that provides continuous, high temporal and spatial resolution measurements of tropospheric Zenith Path Delays (ZPD), from which valuable information about the atmospheric water vapour can be obtained and then used in meteorology.

The Road to GNSS-Meteorology

The principle of ground-based GNSS-meteorology was first outlined in 1992 by Bevis *et al.* and was rapidly followed by several studies [Rocken *et al.*, 1993; Bevis *et al.*, 1994; Rocken *et al.*, 1995; Businger *et al.*, 1996]. In 1998, the European Cooperation in the Field of Scientific and Technical Research (COST) action 716 "*Exploitation of ground-based GPS for climate and numerical weather prediction applications*" was started and the *Royal Observatory of Belgium* (ROB) joined this action. The primary objective of the action was :

¹Nowcasting are qualitative short-term weather predictions (usually within the next 6 hours)

"The assessment of the operational potential on an international scale of the exploitation of ground-based GPS system to provide near real-time observations for Climate and Numerical Weather Prediction applications" [COST-716 Members, 2004]

The COST-716 action stimulated the collaboration between the geodesists and the meteorologists at both the European and the national level and promoted the use of ground-based GNSS tropospheric ZPD in meteorology and climatology. COST-716 also came up with a list of basic requirements to which the GNSS tropospheric ZPD must adhere to in order to be of benefit to these meteorological applications. The action successfully ended in 2004. The COST-716 action was then followed by the European Commission TOUGH project *"Targeting Optimal Use of GPS Humidity Measurements in Meteorology"*. Within TOUGH, a new research area was addressed: the investigation of the possibilities to determine tropospheric slant path delay information from GNSS and to assimilate them into NWP models [van der Marel and Gündlich, 2006; Eresmaa and Järvinen, 2006; Järvinen *et al.*, 2007]

From Demonstration to Operation Phase

The success and the knowledge gained during these two initiatives made GNSS-meteorology a valuable source of information for NWP and nowcasting. Therefore, the people involved in these projects decided to continue their activities and to go towards an operational status within the *Network of European Meteorological Services* (EUMETNET). In 2005, the *EUMETNET GPS Water Vapour Program* (E-GVAP) was set up to collect, on a European scale, near real-time ground-based GNSS tropospheric ZPD estimates and to provide this information to its EUMETNET partners for data assimilation in operational meteorology [Vedel, 2007]. Within E-GVAP, the geodetic community plays an important role by operating the GNSS analysis centres, which provide the GNSS tropospheric ZPD estimates in near real-time. Today, a number of European *National Meteorological Services* (NMS) are actually assimilating operationally near real-time (NRT) GNSS tropospheric ZPD estimates in their regional models [Poli *et al.*, 2007; Jupp, 2006]. Within E-GVAP, this is notably the case of the *Koninklijk Nederlands Meteorologisch*

Instituut (KNMI), Danish Meteorological Institute (DMI), the U.K. Met office and Meteo France.

1.3 Objectives and Outline of the Thesis

The research presented in this thesis was carried out with the **primary objective** of *developing a state-of-the-art analysis strategy to provide ground-based GNSS near real-time (NRT) tropospheric ZPD from a regional network of European permanent stations to be used in operational meteorology*, more particularly in *Numerical Weather Prediction (NWP)* and *nowcasting* applications. A **secondary objective** is that the analysis strategy should be adapted to *set up and maintain an operational analysis centre at ROB in order to provide the meteorologists with NRT tropospheric ZPD estimates and to participate in E-GVAP*. The thesis dissertation is structured as followed:

Chapter 2 sets out the fundamentals of GNSS. It introduces the GNSS constellations, the signals and the observables, as well as the primary error sources acting on GNSS measurements and the way to mitigate them. The chapter ends with a description of the GNSS observation networks and GNSS products used throughout this work.

Chapter 3 focuses on the interaction between the neutral atmosphere and GNSS signal propagation and presents the general formulation of the tropospheric path delay functional model used to develop our GNSS analysis strategy.

Chapter 4 discusses the analysis strategy that we developed to provide the meteorologists with NRT tropospheric ZPD estimates. In this chapter, we also review the requirements imposed on the GNSS tropospheric products to bring benefits in NWP and nowcasting applications. Finally, the sensitivity of the analysis strategy in regard to several processing options is studied and the methodology is optimised accordingly.

Chapter 5 validates the analysis strategy and assesses its performance with respect to the requirements imposed on GNSS-meteorology. In that process, we emphasise the challenges raised by acting as an analysis centre for operational GNSS-meteorology.

In *Chapter 6*, the methodology that has been developed is applied to a nowcasting case: we investigate the added-value brought by processing GNSS observations from national densification networks to access the small-scale structures related to severe weather phenomena.

Finally, *Chapter 7* summarises the research carried out during the thesis and the conclusions to be drawn from this. Some perspectives for further research are also outlined and several recommendations are made.

A problem well stated is a problem half solved.

Charles Franklin Kettering (1876-1958)

2

Fundamentals of Global Navigation Satellite Systems

Summary

This second chapter sets out the fundamentals of Global Navigation Satellite Systems (GNSS) based on the existing literature and using as example the well-known Global Positioning System (GPS). More particularly, the system design, the signal structure, the basic observables and the important error sources acting on the measurements are briefly described. The chapter ends with a short description of the GNSS observation networks and products used in the thesis.

2.1 Introduction

The main objective of *Global Navigation Satellite Systems* (GNSS) is to allow any owner of the proper equipment to determine his position in real-time, within a few meters accuracy, everywhere on Earth, at anytime, in a global reference frame and so whatever the atmospheric conditions could

be. Nowadays, GNSS consists mainly of the American *Global Positioning System - Navigation Satellite Timing and Ranging* (GPS-NAVSTAR) and the Russian *GLObal'naya NAVigatsionnaya Sputnikovaya Sistema* (GLONASS). As the first goal of GNSS is to determine positions in real-time, within a few meters accuracy, these systems naturally found their place in geodesy and geophysics. Indeed, GNSS also allows to compute positions in post-processing with a precision of 2 mm to 3 mm and 7 mm for the horizontal and vertical components respectively. The high level of precision and accuracy achieved by GNSS in the position determination revealed to be of great interest in geodesy and geophysics where high-quality positioning is required, e.g. reference frame realisation, plate tectonic and seismic fault monitoring, volcano deformations... GNSS has thus gradually become a practical "low-cost" tool in many Research and Development (R&D) areas, including atmospheric sciences such as meteorology and climatology (see preface). GPS and GLONASS were however designed around the 70's computer processing capability and electronics. Today, advances in GNSS satellite and receiver technology allow space for modernisation of existing systems and for the creation of new GNSS. Within the next years, GPS and GLONASS will undergo several modernisation steps. New generation of satellites will provide additional signals and superior performances in terms of precision, accuracy, reliability and availability. In addition to the existing systems, the new European Galileo and the Chinese COMPASS will complement the existing GNSS within the next years. The modernised and new GNSS will even more enlarge the GNSS field of applications and increase the performances of existing applications, including GNSS-meteorology, by providing access to new and improved signals and by providing an increased number of observations thanks to the interoperability of the different GNSS.

2.2 Constellations

The first GPS prototype satellite was launched on the 22th February 1978 and the *Full Operational Capability* (FOC) was formally declared on the 17th July 1995. As on the 15th May 2009, 31 GPS satellites (24 + 7 spares) are in orbit [GPS Constellation Status; GPS Yuma Almanacs]. The development of

a Russian GNSS began in 1976, with a first test-satellite launched the 12th October 1982. The GLONASS constellation was completed in 1995 (FOC). Following completion, the system rapidly fell into disrepair with the collapse of the Russian economy. Beginning 2001, Russia committed to restore the system. As on the 15th May 2009, 19 GLONASS satellites were orbiting the Earth [GLONASS Constellation Status; GLONASS Almanacs]. According to the Russian Federal Space Agency, 9 satellites should be launched in 2010 and complete the GLONASS constellation. As far as new GNSS are concerned, two test-technology *Galileo-In-Orbit Validation Element* (GIOVE) A & B have already been launched on the 28th December 2005 and the 27th April 2008 respectively. By early 2014, Galileo is expected to achieve its FOC. At that time, about 85 GNSS satellites should be available. In China, the first COMPASS M-1 satellite was launched on the 14th April 2007 and a second COMPASS satellite followed on the 15th April 2009. China plans to complete COMPASS by launching 30 more orbiters by 2015 [COMPASS FOC] but at the moment only few information can be found on the Chinese system.

Table 2.1 summarises the main characteristics of the 3 GNSS constellations for which information is available, i.e. GPS, GLONASS and Galileo. As it is shown in the table, the three systems are composed of medium Earth orbiters but differ by the number of satellite vehicles (SV), the number of orbital planes, their inclinations with respect to (wrt.) the equator... Despite their differences, the three systems are designed in such a way that at least 6 satellites are simultaneously observable at anytime and everywhere on Earth. If the systems have been thought to be self-sufficient, more and more emphasis has been put in the past years on their complementarity and their interoperability to improve their integrity, their reliability and their performances. The orbital periods are different for each system, such that the ground-track repeatability is also different. This might be useful when processing multi-GNSS observations notably to detect and/or mitigate periodic error sources linked to the constellations such as multipath and orbit mis-modelling. Finally, the reference systems and the system times are also different for the three systems. Transformation between the 3 reference systems and between the 3 time realisations will have to be computed to process multi-GNSS observations. As it will be shown in the next section, the modernised GPS and GLONASS and the new Galileo systems will also

share common signal(s) to ensure this interoperability. More details on the 3 GNSS constellations can be found in [GPS-ICD, 1993; GLONASS-ICD, 2002; GALILEO-ICD, 2006].

	Modernised GPS	Modernised GLONASS	Galileo
Reference system	<i>World Geodetic System 1984 (WGS-84)</i>	<i>Parametry Zemli 1990 (PZ-90)</i>	<i>International Terrestrial Reference System (ITRS) (GTRF)</i>
Satellite identification method	<i>Code Division Multiple Access (CDMA)</i>	<i>Frequency Division Multiple Access (FDMA)</i>	<i>Code Division Multiple Access (CDMA)</i>
Time scale	<i>Coordinated Universal Time (UTC) from USNO</i>	<i>Coordinated Universal Time (UTC) from S.U.</i>	<i>Galileo System Time (GST)</i>
Broadcasted clock model	Clock offset, frequency offset and frequency rate	Clock and frequency offsets	Clock offset, frequency offset and frequency rate
Broadcasted orbit data	Modified Keplerian orbital elements updated every hour	Satellite positions, velocities and accelerations updated every half an hour	Keplerian orbital elements updated every 3 hours
Number of satellites (in FOC)	24 (+6 spares)	21 (+3 spares)	27 (+3 spares)
Current number of satellite	31	19	2
Number of orbital planes	6	3	3
Orbital plane inclination to equator	55°	64.8°	56°
Angle between orbital planes	60°	120°	120°
Satellite slots per orbital plane	4, unevenly spaced	8, evenly spaced	9 (+1 spare), evenly spaced
Semi-major axe	26560km	25440km	29994km
Orbital period	11h58	11h16m	about 14h04m
Ground-track repeatability	1 sidereal : days	8 sidereal days	10 sidereal days

Table 2.1: Characteristics of the 3 main GNSS constellations
Sources: [GPS-ICD, 1993; GLONASS-ICD, 2002; GALILEO-ICD, 2006]

2.3 Signal Structure

The basic GNSS observable is the propagation time of L-band microwave signals between the moment of emission at the satellite and the moment of reception at the ground receiver antenna. The main characteristics of these signals are summarised in Table 2.2. The three systems are equipped by atomic clocks that are used to generate a stable fundamental frequency f_0 common to all satellites and all systems. This fundamental frequency allows to define and to keep a very stable time scale for the system and

allows the synchronisation of all observations. Each satellite also generates the *fundamental carrier-frequencies* modulated by binary *Pseudo-Random Noise* (PRN) codes and by a *navigation message* (NAV) (Figure 2.1). Each chip of the PRN-codes corresponds to an epoch of the GNSS time scale, allowing consequently to transport the GNSS time scale realisation everywhere on Earth. A unique PRN-code is attributed to each GPS and Galileo satellite. The uniqueness of the PRN-codes allows all satellites to share the same carrier-frequencies and permits the receiver to discriminate between the signal sources using the code signatures. This technique is called the *Code Division Multiple Access* (CDMA) [Kaplan and Hegarty, 2005]. In the case of GLONASS, all satellites transmit the same PRN-codes but uses different *carrier-frequencies*. The receiver discriminates the signal sources using the *Frequency Division Multiple Access* (FDMA) [Kaplan and Hegarty, 2005]. The NAV is a binary-code modulated onto the *carrier-frequencies* to broadcast the satellite ephemeris, the constellation health-status, the GNSS time, the UTC-GNSS transformation parameters (leap seconds), the satellite clock synchronisation parameters, the constellation almanac, the ionosphere model parameters... Typically, the same navigation message is transmitted for 1 to 2h, and then updated [Spilker, 1996].

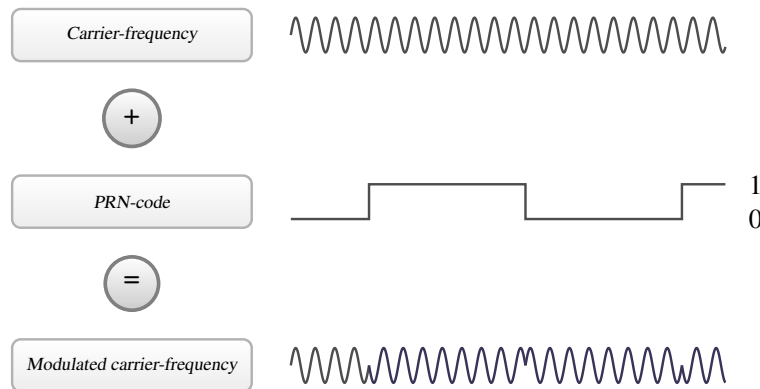


Figure 2.1: Principle of binary phase modulation

	Modernised GPS			Modernised GLONASS			Galileo		
	Name	Central Frequency	Wavelength	Name	Central Frequency	Wavelength	Name	Central Frequency	Wavelength
1 st Carrier	<i>L1</i>	1575.42 MHz	19.05 cm	<i>G1</i>	1602.00 MHz	18.73 cm	<i>E1</i>	1575.42 MHz	19.05 cm
2 nd Carrier	<i>L2</i>	1227.60 MHz	24.43 cm	<i>G2</i>	1246.00 MHz	24.08 cm	<i>E6</i>	1278.75 MHz	23.46 cm
3 rd Carrier	<i>L5</i>	1176.45 MHz	25.50 cm	<i>G3</i>	1201.50 MHz	24.89 cm	<i>E5</i>	1191.79 MHz	25.17 cm

(a) New and modernised radio-frequency carriers

	Modernised GPS		Modernised GLONASS		Galileo	
	Name	Wavelength	Name	Wavelength	Name	Wavelength
1 st Carrier	<i>C/A</i>	293.1 m	<i>SP</i>	586.2 m	<i>E1A</i>	117.27 m
	<i>L1C</i>	293.1 m			<i>E1B</i>	293.1 m
	<i>P(Y)</i>	29.31 m	<i>HP</i>	58.62 m	<i>E1C</i>	293.1 m
	<i>L1M</i>	146.55 m				
2 nd Carrier	<i>L2C</i>	29.31 m	<i>SP</i>	586.2 m	<i>E6A</i>	
	<i>P(Y)</i>	29.31 m	<i>HP</i>	58.62 m	<i>E6B</i>	
	<i>L2M</i>	146.55 m			<i>E6C</i>	
3 rd Carrier	<i>L5C</i>	29.31 m			<i>E5A – I</i>	29.31 m
					<i>E5A – Q</i>	29.31 m
					<i>E5B – I</i>	29.31 m
					<i>E5B – Q</i>	29.31 m

(b) New and modernised PRN-codes modulated on the carrier-waves

Table 2.2: New and modernised GNSS signal characteristics

As described in Table 2.2, each GNSS has its own signal structure design, but all systems share the same fundamental frequency f_0 , fixed at 10.23 MHz. Figure 2.2 illustrates the current GPS signal structure: each satellite emits two radio-frequencies named *L1* (1575.42 MHz, $154 \cdot f_0$) and *L2* (1227.6 MHz, $120 \cdot f_0$) modulated by two PRN-codes, the *Precision Code* (P) and the *Coarse Acquisition Code* (C/A), and by a NAV. Similarly, the current GLONASS signal is composed of two carrier-frequencies, *G1* and *G2*, modulated by

a NAV and by two PRN-codes: the *Standard Precision code* (SP) and the *High-Precision code* (HP).

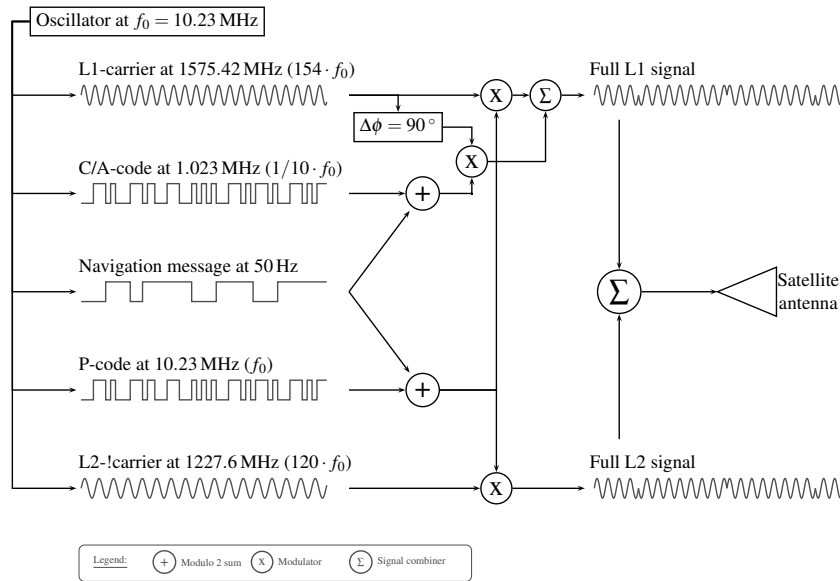


Figure 2.2: Structure of the current GPS signal
(Note that the various waveforms are not to scale)

Within the next years, GPS and GLONASS will undergo several modernisation steps. Modernised GPS satellites will provide a third carrier-frequency signal *L5* dedicated to safety-of-life applications, new civil codes *L2C* and *L5C* and the new (power-increased) M-codes on both *L1* and *L2* carrier-frequencies. A common *L1C* civil code is also under discussion by the corresponding (GPS, Galileo, and possibly GLONASS) authorities. By the end of 2010, GLONASS is expected to achieve a full 24-satellite constellation and modernised GLONASS-K satellites will provide a third carrier-frequency *G3*. With modernised satellites, GLONASS is expected to provide performances comparable to GPS by 2011.

Voluntary Signal Degradations

GPS was designed to satisfy military applications and was thus equipped with proper disposals capable to limit the use of the system by civilian users. The goal of these disposals were to protect the security interests of the U.S. and its Allies by globally denying the full accuracy of the civil system to potential adversaries. The names of these disposals are the *Selective Availability* (SA) and the *Anti-Spoofing* (AS).

Selective Availability (SA) is a technique implemented to intentionally degrade the GPS signal accuracy by degrading the accuracy of the broadcasted ephemeris and by altering (also known as dithering) the satellite clocks. The use of the Selective Availability was discontinued on May 1, 2000. According to the corresponding White House press release, it is not the intent of the U.S. to ever use SA again.

Anti-Spoofing (AS) alters GPS signals by changing the characteristics of the P-code by mixing it with a secret encryption code called the W-code. The resulting encrypted code is named the Y-code (or P(Y)-code). It is the latter that is modulated onto the carriers to prevent the receiver to make P-code measurements (except for receiver equipped with special decryption circuits). *Anti-Spoofing* (AS) is permanently activated on all GPS satellites since the 31st January 1994. Nevertheless, many receiver manufacturers have developed techniques to still be able to make P-code like measurements with only a small addition of noise in the observations. The two main techniques are the *cross-correlation* and the *Z-tracking* techniques and are implemented in high-accuracy geodetic receivers.

2.4 Observables

2.4.1 Pseudorange Observables

As it is illustrated in Figure 2.3, the receiver makes *pseudorange* measurements by replicating the PRN-code generated by the satellite and determining the time offset Δt between the arrival of a particular transition in the PRN-code (of

the satellite) and that same transition in the code replica generated within the receiver. The measured time offset corresponds to the time the signal takes to propagate from the satellite to the receiver, and the *pseudorange* observable is this time offset multiplied by the speed of light in vacuum.

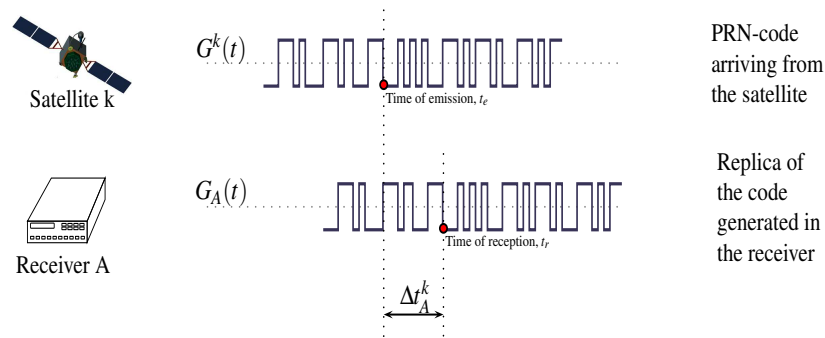


Figure 2.3: Principle of pseudorange measurement

The observable is called *pseudorange* because it is biased by several error sources, in particular, by the synchronisation error between the GNSS satellite clock generating the satellite signals and the GNSS receiver clock generating the code replica. Because of these error sources, the pseudorange measurement does not represent exactly the geometrical distance that separates the satellite and the receiver. The receiver synchronisation error has to be determined along with the position coordinates from the *pseudorange* measurements. To solve for these 4 unknowns (3 coordinates + time synchronisation) the user must simultaneously observe at least 4 GNSS satellites. In addition to the synchronisation errors, the pseudorange is also affected by other effects including atmospheric delays, multipath and receiver noise errors (Section 2.5) which need to be mitigated, modelled or estimated during the processing of the pseudorange observations. The primary error sources acting on the pseudorange observations will be described in Section 2.5.

The GNSS *pseudorange* observable, $R_{A,L_i}^k(t)$, measured on a particular PRN-code of the L_i carrier-frequency at time t by the receiver A on the signal transmitted by the satellite k at a given emission time t_e can be expressed as in [Teunissen and Kleusberg, 1998]:

$$R_{A,L_i}^k(t) = \rho_{A,L_i}^k(t_e) + c \cdot (dt^k(t_e) - dt_A(t)) + I_{A,L_i}^k(t) + T_A^k(t) + \delta_{A,L_i}^{k,R}(t) + \epsilon_{A,L_i}^{k,R}(t) \quad (\text{m}) \quad (2.1)$$

- where
- ✎ ρ_{A,L_i}^k stands for the geometric range between the satellite k and the receiver A
 - ✎ c is the speed of light
 - ✎ t_e is the true time (in the GNSS time scale) of the signal emission
 - ✎ t is the true time (in the GNSS time scale) at the epoch the code entered the receiver antenna
 - ✎ dt^k and dt_A are the offsets of the satellite k and receiver A clocks from GNSS time (Section 2.5.2)
 - ✎ I_{A,L_i}^k and T_A^k are the atmospheric delays imparted respectively to the ionosphere and the troposphere (Section 2.5.4)
 - ✎ $\delta_{A,L_i}^{k,R}$ represents the receiver and satellite hardware delays, the multipath, the relativistic effects and the antenna phase centre variation offsets (Section 2.5)
 - ✎ $\epsilon_{A,L_i}^{k,R}$ represents the pseudorange measurement noise (Section 2.5.8)

2.4.2 Carrier-Phase Observables

Even with the latest advances in code measurement technology, a far more precise observable compared to the pseudorange, is the beat phase of the received carrier-frequency. The measurement principle, illustrated in Figure 2.4, is to compare the phase of the received carrier-frequency with respect to the phase of a replica carrier-frequency generated within the GNSS receiver.

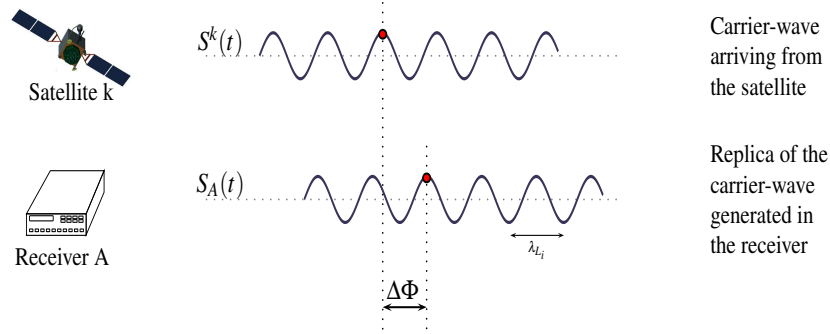


Figure 2.4: Principle of beat phase measurement

The phase of the received carrier-frequency is related to the phase of the emitted carrier-frequency through the time interval required for the signal to propagate from the satellite to the receiver. Ideally, the *carrier-phase* observable would be the total number of full and fractional carrier-cycles between the antennas of the satellite and the receiver. The problem is that a GNSS receiver has no way of distinguishing one carrier-cycle from another. Therefore, the best it can do is to measure the fractional phase $\Delta\Phi$ (ranging from 0 to 1 cycle) and then to use an internal counter to measure the number of full cycles accumulated since the first measurement of a satellite track. The unknown number of cycles associated with the first measurement is referred to as the *initial phase ambiguity*. It remains constant as long as the signal is not interrupted. To use the *carrier-phase* observable for positioning, this *initial phase ambiguity* N must be estimated along with the other unknowns.

Using the same notations as in Equation 2.1, the GNSS *carrier-phase* observable, $\Phi_{A,L_i}^k(t)$, measured at time t by the receiver A on the L_i carrier-frequency transmitted by the satellite k at a given emission time t_e can be modelled as in [Teunissen and Kleusberg, 1998]:

$$\begin{aligned} \Phi_{A,L_i}^k(t) = & \rho_{A,L_i,\Phi}^k(t_e) + c \cdot (dt^k(t_e) - dt_A(t)) + \lambda_{L_i} \cdot N_{A,L_i}^k(t) \\ & - I_{A,L_i}^k(t) + T_A^k(t) + \delta_{A,L_i}^{k,\Phi}(t) + \varepsilon_{A,L_i}^{k,\Phi}(t) \quad (\text{m}) \end{aligned} \quad (2.2)$$

where

- ✎ λ_{L_i} the wavelength of the L_i carrier-frequency
- ✎ N_{A,L_i}^k is the initial phase ambiguity of the L_i carrier-frequency
- ✎ $\delta_{A,L_i}^{k,\Phi}$ represents the receiver and satellite hardware delays, the multipath, the carrier-phase windup, the relativistic and the antenna phase centre variations effects (Section 2.5)
- ✎ $\varepsilon_{A,L_i}^{k,\Phi}$ represents the carrier-frequency measurement noise (Section 2.5.8)

Remark: One can note the negative sign of the ionospheric delay term compared to the positive sign in the pseudorange equation. Indeed, the ionosphere is a dispersive medium that slows down the speed of propagation of signal modulations to below the vacuum speed of light whereas the speed of the propagation of the carrier is actually increased beyond the speed of light. There is there no contradiction with Einstein's pronouncement on the sanctity of speed of light since the carrier-frequency does not transport any information.

2.5 Measurement Decomposition and Error Budget

The purpose of this section is to give the reader an idea of the origin, behaviour and magnitude of the different terms acting in the GNSS pseudorange and carrier-phase observables defined in Equation 2.1 and Equation 2.2 respectively and which have to be accounted for during the GNSS observation processing. We will also briefly introduce some of the error sources that do not appear explicitly in these equations but that represent significant limitations in the position accuracy, if not properly mitigated.

2.5.1 Geometrical Range

The satellite-to-receiver range ρ_A^k is the geometric distance between the satellite antenna at emission time t_e and the receiver antenna at reception time t_r . It is composed of two terms: the *satellite position*, which is available from the NAV or from satellite orbit products (see later in Section 2.7.2), and the *station position*, which is obtained from the GNSS observation processing.

Satellite Orbits

As described in Table 2.1, the NAV broadcasted by the GNSS satellites contains information on the satellite positions. The difference between the satellite position computed using this model and its actual position is the *satellite orbit error*. Typical orbit error for the broadcasted satellite ephemeris ranges from 1 m to 2.5 m [GPS Broadcast Quality]. This is unsatisfactory when millimetre accuracy positioning is targeted, as it is the case in this thesis. This is one of the main reasons why international GNSS observation networks appeared at the end of the 80's to provide high-accuracy orbits computed a posteriori. Nowadays, the *International GNSS Service* (IGS) provides such high-accuracy orbits (at the level of 5 cm to 10 cm in the case of GPS, see later in Section 2.7.2) for various types of applications, from post-processing to real-time [Beutler, 1995; Kouba *et al.*, 1995], and for which the corresponding errors on the positioning remains below the centimetre level.

Station Positions

Station positions are estimated from GNSS-code and/or carrier-phase observations. The method used in this work and presented in Chapter 4 allows computing station positions with a few millimetres of precision [Pottiaux, 2008].

2.5.2 Satellite and Receiver Clock Offsets

The second term acting in Equation 2.1 and Equation 2.2 is due to synchronisation errors between the satellite and receiver clocks and the GNSS system time. The *satellite clock offset* dt^k and the *receiver clock offset* dt_A must be corrected properly and accurately. As described in Table 2.1, to compensate for the drift and aging of the clock, the NAV relays clock correction parameters corresponding to the *satellite clock offset*, the *frequency offset* and the *frequency rate*. Nevertheless, the synchronisation corrections provided by the broadcasted ephemeris have a precision of solely 7 ns [IGS Central Bureau]. More precise synchronisation corrections are estimated by the *International GNSS Service* (IGS) based on observations from a worldwide network of permanent GNSS stations (see later in Section 2.7.1). The IGS

clock corrections have a precision level of 0.1 ns (see later in Section 2.7.2). The *receiver clock offset* with respect to the GNSS system time can take any value within 1 ms, depending on the accuracy of the receiver clock. To access the true epoch of observation, the receiver clock errors are estimated during the pre-processing step of the GNSS observation analysis.

2.5.3 Hardware Delays

PRN-codes and carrier-frequencies also undergo delays when propagating in the electronics of the satellites and the receivers. These delays depend on the frequency used and can reach several nanoseconds. One of the major factors influencing the hardware delays is the temperature as shown in [Sleewaegen, 1999]. As it will be shown later in Section 2.6, this effect will be eliminated during the processing of the GNSS observations by using a proper combination of the GNSS observables.

2.5.4 Atmospheric Delays

As they traverse the Earth's atmosphere, GNSS signals are attenuated and undergo a signal refraction that bends the signal path and modifies the propagation speed of the signals. As already mentioned in the preface, these effects are due, on one hand, to the influence of the ionised part of the atmosphere (the *ionosphere*) and, on the other hand, to the neutral atmosphere (usually referred to as the *troposphere*). Among these effects, the modification of the propagation speed is the largest. The signal path bending and the attenuation effects remain generally negligible for observations taken at an elevation angle above a 10°.

The Ionospheric Delay

The ionosphere is a dispersive medium in the GNSS frequency-band and GNSS signals propagate in it at different speeds, depending on their frequencies. It delays the propagation of the modulations and accelerates the propagation of the carrier-waves. Typical values for the ionospheric delay I_A^k

at zenith range between 10 ns (3 m) at night to 50 ns (15 m) during daytime. At low elevation angles, the delay can be 3 to 5 times higher [Spilker, 1978]. These values can be even larger during high solar activity periods [Warnant and Pottiaux, 2000]. As we will show later in Section 2.6, this effect is mitigated at first order during processing of the GNSS observations.

The Tropospheric Delay

The neutral atmosphere is a non-dispersive medium in the GNSS frequency band and GNSS signals propagate in it at the same speed, independently of their frequencies. The tropospheric delay error T_A^k is modelled and/or estimated during the GNSS observation processing. Typical values for the tropospheric delay at sea level can vary from 8 ns (2.4 m) at the zenith to 80 ns (24 m) at an elevation angle of 5° [Leick, 1990]. The modelling of the tropospheric delay will be addressed in the next chapter.

2.5.5 Cycle Slips

A *cycle slip* is a discontinuity of an integer number of cycles in the measured (integrated) carrier-phase, resulting from a temporary loss-of-lock in the carrier-tracking loop of the GNSS receiver. It occurs when the receiver loses track of the signal transmitted by the satellite. As the receiver is not capable any more to keep track of the phase changes during this period, a certain number of entire phase cycles is lost that induces a “cycle slip” in the carrier-phase measurements. In general, if the signal loss period is rather short, the cycle slip can be “repaired”, i.e. the unknown number of “missing” cycles determined and the carrier-phase observations subsequent to the cycle slip all corrected by this amount. If the cycle slip cannot be recovered, a new initial phase ambiguity is introduced and must be estimated.

2.5.6 Multipath

PRN-codes and carriers-frequencies transmitted by GNSS satellites can be reflected by obstacles (buildings, ground, vehicles...) and reach the receiver

antenna by two or more paths, causing interferences with the direct signal. This phenomenon is named the *multipath* effect and is included in the $\delta_A^{k,R}$ and $\delta_A^{k,\Phi}$ terms of Equation 2.1 and Equation 2.2 respectively. The multipath phenomenon is periodic due to the repetition of the satellite distribution. The multipath depends also of the signal frequency and the largest multipath effects are often found at low elevation angles [Bishop *et al.*, 1985; Georgiadou and Kleusberg, 1988]. The amplitude of this effect can reach a few metres on the pseudorange measurements and a few centimetres on the carrier-phase observations [Sleewaegen, 1999]. Multipath can be mitigated to some extent through appropriate antenna design, antenna placement and special filtering algorithms within the GNSS receivers. More details on multipath effects can be found in [Leick, 2004].

2.5.7 Antenna Models

As illustrated in Figure 2.5, the *Antenna Phase Centre* (APC) is the physical point where the electrical signal is received by the antenna. It depends on the signal frequency and varies with the direction of the incoming signal. The APC is a virtual point not necessarily located at the geometrical centre of the antenna. To relate properly a computed GNSS position to a surveying monument, the relationship between the APC and the external *Antenna Reference Point* (ARP) must be known as well as the relation between the ARP and the monument marker. The distance that separates the APC and the ARP is referred to as the *Antenna Phase Centre Eccentricity* (APCE). It depends on the elevation and azimuth of the satellite, the intensity and the frequency of the signal. The eccentricity is decomposed in terms of a constant *Phase Centre Offset* (PCO) and the *Phase Centre Variations* (PCV). The largest offset is in height and can be as large as 10 cm. Antenna PCV can reach several centimetres. These effects are mitigated by using proper antenna calibration models such as the one illustrated Figure 2.6. These models consist in either *relative corrections* (wrt. the reference antenna AOAD/M_T from Allen Osborne Associates Dorne Margolin T, [Mader, 1999a]) or *absolute corrections* (anechoic chambers calibration, [Schupler *et al.*, 1994] or robot calibration [Menge *et al.*, 1998]). The generation of a consistent absolute phase centre correction model for GPS receiver and satellite antennas is discussed in

[Schmid *et al.*, 2007]. The models used in this work are those of the IGS [IGS Antenna Files]. Models for antenna missing in the IGS files were collected from [NGS Web Site; Mader, 1999a,b].

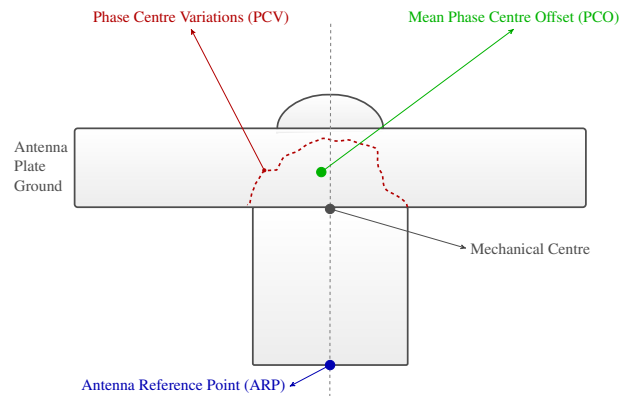


Figure 2.5: Geometrical interpretation of the antenna phase centre variations

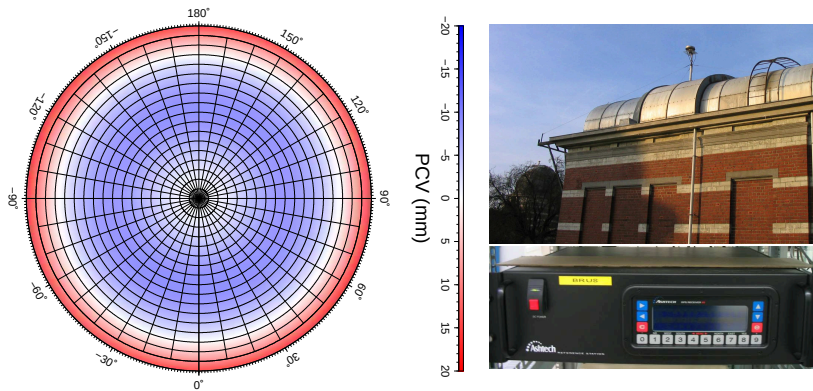


Figure 2.6: Left: example of absolute antenna calibration model (AOAD/M_T, Allen Osborne Associates Dorne Margolin T) - right: antenna and receiver located in Brussels (BRUS), Belgium

2.5.8 Measurement Noise

The *pseudorange* and *carrier-phase* measurements are finally affected by a *measurement noise* that is related to the maximum resolution that can be reached when comparing the original PRN-code or carrier-phase coming from the satellite to its replica within the receiver. According to [Botton *et al.*, 1997], the measurement noise of geodetic receivers is expected to be less than 1 % of the wavelength of the signal. From the Septentrio geodetic receiver specifications and from Table 2.2, we derived Table 2.3. A theoretical resolution of about 1 mm can thus be achieved when using the carrier-phase observables.

Signal	Wavelength	Measurement Noise	Reference
GPS PRN-codes Observables			
<i>C/A</i> code (*)	293.1 m	5 to 20 cm	[POLARX3G]
<i>P(Y)</i> code	29.31 m	10 cm	[POLARX3]
<i>L5C</i> code	29.31 m	6 cm	[POLARX3G]
GLONASS PRN-codes Observables			
<i>SP</i> code	293.1 m	7 to 25 cm	[POLARX3]
<i>HP</i> code	29.31 m	10 cm	[POLARX3]
Galileo PRN-codes Observables			
<i>E1</i> code	293.1 m	8 cm	[POLARX3G]
<i>E5a/E5b</i> code	29.31 m	6 cm	[GENERX1]
<i>E6</i> code	146.55 m	6 cm	[GENERX1]
GPS Carrier-phase Observables			
<i>L1</i> phase	19.05 cm	1 mm	[POLARX3G]
<i>L2</i> phase	24.43 cm	1 mm	[GENERX1]
<i>L5</i> phase	25.50 cm	1.5 mm	[POLARX3]
GLONASS Carrier-phase Observables			
<i>G1</i> phase	18,73 cm	1 mm	[POLARX3]
<i>G2</i> phase	24,08 cm	1 mm	[POLARX3]
<i>G5</i> phase	24,89 cm	1.5 mm	[POLARX3]
Galileo Carrier-phase Observables			
<i>E1</i> phase	19,05 cm	1 mm	[GENERX1]
<i>E5</i> phase	25,17 cm	1,5 mm	[POLARX3]
<i>E6</i> phase	23,46 cm	1.1 mm	[GENERX1]

Table 2.3: Measurement noise of the GNSS PRN-code and carrier-phase observations (*) with code smoothing

2.6 Combinations of GNSS Observables

Differencing and forming linear combinations of the GNSS observables from different frequencies helps to correct or to mitigate some of the error sources, allowing to reach consequently higher accuracy. For complete and detailed mathematical developments, the reader is referred to [Teunissen and Kleusberg, 1998; Leick, 1995; Botton *et al.*, 1997; Leick, 2004]. Hereafter, the mathematical expressions are derived for carrier-phase observables only, but similar expressions can be written for the PRN-code observations.

2.6.1 Differences of Observables

In the carrier-phase observables (Equation 2.2) of two satellites k and l recorded at the same time by the same receiver A , the *receiver clock offset* and the *receiver hardware delay* appear identically in both measurements and can therefore be eliminated. By differencing Φ_A^k and Φ_A^l at the same epoch t , we obtain the *satellite carrier-phase single-difference observable*:

$$\begin{aligned} \nabla\Phi_A^{k,l}(t) = & \nabla\rho_{A,\Phi}^{k,l}(t_e) + c \cdot dt^{k,l}(t_e) + \lambda \cdot \nabla N_A^{k,l}(t) - \nabla I_A^{k,l}(t) \\ & + \nabla T_A^{k,l}(t) + \nabla\delta_A^{k,l,\Phi}(t) + \nabla\epsilon_A^{k,l,\Phi}(t) \quad (\text{m}) \end{aligned} \quad (2.3)$$

Instead of considering the single-difference observables formed between two satellites, the single-differences between two stations A and B observing simultaneously the same satellite k can also be formed. The signals transmitted by this satellite can be combined to eliminate the *satellite clock offset* and the *satellite hardware delay*. By differencing Φ_A^k and Φ_B^k at the same epoch t , we obtain the *receiver carrier-phase single-difference observable*:

$$\begin{aligned} \nabla\Phi_{A,B}^k(t) = & \nabla\rho_{A,B,\Phi}^k(t_e) + c \cdot dt_{A,B}(t) + \lambda \cdot \nabla N_{A,B}^k(t) - \nabla I_{A,B}^k(t) \\ & + \nabla T_{A,B}^k(t) + \nabla\delta_{A,B}^{k,\Phi}(t) + \nabla\epsilon_{A,B}^{k,\Phi}(t) \quad (\text{m}) \end{aligned} \quad (2.4)$$

The *carrier-phase double-difference observable* is obtained by differencing two *receiver carrier-phase single-difference observables* $\nabla\Phi_{A,B}^k$ and $\nabla\Phi_{A,B}^l$, carried out at the same epoch t , relatively to the satellites k and l (Figure 2.7):

$$\begin{aligned} \nabla\Delta\Phi_{A,B}^{k,l}(t) = & \nabla\Delta\rho_{A,B,\Phi}^{k,l}(t) + \lambda \cdot \nabla\Delta N_{A,B}^{k,l}(t) - \nabla\Delta I_{A,B}^{k,l,\Phi}(t) \\ & + \nabla\Delta T_{A,B}^{k,l}(t) + \nabla\Delta\delta_{A,B}^{k,l}(t) + \nabla\Delta\varepsilon_{A,B}^{k,l,\Phi}(t) \quad (\text{m}) \quad (2.5) \end{aligned}$$

The *carrier-phase double-difference observable* eliminates the satellite and receiver clock offsets, as well as their respective hardware delays. The down side is that their noise is higher than the original raw observations (by about a factor of $\sqrt{2}$). Usually, using the carrier-phase double-difference observable allow more accurate positioning than the raw carrier-phase observables and consequently, they are often the basic observable in processing techniques for sub-centimetre accuracy positioning.

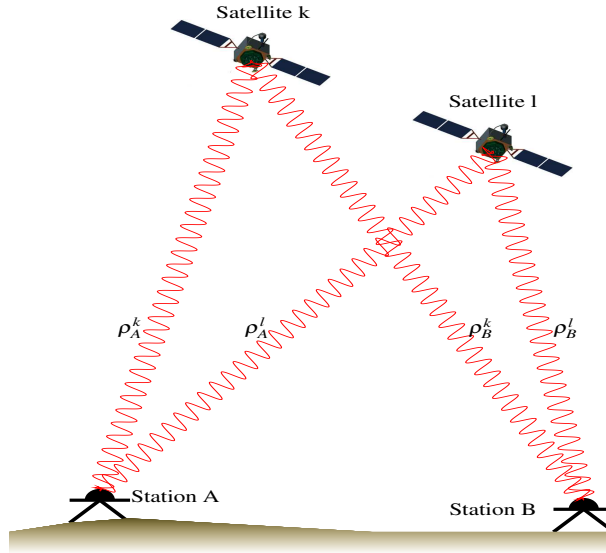


Figure 2.7: Principle of double-difference combination

2.6.2 Frequency Combinations

Linear combinations of PRN-code and/or carrier-phase observables are formed using either the single- or the double-difference measurements. Hereafter, we give the general form of the two-frequency linear combination of PRN-code and carrier-phase measurements based on double-difference observations, as it will be the basic observable throughout this work. Let us denote by $\nabla\Delta\Phi_{[f_1]}$, $\nabla\Delta\Phi_{[f_2]}$ the carrier-phase double-difference observables on the first and second frequency respectively and by $\nabla\Delta R_{[f_1]}$, $\nabla\Delta R_{[f_2]}$ the corresponding double-difference pseudorange observables. The general form of the linear combination of carrier-phase and PRN-code measurements based on double-difference observations can be written as

$$\nabla\Delta\chi_{A,B,[n_1,n_2,m_1,m_2]}^{k,l}(t) = n_1 \cdot \nabla\Delta\Phi_{A,B,[f_1]}^{k,l}(t) + n_2 \cdot \nabla\Delta\Phi_{A,B,[f_2]}^{k,l}(t) + m_1 \cdot \nabla\Delta R_{A,B,[f_1]}^{k,l}(t) + m_2 \cdot \nabla\Delta R_{A,B,[f_2]}^{k,l}(t) \quad (\text{m}) \quad (2.6)$$

where n_1 , n_2 , m_1 , m_2 , are real constants. The resulting ambiguity term associated with the linear combination of the carrier-phase double-difference measurements can be written as

$$\nabla\Delta N_{A,B,[n_1,n_2]}^{k,l} = n_1 \cdot \nabla\Delta N_{A,B,[f_1]}^{k,l} + n_2 \cdot \nabla\Delta N_{A,B,[f_2]}^{k,l} \quad (2.7)$$

and the “virtual” wavelength of the linearly combined signals is given by

$$\lambda_{[n_1,n_2,m_1,m_2]} = \frac{c}{(n_1 + m_1) \cdot f_1 + (n_2 + m_2) \cdot f_2} \quad (\text{m}) \quad (2.8)$$

According to [Lienen, 1997], the ionospheric amplification factor which describes the first-order ionospheric effect on the linear combination is given by

$$V_{ION,\chi,[n_1,n_2,m_1,m_2]} = \frac{(n_1 + m_1) \cdot f_2 + (n_2 + m_2) \cdot f_1}{f_{[n_1,n_2,m_1,m_2]}} \quad (2.9)$$

and the “noise level” associated with the linear combination can be expressed as

$$\sigma_{\chi,[n_1,n_2,m_1,m_2]} = \sqrt{(n_1 \cdot \sigma_{\Phi,[f_1]})^2 + (n_2 \cdot \sigma_{\Phi,[f_2]})^2 + (m_1 \cdot \sigma_{R,[f_1]})^2 + (m_2 \cdot \sigma_{R,[f_2]})^2} \quad (2.10)$$

Special linear combinations can be formed using a specific set of (n_1, n_2, m_1, m_2) coefficients. The most commonly used linear combinations are summarised in Table 2.4. The ionosphere-free carrier-phase double-difference linear combination mitigates the first-order ionosphere delay errors and is therefore commonly used in precise geodesy. It is the basic observable used in this work. Using carrier-phase double-difference measurements only, it reads:

$$\nabla \Delta \Phi_{L3} = \nabla \Delta \Phi_{L1} - \frac{f_{L2}}{f_{L1}} \nabla \Delta \Phi_{L2} \quad (\text{m}) \quad (2.11)$$

The wide-lane combination is often used (along with the narrow-lane combination) to facilitate the estimation of the carrier-phase ambiguities. Indeed, its long wavelength (86cm) decreases the impact of the various error sources and helps thus to fix the ambiguities to their integer values.

Denomination	Equation	λ (cm)	σ_χ	Main usage
L1	Φ_{L1}	19.03	σ_1	Primary observable
L2	Φ_{L2}	24.42	σ_2	Primary observable
Ionospheric-free	$\Phi_{L3} = \Phi_{L1} - \frac{f_{L2}}{f_{L1}} \Phi_{L2}$	48.44	$1.26 \cdot \sigma_1$	Ionospheric delay mitigation
Geometric-free	$\Phi_{L4} = \Phi_{L1} - \frac{f_{L1}}{f_{L2}} \Phi_{L2}$	∞		Geometric errors mitigation
Narrow-laning	$\Phi_{NL} = \Phi_{L1} + \Phi_{L2}$	10.70	$1.41 \cdot \sigma_1$	Ambiguity resolution
Wide-laning	$\Phi_{WL} = \Phi_{L1} - \Phi_{L2}$	86.19	$1.41 \cdot \sigma_1$	Ambiguity resolution

Table 2.4: Most often used GPS carrier-phase frequency linear combinations
Sources: [Beutler et al., 2007; Liu, 2003]

2.7 GNSS Services, Networks and Products

2.7.1 GNSS Services and Observation Networks

Today, a large number of *Continuous Operating GNSS Reference Stations* (CORS) are operating for multi-disciplinary applications ranging from surveying to ground-based GNSS atmospheric remote sensing. A part of these stations are included in international observation networks. This participation ensures that all stations comply with a common set of standards for site monumentation, receiver and antenna equipment, data exchange format and that they maintain up to date auxiliary data. In addition, the GNSS tracking data from these stations are freely available through the Internet. The two main CORS described hereafter are the IGS and EPN networks.

The International GNSS Service

Since 1991, the international scientific community made a considerable effort to promote international standards concerning GNSS data acquisition and analysis. This was done through the deployment and maintenance of a global GNSS observation network. All the activities are supervised by the *International GNSS Service* (IGS), which is based on voluntary contributions from organisations all over the world. The IGS became a fully operational service in 1994 under the umbrella of the *International Union of Geodesy and Geophysics* (IUGG). The *International GNSS Service* (IGS) is committed to provide the highest quality data and products as the standard for GNSS in support of Earth science research, multidisciplinary applications, and education. Therefore, the IGS strives to provide the highest quality, reliable GNSS data and products, openly and readily available to all. The IGS also collects, archives and distributes GNSS observational data from the IGS permanent network. The IGS permanent network consists today of about 420 stations and is illustrated in Figure 2.8. More details on the IGS can be found at the IGS central bureau web site [IGS Central Bureau].

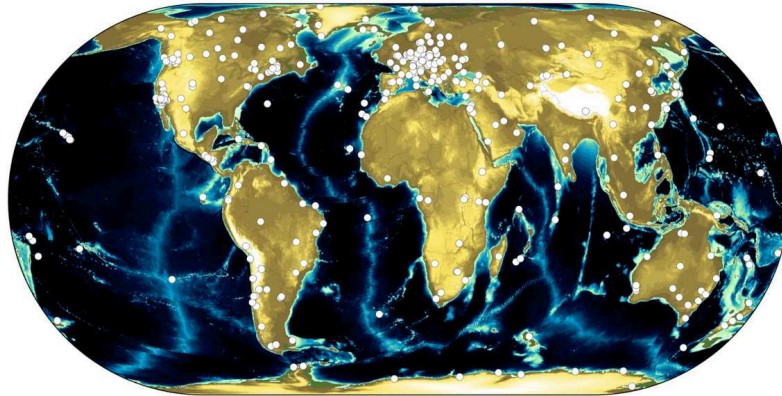


Figure 2.8: The IGS permanent network (IGS)
(Status: June 2009)

The EUREF Permanent Network

The *EUropean REference Frame* (EUREF) is the *International Association of Geodesy* (IAG) [IAG Web Site] Regional Reference Frame sub-commission for Europe. EUREF is responsible for defining, providing access and maintaining the *European Terrestrial Reference System* (ETRS89), which is recommended by the European Commission (EC) for use in all European Union (EU) member states [Bruyninx *et al.*, 2009]. A key instrument in maintaining the ETRS89 is the *EUREF Permanent Network* (EPN) (Figure 2.9). EUREF created the EPN in 1996 based on a partnership with site operators of permanent GNSS sites who are willing to share their data with the public. It is the European densification of the global IGS permanent network [Bruyninx, 2004]. In June 2009, the network consisted of 223 permanent GNSS stations. Its GNSS observations are extensively used by the public, the *National Mapping Agencies* (NMA) and the researchers [Bruyninx, 2004]. EPN stations provide daily and hourly data (93 % of the stations) in the RINEX format as well as real-time data (48 % of the stations). As for October 2009, 49 % of the EPN stations are observing GPS and GLONASS satellite signals. More details on the EPN can be found at the EPN web site [EPNCB Web Site].

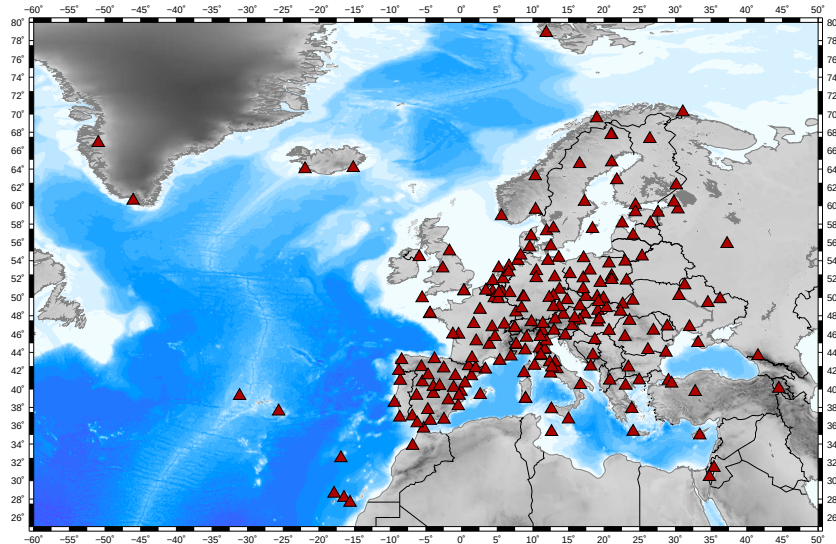


Figure 2.9: The EUREF Permanent Network (EPN)
(Status: June 2009)

National Densification Networks

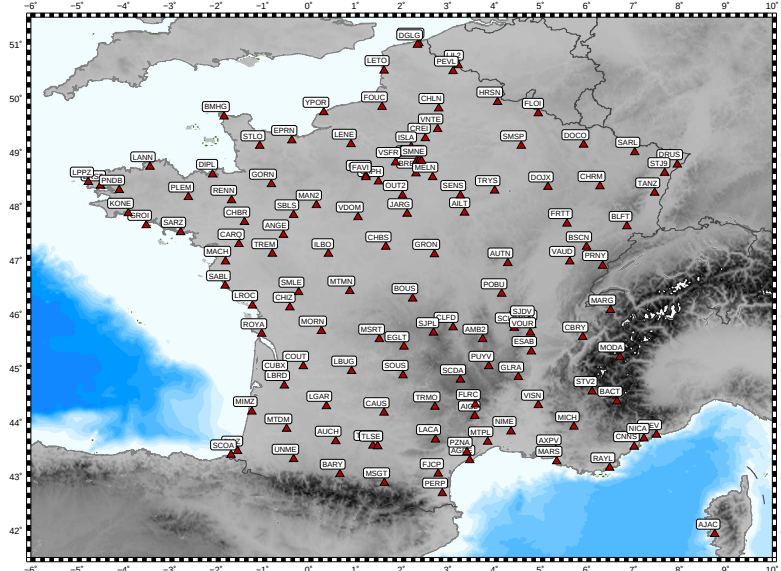
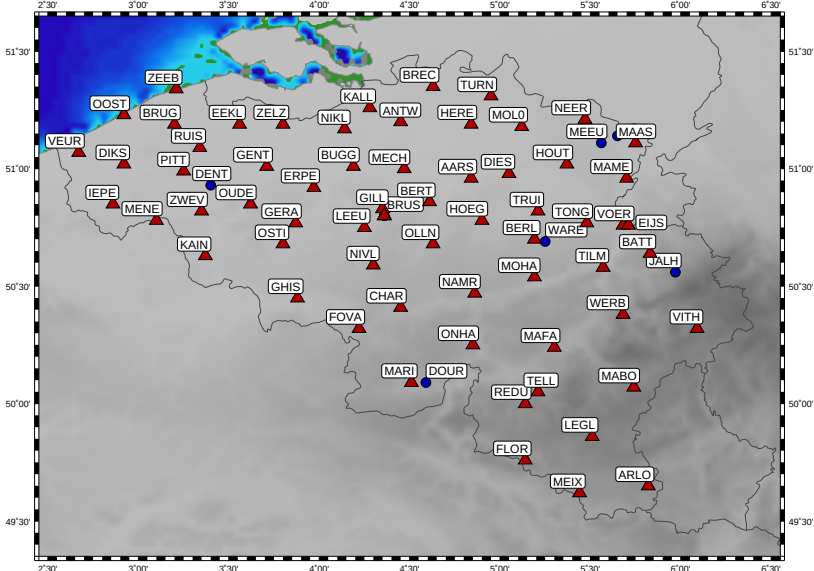
Apart from these two main CORS, national densification networks also exist. They are mostly used to maintain a national reference system in the country and to provide positioning corrections for field applications. Among these national densifications, one can cite the French *Réseau GNSS Permanent* (RGP), the German *Geodetic REFerence* (GREF), the German *SATellite POSitioning Service* (SAPOS) and the English *Ordnance Survey network* (OS net). These GNSS national networks are illustrated from Figure 2.10 to Figure 2.13. The first continuously operating GPS reference station in Belgium was installed in 1992 by the *Royal Observatory of Belgium* (ROB) in Brussels and was mainly targeting scientific research. Over the years, several additional tracking stations have been installed in Belgium. The ROB network was extended, but also each of the regions (Flanders, Wallonia, and Brussels) installed their own network of permanent GPS stations (Figure 2.10) that are used as benchmarks for determining positions in the ETRS89 or Belgian Lambert 2008 coordinate systems [Voet, 2008; Lambert 2008].

The ROB GNSS Network: the ROB has installed several continuously operating GPS reference stations in Belgium. The primary goal of these stations is the integration of Belgium in international reference systems. For that purpose, the station BRUS (located in Uccle, at the ROB), is participating to the IGS since 1993 and it is part of the ITRS reference network. Since 1996, four stations (BRUS, DENT, DOUR, and WARE) participate to the EPN and are part of the ETRS89 reference network.

The FLEPOS Network: the Flemish government established a Real-Time Kinematic (RTK) GPS-network based on 37 permanent GPS reference stations. This public *FLEmish POSitioning Service* (FLEPOS) is active since 2002 and is operated by the *Agentschap voor Geografische Informatie Vlaanderen* (AGIV). The Flemish government aims at an accurate, reliable and uniform positioning for all surveys by offering this service free of charge to all users, public and private. Since February 2007, FLEPOS data can also be downloaded in real-time thanks to the usage of the *Networked Transport of RTCM via Internet Protocol* (NTRIP). More details can be found in [FLEPOS Web Site].

The WALCORS Network: the Walloon government established an RTK GPS-network of 23 GPS reference stations. The service of the *WALloon Continuously Operating Reference Stations* (WALCORS) is operational since 2003 and is operated by the "Direction de la Topographie et de la Cartographie (D.432)" of the Walloon ministry "de l'Equipement et des Transports". More details can be found in [WALCORS Web Site].

The GPSBru Network: the *National Geographic Institute* (NGI) established an RTK GPS reference station in the Brussels region. The station is located in Uccle on the premises of the *Royal Observatory of Belgium* (ROB). More details can be found in [GPSBru Web Site].



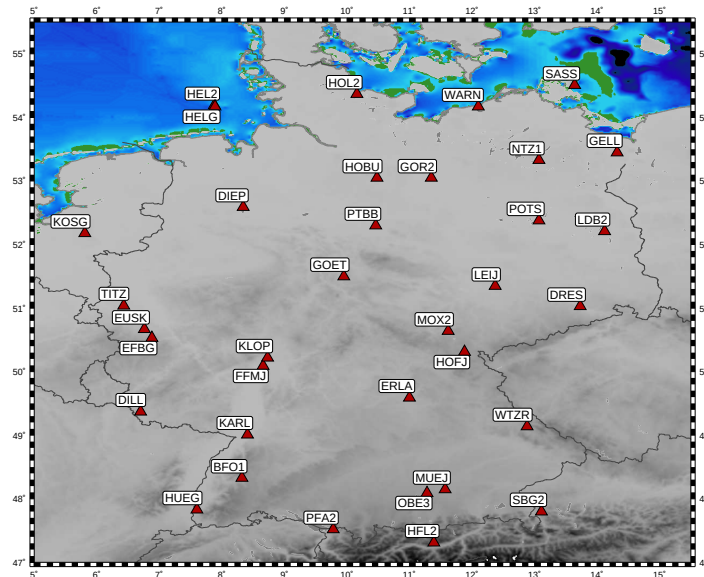


Figure 2.12: The German “Geodetic REFerence” (GREF) permanent network (Status: June 2009)

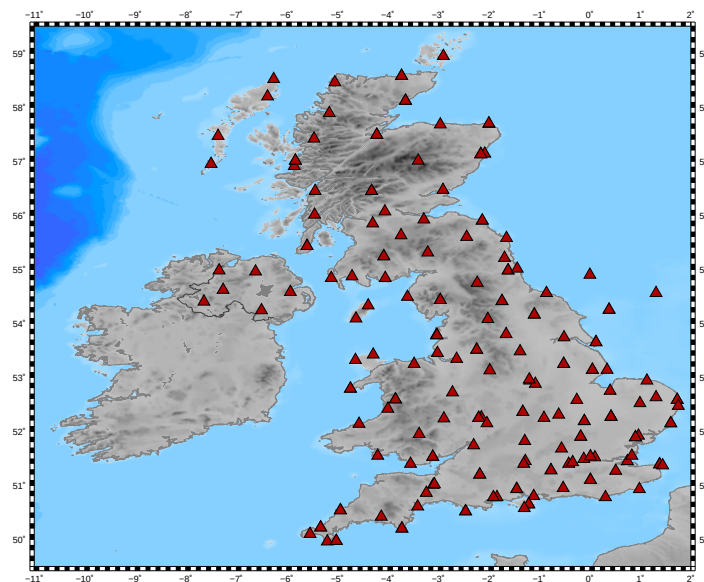


Figure 2.13: The English Ordnance Survey permanent network (OS net) (Status: June 2009)

2.7.2 GNSS Products

Orbits and Earth's Orientation Parameters

To carry out our research, we mainly used GNSS products (e.g. orbits and Earth orientation parameters) from the IGS. As illustrated in Table 2.5, they are available in various flavours (final, rapid, ultra-rapid), differing by their latency, the extend of the GNSS tracking network used for their computation and their quality. An overview of the IGS products, a guide to using them and a description of the analysis centre modelling can be found in [IGS Analysis Centre Web Site; Ray and Griffiths, 2008; Dow *et al.*, 2009; Kouba, 2008]. The IGS products are produced from a combination of all the individual contributions provided by each of the IGS analysis centres.

Tropospheric Products

We also used the legacy tropospheric product for post-processing applications described in [Söhne and Weber, 2002]. Basically, the EPN combined tropospheric solution (consisting of tropospheric path delay estimate time series for each site) is a combination of the individual tropospheric solutions provided by the 16 *Local Analysis Centres* (LAC) participating in EUREF. The EPN combined tropospheric solution is available since GPS week 1108 (June 2001) and each site included in the combination is at least processed by 3 LAC. The combination process allows improving the precision of the tropospheric solution notably by improving the solution consistency, eliminating outliers and excluding analysis centre deficiencies. Currently, the weekly mean bias of the individual LAC with respect to the combined solution is below the 2mm with nearly the same standard deviation. According to [Söhne and Weber, 2002], it is the same order of magnitude as the biases and the standard deviations of an individual IGS analysis centre solutions with respect to the IGS troposphere combination.

	Accuracy	Latency	Update	Sampling interval	Nr. AC contributing	Quality assessment	Usage
GNSS orbit products							
Broadcast (GPS)	~ 160cm	real-time	daily	2 hours			post-processing
IGS final (GPS)	~ 2.5 cm	11 – 17 days	weekly	15 min		robust	post-processing
IGS final (GLONASS)	< 15 cm	2 weeks	weekly	15 min	5 (4) (***)	not robust	post-processing
IGS rapid (GPS)	~ 2.5 cm	17 – 41 hours	daily	15 min	8	robust	rapid post-processing
IGS ultra-rapid (GPS) (observed half)	~ 3 cm	3 – 9 hours	4 times / day (*)	15 min	7 (2) (**)	fairly robust	near real-time and real-time applications
IGS ultra-rapid (GPS) (predicted half)	< 5 cm	real-time	4 times / day (*)	15 min	7 (2) (**)	marginally robust	near real-time and real-time applications
IGS real-time (GPS)	~ 5 – 10 cm	real-time	real-time	15 min			near real-time and real-time applications
Earth orientation parameter products							
IGS final	~ 0.03 mas	13 – 20 days	weekly	daily	8 (1) (**)	robust	post-processing
IGS rapid	~ 0.06 mas	17 – 41 hours	daily	daily	8	robust	rapid post-processing
IGS ultra-rapid (observed half)	~ 0.1 mas	3 – 9 hours	4 times / day (*)	6 hours	7 (2) (**)	fairly robust	near real-time and real-time applications
IGS ultra-rapid (predicted half)	< 1 mas	real-time	4 times / day (*)	6 hours	7 (2) (**)	very weak	near real-time and real-time applications
GNSS tropospheric products							
IGS final	4 mm	< 4 weeks	weekly	2 hours			post-processing
IGS ultra-rapid	6 mm	2 – 3 hours	every 3 hours	1 hour			near real-time and real-time applications
GNSS ionospheric products							
	(ionosphere TEC grids)						
IGS final	2 – 8 TECU	~ 11 days	weekly	2 hours 5° long/2.5° lat			post-processing
IGS ultra-rapid	2 – 9 TECU	< 24 hours	daily	2 hour 5° long/2.5° lat			near real-time and real-time applications

Table 2.5: Characteristics of the IGS products [IGS Central Bureau; Dow et al., 2009; Ray and Griffiths, 2008; Ray, 2010] (*) At 03:00,09:00,15:00,21:00 UTC - (**) Indicates analysis centre contributions that are weaker than others, thus not included in the combined solution - (***) One GLONASS contribution will end early 2010

We have no right to assume that any physical laws exist, or if they have existed up to now, that they will continue to exist in a similar manner in the future.

Max Planck (1858-1947),
German physicist.

3

Physical and Functional Modelling of the Troposphere

Summary

This third chapter tackles the interaction between the neutral atmosphere and the GNSS signal propagation (refraction phenomenon): the physical modelling of the delay induced by this atmospheric layer, the order of magnitude and the variability of this effect are given hereafter. Finally, the general formulation of the tropospheric path delay functional model used in this work is presented.

3.1 Introduction

As an electromagnetic wave propagates from outer space towards the Earth's surface, it traverses different atmospheric layers and interacts with them. The main interaction is named the atmospheric refraction. In addition to signal attenuation, this phenomenon bends the path followed by the wave and modifies its propagation speed. As already mentioned in Section 2.5.4,

the atmospheric refraction effect on GNSS signals is bound, on the one hand, to the effect of the *ionised atmosphere* and, on the other hand, to the effect of the *neutral atmosphere*. As seen in Section 2.6.2, the delay induced by the ionosphere is eliminated at first-order by forming the ionosphere-free linear combination of the GNSS phase observables. In this chapter, the interaction between the troposphere and the GNSS signal propagation (refraction phenomena) is addressed. The estimation of the excess propagation path length based on the tropospheric path delay functional model, as it is implemented in most of the GNSS software used for precise geodesy, is presented. Therefore, the notions of *Slant Path Delay* (SPD) and the associated concept of *mapping function* (*mf*) — that describe the dependence of the radio excess propagation path relatively to the direction from which the signal is coming and where the assumption of a horizontally symmetric atmosphere is pre-supposed — are introduced. Then, after some words about the *a priori models* of the tropospheric path delay, the estimation of *site-specific tropospheric parameters* that can be seen as correction parameters to the *a priori* model is explained. Finally, since the presence of horizontal asymmetries in the atmospheric refractivity is evident [Davis *et al.*, 1993; MacMillan, 1995] correction terms for the mapping functions, usually referred to as *horizontal gradient parameters*, which takes into account such asymmetries, are discussed.

3.2 Physical Modelling of the Tropospheric Path Delay

3.2.1 Tropospheric Refractivity Indexes

The velocity v of an electromagnetic wave in a medium depends on the *refractive index* n of this medium. If we denote by c the speed of light in vacuum, the refractive index n is defined by

$$n = \frac{c}{v} \quad (3.1)$$

As the GNSS signal propagates in the neutral atmosphere towards the Earth's surface, the atmosphere becomes denser and the refractive index increases: the GNSS ray gradually bends more intensively according to Snell's law and satisfies the Fermat's principle that light and electromagnetic waves propagate along the path taking the shortest possible time. Because changes in the refractive index n of only a few parts in a million can have an important impact on the radio-wave propagation, and because values of the refractive index are near the unity, it is more convenient to work in parts per million above the unity. Therefore, we introduce the notion of *refractivity index* N as given in [Hall, 1979]:

$$N = 10^6 \cdot (n - 1) \quad (3.2)$$

Because the troposphere consists of a mixture of different gases, its refractivity index is the sum of the contribution of each constituent that composes the troposphere. Using the expression of the refractivity index of a gas made of q components from [Debye, 1929] and transposing it into the case of the troposphere, we have

$$N_{trop} = \sum_{i=1}^q \left(A_i + \frac{B_i}{T} \right) \cdot \rho_i \quad (3.3)$$

where  A_i and B_i are some constants characterising a specific component

 T is the temperature of the medium in Kelvin

 ρ_i is the density of the i^{th} constituent in $\text{kg} \cdot \text{m}^{-3}$

Due to the different nature of these constituents, the (total) tropospheric refractivity index is usually divided into two parts referred to as the "dry" (or hydrostatic) component and the "wet" (or non-hydrostatic) component:

$$N_{trop} = \sum_{i=1}^{q_{dry}} \left(A_i + \frac{B_i}{T} \right) \cdot \rho_i + \left(A_v + \frac{B_v}{T} \right) \cdot \rho_v \quad (3.4)$$

where the summation in the first term of the right member is made over all "dry" constituencies of the troposphere. The second term in the right member accounts for the water vapour contribution. In this equation, ρ_v is the density of the water vapour. The constants A_i , B_i , A_v and B_v describe the effect of the induced and permanent dipole moments respectively. Since none of the dry gases possess a permanent dipole moment, all the B_i constants are equal to zero in the summation term. Water vapour possesses both types of dipole moment. Both the dry and the wet components of the refractivity are non dispersive at microwave frequencies, which means that in the troposphere carrier-phases and PRN-codes do propagate at the same speed.

Using the equation of the state for the i^{th} component, $P_i = \rho_i \cdot R_i \cdot T$, R_i being the universal gas constant for the i^{th} component, the tropospheric refractivity index N of the neutral atmosphere can be re-written as in [Crane, 1976]:

$$N_{trop} = k_1 \cdot \frac{P_{dry}}{T} + k_2 \cdot \frac{e}{T} + k_3 \cdot \frac{e}{T^2} \quad (3.5)$$

where

- ✎ P_{dry} is the partial pressure of all dry gases in hPa
- ✎ e is the partial pressure of water vapour in hPa
- ✎ $k_i, i \in \{1, 2, 3\}$, are empirical constants in Kelvin

Remark: The exact equation of state reads $P_i = Z_i \cdot \rho_i \cdot R_i \cdot T$, where the Z_i coefficients are the compressibility factors [Thayer, 1974]. They are included in the refractivity model to correct the corresponding constituent for the deviations from the ideal gas law. Explicit expressions of the compressibility factors for the dry and the wet components are given in [Owens, 1967]. They are very close to the unity with a maximum deviation of the order of a few parts per thousands. Therefore, in most tropospheric refractivity models, ideal gas behaviour is assumed and the inverse compressibility factors have a constant value equal to the unity.

The refractivity constants k_i have been determined by many investigators such as [Smith and Weintraub, 1953; Boudouris, 1963; Essen and Froome, 1963;

Hartmann and Leitinger, 1984; Thayer, 1974]. Table 3.1 gives the most commonly used set of values for the k_i constants. The values of the different set of k_i coefficients are very consistent. [Davis *et al.*, 1985] gives the following interpretation of the equation: the first term characterises the effect of the induced dipole moment of the dry constituencies, the second term is due to the dipole moment of water vapour and the third term represents the dipole orientation effects of the permanent dipole moment of water vapour molecules. Equation 3.5 can be finally rewritten as

$$N_{trop} = \underbrace{k_1 \cdot \frac{P_{tot}}{T}}_{N_{dry}} + \underbrace{((k_2 - k_1) \cdot T + k_3) \cdot \frac{e}{T^2}}_{N_{wet}} \quad (3.6)$$

which is only a function of the total pressure P_{tot} , the temperature T and the partial pressure of water vapour e . Equation 3.6 is often referred to as the *Smith-Weintraub equation* [Smith and Weintraub, 1953]. When using the k_i constants from [Smith and Weintraub, 1953] listed in Table 3.1, the refractivity values derived from Equation 3.6 are accurate to about 0.5 % at frequencies below 30 GHz. A discussion of the accuracy of the k_i coefficients can be found in [Rüeger, 2002].

Authors/References	k_1 in (K/hPa)	k_2 in (K/hPa)	k_3 in (K ² /hPa)
[Smith and Weintraub, 1953]	77.61 ± 0.01	72 ± 9	$(3.75 \pm 0.03) \cdot 10^5$
[Boudouris, 1963]	77.593 ± 0.08	72 ± 10	$(3.754 \pm 0.03) \cdot 10^5$
[Essen and Froome, 1963]	77.624	64.7	$3.719 \cdot 10^5$
[Thayer, 1974]	77.6036 ± 0.014	64.8000 ± 0.080	$(3.7760 \pm 0.004) \cdot 10^5$
[Bevis <i>et al.</i> , 1994]	77.60 ± 0.05	70.40 ± 2.20	$(3.739 \pm 0.012) \cdot 10^5$

Table 3.1: Experimental values of the k_1 , k_2 and k_3 constants

3.2.2 Excess Propagation Path Length

According to Fermat's principle, the propagation delay induced by the tropospheric refraction phenomena can be expressed as an equivalent excess of propagation time. As illustrated in Figure 3.1, the *excess propagation time* Δt of a radio-frequency signal χ traversing a medium with refractive index n compared to the propagation time of the same signal in vacuum reads

$$\Delta t(\varepsilon, \alpha) = \int_S \frac{1}{v(s)} \cdot ds - \int_G \frac{1}{c} \cdot dg \quad (\text{s}) \quad (3.7)$$

- where
- ✎ S is the actual curved path of the radio-signal transmitted from a satellite to a receiver on the ground
 - ✎ G is the straight line distance (vacuum distance)
 - ✎ s and g are respectively the curvilinear index along the actual signal path S and the path in vacuum conditions G
 - ✎ v is the wave velocity
 - ✎ ε , α and c are respectively the elevation angle, the azimuth angle and the speed of light in vacuum

Remark: Since the phase delay depends on the portion of the atmosphere the signal has to traverse, the phase propagation delay will primarily vary with the elevation angle ε of the direction of arrival of the signal. In the actual atmosphere, the phase propagation delay will usually also vary with the azimuth angle α of the direction of arrival of the signal.

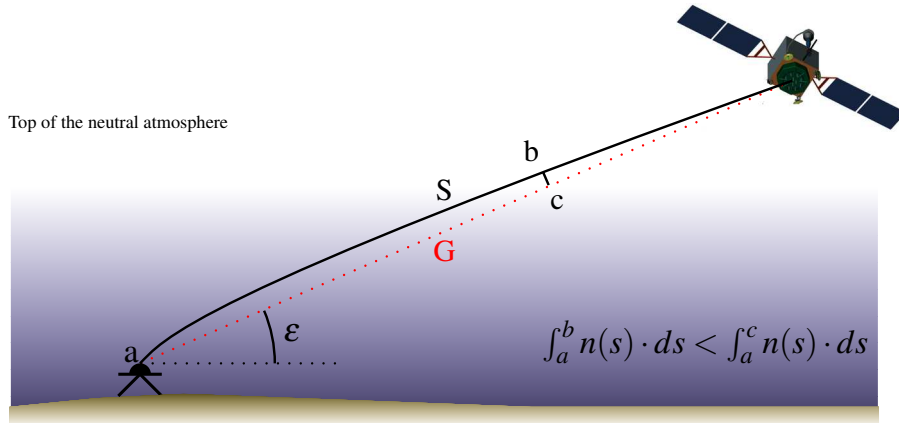


Figure 3.1: Effect of the atmospheric refraction on the GNSS signal propagation in a horizontally stratified atmosphere in which the refractive index decreases with height [Elgered, 1993] (black curve: actual path - red dotted line: vacuum condition path)

Using the same notations as in Equation 3.7 and the tropospheric refractive index n given in Equation 3.1, the excess propagation time Δt can be expressed as an equivalent *excess propagation path length* $\Delta\rho$. This is obtained by multiplying the propagation time delay Δt by the speed of light in vacuum. It reads

$$\Delta\rho(\varepsilon, \alpha) = \int_S n(s) \cdot ds - \int_G dg \quad (\text{m}) \quad (3.8)$$

The first term in the equation above corresponds to the "true" electric path while the second term is the geometrical path that the signal would have travelled in vacuum (Figure 3.1). The length difference between the curved path S and the geometrical path G in Equation 3.8 is referred to as the *bending effect* of the tropospheric refraction and reads

$$B(\varepsilon) = \int_S ds - \int_G dg \quad (\text{m}) \quad (3.9)$$

In [Kouba, 1979] an empirical model is given to estimate the tropospheric bending effect on the GNSS signal. The model reads

$$B(\varepsilon) = \frac{1.92}{\varepsilon^2 + 0.6} \quad (\text{m}) \quad (3.10)$$

where $B(\varepsilon)$ is the excess path length due to the signal bending at the elevation angle ε . This bending effect ranges from exactly zero at zenith to a few metres at the horizon. For elevation angles above 10° , the bending effect remains within the 2cm, decreases rapidly with the elevation angle and can thus be neglected. When the bending effect on the signal propagation can be neglected, Equation 3.8 can be approximated by

$$\Delta\rho(\varepsilon, \alpha) \approx 10^{-6} \cdot \int_S N(s) \cdot ds \quad (\text{m}) \quad (3.11)$$

3.2.3 Tropospheric Zenith Path Delays

The *total tropospheric Zenith Path Delay* (ZPD), indicated by $\Delta\rho_{tot}^z$, is the integral of the total tropospheric refractivity profile in the zenith direction and reads

$$\Delta\rho_{tot}^z(h) = 10^{-6} \cdot \int_{h_s}^{\infty} N_{trop}(h) \cdot dh \quad (\text{m}) \quad (3.12)$$

where

-  h is the height above the station in metres
-  h_s is the height of the station above the ground in metres
-  N_{trop} is the total tropospheric refractivity index

It is exactly this tropospheric ZPD that needs to be estimated during the GNSS data processing to account for the $\nabla\Delta T_{A,B}^{k,l}(t)$ term in the carrier-phase double-differences (Equation 2.5) and for which a functional modelling is presented in the second part of this chapter.

Using the same notations and the dry/wet decomposition of the tropospheric refractivity index (N_{dry}/N_{wet}), the tropospheric ZPD can be decomposed into the *Zenith Hydrostatic path Delay* (ZHD), indicated by $\Delta\rho_{dry}^z$, and the *Zenith Wet path Delay* (ZWD), indicated by $\Delta\rho_{wet}^z$. They read respectively

$$\Delta\rho_{dry}^z(h) = 10^{-6} \cdot \int_{h_s}^{\infty} N_{dry}(h) \cdot dh \quad (\text{m}) \quad (3.13)$$

$$\Delta\rho_{wet}^z(h) = 10^{-6} \cdot \int_{h_s}^{\infty} N_{wet}(h) \cdot dh \quad (\text{m}) \quad (3.14)$$

3.2.4 Order of Magnitude, Key Parameters and Variability

Examples of typical tropospheric hydrostatic and wet path delay distributions derived from 13 years of radiosonde observations carried out in Brussels are given in Figure 3.2 and Figure 3.3. Details on radiosonde observations can be found in (Appendix E).

In Europe, the total tropospheric ZPD varies from about 2.25 m to 2.65 m at sea level, and can reach up to 50 m for a satellite at an elevation angle of 3° . About 90 % of the total tropospheric ZPD stems for the dry component [Janes *et al.*, 1989], with typical values at sea level ranging from 2.20 m to 2.40 m at zenith. The wet component has lower values and ranges typically between a few millimetres and 0.50 m. These values depend on the geographical location as well as on the altitude of the observation site. The tropospheric ZHD depends mainly on the pressure (Equation 3.6) and therefore varies quite slowly in time (about 2 cm per 12 hours) according to the pressure field variations [Mueller and Zerbini, 1989]. The tropospheric ZWD depends on the water vapour distribution and changes much faster in both space and time. In addition, its variations are about two to three times larger than those in the tropospheric ZHD [Treuhart and Lanyi, 1987; Mueller and Zerbini, 1989]. Because of the high variability of the water vapour distribution in the atmosphere, it is considered to be one of the major error sources remaining in space geodesy.

Remark: *Most of the atmospheric water vapour content is located in the first kilometres of altitude. Therefore, up to an altitude of 5 km, the variability of the tropospheric refractivity is dominated by the wet component. Above this altitude, the variability is dominated by the dry component [de Haan, 2008].*

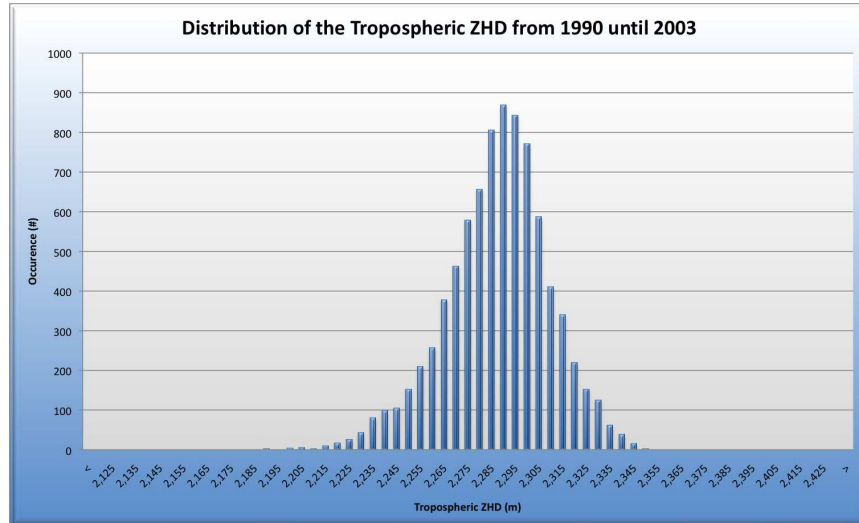


Figure 3.2: Distribution of tropospheric ZHD derived from 13 years of radiosonde observations (1990-2003) carried out in Uccle (Brussels), Belgium (note that the tropospheric ZHD was not reduced at sea level in this figure)

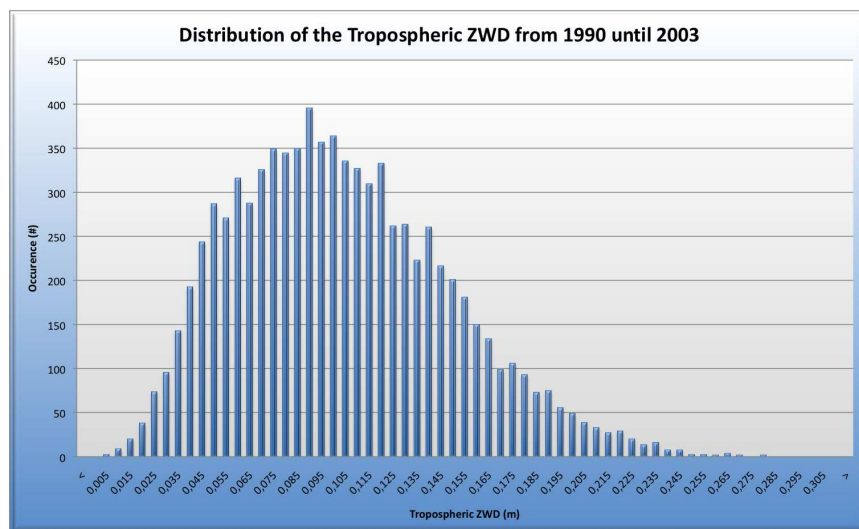


Figure 3.3: Distribution of tropospheric ZWD derived from 13 years of radiosonde observations (1990-2003) carried out in Uccle (Brussels), Belgium

3.3 Functional Modelling of the Tropospheric Path Delay

The functional model of the tropospheric path delay, as it is implemented in GNSS processing softwares used for precise geodesy, is of the form given in the *International Earth Rotation Service* (IERS) convention 2003 [McCarthy and Petit, 2004]. It relies on the dry/wet decomposition of the refractivity index N (Equation 3.6) and includes 3 parts: an *a priori model* for the tropospheric ZPD, *site-specific tropospheric parameters* which account for deviations to the tropospheric a priori ZPD model and *horizontal gradient parameters* which account for the deviations to the assumption of horizontally symmetric atmosphere made in the two first parts of the functional model. In the GNSS processing software used in this thesis, i.e. the *Bernese GPS software* version 5.0 [Beutler *et al.*, 2007], the time evolution in the functional model is represented as piece-wise linear functions between successive epochs of estimation and reads

$$\begin{array}{c}
 \text{Functional Model} \\
 \Delta \rho_A^k(t, \alpha, z)
 \end{array}
 =
 \left\{
 \begin{array}{l}
 \text{A Priori Tropospheric ZPD Model} \\
 \Delta \rho_{apr,A}(t) \cdot mf_{apr}(z_A^k) \\
 + \\
 \text{Site-Specific Tropospheric Parameters} \\
 \Delta \rho_{corr,A}(t) \cdot mf_{corr}(z_A^k) \\
 + \\
 \text{Horizontal Gradient Parameters} \\
 \Delta^n \rho_A(t) \cdot \frac{\partial mf}{\partial z} \cdot \cos(\alpha_A^k) + \Delta^e \rho_A(t) \cdot \frac{\partial mf}{\partial z} \cdot \sin(\alpha_A^k)
 \end{array}
 \right.
 \quad (3.15)$$

- where
- ✎ t is the observation epoch
 - ✎ z_A^k, α_A^k stand respectively for the zenith and azimuth angles of the GNSS satellite k observed from the station A
 - ✎ $\Delta\rho_A^k(t)$ is the true tropospheric (slant) path delay between the station A and the satellite k
 - ✎ $\Delta\rho_{apr,A}(t) \cdot mf_{apr}(z_A^k)$ is the a priori tropospheric slant path delay (composed of an a priori tropospheric ZPD model and its associated mapping function)
 - ✎ $\Delta\rho_{corr,A}(t) \cdot mf_{corr}(z_A^k)$ is a (time-dependent) site-specific tropospheric slant path delay correction parameter (composed of a tropospheric ZPD correction and its associated mapping function)
 - ✎ $\Delta^n\rho_A(t), \Delta^e\rho_A(t)$ are the (time-dependent) horizontal north-south and east-west tropospheric gradient parameters

3.3.1 Slant Path Delays and Mapping Functions

The radio frequency signals recorded by a GNSS receiver usually do not arrive from the zenith direction but from slant directions. The tropospheric propagation delay depends thus on the actual path that the GNSS signals traverse through the atmosphere and is therefore function of the satellite elevation angle. As illustrated in Figure 3.4, the closer to the horizon the GNSS satellite is, the bigger the portion of the atmosphere the GNSS signals have to traverse to reach the receiver's antenna and, consequently, the higher the impact of the atmospheric refractivity on the GNSS signals will be. *Mapping functions* describe the dependence of the radio excess propagation path relatively to the direction from which the signal is coming. Neglecting the bending effect introduced in Section 3.2.2, and assuming a horizontally layered atmosphere (i.e. that the refractivity index N is only a function of the altitude), the tropospheric *Slant Path Delay* (SPD) between a GNSS receiver A and a satellite k , indicated by ρ_A^k , can be expressed as

$$\rho_A^k = 10^{-6} \cdot \int_A^k N(s) \cdot ds \quad (\text{m}) \quad (3.16)$$

Indicating by $\Delta\rho_{tot}^z$ the total propagation path delay in the zenith direction and by $\Delta\rho_{tot}^\varepsilon$ the total tropospheric propagation delay at an elevation angle ε , the *mapping function* $mf_{tot}(\varepsilon)$ is defined by

$$mf_{tot}(\varepsilon) = \frac{\Delta\rho_{tot}^\varepsilon}{\Delta\rho_{tot}^z} \quad (3.17)$$

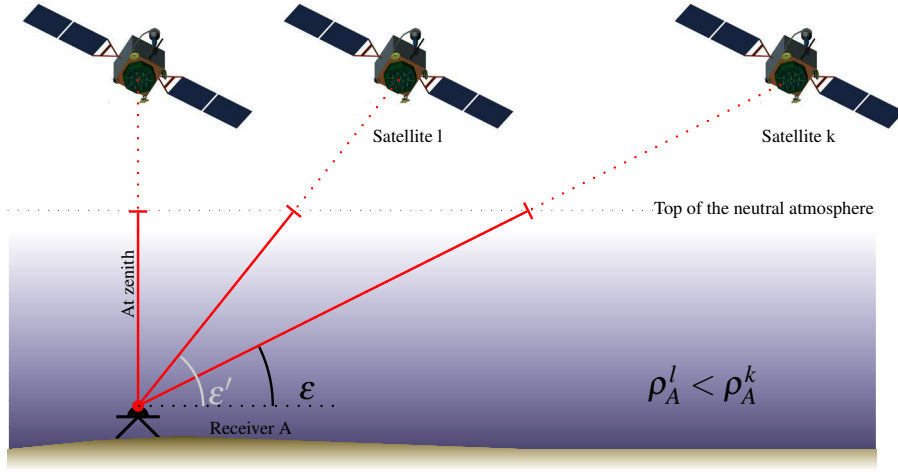


Figure 3.4: Tropospheric propagation delay as a function of the actual path followed by the GNSS signals in the Earth's atmosphere

The *Slant Path Delay* (SPD) can thus be written as the product of the tropospheric ZPD and the *mapping function* (mf) as follows

$$\Delta\rho_{tot,A}^k(t,z) = \Delta\rho_{tot,A}^z(t) \cdot mf(z_A^k) \quad (\text{m}) \quad (3.18)$$

Over the past decades, geodesists have developed a large variety of *mapping functions*. Using the assumption of a horizontally stratified atmosphere, i.e. that spherical constant-height layer surfaces can be approximated by plane surfaces, the simplest mapping function that can be used is the cosecant of the elevation angle. According to [Bean and Dutton, 1966], this mapping function produces reasonably accurate results when compared to results obtained from

raytracing of radiosonde profiles for elevation angles above 20° . Nevertheless, since this simple mapping function does not properly account for the curvature of the Earth's atmosphere, it will unavoidably produce errors on the order of decimetres for SPD at lower elevation angles, which is unsatisfactory for precise geodesy. To solve for this deficiency, various mapping functions have been developed and can be found in the literature [Saastamoinen, 1972, 1973; Marini, 1972; Chao, 1974; Davis *et al.*, 1985; Ifadis, 1992] and [Herring, 1992]. Most of them rely on the *normalised continued fraction* developed by Marini [Marini, 1972], which fits for nearly the whole range of zenith angles and reads

$$mf(\varepsilon) = \frac{1 + \frac{a}{1 + \frac{b}{1 + \frac{c}{1 + \dots}}}}{\sin(\varepsilon) + \frac{a}{\sin(\varepsilon) + \frac{b}{\sin(\varepsilon) + \frac{c}{\sin(\varepsilon) + \dots}}}} + \delta m \quad (3.19)$$

The various mapping functions differ mainly in the way the a , b , $c \dots$ coefficients are determined. The performances of these different models have been assessed by [Janes *et al.*, 1989; Janes *et al.*, 1991], [Mendes and Langley, 1994] and [Estefan and Sovers, 1994]. To accurately map the tropospheric ZPD down to an elevation angle of 3° , three coefficients a , b and c are sufficient [Niell, 1996]. Among these models, the *New Mapping Functions* (NMF) proposed by Niell in [Niell, 1996] are commonly used in GNSS data processing. However, in the past few years, the usage of *Numerical Weather Prediction* (NWP) models for deriving new *mapping functions* (mf) has been investigated to determine the three coefficients and has shown to improve the mapping functions used in geodesy [Niell, 2000; Boehm and Schuh, 2004].

The New Mapping Functions (NMF) [Niell, 1996]

In 1996, Niell proposed his *New Mapping Functions* (NMF). These are two separate mapping functions for the hydrostatic and wet tropospheric path delays, based on the normalised continued fractions given in Equation 3.19, and truncated to the first three terms. Niell gives for each mapping function a specific set of a , b and c coefficients, which were determined using one year of raytracing of radiosonde profiles, primarily from the northern hemisphere

[Niell, 1996]. The model assumes longitudinal homogeneity and symmetry between the northern and the southern hemispheres. The spatial and temporal variability of the mapping functions is accounted for through the latitudinal (station coordinates) and the seasonal (day of year) dependence of the a , b and c coefficients. Because of these hypotheses, the NMF present major deficiencies in their temporal behaviour (only a mean seasonal dependence is taken into account) and also large static deficiencies in certain areas (only radiosonde from the northern hemisphere have been considered along with the symmetry hypothesis) [Boehm *et al.*, 2006].

The Isobaric Mapping Functions (IMF) [Niell, 2000]

To account for the NMF deficiencies, Niell proposed two new mapping functions (one for the dry and one for the wet component), which use the output of global NWP models to provide in-situ information of the state of the atmosphere at the epoch of observation and to derive the three coefficients (a, b, c) of the normalised continued fraction form (Equation 3.19). The IMF avoid making raytracing calculations by using a single meteorological parameter for each of the hydrostatic and wet components, to be used with the geographic location, to calculate the mapping function [Niell, 2000]. For the hydrostatic mapping function, Niell uses the height of the 200 hPa geopotential (z_{200}). For the wet mapping function, the ratio of the wet path delay along a straight line at 3.3° and its zenithal value ($smfw3$) is used. The global NWP models of the *European Centre for Medium-Range Weather Forecasting* (ECMWF) and the *National Centres for Environmental Prediction* (NCEP) provide z_{200} and $smfw3$ values every 6 hours with spatial resolution of 2.5° in longitude and 2° to 2.5° in latitude [Vey *et al.*, 2006] that can be used to derive the IMF coefficients. Both mapping functions consider the atmosphere to be azimuthally symmetric. However, models for the hydrostatic and wet gradients are given to correct for the azimuth asymmetries.

The Vienna Mapping Functions [Boehm and Schuh, 2004]

The *Vienna Mapping Functions* (VMF) developed by Boehm and Schuh are also derived from the continued fraction form proposed by Marini in [Marini, 1972]. The three coefficients a , b and c , different for the dry and the wet

mapping functions, are obtained by Least-Squares adjustment based on direct raytracing through the pressure levels at ten different initial elevation angles (90° , 70° , 50° , 30° , 20° , 15° , 10° , 7° , 5° and 3.3°) through the ECMWF NWP model. The adjustment shows that the three coefficients are enough to map the tropospheric ZPD to an elevation angle down to 3° with residuals less than 2 mm. A description of the raytracing can be found in [Boehm and Schuh, 2003]. An improved version, referred to as VMF1, has been published in [Boehm *et al.*, 2006]. They are currently the most accurate mapping functions that are available for the whole history of GNSS observations [Boehm *et al.*, 2006]. They are illustrated in Figure 3.5 for the 28th January 2008 for the GNSS station of Ny-Alesund, Norway (NYA1).

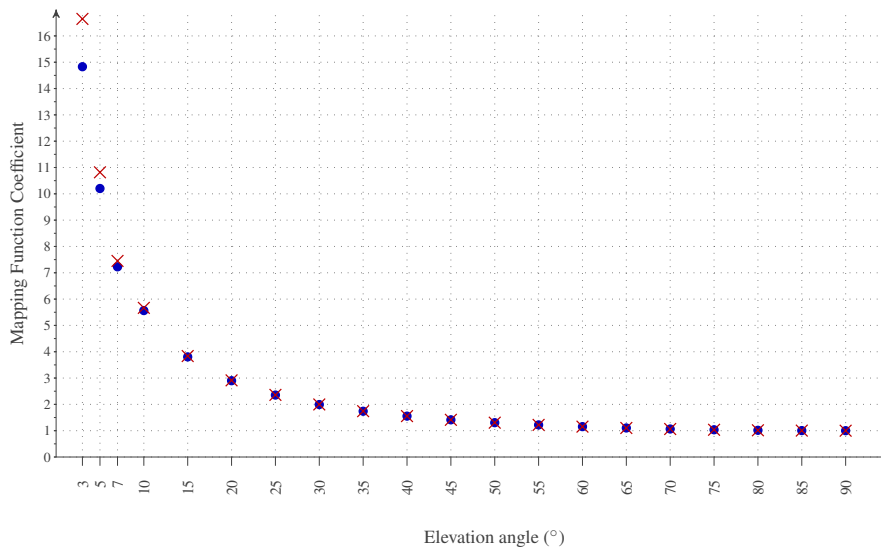


Figure 3.5: Coefficients of the dry (blue dots) and wet (red crosses) VMF1 for the 28th January 2008 at the GNSS station of Ny-Alesund, Norway (NYA1)

The Global Mapping Functions (GMF) [Boehm *et al.*, 2006]

The *Global Mapping Functions* (GMF) are empirical models based on the global grids ($15^\circ \times 15^\circ$) of monthly profiles of pressure, temperature and humidity from the *ECMWF 40 years re-analysis data* (ERA40) [Uppala *et al.*,

2005]. The coefficients of the GMF have been derived from 3 years of ECMWF data and are provided as a spherical harmonics expansion up to degree and order 9 on a global grid [Boehm *et al.*, 2006]. As for the NMF, the values of the coefficients require only the station coordinates and the day of year as input parameters. As compared to the VMF1, slight degradation in short-term precision occurs when using the GMF. However, the regional height bias and annual errors are significantly reduced as compared to NMF [Boehm *et al.*, 2006].

Discussions

Table 3.2 summarises the main mapping functions used today. Mapping functions based on NWP model data such as the IMF and the VMF can be considered today as state-of-the-art mapping functions when targeting high-accuracy geodesy applications. They provide a high temporal and spatial resolution and therefore, they capture the real atmospheric conditions much better than previously developed mapping functions (e.g. the NMF). Nevertheless, they require the NWP data to be available at the epoch of the GNSS observations and are much more demanding in terms of computing power and time. Although these new mapping functions have been available for some years now, the NMF remain widely used in GNSS because of its global validity and its simplicity in implementation (no meteorological data, no raytracing, only dependent of the station location and the day of the year). Out of the four mapping functions presented in this section, only the NMF are available in the current version of the *Bernese GPS software*, which is the GNSS observation processing software used in this work. The impact of this issue will be discussed later in Section 4.4.5.

Models	Type	Technique	Spatial resolution	Temporal resolution	$\varepsilon_{\min}$ (")	Input
NMF	Empirical	Derived from radiosonde launches	5 latitude bands	Annual	3	ϕ , H, DOY
GMF	Empirical	Spherical expansion to order and degree 9 of gridded VMF1 data	Degree/order 9	Annual	3	λ , ϕ , H, DOY
VMF1	Site values	Interpolated from local $0.25^\circ \times 0.25^\circ$ grids derived from ECMWF data	A list of GNSS, VLBI, DORIS sites	Every 6 hours	3	λ , ϕ , H, DOY, ECMWF data
	Grid values	Derived from ECMWF data	$2.5^\circ \times 2.0^\circ$	Every 6 hours	3	λ , ϕ , H, DOY, ECMWF data

Table 3.2: Summary of the commonly used mapping functions

3.3.2 A Priori Tropospheric Path Delay Models

Since it is not possible to accurately model the partial pressure profile of the water vapour from (only) surface measurements of the temperature, pressure and humidity, the tropospheric ZWD remains unsatisfactory estimated by any a priori model, especially when high-accuracy positioning is targeted. Therefore, it is advised to only use an a priori model for the hydrostatic component and to account for the non-hydrostatic part by estimating the so-called site-specific tropospheric parameters (see later in Section 3.3.3). The a priori tropospheric ZHD model requires some input parameters like, e.g., pressure, temperature and humidity. Values for these meteorological parameters can be obtained either from in-situ measurements (e.g. from the *Receiver Independent EXchange Format* (RINEX) meteorological files) or by a specific model of the atmosphere. In-situ meteorological measurements are not globally available and are not always reliable: as illustrated in Table 3.3, small biases in the ground meteorological data have a significant impact on the tropospheric ZPD estimation. Using in-situ meteorological measurements is therefore not recommended for this thesis.

T (°C)	P (mbar)	U (%)	$ \frac{\partial \Delta \rho}{\partial T} $ (mm/°C)	$ \frac{\partial \Delta \rho}{\partial P} $ (mm/mbar)	$ \frac{\partial \Delta \rho}{\partial U} $ (mm/%)
0°	1000	50	3	2	0.6
30°	1000	50	14	2	4
0°	1000	100	5	2	0.6
30°	1000	100	27	2	4

Table 3.3: Tropospheric ZPD as a function of the temperature T , the pressure P and the relative humidity U . Source: [Beutler et al., 2007]

When accurate in-situ meteorological measurements cannot be used, values from an atmospheric model have to be considered. In this context, the *Standard (constant) Pressure and Temperature* (SPT) model values as a function of the height using Berg's power law [Berg, 1948] are commonly used (e.g. along with the NMF). Nevertheless, as SPT values and Berg's power law do not depend on the epoch and location, it is considered as a rough approach. Along with the GMF developments, Boehm *et al.* proposed its *Global Pressure and Temperature* (GPT) model [Boehm *et al.*, 2007]. As for the GMF, GPT is

based on 3 years of $15^\circ \times 15^\circ$ global grids of monthly averaged profiles of the pressure and temperature from the ERA40 [Uppala *et al.*, 2005] and is provided as a spherical harmonic expansion up to degree and order 9.

Once a priori values for the pressure and temperature have been derived, an a priori tropospheric ZHD model can be computed. Two main a priori models are widely used: they are the Saastamoinen [Saastamoinen, 1972] and the Hopfield [Hopfield, 1969b] models. We give here the expression for the hydrostatic a priori model developed by Saastamoinen. The model of Saastamoinen assumes that the dry atmosphere is in hydrostatic equilibrium. Based on the approximations presented in [Saastamoinen, 1972] and in [Davis *et al.*, 1985], the final expression for the tropospheric ZHD (Equation 3.13) can be written as in [Davis *et al.*, 1985] and [Elgered, 1993]:

$$\Delta\rho_{hydro}^z = (0.0022768 \pm 5 \cdot 10^{-7}) \cdot \frac{P_0}{f(\phi, H)} \quad (\text{m}) \quad (3.20)$$

where

-  P_0 is the total ground pressure at the station in hPa
-  H is the height of the station above the ellipsoid in metres
-  ϕ is the latitude in degree
-  and the function $f(\phi, H)$ is used to model the variations of the acceleration due to the gravity in function of the latitude and the height of the station, and reads

$$f(\phi, H) = (1 - 0.00266 \cdot \cos(2\phi) - 2.8 \cdot 10^{-7} \cdot H) \quad (3.21)$$

This model is quite often used in practice because of its simplicity (the only meteorological measurement needed is the total ground pressure) and because of its high accuracy. Indeed, according to [Kleijer, 2004], the constant in Equation 3.20 is accurate to as $0.5 \text{ mm}/\text{bar}$. A complete discussion of the error acting in this equation can be found in [Elgered *et al.*, 1991]. More details on the Saastamoinen and Hopfield models can be found in [Saastamoinen, 1972; Davis *et al.*, 1985; Kleijer, 2004; Elgered *et al.*, 1991; Dejong, 1991; Hopfield, 1969a,b, 1971a,b] and [Hopfield, 1978]

Even more realistic a priori tropospheric ZHD models can be obtained using NWP model data. VMF1 is provided directly along with tropospheric ZHD values from raytracing through the NWP model grid. The use of VMF1 along with ECMWF tropospheric ZHD is considered today as the most accurate model of the hydrostatic delay. The GMF/GPT tropospheric ZHD combination gives also good results, consistent with VMF1/ECMWF tropospheric ZHD [Steigenberger *et al.*, 2009].

Remark: The a priori tropospheric ZPD model $\Delta\rho_{apr}$ may also be time-dependent (for a fixed z) if e.g., meteorological observations are used for its computation. One has also to note that the a priori model may be computed, while the site-specific tropospheric ZPD and horizontal gradient parameters must be estimated during the processing within the Least-Squares adjustment or the Kalman filter procedure.

Table 3.4 summarises the main hydrostatic a priori models used today. In the current version of the *Bernese GPS software*, only the Saastamoinen and the Hopfield models along with in-situ measurements or SPT values are available. The use of the Saastamoinen model (with SPT values as input) along with the hydrostatic NMF is thus the more accurate approach globally available in the software. It will be used as hydrostatic a priori model in this thesis.

Models	Type	Technique	Spatial resolution	Temporal resolution
RINEX meteo	In-situ obs.	Observations	At meteorological sensors	Sensors frequency
SPT	Empirical	Constant values extrapolated to height of site	-	-
GPT	Empirical	Spherical expansion to order and degree 9 of ECMWF data	Degree/order 9	Annual
ECMWF ZHD	Site values	Interpolated from local $0.25^\circ \times 0.25^\circ$ grids derived from ECMWF data	A list of GNSS, VLBI, DORIS sites	Every 6 hours
	Grid values	Derived from ECMWF data	$2.5^\circ \times 2.0^\circ$	Every 6 hours

Table 3.4: Summary of the commonly used a priori tropospheric ZPD models

3.3.3 Site-Specific Tropospheric Parameters

In high-accuracy GNSS applications, the tropospheric bias remaining after the use of only the a priori tropospheric ZHD model and its associated dry mapping function remains too large to reach the requested positioning accuracy and this bias must be corrected. Therefore, during the Least-Squares adjustment or the Kalman filtering, the so-called *site-specific tropospheric parameters* are estimated based on the GNSS observations themselves. The station and time dependent site-specific tropospheric parameters accounts thus for the tropospheric ZHD mis-modelling, the path bending and for the wet part of the tropospheric ZPD. Again, to represent the tropospheric delay at any elevation angle, a mapping function is required. Since most of the tropospheric ZHD has been accounted for by the a priori hydrostatic model, the mapping function used is the wet mapping function. It is thus particularly important to have the best a priori hydrostatic model possible to ensure a proper use of the dry and wet mapping functions.

3.3.4 Horizontal Tropospheric Gradient Parameters

The a priori tropospheric ZHD model, the site-specific tropospheric parameters and the mapping functions associated have considered the atmosphere to be horizontally layered and entirely symmetric along the azimuth. Especially when using low-elevation observations, the azimuthal asymmetry of the local troposphere increases and must be accounted for [Beutler *et al.*, 2007]. Estimating *horizontal tropospheric gradient parameters* copes with these asymmetries. As shown in [Rothacher *et al.*, 1998] and [Meindl *et al.*, 2004], it improves the station coordinate repeatabilities by a factor of 2 for the horizontal component and by about 20% for the vertical component. The horizontal tropospheric gradient parameters then comply with the fact that the direction of the so-called *tropospheric zenith* (i.e. the direction with minimal tropospheric delay) and the corresponding tropospheric zenith distance $\tilde{z}$ might not be identical to the geometrical (ellipsoidal) zenith distance z . The mapping functions given in Section 3.3.1 are provided with mathematical expressions of these gradients. More details on gradient parameter estimations are given in

[Meindl *et al.*, 2004] and [Kleijer, 2004]. The use of horizontal tropospheric gradient parameters will be discussed in the next chapter.

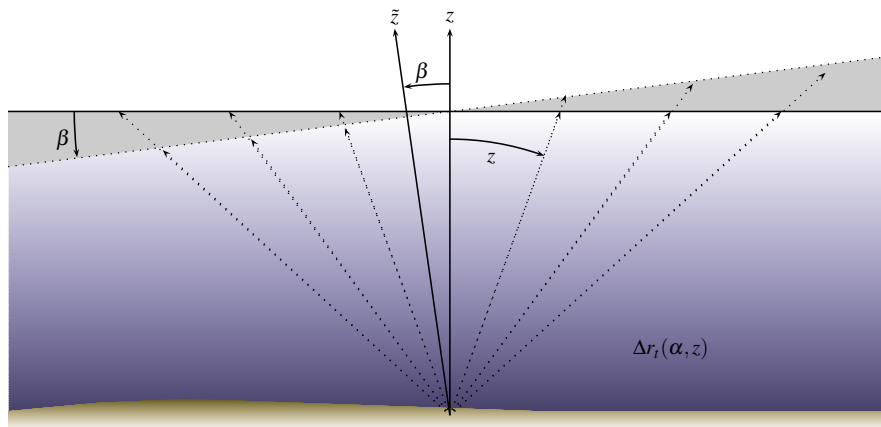


Figure 3.6: The tilting method applied to estimate horizontal tropospheric gradient parameters in the Bernese GPS software version 5.0 relies on the fact that the tropospheric zenith direction $\tilde{z}$ (which is the direction with minimal tropospheric delay) differs from the geometric zenith direction z when the refractivity field is not symmetric.

The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.

Philip W. Anderson "More Is Different"
Science magazine (1972)

4

Ground-Based GNSS Tropospheric Path Delay Estimation

Summary

This fourth chapter is devoted to the development of our GNSS analysis strategy to estimate near real-time (NRT) tropospheric Zenith Path Delays (ZPD) from a European network of GNSS observations to be used in operational meteorology. For this purpose, the requirements imposed on the tropospheric GNSS products are first outlined. They served us as guidelines to establish our processing strategy. Then, the strategy is presented and finally its sensitivity with respect to several analysis parameters is tested.

4.1 Introduction

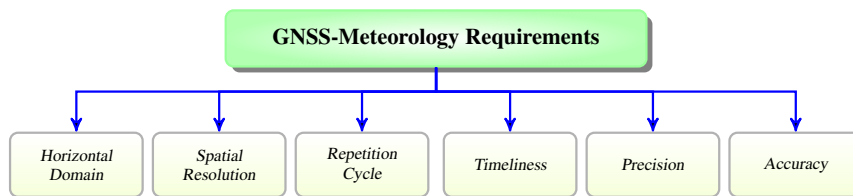
The GNSS analysis strategy presented in this thesis was designed around the *Bernese GPS software* version 5.0 [Beutler *et al.*, 2007], which is a software developed by the Astronomical Institute, University of Berne, to

meet the highest quality standards for geodetic and other applications using *Global Navigation Satellite Systems* (GNSS). In its current version 5.0, both active GNSS are supported: the American GPS and the Russian GLONASS (Section 2.2). Parameter estimation is based on a Gauss-Markov model of full rank and Least-Squares (LSQ) estimation (Appendix A). According to [Beutler *et al.*, 2007], the software is particularly suited for an automatic processing of large networks of permanent GNSS stations and for troposphere monitoring. The *Bernese GPS software* is thus particularly adequate to reach the primary and secondary objectives targeted in this work (see preface, Section 1.3). To be of benefits to operational meteorology, more particularly in *Numerical Weather Prediction* (NWP) and *nowcasting* applications, the GNSS NRT tropospheric ZPD estimates must adhere to several requirements. These requirements imposed on GNSS-meteorology are reviewed in Section 4.2 and served as primary guidelines to establish the processing strategy developed in this work. The latter will be presented in Section 4.3. Moreover, while developing the analysis strategy, its sensitivity with respect to several analysis options revealed to be significant. The sensitivity of the analysis strategy with respect to these options was thus carefully studied and the analysis strategy was optimised accordingly. The results of the most relevant sensitivity tests will be presented in Section 4.4.

4.2 GNSS-Meteorology Requirements

The *Network of European Meteorological Services* (EUMETNET) is a network of 24 European national meteorological services that provides a framework to organise cooperative programs between the members in various fields of basic meteorological activities such as observing systems, data processing and Research and Development (R&D) [EUMETNET Web Site]. Within EUMETNET, the meteorologists started in 2005 the *EUMETNET GPS Water Vapour Program* (E-GVAP) to collect on a European scale near real-time ground-based GNSS tropospheric path delay estimates and to provide this information to its EUMETNET partners for operational meteorology. Until now, only tropospheric ZPD estimates (no horizontal tropospheric gradient) are requested by the meteorologists: few investigations have been carried out to

use ground-based GNSS tropospheric *Slant Path Delays* (SPD) (Section 3.3.1) in meteorological models (see TOUGH deliverables at TOUGH Web Site). The results were encouraging [Vedel and Sattler, 2006] but no clear systematic improvement could be attributed to the use of these additional parameters. The assimilation of tropospheric SPD estimates in meteorological models needs further research investigations before using them in operational meteorology. This research is currently ongoing. To advantage the meteorological applications, the tropospheric ZPD estimated from GNSS observations must adhere to a list of requirements. The latest update of these requirements is gathered in the *User Requirements Document* (URD) [Barlag *et al.*, 2004] and expresses conditions in terms of



To define the user requirements for ground-based GNSS meteorological products, the meteorologists used as starting point generic requirements for humidity observations, independent of the observation system used. These generic requirements were gathered from *World Meteorological Organisation* (WMO) [WMO Web Site] documents, summarising the needs of several user communities for meteorological products [CBSWG, 1996]. Table 4.1 summarises these requirements. It presents requirements for two major classes of operational meteorology applications: qualitative, short-term weather prediction (*nowcasting*) and *Numerical Weather Prediction* (NWP). These requirements are somehow “high-end” requirements to be targeted on the long-term and do not represent hard cut-off values of “good/no good”. When two values are specified, the first one is the targeted value while the second one is a threshold beyond which data may have a marginal use, but still might be useful for meteorologists (e.g. in 3-D and 4-Dvar analysis) [Barlag *et al.*, 2004]. A new update of the URD was discussed in 2008 but the document was left untouched as no real need of change could be emphasised at that

moment. This work mainly focuses the GNSS-meteorology requirements in terms of NWP (3rd column) but, when possible, requirements for *nowcasting* applications will also be targeted.

	Numerical Weather Prediction				Nowcasting			
	Generic requirements		GNSS-meteorology		Generic requirements		GNSS-meteorology	
	Target	Threshold	Target	Threshold	Target	Threshold	Target	Threshold
Horizontal domain	Regional		Regional		Sub-regional		Europe to national	
Spatial resolution	10 km	250 km	30 km	100 km	5 km	50 km	10 km	100 km
Repetition cycle	30 min	12 hrs	15 min	60 min	15 min	60 min	5 min	60 min
Timeliness	30 min	120 min	30 min	90 min	5 min	30 min	5 min	30 min
Precision	6 mm	30 mm	3 mm	10 mm	6 mm	30 mm	6 mm	30 mm
Accuracy	6 mm	30 mm	3 mm	10 mm	6 mm	30 mm	6 mm	30 mm

Table 4.1: GNSS-meteorology requirements for Numerical Weather Prediction (NWP) and nowcasting applications [Barlag et al., 2004]

4.2.1 Horizontal Domain

The *horizontal domain* is the spatial extension of the observation network. The GNSS processing analysis developed here aims to fulfil the required horizontal domain for both classes of meteorological applications pointed out by the URD. Nowcasting applications are short-term weather predictions carried out in regions that can extend from national-wide to European-wide areas. NWP are weather predictions that are carried out in larger (European-wide) areas. The GNSS network considered in this work should thus at least cover a large part of Europe, preferably be centred on the area for which (national or regional) nowcasting is targeted, i.e. the BENELUX, southeast of England, the Channel and the north of France.

4.2.2 Spatial Resolution

The *spatial resolution* of an analysis centre solution is the average horizontal separation distance of the observations, i.e. the inter-station distance. The 30km to 100km target-threshold specified in the URD corresponds to the

typical scale at which most of the meteorological phenomena related to the water vapour and hydrometeors happen, i.e. the *mesoscale* (Section F.1.1). It also corresponds to the typical resolution of the NWP models used (or targeted) by the meteorological agencies participating in E-GVAP, such as the *HI-Resolution Local Area Model*, HIRLAM [Unden *et al.*, 2002], the French regional *ALADIN* model [ALADIN Web Site] and the *COSMO* model [COSMO Web Site]. Reaching this spatial resolution is thus important to describe properly the water vapour geospatial distribution, its time evolution, and to bring real benefits from ground-based GNSS tropospheric ZPD in NWP and nowcasting applications.

4.2.3 Repetition Cycle

The *repetition cycle* of a solution is the effective sampling rate at the same location, i.e. the sampling rate at which the tropospheric ZPD are estimated. It might differ from station to station but usually the same repetition cycle is applied to all GNSS stations. The 60min threshold specified in the URD corresponds to the repetition cycle necessary to describe the large mesoscale structures and to start bringing improvements in the meteorological applications. But structures related to water vapour and hydrometeors change much faster in space and time (Section 3.2.4). A repetition cycle of 5 min to 15 min as targeted in the URD is thus important to sense and record the evolution of these quick variations.

4.2.4 Timeliness

The *timeliness* is the delay from the time of the last observation analysed up to the time of receipt of the GNSS product by the meteorologist community. To be of benefit to operational NWP applications, we consider that at least 95 % of the near real-time tropospheric ZPD must be provided within this *timeliness* limit. Due to the update frequency and the start epoch of their analysis, the timeliness for regional NWP targets 30min, while this requirement is less strong for global NWP applications, where it is between 60min and 90min depending on the meteorological analysis centre. Since our NRT tropospheric

ZPD estimates will be assimilated in both regional and global NWP models, the 30 min timeliness requirement is aimed here.

4.2.5 Precision and Accuracy

For NWP applications, there is an implicit requirement that observation errors should be uncorrelated in space and in time and that the observations should be free of any bias. It imposes thus strong requirements (3 mm to 10 mm of tropospheric ZPD) in terms of *precision and accuracy*. Nowcasting applications are more concerned with relative values (i.e. the horizontal tropospheric gradients and their time evolution) than with absolute accuracy. As a consequence, small correlations in the network can be tolerated, though discontinuities should be avoided. Therefore, *nowcasting* requirements in terms of precision and accuracy (6 mm to 30 mm of tropospheric ZPD) are slightly relaxed as compared to NWP requirements.

4.3 GNSS Analysis Methodology

Primary Objective

The primary objective of the GNSS analysis strategy developed in this chapter is to provide NRT tropospheric ZPD estimates from a European regional network of GNSS permanent stations to be used in operational *Numerical Weather Prediction* (NWP) and *nowcasting* applications. This analysis strategy must thus provide tropospheric ZPD estimates that comply with the GNSS-meteorology requirements mentioned in previous section and summarised in Table 4.1.

Methodology Principles

To reach this objective, a 2-step analysis strategy was developed based on ionosphere-free GNSS carrier-phase double-difference measurements (Equation 2.11) in a network approach and performed using the *Bernese GPS software* version 5.0 [Beutler *et al.*, 2007]. This approach was chosen

to mitigate (most of) the error sources (Section 2.5) acting in the GNSS mathematical model (Section 2.4), to access the highest precision and to remain with the station positions (Section 2.5.1), the carrier-phase ambiguities (Section 2.4.2) and the tropospheric path delays (Section 2.5.4) as only unknowns (Equation 2.11). The global structure of the analysis strategy is presented in Figure 4.1. Because of the high correlations between the station coordinates and the tropospheric ZPD parameters, the station coordinates must be known before estimating the tropospheric ZPD parameters in the Least-Squares (LSQ) estimation. The first step of our analysis strategy (orange box) consists thus in providing precise site coordinates for all stations that will be fixed during the near real-time tropospheric ZPD estimation (second step of the analysis strategy, red box). In addition to these two steps, several mechanisms have been set up to prepare the analysis (preparation step, blue box) and to monitor the quality and the integrity of the NRT tropospheric ZPD estimates (monitoring scheme, green box). The different steps are explained hereafter, while a detailed analysis of the processing options impacting the NRT tropospheric ZPD estimation will be discussed in the next section.

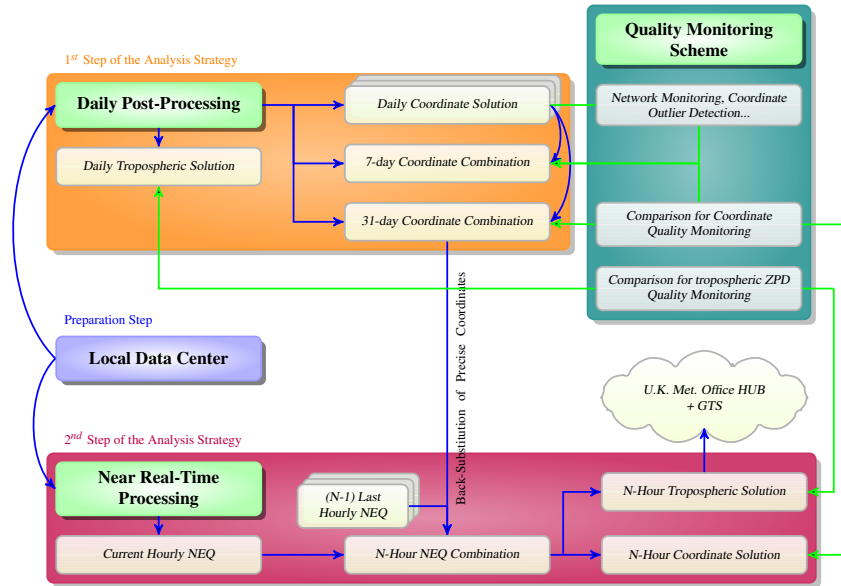


Figure 4.1: Global structure of our 2-step GNSS analysis strategy

Preparation Step

Prior to the first and second steps of the analysis strategy, some information needs to be gathered and prepared as input to the analysis. This information is updated hourly, prior to the second step run of the analysis strategy, and includes notably

- All GNSS observations (Section 2.7.1) that will be processed
- All GNSS products (Section 2.7.2) such as the IGS satellite orbits and clocks that will be used during the processing
- All GNSS station information files (station log files) with up to date antenna and receiver hardware information
- All *Bernese GPS software* specific files such as receiver description, satellite manoeuvre information and a priori coordinate set
- Updated version of certain models such as the antenna calibration models (Section 2.5.7)

First Step: Determination of Precise Coordinates

As a first step, a GNSS post-processing analysis strategy (orange box of Figure 4.1) is used to estimate precise site coordinates on a daily basis. When analysing the ionosphere-free GNSS carrier-phase double-difference observations (Equation 2.11), station coordinates, tropospheric ZPD parameters and horizontal tropospheric gradient parameters are solved. Carrier-phase ambiguities are fixed to their integer values when possible using the *Quasi Ionosphere-Free* (QIF) technique described in [Mervart, 1995a,b]. *IGS Rapid orbits* (IGR, Section 2.7.2) are used, kept fixed and bad satellites or stations are excluded based on the post-fit residuals analysis. To optimise the use of low-elevation observations, i.e. at 10° and below, an elevation-dependent weighting function $\mathcal{W}(z) = \cos^2(z)$, z being the zenith angle of the observed satellite, is applied. The daily site coordinates are then stacked to obtain a cumulative coordinate solution over the last 31-days. The repeatability of the site coordinates is continuously monitored and outliers in the station coordinates are removed from the daily solutions (green box of Figure 4.1). The cumulative coordinate solution is updated daily.

Second Step: Near Real-Time Tropospheric Delay Estimation

The near real-time step of the analysis strategy (red box of Figure 4.1) is run every hour and provides the tropospheric ZPD estimates that are sent to the meteorologists. In this step, the analysis of the ionosphere-free GNSS carrier-phase double-difference observations (Equation 2.11) from the last hour provides a Normal Equation (NEQ) containing unconstrained tropospheric path delay parameters. The analysis of the hourly GNSS observations uses the *IGS Ultra-rapid orbits* (IGU) and the carrier-phase ambiguities are left float. Then, the (current hour) tropospheric ZPD solution is computed by combining the current NEQ with the respective NEQ obtained from the analysis of the previous hours (sequential adjustment in time). Each NEQ contains for each station several tropospheric ZPD parameters per hour evenly distributed in time according to the repetition cycle. During the combination process, the station coordinates are fixed to the cumulative coordinate solution obtained in the post-processing analysis and relative constraints are applied to the tropospheric path delay parameters. Once estimated, the tropospheric ZPD are formatted in the COST-716 format [COST-716, 2003] and made available to the meteorological community through the *Global Telecommunication System* (GTS) [GTS Web Site] of the *World Meteorological Organisation* (WMO) [WMO Web Site] and a central hub (ftp server) managed by the U.K. Met. Office.

Functional Model of the Tropospheric Path Delay

In both steps of the analysis strategy, the tropospheric ZPD estimation process is based on the mathematical model given in Equation 3.15: a Saastamoinen-based hydrostatic a priori model (Equation 3.20) using *Standard Pressure Temperature* (SPT) model values (Section 3.3.2) and converted down to the satellite elevation using the dry NMF of Niell (Section 3.3.1) is used, while site-specific tropospheric path delay parameters (Section 3.3.3) are estimated using the wet NMF (Section 3.3.1) to account for the wet path delay and for the deviation from the hydrostatic a priori model. Horizontal tropospheric gradient parameters are only estimated in the post-processing step of the strategy.

Quality Monitoring Scheme (QMS)

To ensure a stable and reliable service to the meteorologists, the analysis strategy includes also a *Quality Monitoring Scheme* (QMS). This QMS continuously checks the site coordinates and the NRT tropospheric ZPD by comparing them to the other E-GVAP near real-time solutions. It also performs regular comparisons with the IGS, the EUREF and our post-processed solutions, as well as with external references (radiosonde, water vapour radiometer and NWP data). In this context, our post-processed solution (obtained from the 1st step of the analysis strategy) presents several differences with respect to the near real-time analysis: it uses notably a 24-hour observation window, better quality orbits and the ambiguities are fixed to their integer values when possible. As a result, the tropospheric parameter estimation of our post-processing analysis is less subject to analysis noise and its tropospheric ZPD estimates can be considered as "ground-reference" to assess the precision of the NRT tropospheric ZPD. This issue will be addressed in the next chapter (Section 5.4). In addition, the post-processing analysis strategy allows a robust monitoring of the GNSS network (data quality, receiver/antenna changes or problems, multipath...) and the repeatability of the site coordinates with respect to the cumulative coordinate solutions provides an indication of the quality of the tropospheric ZPD at the site. This issue will be addressed later in this chapter (Section 4.4.3). Finally, the post-processed tropospheric ZPD estimates can be used for the re-analysis of special meteorological case as it will be the case in Chapter 6.

Remark: *The first step of the analysis strategy aims to provide precise coordinates for*

- *All stations processed in the second step of the analysis strategy*
- *All stations pending approval to be added to the second step of the analysis strategy*
- *All stations that can be used as replacement in case of failure of a station in the second step of the analysis strategy*
- *All stations that we want to include in the second step of our analysis strategy but for which no near real-time dataflow is available yet*

- *All stations included to improve the spatial resolution requirement in case of re-analysis for a special meteorological case*

The network processed in the first step of the analysis strategy includes today about 460 GNSS permanent stations.

4.4 Sensitivity and Optimisation

Once the global structure of the GNSS analysis strategy was established (Figure 4.1), its sensitivity was tested and the methodology was optimised with respect to the requirements (Section 4.2). Indeed, changes in the analysis options such as the observation cut-off angle, the antenna calibration models or the ocean tide loading model might impact the tropospheric ZPD estimates above the precision and accuracy targeted by the URD. In addition, the processing options related to the functional model of the tropospheric path delay (Equation 3.15) have to be fine-tuned to meet the GNSS-meteorology requirements, notably in terms of repetition cycle and timeliness. The impact of these analysis options was thus carefully assessed based on specific test campaigns. The most relevant ones are summarised in Figure 4.2 and discussed hereafter.

4.4.1 Network Considerations

Estimation of the Absolute Tropospheric Path Delay

The developed GNSS analysis strategy uses the functional model presented in Section 3.3 to derive the tropospheric ZPD estimates. In a GNSS network with inter-station spacing of less than several hundred of kilometres, receivers at both endpoints of a short baseline observe the GNSS satellites with very similar elevation angles. The differential tropospheric delay $\nabla \Delta T_{A,B}^{k,l}$ in the carrier-phase double-difference observations (Equation 2.5) becomes thus only sensitive to the differential or relative tropospheric ZPD (i.e. $\nabla \rho_A^z - \nabla \rho_B^z$) and not anymore to the absolute value of the delay (i.e. $\nabla \rho_A^z$ and $\nabla \rho_B^z$). In such network, one may thus infer properly the relative tropospheric ZPD

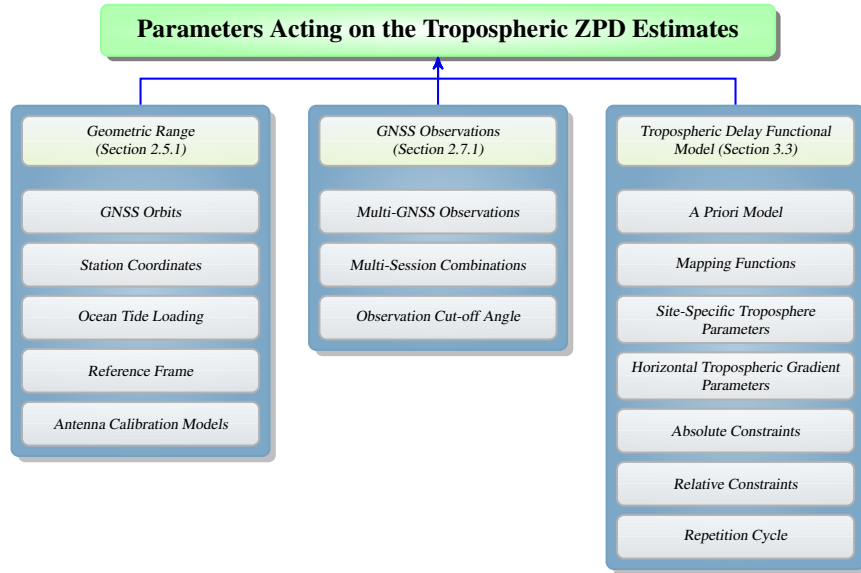


Figure 4.2: Global structure of the sensitivity and optimisation tests (gray boxes: analysis options acting on the quality of the tropospheric ZPD estimate - light green boxes: corresponding term in the ionosphere-free double-difference carrier-phase observations)

solely. To derive absolute values of the tropospheric ZPD for all sites, at least one reference station within the network must be able to provide absolute tropospheric path delays and thereby to allow transforming all relative delays into absolute tropospheric ZPD. To measure absolute tropospheric path delays (and its changes with time), the network should thus better have a large diameter and/or include stations separated by at least several hundreds of kilometers. [Duan *et al.*, 1996] recommended to use remote stations which are at least 500km distant from the core network. However, very long baselines (e.g. inter-station distances of 4000km and above) are not recommended since the number of carrier-phase double-difference observations will dramatically be reduced due to different visibility conditions at both endpoints of the baseline.

Horizontal Domain and Spatial Resolution

To assess the impact of changes in the analysis options on the tropospheric ZPD estimates, a test network of European GNSS stations from the EPN and the IGS permanent network (Section 2.7.1) was defined taking into consideration the horizontal domain of the primary European NWP models assimilating ground-based GNSS tropospheric ZPD (see below). The horizontal domain of these NWP models covers largely Europe (Section 4.2.1). Moreover, NWP and nowcasting applications have both strong requirements in terms of spatial resolution. Because of the wide spatial extension of the requested horizontal domain, the spatial resolution targeted by these meteorological applications cannot be achieved for the whole of Europe. Two regions of interest, both centred over the BENELUX and the north of France (Section 4.2.1), were thus determined:

- The **main area of interest** in which all GNSS-meteorology requirements must be satisfied. As illustrated in Figure 4.3 (inner dashed rectangle), this area covers from 44° N to 57° N and from 3° W to 12° E and is (quasi) identical to the horizontal domain of the ALADIN-Belgium NWP model.
- The **extended area of interest** in which all GNSS-meteorology requirements but the spatial resolution must be satisfied. This area (outer dashed rectangle) will be filled with GNSS sites following a “best effort principle”. The area covers from 37° N to 66° N and from 10° W to 25° E and covers the horizontal domain of most of the NWP models used in western EUROPE (i.e. the HIRLAM (H11), the Swiss COSMO, the German COSMO-DE, the French ALADIN-France and the French AROME NWP models).

Test Campaign Network

From all the aforementioned considerations, we determined primary recommendations to set up our GNSS test network:

- The network extension should not be too narrow (a diameter preferably above 1000km)
- The network should include a few remote stations separated from the core network by “long” inter-distances (preferably in the 500-2500km range)

- The network should include remote stations located outside the extended area of interest to mitigate the border effects and thereby ensure the quality of the tropospheric ZPD estimates within the area(s) of interest
- Considering the number of GNSS stations that will be included to satisfy the spatial resolution requirement in the main area of interest and the “best effort principle” in the extended area of interest, the processing of the network will have to be carried out on a sub-networks (clusters) basis (see later Section 4.4.4 for details)
- The network should include stations equipped with multi-GNSS receivers and antenna when possible

Based on these recommendations, a minimal set of GNSS stations to be included in the test network was established. This network is illustrated in Figure 4.3. The set of station consists of 60 IGS and EPN stations covering the whole of Europe and includes a few remote sites located outside the extended area of interest, notably in Greenland and in the Atlantic region.

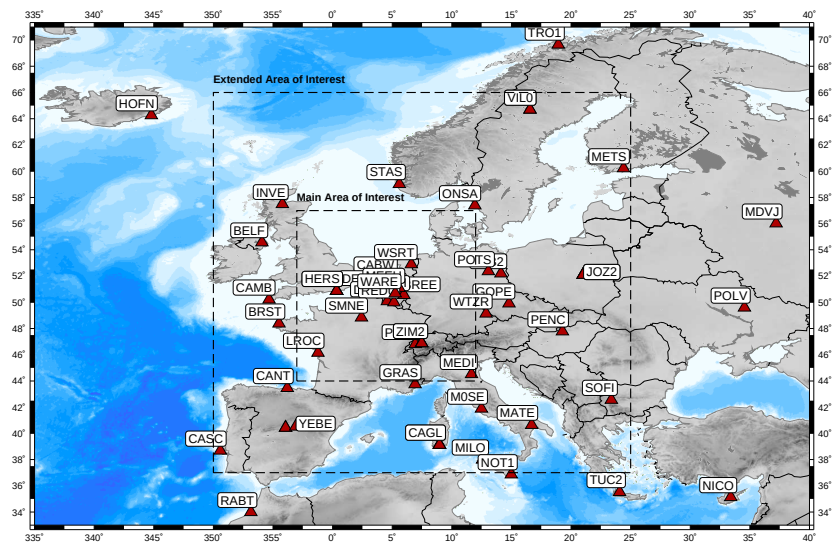


Figure 4.3: European regional network of GNSS stations used to test the sensitivity of our GNSS analysis strategy. A few stations, notably in Greenland and in the Atlantic regions, are located outside the map

4.4.2 Local Data Centre

As already pointed out in Section 4.3, the GNSS-meteorology requirements impose to gather in near real-time all necessary inputs for the analysis. To reach this goal, a *Local Data Centre* (LDC) was set up to collect all this information. The global structure of the LDC is presented in Figure 4.4 and gathers auxiliary information such as GNSS observations, GNSS products, station logfiles and *Bernese GPS software* specific files. The collection of this information must be robust (no single point of failure tolerated) and quick (to let a maximum of time for the analysis). Therefore, particular effort was dedicated to the usage of redundant information sources and to the parallelisation of the dataflow, more specifically for GNSS observations and orbits. This issue will be discussed later in Chapter 5.

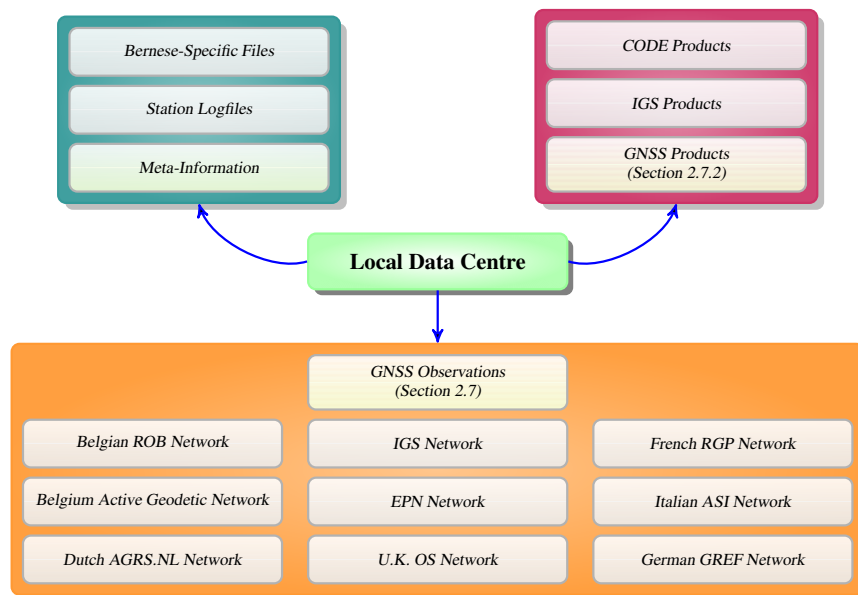


Figure 4.4: Global structure of our local data centre

4.4.3 Site's Coordinates

Back-Substitution of Site's Coordinates

In the tropospheric ZPD estimation process, the stations coordinates must be kept fixed or heavily constrained to decorrelate both parameters. This procedure is referred to as the *back-substitution of the site's coordinates* (Figure 4.5) and is explained in [Beutler *et al.*, 2007]. The precise coordinates (for all sites within the analysed network) used in the back-substitution procedure are provided by the first step of the analysis strategy (Section 4.3). Both approaches, fixing or heavily constraining (0.1 mm) the site coordinates, have been tested and provided similar results in terms of tropospheric ZPD estimates. However, fixing the site coordinates reduces the number of unknowns to be estimated in the LSQ adjustment and thereby, increases the robustness of the tropospheric ZPD estimation. The last approach was thus chosen.

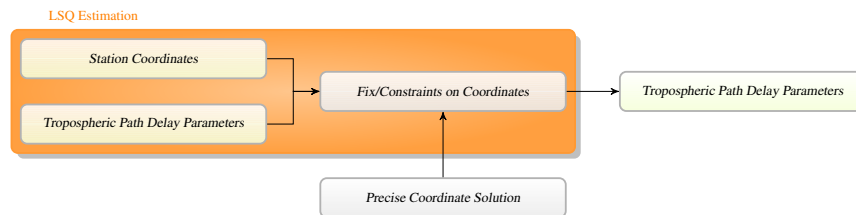


Figure 4.5: Back-substitution of precise coordinates during the LSQ estimation of the near real-time tropospheric ZPD

Impact of Coordinate Errors

When fixing the site coordinates, any error in the determination of the site coordinates will impact the tropospheric ZPD estimates. As a *rule of the thumb*, a 9 mm bias in the up component of the site coordinate corresponds roughly to a bias of 3 mm in the tropospheric ZPD estimates [Beutler *et al.*, 2007], which is the precision and accuracy targeted by the URD. This rule of thumb assumes that the GNSS satellites are uniformly distributed over the sky above the observing sites, which is not true [Santerre, 1991]. The actual impact of coordinate errors on the tropospheric ZPD estimates was thus tested:

a fictitious 1-cm error was introduced in the site coordinate of the GNSS station located in Onsala (ONSA), Sweden, while keeping the site coordinates of all other GNSS stations to their true (estimated) values. The NRT tropospheric ZPD obtained using erroneous coordinates for Onsala were compared to those obtained with true coordinates for Onsala, and this for all sites within the test network during 1 day. Four types of fictitious coordinate errors were tested:

- A 1-cm error in the vertical component
- A 1-cm error in the north component
- A 1-cm error in the east component
- A 3-mm error in all three components

Figure 4.6 illustrates the impact of these fictitious coordinate errors on the tropospheric ZPD time series of Onsala. As predicted by the rule of the thumb, the largest impact in terms of tropospheric ZPD bias was observed for the 1-cm fictitious error introduced in the vertical component. Nonetheless, the recorded bias is slightly below the value predicted by the rule of the thumb with a value of 2.14 mm instead of the 3.3 mm predicted. Introducing a 1-cm fictitious error in the north and east coordinate of Onsala revealed smaller biases (1 mm and 0.45 mm respectively), but doubled the impact in terms of variability (standard deviations of about 0.80 mm with respect to 0.40 mm for the 1-cm error introduced in the vertical component). For all tested solutions, in addition to the bias, variability on the 1-hour scale was observed (Figure 4.6). All solutions obtained with fictitious errors deviated from the “true” solution with a peak-to-peak amplitude up to 5.40 mm, which is above the precision targeted by the URD.

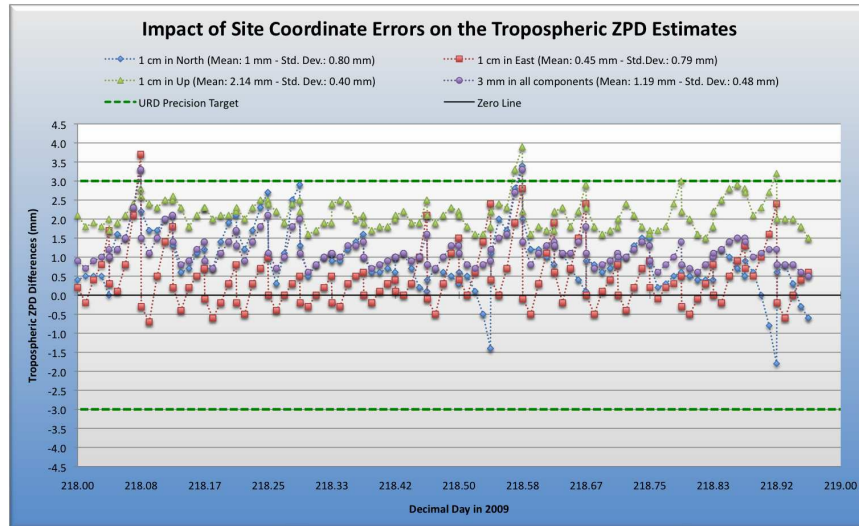


Figure 4.6: Impact of a 1-cm fictitious site coordinate errors at the GNSS site of Onsala, Sweden, on its tropospheric ZPD estimates

Because of the network approach, the Least-Squares adjustment tries to minimize the post-fit residuals of all ionosphere-free GNSS carrier-phase double-difference observations, introducing a fictitious error in the site coordinates of Onsala did not impact the estimates of Onsala solely, but also impacted the tropospheric ZPD of the other GNSS sites within the test network (Table 4.2). Nevertheless, the maximal differences between the estimated tropospheric ZPD of the other sites remained usually below the 0.5 mm level for all tested solutions, with a few exceptions for which the maximal deviation reached up to 1.45 mm (for the station of Potsdam in Germany and when using the 1-cm fictitious error in the north coordinate solution). The test taught us that for GNSS-meteorology, the site coordinates must be known with a precision and accuracy at the millimetre level. Horizontal components of the site coordinates are slightly less critical and usually also better known. A proper monitoring of the site coordinates and the detection of the daily coordinate outliers is thus strictly necessary.

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
1-cm Error in the North Component - Average values over the complete network									
Mean	-0.16	0.34	0.04	0.09	0.08	1.54	11.14	-0.05	10680
Std. Dev.	0.40	0.56	0.21	0.12	0.57	2.46	27.95	0.19	10680
Max. Dev.	-1.64	3.06	0.96	0.71	-2.88	12.57	187.86	-1.20	10680
1-cm Error in the East Component - Average values over the complete network									
Mean	-0.23	0.15	-0.03	0.07	-0.01	-2.22	16.61	-0.05	10440
Std. Dev.	0.23	0.52	0.09	0.11	0.53	2.81	26.48	0.05	10440
Max. Dev.	-0.97	3.55	0.48	0.72	3.26	-8.05	89.39	-0.10	10440
1-cm Error in the Vertical Component - Average values over the complete network									
Mean	-0.20	0.07	-0.05	0.06	-0.02	-1.28	7.86	-0.06	10870
Std. Dev.	0.31	0.55	0.33	0.06	0.30	2.10	15.57	0.07	10870
Max. Dev.	1.70	3.83	2.19	0.34	1.78	-8.99	98.14	-0.25	10870
3-mm Error in the Three Components - Average values over the complete network									
Mean	-0.15	0.15	-0.02	0.05	0.05	0.13	25.92	-0.05	9795
Std. Dev.	0.19	0.48	0.20	0.07	0.35	4.40	41.43	0.08	9795
Max. Dev.	0.65	3.15	1.21	0.43	2.06	-14.59	183.08	-0.38	9795

Table 4.2: Statistics of the tropospheric ZPD differences between the 1-cm fictitious ONSA-coordinate error solutions and the true ONSA-coordinate solution, averaged over all stations but Onsala within the test network

Coordinate Monitoring and Cumulative Coordinate Solutions

The aforementioned results demonstrated that even small errors in the site coordinate determination must be identified and removed. Therefore, the daily NEQ obtained from the post-processing analysis are stacked to obtain two cumulative coordinate solutions, respectively over the last 7-days and over the last 31-days. In the framework of the Quality Monitoring Scheme (QMS), the daily coordinates are then compared to the cumulative solutions and daily coordinate outliers are identified and removed from the coordinate solutions on per station and per day basis. The cumulative solutions obtained in this way present several advantages with respect to the raw daily coordinate solutions:

- They are cleaned from the daily coordinate outliers
- They provide station coordinates of better precision and accuracy [Beutler *et al.*, 2007]

- They offer more continuity and robustness, e.g. when the observations of a GNSS station are unavailable or unreliable for some days

In terms of continuity and robustness, the monthly cumulative solution offers a clear advantage over the weekly cumulative solution in case GNSS observations are unavailable or unreliable for a few consecutive days. We opted thus for the use of monthly cumulative solutions in the back-substitution procedure (Figure 4.5) of the GNSS site coordinates. The performances of the 1st step of the analysis strategy in terms of precise coordinate determination will be addressed later in Chapter 5.

4.4.4 Sequential LSQ Adjustment in the Space Domain

When large networks are analysed, data from all GNSS stations cannot be processed in a single LSQ estimation. According to [Beutler *et al.*, 2007], if the number of stations is much larger than 30, the memory and processing time consumption may become very large due to the number of parameters to be estimated in the LSQ estimation. To overcome this problem, the procedure presented in Figure 4.7 was set up: groups of baselines, referred to as *clusters*, are formed and processed independently. Then, during the final stage of the analysis, the NEQ obtained from each independent cluster analysis are combined in a sequential LSQ adjustment to produce the anticipated results. The cluster (sequential) adjustment takes into account all correlations between the baselines of each cluster, while correlations between baselines in different clusters are however lost. Nevertheless, processing cluster adjustment solutions is identical with processing all observations in a common adjustment if there is no correlation of the original observations [Beutler *et al.*, 2007]. Clusters have therefore to be carefully selected for ensuring minimum overlaps to minimize the effects of neglecting these correlations. The cluster adjustment method is applied in both steps of the analysis strategy. Figure 4.8 illustrates the attribution of the baselines in clusters for the near real-time step of the analysis strategy. Up to 11 clusters of about 40 GNSS sites are formed in the post-processing analysis step.

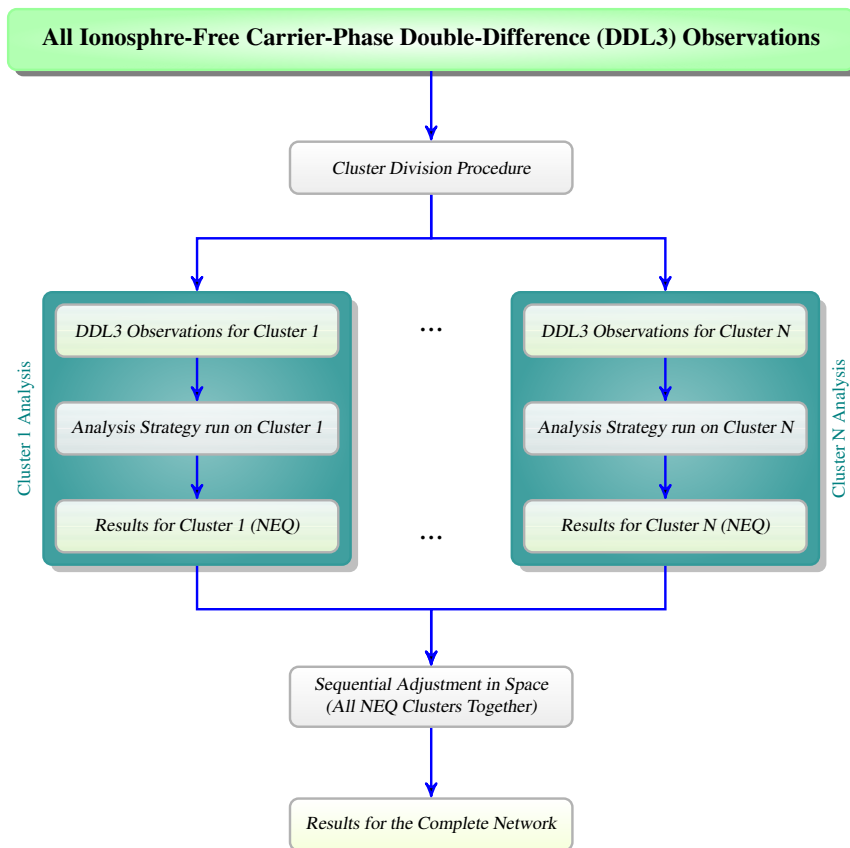


Figure 4.7: Principle of sequential Least-Squares adjustment in the spatial domain

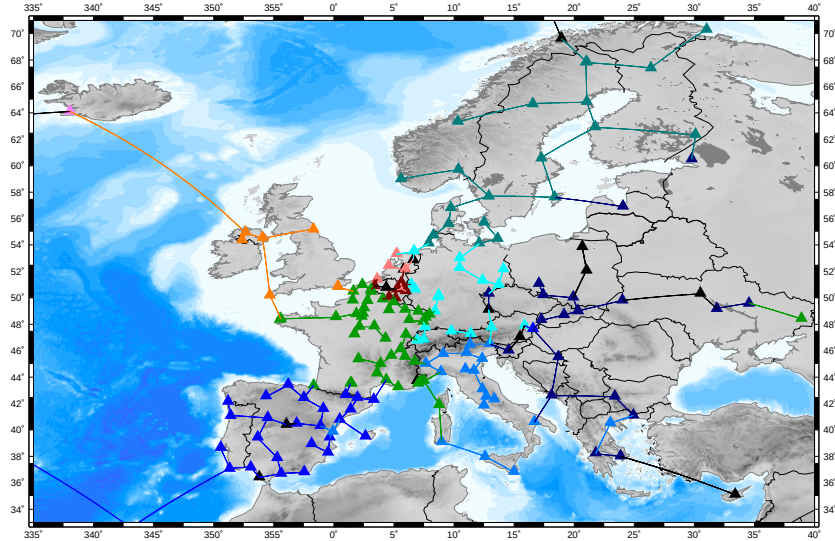


Figure 4.8: Example of baseline attribution per cluster during our near real-time analysis strategy. Each color represents a different cluster attribution. Epoch of observation: 5th January 2010, between 00 UTC and 01 UTC

4.4.5 Functional Model of the Tropospheric Path Delay

The tropospheric path delay functional model implemented in the *Bernese GPS software* version 5.0 [Beutler *et al.*, 2007] and used in our 2-step analysis strategy is based on the mathematical model given in Equation 3.15. The time evolution of the tropospheric path delay is modelled by piece-wise linear functions as shown in Figure 4.9. To meet the GNSS-meteorology requirements, the different parts of the mathematical model need to be fine-tuned. The most relevant tests related to the sensitivity and the optimisation of the tropospheric path delay functional model is illustrated in Figure 4.10 and are discussed hereafter. All part of the model are concerned (orange box), i.e. the *a priori model*, the *mapping functions*, the *site-specific tropospheric path delay parameters* and the *horizontal tropospheric gradient parameters*. In addition, several processing options (red box), such as the absolute and relative constraints and the repetition cycle, may impact directly the tropospheric ZPD estimated using this functional model. Their impact is also discussed hereafter.

Remark: Unless specified otherwise, the different tests have been carried out using the 60 GNSS stations of the test network Figure 4.3.

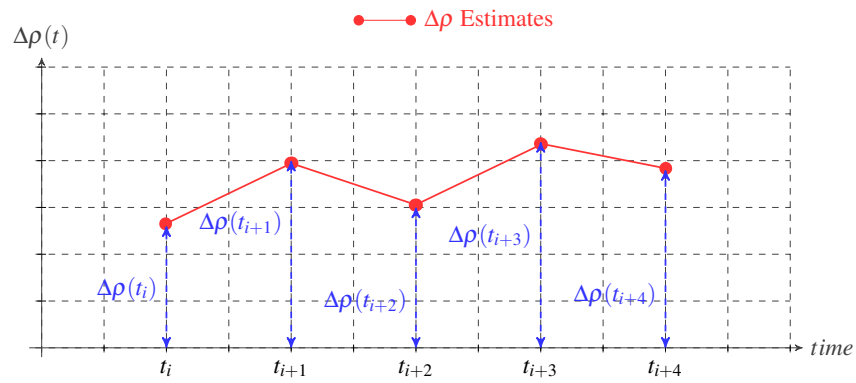


Figure 4.9: Modelling the time evolution of the tropospheric path delay $\Delta\rho$ by piece-wise linear functions

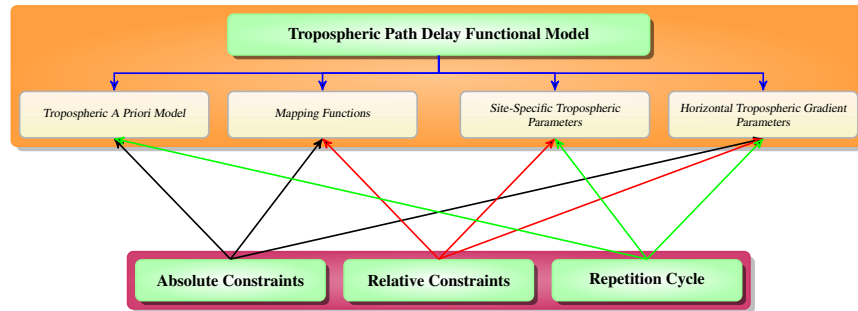


Figure 4.10: Global structure of the sensitivity and optimisation tests related to the functional model of the tropospheric path delay

Mapping Functions, A priori Model and Observation Cut-off Angles

Today, state-of-the-art mapping functions are based on *Numerical Weather Prediction* (NWP) model data (Chapter 3). In this context, the online version of the IERS Conventions [IERS Conventions Update], which updates the 2003 recommendations [McCarthy and Petit, 2004], advises to use the *Vienna Mapping Functions* (VMF1). Although these mapping functions have been available for some years now, they aren't implemented in the *Bernese GPS software* version 5.0. Hereafter, the impact of this software limitation on our tropospheric ZPD estimates is discussed. Using the NMF along with SPT values as input for the Saastamoinen-based a priori hydrostatic model introduces two types of errors: uncertainties in the *mapping functions* (*mf*) coefficients and uncertainties in the a priori hydrostatic model.

Mapping Function Coefficient Uncertainties: To assess the error made on the tropospheric ZPD estimates (purely) due to the NMF coefficient uncertainties, we differentiated, for a period covering the 1st January 2004 to the 31st December 2009, the tropospheric ZHD and the tropospheric ZWD obtained by mapping SPD values from different elevation angles to the zenith using the NMF and the VMF1 (considered here as “ground-truth”). The procedure of this test is illustrated in Figure 4.11 and evolves as follow:

- ✎ The a priori dry (or wet) tropospheric ZPD is mapped to several elevation angles down to 3° using the dry (or wet) VMF1 to obtain the most realistic values possible of the dry (or wet) SPD at these elevation angles.
- ✎ Then, the obtained dry (or wet) SPD values are mapped back to the zenith using the dry (or wet) NMF and the differences to the original a priori value are computed.

In the case of the dry mapping functions, realistic tropospheric ZHD values were obtained from the GPT (Section 3.3.2) and used as a priori model. Because no proper a priori model of the tropospheric ZWD exists, a fictitious constant value of 0.35 m was used, which can be seen as an extreme value (see Figure 3.3 for typical values at Brussels). This procedure was applied to 96 GNSS sites in Europe.

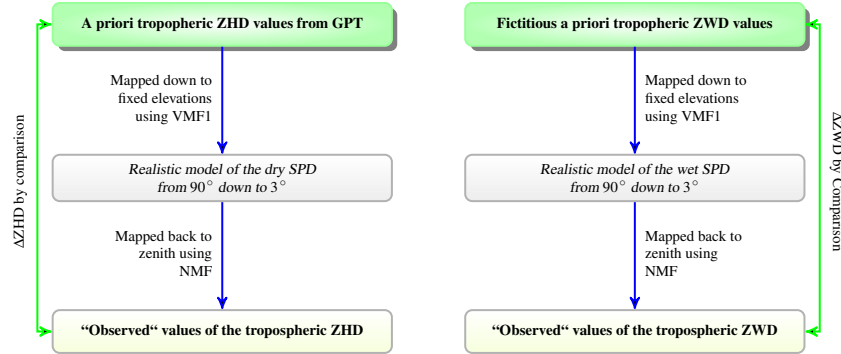


Figure 4.11: Procedure applied to test the impact of uncertainties in the NMF coefficients on our tropospheric ZPD estimates

The average tropospheric ZHD and ZWD biases (over the 2004-2009 period) induced by the NMF uncertainties at different elevation angles are illustrated in Figure 4.12 for Brussels, Belgium. Down to an elevation angle of 10° , the tropospheric ZHD biases remain below 0.2 mm and the tropospheric ZWD biases are below 0.05 mm. In average, and using an observation cut-off angle of 10° , these biases can thus be neglected.

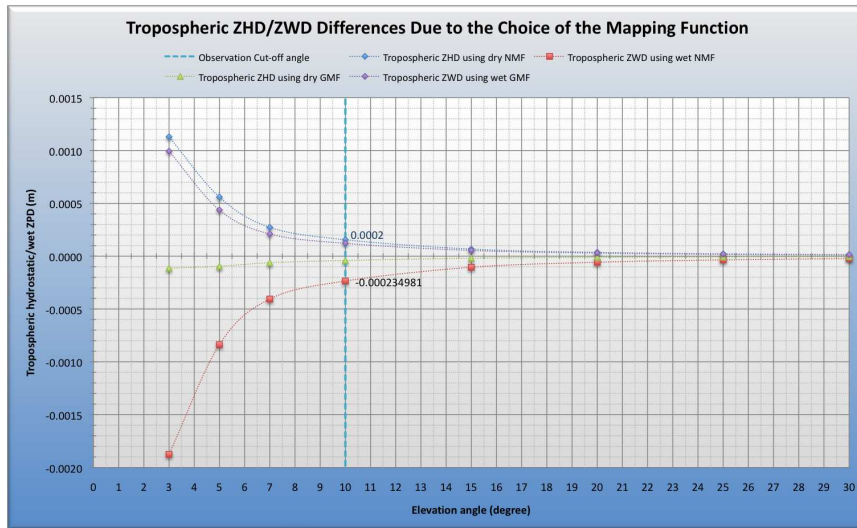


Figure 4.12: Tropospheric ZHD and ZWD biases observed due to NMF coefficient uncertainties at different elevation angles (Average value over the 2004-2009 period)

However, the coefficients of the mapping functions varies with respect to the epoch of the year. As illustrated in Figure 4.13, the coefficients of the wet VMF1 clearly emphasise much more variability than the empirical NMF and GMF ones, corresponding to the use of real atmospheric data from NWP models. At the opposite, the wet NMF uses a single coefficient constant over the year, missing thereby the annual atmospheric water vapour cycle. Moreover, the mapping function coefficients depend on the geographical location. Therefore, the average total tropospheric ZPD biases induced by the (dry+wet) NMF uncertainties at 10° over the 2004-2009 period and its variability along the time (standard deviation) were computed for different locations in Europe. They are presented in Figure 4.14 and Figure 4.15 respectively.

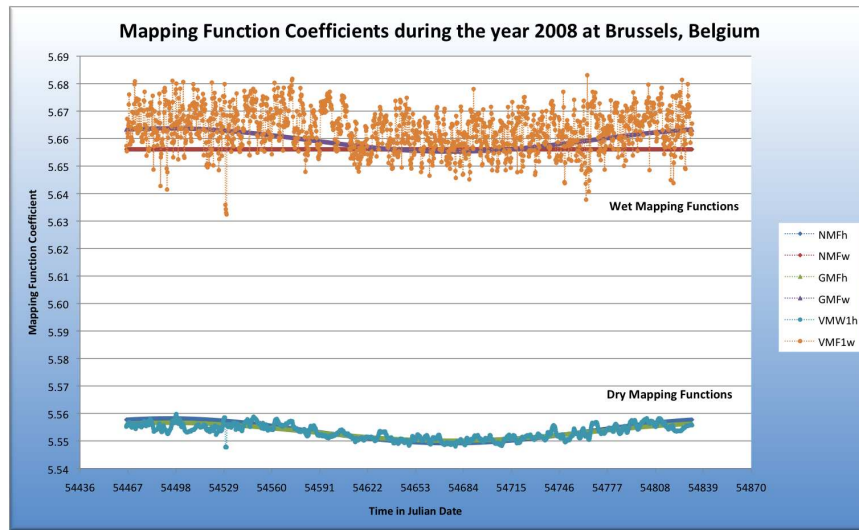


Figure 4.13: Coefficients of the three mapping functions (NMF, GMF and VMF1-hydrostatic and wet) at 10° during the year 2008 in Brussels, Belgium

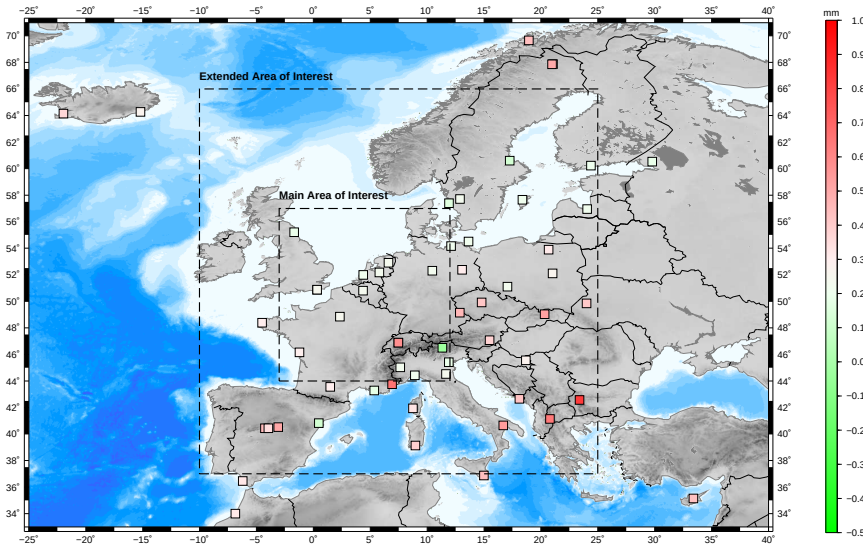


Figure 4.14: Geospatial distribution of the total tropospheric ZPD bias induced by the Niell Mapping Functions (NMF) coefficient uncertainties at 10° , averaged over the 2004-2009 period

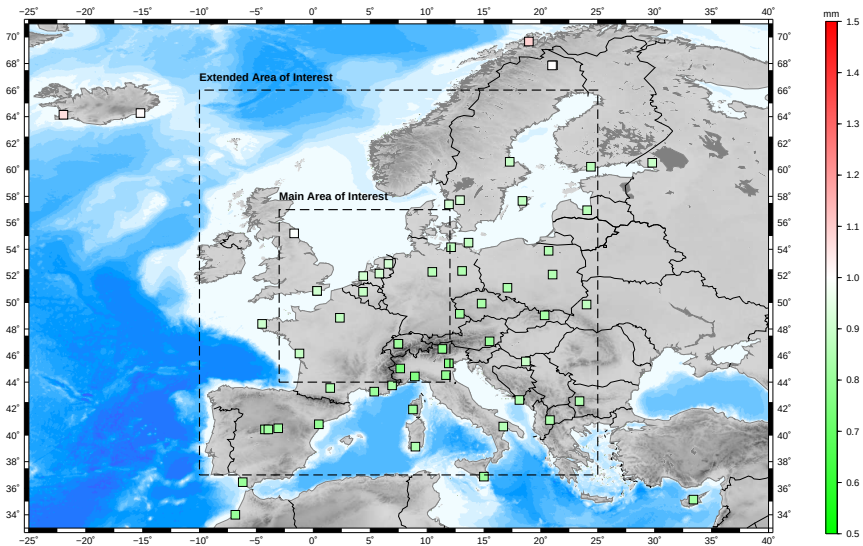


Figure 4.15: Geospatial distribution of the time variability of the total tropospheric ZPD bias induced by the Niell Mapping Functions (NMF) coefficient uncertainties at 10° over the 2004-2009 period

The investigations show that in central and western Europe, the total tropospheric ZPD biases induced by the NMF coefficient uncertainties at 10° remain within 1 mm, with a median value of about 0.3 mm. The time variability of these biases remains within 1.1 mm for all sites, with a median value of about 0.8 mm. To conclude, the impact of the NMF coefficient uncertainties on our tropospheric ZPD estimates tends to slightly overestimate the tropospheric ZPD but using an observation cut-off angle of 10° , this effect can usually be neglected.

Uncertainties in the a Priori Model: In [Boehm *et al.*, 2007], the authors studied the pressure differences between GPT-derived and SPT-derived values. In latitudes ranging from 35° N to 75° N, these pressure differences range from -3.9 hPa to 3.9 hPa, with typical uncertainties of 3 hPa to 4 hPa. Using Equation 3.20, these pressure differences can be converted in their equivalent tropospheric ZHD, which range thus from -8.97 mm to 8.97 mm, with typical equivalent uncertainties of 6 mm to 9 mm. This bias in the a priori hydrostatic model introduced by using SPT values will have to be taken into account while estimating the site-specific tropospheric parameters. However, site-specific tropospheric parameters are estimated using the wet mapping function. This will thus cause errors due to the use of the improper mapping function (the wet instead of the dry mapping function), as the considered tropospheric ZPD errors are part of the dry atmosphere. Because the differences between the dry and the wet mapping function coefficients increase with decreasing elevation angles, the maximal impact will be observed at 10° , which is the lowest elevation angle allowed in our analysis strategy. Taking into consideration the maximal bias of the a priori hydrostatic model, i.e. ± 8.97 mm (resp. ± 17.97 mm if we include the maximal uncertainty), the differences in the NMF coefficients for Brussels at 10° , the bias introduced in our tropospheric ZPD remains within ± 0.15 mm (resp. ± 0.31 mm), which can be neglected. At an elevation angle of 3° , this error grows up to ± 1 mm (resp. ± 2 mm). The same analysis was carried out for different locations in Europe. For all sites investigated, this error remains negligible.

Absolute Constraints

In a Least-Squares adjustment, the estimated parameters can be constrained to their a priori values by constraining the parameter improvement to a specific value (Section A.4). This is referred to as *absolute constraints*. Figure 4.16 illustrates the principle of applying absolute constraints to the tropospheric path delay functional model. As shown in this figure, the absolute constraints imposes thus on the tropospheric ZPD estimates (red curve) to not deviate too much from the a priori model (green curve, Section 3.3.2).

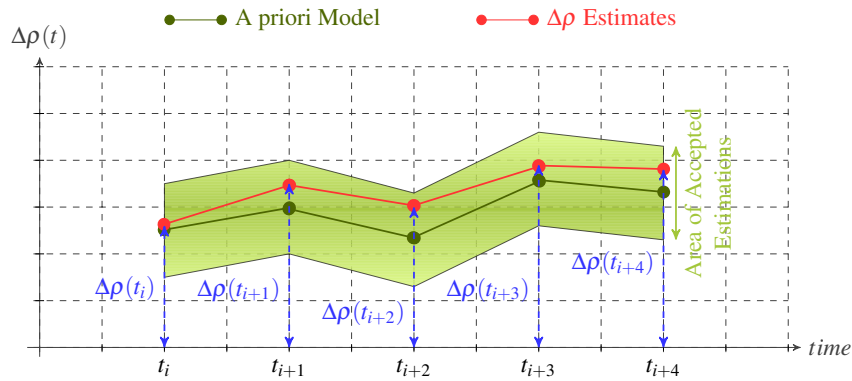


Figure 4.16: Principle of absolute constraints applied to the tropospheric path delay functional model

No proper a priori model exists for the wet tropospheric path delay (Section 3.3.2). Therefore, only an hydrostatic a priori model was applied in our analysis strategy (Saastamoinen-based model along with the Berg's power law and SPT model values). This can be considered as a very rough approximation of the hydrostatic path delay (Section 3.3.2) and the actual tropospheric ZPD can thus deviate largely from the a priori model. Therefore, applying effective absolute constraints is expected to potentially introduce artificial biases in the tropospheric ZPD estimates. This hypothesis was tested by comparing 7 tropospheric ZPD solutions obtained by applying different absolute constraints, i.e. 1 m, 50 cm, 35 cm, 25 cm, 15 cm, 10 cm and 5 cm, and comparing them to the solution obtained without any absolute constraint. The comparison was carried out over a 15-day period, from 1st September 2008 to

15th September 2008. The tropospheric ZPD differences between the solutions obtained with different absolute constraints and the unconstrained solution are illustrated in Figure 4.17 for the site of Poltava (POLV), Ukraine.

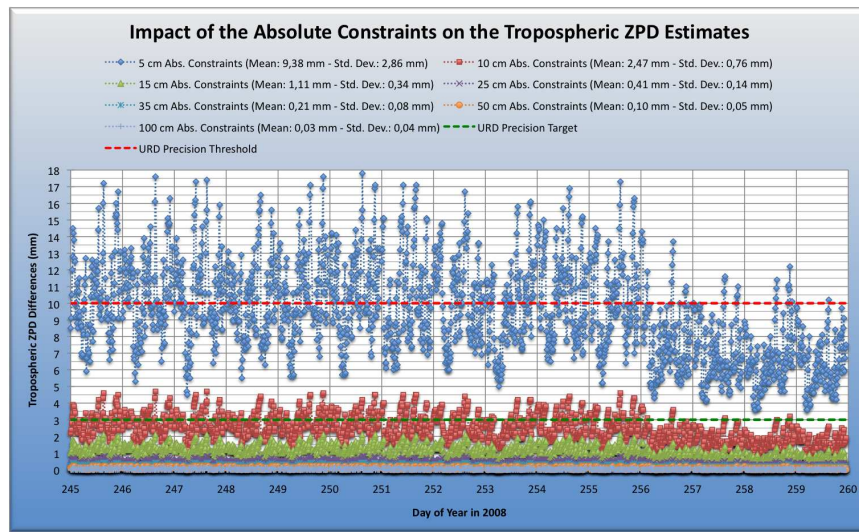


Figure 4.17: Differences between tropospheric ZPD time series computed with different absolute constraints and the unconstrained tropospheric ZPD time series at the GNSS station in Poltava (POLV), Ukraine

From this test, we can conclude that applying absolute constraints on our tropospheric ZPD estimates induces mainly a bias on which short-term variations are super-imposed. The sensitivity to the site coordinates (mainly the vertical component) is also increased: a clear jump in the tropospheric ZPD differences is visible around the day of year 256 and is due to a slight change in the station coordinates. The statistics of this sensitivity test for absolute constraint values of 50 cm, 25 cm, 10 cm and 5 cm, averaged over the 60 GNSS sites of the test network (more than 85342 common observations in total), are summarised in Table 4.3. It shows that, on one hand, applying weak absolute constraints (25 cm and above) has mostly no impact on the estimated tropospheric ZPD (no bias, standard deviations of quasi zero and maximal deviations of a few tens of millimetres). Values of the *skewness* (Section B.4) and *kurtosis* (Section B.5) generally remained close to those of

a normal distribution (i.e. zero and 3 respectively). However, the maximal deviation of the skewness indicated that setting up weak absolute constraints can occasionally cause to estimate slightly dryer tropospheric ZPD (moderate positive skewness value). On the other hand, applying slightly stronger absolute constraints mainly introduce a site-specific bias the tropospheric ZPD estimates (up to 14.37mm with a standard deviation of a few tens of millimetres and some peaks) between the solutions. The tropospheric ZPD tends to be underestimated (drier) compared to the unconstrained solution. When even stronger absolute constraints were applied (here 5 cm), the tropospheric ZPD estimates were highly degraded: extreme values of the bias of up to 14.60mm, and of the maximal deviations of up to 19.49mm has been recorded for the site of Noto (NOT1), Italy. No clear geographical dependency pattern, such as a latitude dependency, was detected for any of the absolutely constrained solutions. From the results of this sensitivity test, we decided to not apply any absolute constraint on our tropospheric ZPD estimates.

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
The 50cm Absolute Constraint Solution - Average values over the complete network									
Mean	0.00	0.18	0.09	0.05	0.00	0.18	2.99	-0.00	85818
Std. Dev.	0.01	0.05	0.04	0.01	0.11	0.65	1.33	0.00	85818
Max. Dev.	0.10	0.12	-0.08	-0.05	-0.16	2.31	4.22	-0.01	85818
The 25cm Absolute Constraint Solution - Average values over the complete network									
Mean	0.13	0.61	0.35	0.10	0.16	0.33	2.95	-0.01	85562
Std. Dev.	0.08	0.24	0.14	0.03	0.24	0.30	0.69	0.01	85562
Max. Dev.	0.17	0.59	-0.30	0.09	-0.46	1.10	2.52	-0.04	85562
The 10cm Absolute Constraint Solution - Average values over the complete network									
Mean	1.03	3.73	2.13	0.52	1.59	0.48	2.99	-0.04	85342
Std. Dev.	0.46	1.50	0.84	0.23	0.73	0.31	0.55	0.05	85342
Max. Dev.	-0.93	3.57	-1.83	0.60	1.90	1.20	2.69	-0.26	85342
The 5cm Absolute Constraint Solution - Average values over the complete network									
Mean	3.99	14.17	8.13	1.93	6.04	0.47	2.98	-0.15	85351
Std. Dev.	1.73	5.61	3.17	0.85	2.73	0.32	0.56	0.17	85351
Max. Dev.	-3.59	13.33	-6.96	2.22	7.04	1.20	2.69	-0.96	85351

Table 4.3: Statistics of the tropospheric ZPD differences between the absolutely constrained solutions and those obtained without absolute constraint

Relative Constraints

In a Least-Squares adjustment, it is also possible to constrain the time evolution of a parameter (Section A.4). This is referred to as *relative constraints*. Figure 4.18 illustrates the principle of applying relative constraints to the tropospheric path delay functional model. As shown in this figure, the relative constraint imposes on each tropospheric ZPD estimate to not deviate too much from previous estimation.

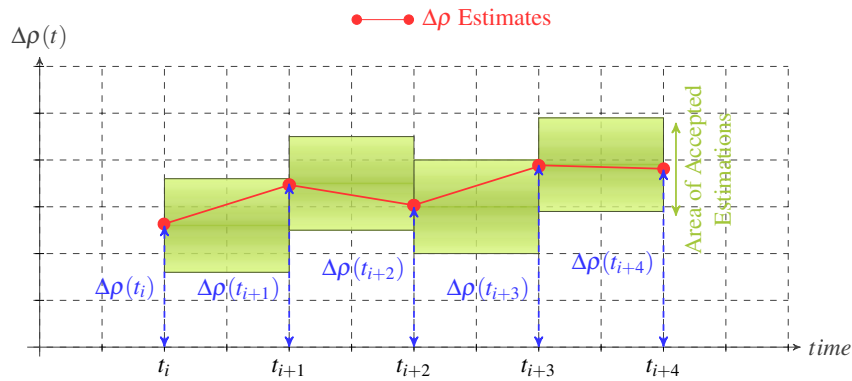


Figure 4.18: Principle of relative constraint applied to the tropospheric path delay functional model

Applying relative constraints can be interesting when the parameter estimation frequency, i.e. the repetition cycle, is close to the characteristic time of the variations of the estimated physical parameter. The impact of the latest on the tropospheric ZPD will be discussed in the next section. In the case of the tropospheric ZPD estimation, the relative constraints are used to constrain the value estimated by the functional model (Equation 3.15) with respect to the quick variations associated with the water vapour and the hydrometeors (Section 3.2.4). Relative tropospheric ZPD constraints are thus particularly effective when using a repetition cycle in the range of 5 min to 20 min (Section 3.2.4). Because of the large range of tropospheric path delay variations within a time scale of 1 hour and above, the relative constraints have to be quite loose when using such a repetition cycle (i.e. 60 min and above) and their use becomes thereby of less interest.

To determine the impact of using relative constraints on the quality of our tropospheric ZPD estimate, the tropospheric ZPD solutions computed using the 15 min repetition cycle targeted in the URD and different relative constraints were compared to the tropospheric ZPD solution obtained from the post-processing analysis for a 15-day period covering the 1st September 2008 to the 15th September 2008. This comparison is illustrated in Figure 4.19 for the GNSS site of Onsala (ONSA), Sweden. For this GNSS station, most of the tropospheric ZPD differences remain within the precision targeted in the URD, i.e. 3 mm, except for some peaks that reached the precision threshold. For other GNSS sites, such as the one located in Brussels (BRUS, Figure 4.20), Belgium, the impact of changing the relative constraints is much higher and regularly exceeds the precision target (or even the threshold) specified in the GNSS-meteorology requirements.

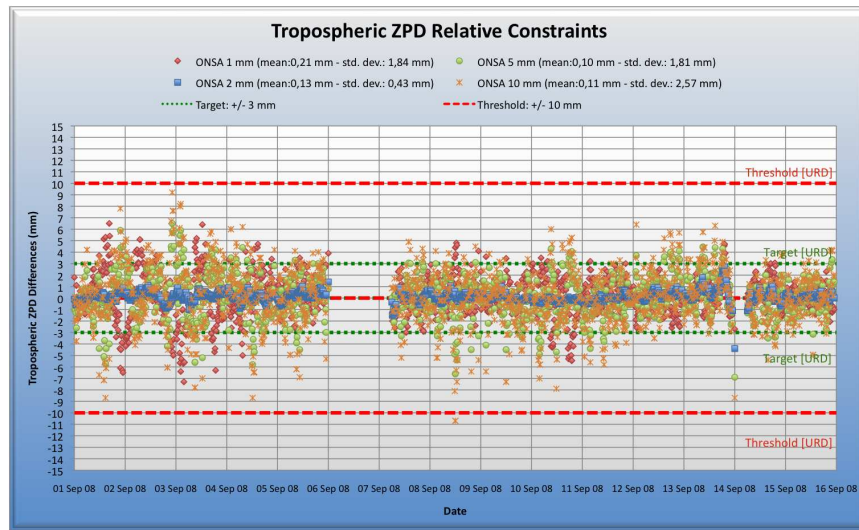


Figure 4.19: Tropospheric ZPD differences between the near real-time solutions obtained using different relative constraints and the post-processed tropospheric ZPD solution for the GNSS station located in Onsala, Sweden (period covering the 1st September 2008 to the 15th September 2008)

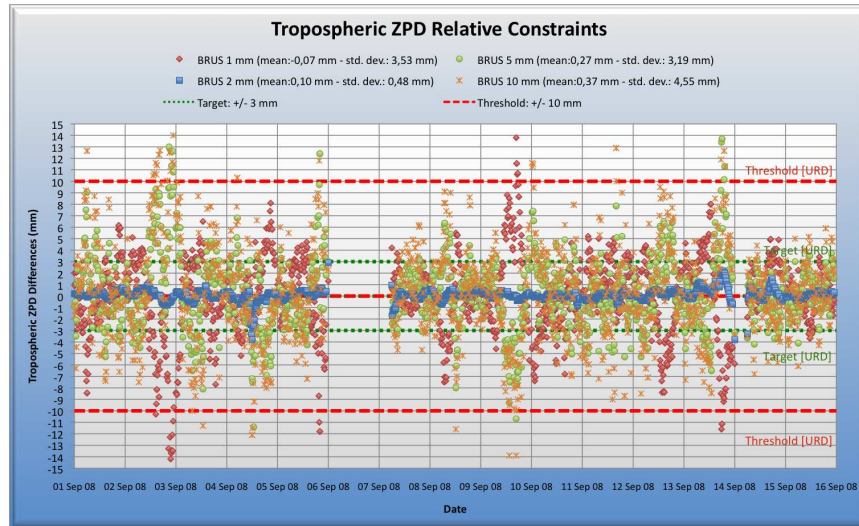


Figure 4.20: Tropospheric ZPD differences between the near real-time solutions obtained using different relative constraints and the post-processed tropospheric ZPD solution for the GNSS station located in Brussels, Belgium (period covering the 1st September 2008 to the 15th September 2008)

The statistics of this sensitivity test for relative constraints of 0.1 mm, 1 mm, 2 mm, 5 mm and 10 mm are summarised in Table 4.4. Averaged over the 60 GNSS sites (more than 74000 common observations in total), the tropospheric ZPD tend to follow a normal distribution (no large skewness nor kurtosis values) centred around zero. No systematic under- or overestimation of the tropospheric ZPD estimates was emphasised (see skewness values). The mean standard deviation remain within a few millimetres (except for the 0.1 mm and 10 mm relative constraints). With large maximal deviations, it reveals that the impact of the relative constraints on the quality of the tropospheric ZPD clearly depends on the GNSS site (Figure 4.20 and Figure 4.19), notably through the quality of its raw observations. On one side, relative constraints of 10 mm are not sufficient to confine the tropospheric ZPD differences in the 10 mm precision threshold specified in the URD. At the opposite, too tight relative constraints degrade significantly the precision of the tropospheric ZPD. No clear and significant bias could be emphasised in any of the tested solutions. Neither could be emphasised a clear geographical dependency

pattern nor any linear trend in the time series. Because the choice of the relative constraints clearly depends on the site (observation quality, location, environmental effect, climate, altitude...) no optimal and unique value could be determined. Nevertheless, a relative constraint of 2 mm seems to be a good compromise, allowing space for tropospheric ZPD variations, but sufficiently tight to bring improvements in the precision of the tropospheric ZPD. This assertion will be validated later in Chapter 5.

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
0.1mm Relative Constraint Solution - Average values over the complete network									
Mean	-31.00	31.38	0.52	9.52	-13.63	-0.03	3.73	0.04	73893
Std. Dev.	7.29	7.51	0.50	2.17	29.92	0.23	0.44	0.17	73893
Max. Dev.	18.70	-19.28	-1.26	-5.67	55.34	0.96	1.33	-0.48	73893
1mm Relative Constraint Solution - Average values over the complete network									
Mean	-8.09	8.56	0.22	2.62	1.19	-0.00	3.42	0.01	74151
Std. Dev.	2.15	2.27	0.17	0.69	8.65	0.16	0.26	0.03	74151
Max. Dev.	4.59	-4.96	0.38	1.47	-13.98	-0.36	0.63	-0.08	74151
2mm Relative Constraint Solution - Average values over the complete network									
Mean	-1.90	2.20	0.12	0.56	0.06	0.09	4.13	0.01	73759
Std. Dev.	0.71	0.84	0.10	0.21	2.29	0.33	0.65	0.02	73759
Max. Dev.	-1.80	3.00	0.26	0.75	4.76	-0.99	2.28	-0.06	73759
5mm Relative Constraint Solution - Average values over the complete network									
Mean	-9.20	9.32	0.09	2.86	-2.18	0.00	3.62	0.00	74047
Std. Dev.	2.91	2.82	0.18	0.84	9.61	0.14	0.37	0.05	74047
Max. Dev.	-9.30	8.48	-0.40	2.09	17.57	0.42	1.32	0.12	74047
10mm Relative Constraint Solution - Average values over the complete network									
Mean	-13.86	14.07	0.13	4.21	-1.12	-0.01	3.75	-0.00	74016
Std. Dev.	5.06	4.83	0.20	1.38	15.00	0.14	0.46	0.05	74016
Max. Dev.	-17.24	15.23	-0.52	3.46	-29.64	0.43	1.47	0.16	74016

Table 4.4: Statistics of the tropospheric ZPD differences between the near real-time solutions computed using different relative constraints with respect to the post-processed solution (mean statistics over all GNSS sites)

Repetition Cycle

In the *Bernese GPS software* version 5.0, piece-wise linear functions are used to represent the time evolution of the tropospheric path delays. As shown in Figure 4.9, the tropospheric parameters $\Delta\rho$ are modelled in each particular time interval $[t_i, t_{i+1}]$ by a linear function. The repetition cycle requirement specified in the URD corresponds to the length of the interval $[t_i, t_{i+1}]$. As specified in Table 4.1, the repetition cycle requested for NWP applications ranges between 15 min (target) and 60 min (threshold). Of course, the smaller repetition cycle used, the better the quick variations of the tropospheric path delay (Section 3.2.4) are captured and represented. In addition, the shorter the repetition cycle, the smaller the possible dephasing between the estimated and the actual tropospheric path delay values (Figure 4.21). A small repetition cycle is thus highly preferable to bring a real added-value in NWP and nowcasting applications.

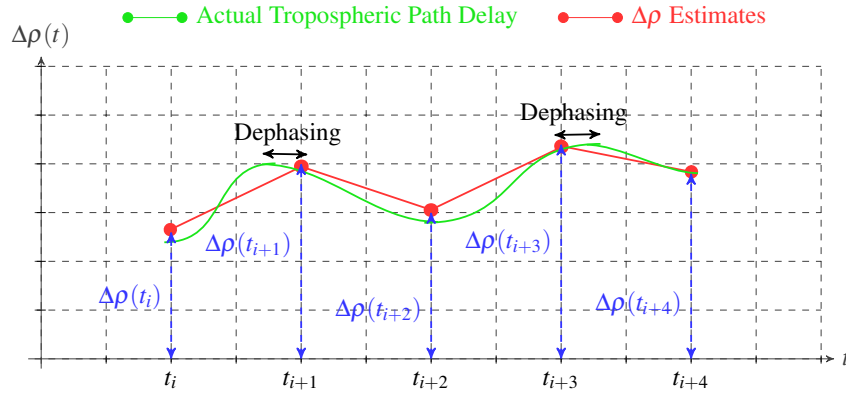


Figure 4.21: Dephasing in the tropospheric ZPD estimates $\Delta\rho$ due to a poor repetition cycle

Changing the repetition cycle changes the number of parameters to be estimated in the LSQ adjustment. But it might also impact the quality of our tropospheric ZPD estimate. Tropospheric ZPD solutions obtained with 5 different repetition cycles, i.e. 60 min, 30 min, 15 min, 10 min and 5 min, were thus compared to test the sensitivity to this option parameter. The comparison was carried out over 1 day (6th Augustus 2009). The 5-min

repetition cycle could not be applied because of numerical instabilities in the processing software, probably due to a lack of GNSS observations and too high correlations between the unknown parameters to be estimated. All other repetition cycles could be successfully applied. Since the relative constraint setup might impact the results of the comparison, different repetition cycles were first evaluated without applying any relative constraint. Because a small repetition cycle is better for meteorological applications, the 10min repetition cycle was chosen as reference solution and compared to the 3 others repetition cycle solutions. The tropospheric ZPD differences between the 60-min, 30-min and 15-min repetition cycles solutions with respect to the 10-min repetition cycle solution are represented in Figure 4.22 for the site of Dentergem (DENT), Belgium. The figure shows that changing the repetition cycle induces large variations in the tropospheric ZPD time series. These variations are largely above the precision targeted in the URD, with a peak-to-peak amplitude of about 21 mm. This held true when analysing the results for the complete network. The statistics of this sensitivity test are summarised in Table 4.5. The table shows that, averaged over the 60 GNSS sites (more than 1145 common observations in total), the tropospheric ZPD differences follow a quasi-normal distribution (no significant mean skewness nor mean kurtosis values) with a mean bias up to -2.79 mm and a mean standard deviation of 5.69 mm for the 60-min repetition cycle solution. Peak-to-peak discrepancies up to 41.61 mm, 42.34 mm and 36.7 mm are observed for the 60-min, 30-min and 15-min repetition cycle solutions respectively. The bias and the variability of the tropospheric ZPD are largely site-specific (large values of the maximal deviation of the bias and standard deviation). Significant values of the skewness and kurtosis are also observed for some sites.

To reduce the large differences observed between the different solutions, relative constraints were applied on the tropospheric ZPD estimates with a specific value for each repetition cycle solution:

- The 60-min repetition cycle was associated with a relative constraint of 4 mm
- The 30-min repetition cycle was associated with a relative constraint of 2.5 mm
- The 15-min repetition cycle was associated with a relative constraint of 2 mm
- The 10-min repetition cycle was associated with a relative constraint of 1.5 mm

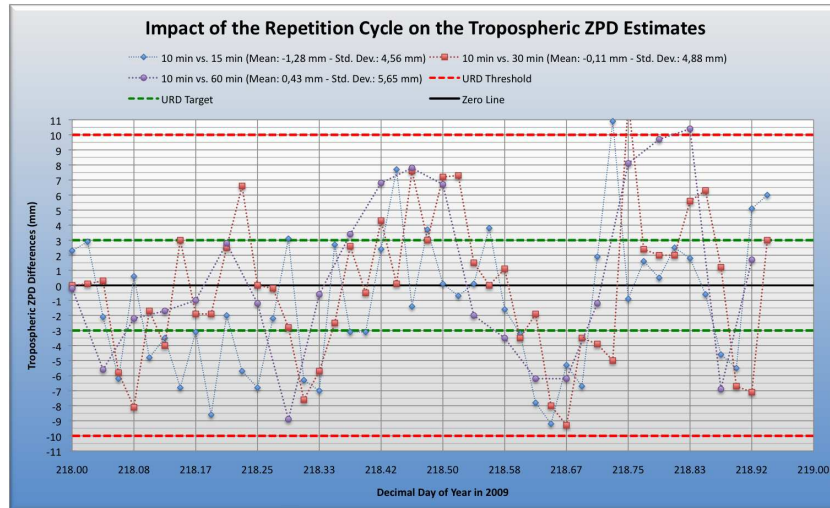


Figure 4.22: Time series of tropospheric ZPD differences between our near real-time solution computed with different repetition cycles with respect to the 10-min repetition cycle solution at the GNSS station located in Dentergem (DENT), Belgium (no relative constraint applied)

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
The 60-min Solution wrt. the 10-min Solution - Average values over the complete network - Not constrained									
Mean	-8.12	15.37	2.48	5.69	5.69	0.25	3.44	2.60	1145
Std. Dev.	3.90	7.34	1.42	1.54	14.49	0.77	2.10	5.00	1145
Max. Dev.	-12.18	29.43	-5.27	4.78	35.77	2.42	8.07	12.94	1145
The 30-min Solution wrt. the 10-min Solution - Average values over the complete network - Not constrained									
Mean	-9.82	14.04	1.17	4.95	3.09	0.19	3.56	1.96	2290
Std. Dev.	4.54	6.88	1.34	1.42	14.97	0.57	1.62	3.61	2290
Max. Dev.	-14.98	27.36	-5.80	4.16	35.98	1.52	5.44	11.32	2290
The 15-min Solution wrt. the 10-min Solution - Average values over the complete network - Not constrained									
Mean	-12.36	12.44	-0.22	5.15	-0.63	0.07	3.72	2.73	2290
Std. Dev.	4.01	6.86	1.12	1.31	15.97	0.69	1.72	3.34	2290
Max. Dev.	-10.14	26.56	2.86	3.42	39.73	2.29	7.79	-10.86	2290

Table 4.5: Statistics of the unconstrained tropospheric ZPD differences between the near real-time solution computed with different repetition cycles with respect to the 10-min repetition cycle solution

The relative constraints associated with a specific repetition cycle were chosen taking into account the expected variation range, the typical formal errors of the estimated parameters and empirical tests. The different repetition cycle solutions were compared as above. Figure 4.23 illustrates again the time evolution of the tropospheric ZPD differences for the site of Dentergem (DENT), Belgium, over the same day, but obtained using relative constraints. The differences between the solutions are significantly reduced compared to the comparison carried out without relative constraints. However, they remain at the level of the precision targeted by the URD. This holds true when analysing the results for the complete network. The statistics of this sensitivity test for the 60 sites are presented in Table 4.6. Averaged over the 60 GNSS sites (more than 1349 common observations in total), the tropospheric ZPD differences follow a quasi-normal distribution with a mean bias up to 1.24 mm and a mean standard deviation up to 2.53 mm for the 60-min repetition cycle solution. Peak-to-peak discrepancies of about 12.94 mm, 10.36 mm and 10.24 mm are recorded for the 60-min, 30-min and 15-min repetition cycle solution respectively. Compared to the solutions obtained without relative constraint, the standard deviations are here reduced for all solutions and remaining differences between the tested solutions are to be assigned to the (non completely equivalent) relative constraint setup. The maximal deviations are also significantly reduced for all statistics. One can note the sign inversion of the maximal deviation of the skewness: there is now a slight tendency to overestimate the tropospheric ZPD as the repetition cycle becomes larger than the 10-min reference solution. From Figure 4.22 and Figure 4.23, it is not clear which repetition cycle solution is the best solution, as it is too much influenced by the relative constraint setup. But, as illustrated in Figure 4.24, the overall trends of the time series are very similar, while some dephasing are clearly visible. The 10-min and 15-min repetition cycle solutions are the closest (in terms of bias and standard deviation) but some more tuning at the relative constraints needs to be done to make them equivalent. For an operational service and a large network, we opted thus for the 15-min repetition cycle targeted in the URD. The assessment in terms of precision and accuracy will be done later in Chapter 5.

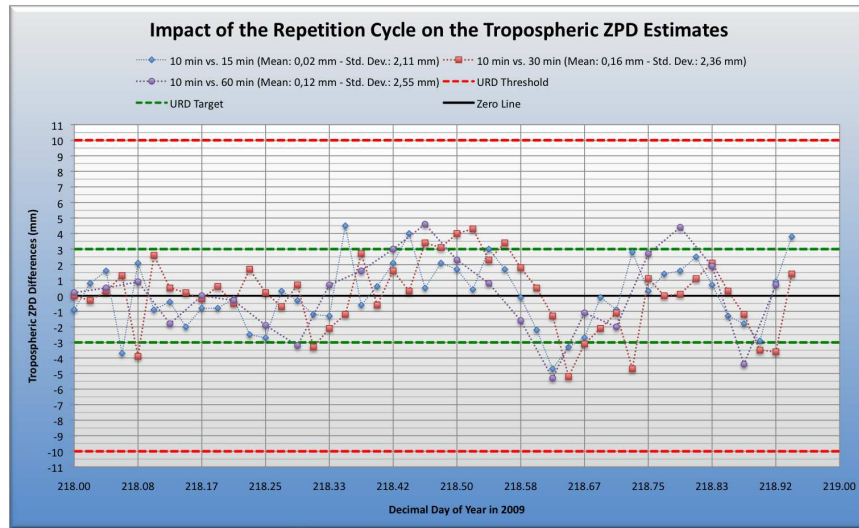


Figure 4.23: Time series of the tropospheric ZPD differences between the near real-time solution computed with different repetition cycles and the 10-min repetition cycle solution at the GNSS station located in Dentergem (DENT), Belgium (relative constraints applied)

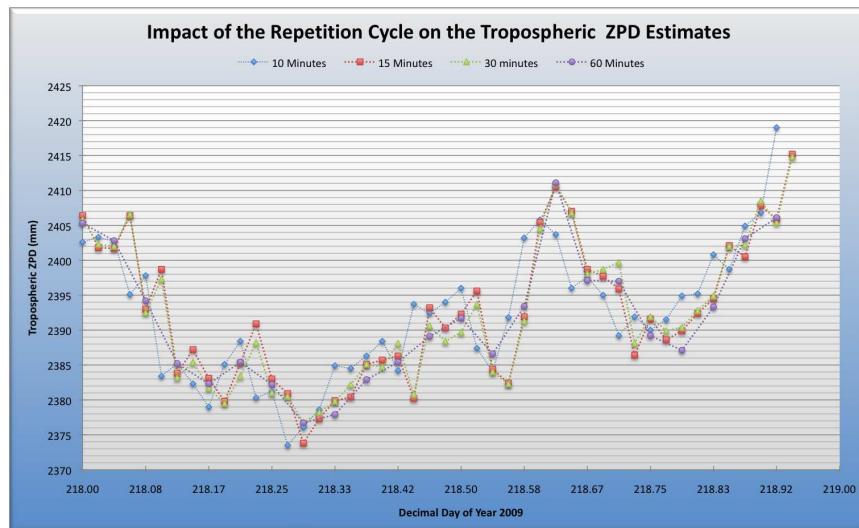


Figure 4.24: Time series of the tropospheric ZPD estimated using different repetition cycles at the GNSS station located in Dentergem (DENT), Belgium (relative constraints applied)

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
The 60-min Solution wrt. the 10-min Solution - Average values over the complete network - Constrained									
Mean	-3.74	6.72	1.24	2.53	1.04	0.15	3.23	-0.12	1349
Std. Dev.	1.98	2.57	0.90	0.79	6.37	0.57	1.10	2.21	1349
Max. Dev.	-5.26	7.68	-2.93	-2.40	11.88	-1.61	3.44	6.72	1349
The 30-min Solution wrt. the 10-min Solution - Average values over the complete network - Constrained									
Mean	-3.20	5.26	0.83	1.84	1.65	0.14	3.13	0.09	2650
Std. Dev.	1.81	2.64	0.77	0.78	5.06	0.46	0.77	1.83	2650
Max. Dev.	-4.30	-6.06	-2.29	-1.76	-9.45	-1.13	2.19	5.37	2650
The 15-min Solution wrt. the 10-min Solution - Average values over the complete network - Constrained									
Mean	-3.56	4.50	0.44	1.66	-0.20	0.05	3.53	0.44	2627
Std. Dev.	1.74	1.95	0.60	0.59	4.93	0.52	1.01	1.52	2627
Max. Dev.	-4.94	-5.30	1.80	-1.59	-7.94	-1.32	2.77	-4.63	2627

Table 4.6: Statistics of the tropospheric ZPD differences between the near real-time solution computed with different repetition cycles with respect to the 10-min repetition cycle solution

Horizontal Tropospheric Gradient Parameters

At low observation elevation angles, the asymmetry of the local troposphere at an observation site gets more and more important and must be accounted for by estimating horizontal tropospheric gradient parameters [Beutler *et al.*, 2007]. As illustrated in Figure 3.6, the *Bernese GPS software* version 5.0 implements the tilting method to estimate these horizontal tropospheric gradient parameters. According to [Beutler *et al.*, 2007], to properly estimate tropospheric gradient parameters, the observation elevation cut-off angle should be as low as possible, preferably 3° , and at most 10° . At these low elevation angles, error sources such as the multipath and the observation noise (Section 2.5) become more and more important. Their impact is even more significant that only 1 hour of observations is used: on such short observation sessions, error sources cannot be decorrelated due to poor changes in the satellite geometry during the session. The use of a longer observation session is thus required for a proper estimation of the horizontal tropospheric gradient parameters [Rocken, 2004]. In addition, below 10° of elevation angle, errors in the NMF coefficients might become significant. Using an observation cut-off

angle of 10° , the estimation of horizontal tropospheric gradient parameters do not bring significant improvements of the tropospheric ZPD, albeit an increase of the number of parameters to be estimated and the associated increase of computation time. Moreover, horizontal tropospheric gradient parameters are not used (until now) in GNSS meteorological applications (Section 4.2). For all these reasons, no horizontal tropospheric gradient parameters are estimated in the near real-time analysis.

4.4.6 Sequential Adjustment in the Time Domain

As we will show later in this section, the processing of only a single hour of GNSS observations does not provide tropospheric ZPD estimates of sufficient precision and accuracy with respect to the GNSS-meteorology requirements. This problem is due, on one hand, to the limited number of GNSS observations with respect to the number of unknowns to be estimated and, on the other hand, to the strong correlations between the different unknown parameters and the unmodelled systematic errors. To better decorrelate these unknowns, longer observation sessions are necessary. To increase the observation session length, while saving the processing time, a sequential adjustment in time [Beutler *et al.*, 2007] of the last N hour NEQ is carried out during the estimation of the tropospheric ZPD estimation (red box of Figure 4.1, Section A.3). To determine the minimal number N of NEQ to be combined in the *sequential adjustment in time* to achieve the precision targeted in the URD, the tropospheric ZPD solutions obtained with $N = \{1, 2, 3, 4, 5, 6, 7, 8, 12\}$ were compared to the tropospheric ZPD solution obtained for $N = 24$ (considered here as 'ground-truth') during the day of year 218 in 2009. The tropospheric ZPD differences between the solutions obtained by stacking different numbers of NEQ with respect to the 24-hour solutions are illustrated in Figure 4.25 for the GNSS station located in Onsala (ONSA), Sweden. The figure shows that the number N of combined NEQ significantly degrades the quality of the tropospheric ZPD estimates, when N is too small. This is particularly clear when processing a single hour of GNSS observations ($N = 1$, blue diamond curve).

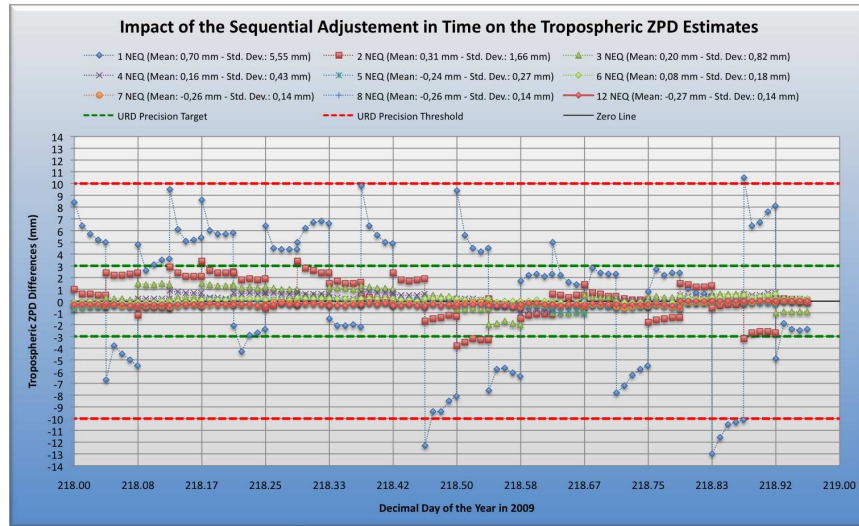


Figure 4.25: Tropospheric ZPD differences between the solutions computed by stacking different numbers of NEQ and the solution computed with 24 NEQ at the GNSS station located in Onsala, Sweden

The statistics of this sensitivity test for all GNSS sites are summarised in Table 4.7. Tropospheric ZPD solutions obtained with less than 3 NEQ emphasise clear 'jumps' in the time series of several millimetres between successive NRT processing runs. This is probably due to very short observation time during which not enough change in system geometry occurred to allow to decorrelate properly the different unknown parameters and to estimate thereby a proper absolute value for the tropospheric ZPD (Section 4.4.1). At the opposite, stacking more than 6 NEQ seems to not bring any more significant improvements in the quality of the tropospheric ZPD estimates. The optimal number of NEQ to be stacked is thus between 4 and 6. As shown in Figure 4.26, using values of N between 4 and 6, the bias remains within 0.5 mm, the standard deviation within 1 mm and the absolute value of the maximal deviation within 2.6 mm for all stations. Values of these statistics remain nonetheless site-specific. Stacking only 4 NEQ still provides an impact below the precision targeted in the URD and can be considered to reduce the number of unknown parameters when a large network is analysed. This also allows to speed up the processing to reach the timeliness requirement. Using

6 NEQ reduces nonetheless slightly more the impact and offers a bit more robustness in operational routine.

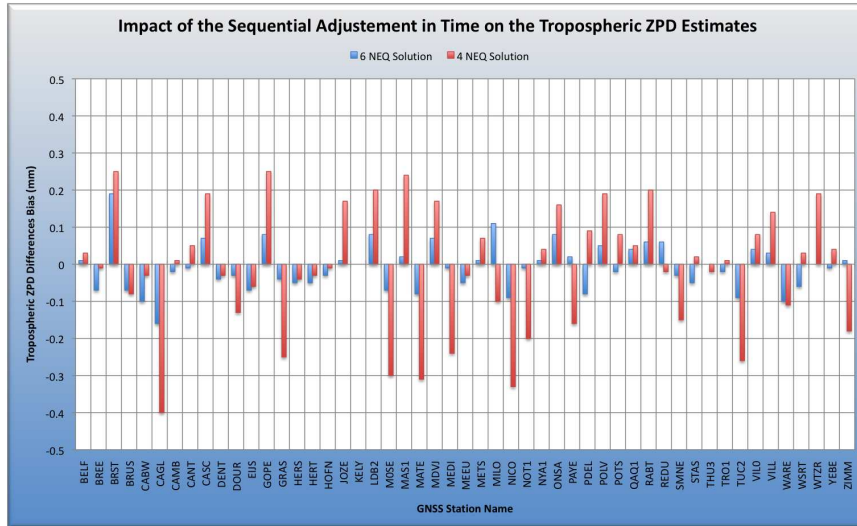


Figure 4.26: Bias of the tropospheric ZPD differences between the solutions computed by stacking 4 or 6 NEQ and the solution computed with 24 NEQ for the GNSS station located in Onsala, Sweden

4.4.7 Reference Frame Realisation and Antenna Models

Background and Campaign Setup

The *International Terrestrial Reference Frame* (ITRF) 2005 is realised by an estimation of station positions and velocities observed by the main space geodetic techniques, i.e. *Very Long Baseline Interferometry* (VLBI), *Satellite Laser Ranging* (SLR), *Doppler Orbitography Radiopositioning Integrated by Satellite* (DORIS) and *Global Navigation Satellite Systems* (GNSS) [Altamimi *et al.*, 2007]. The GNSS contribution to the ITRF was computed using relative antenna calibration models. On the 5th November 2006, the IGS switched from relative to absolute antenna models and ITRF 2005 [Gendt, 2006]. The IGS05 was created by correcting the ITRF2005 for station-dependent coordinate differences between the absolute (more precise) and relative antenna calibration models (Section 2.5.7). The “corrected ITRF2005” was then re-aligned with

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
1 Normal Equation - Average values over the complete network									
Mean	-17.63	18.03	0.14	7.10	-0.92	-0.04	3.27	-4.42	5838
Std. Dev.	5.03	6.73	1.26	1.81	21.14	0.55	0.90	6.90	5838
Max. Dev.	-12.97	24.97	4.39	5.75	39.39	1.55	2.42	26.62	5838
2 Normal Equations - Average values over the complete network									
Mean	-5.54	5.91	0.01	2.42	0.98	0.02	2.93	-2.57	5843
Std. Dev.	2.26	2.76	0.57	0.84	6.83	0.39	0.72	3.51	5843
Max. Dev.	-9.26	12.19	1.79	2.55	15.32	1.07	2.43	10.42	5843
4 Normal Equations - Average values over the complete network									
Mean	-1.30	1.33	-0.01	0.59	0.15	0.07	2.74	-1.01	5843
Std. Dev.	0.61	0.52	0.16	0.26	1.54	0.28	0.49	0.87	5843
Max. Dev.	-1.10	1.17	-0.39	0.47	-2.74	0.84	1.48	1.61	5843
6 Normal Equations - Average values over the complete network									
Mean	-0.49	0.46	-0.01	0.21	-0.06	-0.09	3.30	-0.25	5843
Std. Dev.	0.23	0.27	0.06	0.09	0.60	0.65	1.18	0.34	5843
Max. Dev.	-0.51	1.04	0.20	0.19	1.37	1.98	5.26	1.07	5843
8 Normal Equations - Average values over the complete network									
Mean	-0.33	0.33	0.01	0.15	-0.07	-0.11	3.11	-0.05	5843
Std. Dev.	0.41	0.31	0.27	0.08	0.44	0.64	0.81	0.28	5843
Max. Dev.	-1.87	0.87	-0.90	0.34	-1.44	1.49	3.31	1.02	5843
12 Normal Equations - Average values over the complete network									
Mean	-0.30	0.29	0.01	0.14	-0.08	-0.03	3.09	0.00	5843
Std. Dev.	0.44	0.29	0.27	0.08	0.42	0.70	0.70	0.28	5843
Max. Dev.	-1.90	0.91	-0.91	0.36	-1.44	1.61	2.34	0.99	5843

Table 4.7: Statistics of the tropospheric ZPD differences between the near real-time solutions computed using different number of NEQ with respect to the 24-hour solution

the ITRF2005 through a 7-parameter transformation [Ferland, 2006] using more than 130 IGS reference stations. The resulting set of station velocities (same as ITRF2005) and coordinates is known as the IGS05. Indeed, antenna changes tend to generate discontinuities in the station coordinates. The new (absolute) antenna calibration models should in principle take into account for the antenna changes without causing these discontinuities. Starting with GPS week 1400 (i.e. 1st November 2006), all IGS products, including the orbits

were computed using the IGS05 and the absolute antenna calibration models. For the sake of consistency, because we are using these IGS products, it was mandatory to also use the IGS05 and the absolute antenna calibration models in our analysis after the 1st November 2006. Therefore, the impact of switching to the new IGS standards (IGS05 reference frame realisation and absolute antenna calibration models) in the 2-step analysis strategy was assessed using 2 months of observations covering the 1st October 2006 to the 30th November 2006. The campaign setup details have been reported in [Pottiaux, 2008].

Impact on the Precise Coordinate Determination

In a first stage, the analysis strategy was changed to introduce the IGS05 along with the absolute antenna calibration models in the post-processing analysis strategy and the impact on the site coordinate repeatability was assessed. The switch to the new IGS standards revealed an overall improvement of about 43 %, 55 % and 29 % respectively in the north, the east and the vertical components of the coordinate repeatability. According to the results obtained in Section 4.4.3 on the impact of site's coordinate errors on the determination of the tropospheric ZPD estimates, we can derive the expected impact on the quality of the tropospheric ZPD estimates due to the vertical repeatability improvement: before the switch to the new IGS standards, the vertical coordinate repeatability of the 60 GNSS stations ranged from 2.14mm up to 7.92mm. With an overall improvement of 29% in the vertical coordinate repeatability, and using the rule of the thumb presented in Section 4.4.3 an overall improvement of the quality of the tropospheric ZPD in the range of 0.71mm up to 2.64mm is thus expected. In addition to the coordinate repeatability improvements, the switch to the new IGS standards introduced a change in the coordinates of the stations. Again, this will impact the tropospheric ZPD estimates accordingly (Section 4.4.3). Changes in the site coordinates in the 2mm - 24.7mm, 1.2mm - 15.8mm and 0.4mm - 8.9mm ranges were recorded for the vertical, north and east component respectively. According to the rule of the thumb, the expected bias introduced in the tropospheric ZPD due to the difference in the vertical component of the site coordinates should range from 0.66mm up to 8.23mm.

Impact on the Tropospheric ZPD Estimates

The impact on the tropospheric ZPD estimates was then assessed by differencing the tropospheric ZPD time series obtained using the IGS05 reference frame realisation and absolute antenna calibration models with respect to the ones obtained using the IGS00 (the previous IGS reference frame realisation) and relative antenna calibration models. For a given station, the differencing removes the signals common to both time series, leaving as residual the impact of the reference frame realisation and antenna calibration models change. This impact is illustrated in Figure 4.27 for the GNSS sites located in Rabat (RABT), Morocco, Kangerlussuaq (KELY), Greenland, and Brussels (BRUS), Belgium. The tropospheric ZPD differences clearly reveal station-specific bias associated with epoch-wise variability. The statistics of this sensitivity test for the complete network are summarised in Table 4.8.

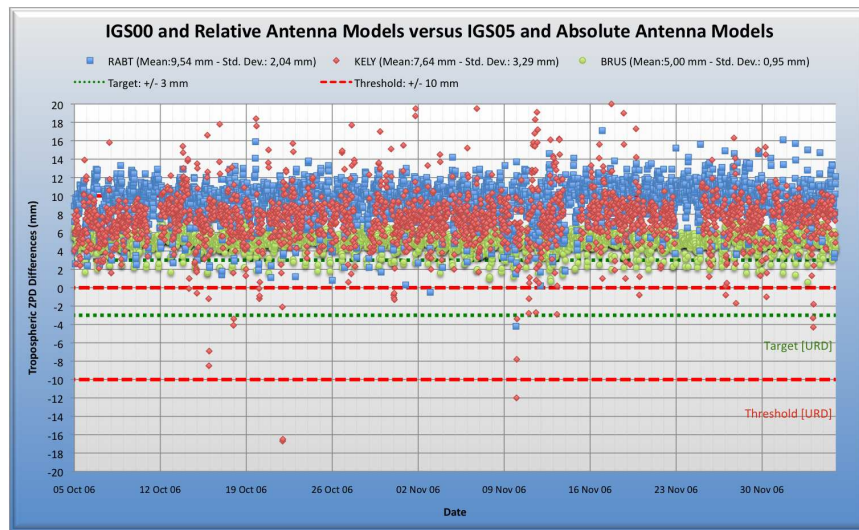


Figure 4.27: Tropospheric ZPD differences between the IGS05 reference frame realisation and absolute antenna calibration models solutions and the IGS00 reference frame realisation and the relative antenna calibration models solutions for the GNSS site located in Rabat (RABT), Morocco, Kangerlussuaq (KELY), Greenland and Brussels (BRUS), Belgium

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
Mean	-13.19	4.02	-5.51	1.48	4.30	0.69	8.80	0.00	133753
Std. Dev.	7.29	5.99	1.49	0.59	12.39	0.81	10.12	0.02	133753
Max. Dev.	-37.41	23.28	-4.02	1.90	-47.27	2.79	43.97	0.07	133753

Table 4.8: Statistics of the tropospheric ZPD differences between the IGS05 reference frame realisation and absolute antenna calibration models solutions and the IGS00 reference frame realisation and the relative antenna calibration models solutions averaged over the 60 GNSS stations of the test network

The station-specific biases range from -2.51 mm to -9.53 mm, with a mean value of -5.51 mm. These values are in perfect agreement with the expected values derived from the changes in the vertical coordinate component of the sites (see the aforementioned results). The tropospheric ZPD estimates are distributed around the station-specific bias with a sharper peak than a normal distribution (high kurtosis value) and a slight tendency to produce under-estimated tropospheric ZPD (positive skewness). The standard deviations of the tropospheric ZPD differences range from 0.81 mm to 3.38 mm, with a mean value of 1.48 mm. These values are in agreement with the expected values derived from the coordinate repeatability improvements. For all sites, the correlation coefficients between the two tested solutions are very high, with values above 0.99. As illustrated in Figure 4.27, the tropospheric ZPD differences emphasise epoch-wise discrepancies of large amplitudes. The largest value is recorded for the GNSS site located in Kangerlussuaq (KELY), Greenland with -42.97 mm. These epoch-wise discrepancies between the two solutions can be seen as “outliers” to be attributed to the IGS00 solution, as the IGS05 tropospheric ZPD time series looks more realistic. Nonetheless, the accuracy of both solutions will be discussed later in Chapter 5.

4.4.8 Ocean Tide Loading

Background and Campaign Setup

The *Ocean Tide Loading* (OTL) effect is the elastic response of the lithosphere (Earth’s crust) to *ocean tides*: it consists in deformations of the sea floor and

coastal land that result from the changing mass distribution of the water in the oceans due to the gravitational attractions of the Moon and the Sun (ocean tides). The deformations of the lithosphere due to the OTL produce periodic variations of the GNSS site positions. As illustrated in Figure 4.28, the site displacements induced by this phenomenon can reach tens of millimetres in the vertical for stations near continental shelves. The largest contribution (M_2 -wave) of this effect does not exceed 5 cm of amplitude in the vertical and 2 cm of amplitude in the horizontal [Hugentobler, 2005]. In some European areas, such as the Cornwall, south-west England, the land moves through a range of up to 14 cm in around 6 hours [Penna *et al.*, 2008]. The OTL effect has mainly semi-diurnal, diurnal, monthly, semi-annual and annual periods. In GNSS, models of this effect are based on per station, per coordinate component and per tidal constituent specific amplitude and phase coefficients computed using ocean tide models and coastal outline data. OTL coefficients for the 11 primary tidal constituents (M_2 , S_2 , N_2 , K_1 , O_1 , P_1 , Q_1 , M_f , M_m , S_{sa}) can be obtained from the *ocean tide loading provider* at Chalmers University [OTL Provider Web Site] for the main existing ocean tide models, which are listed in Table 4.9.

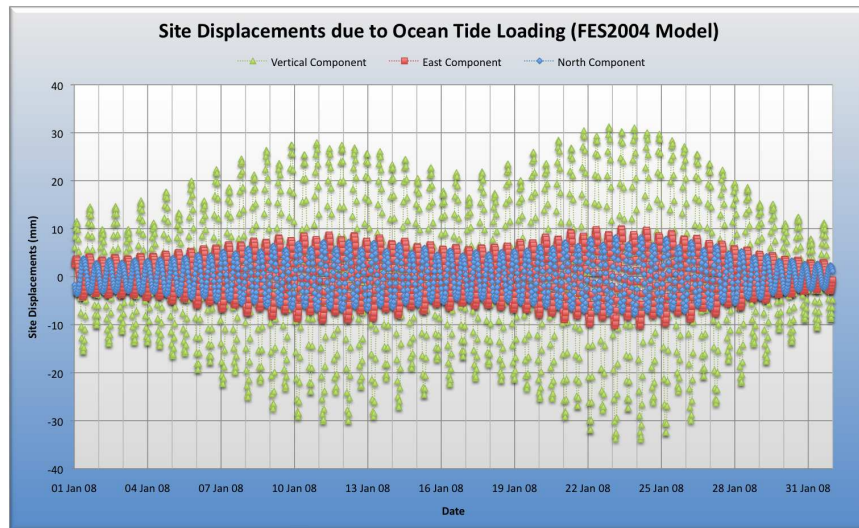


Figure 4.28: Vertical and horizontal displacements due to the ocean tide loading for the GNSS site located in Rabat (RABT), Morocco (computed from the FES2004 model, during the period covering the 1st January 2008 to the 31st January 2008)

Model Code	Reference	Input	Resolution
Schwiderski	Schwiderski [1980]	Tide gauge	1° x 1°
CSR3.0, CSR4.0	Eanes [1994]	Topex/Poseidon altimetry	1° x 1°
	Eanes, R. and Bettadpur, S. V. [1995]	Topex/Poseidon + LEPR loading	0.5° x 0.5°
TPXO.5, TPXO.7.0, TPXO.7.2	TPXO.6.2, TPXO.7.1, Egbert <i>et al.</i> [1994]	Inverse hydrodynamic solution from T/P Altim.	256 x 512
FES94.1, FES95.2	Le Provost <i>et al.</i> [1994]	Numerical model	0.5° x 0.5°
FES98	Le Provost <i>et al.</i> [1998]	Numerical model + altimetry data assimilation	0.5° x 0.5°
FES99	Lefèvre <i>et al.</i> [2000]	Numerical model	0.25° x 0.25°
FES2004	Lyard <i>et al.</i> [2006]	Numerical model	0.125° x 0.125°
GOT99.2, GOT00.2	Ray [1999]	Topex/Poseidon	0.5° x 0.5°
NAO99.b	Matsumoto <i>et al.</i> [2000]	Numerical model + Topex/Poseidon assimilation	0.5° x 0.5°

Table 4.9: Ocean tide models available at the automatic ocean tide loading provider, Chalmers University [OTL Provider Web Site]

For quite a long time, the *Goddard Ocean Tide* model GOT00.2 [Ray, 1999] was widely used to compute the OTL site displacements in GNSS applications. It was notably recommended to the IGS and EPN analysis centres to use this model. Recently, the *Centre National d'Etudes Spatiale* (CNES) issued the new *Finite Element Solution* ocean tide model, FES2004 [Lyard *et al.*, 2006]. Both models are global hydrodynamic tide models assimilating tide gauges and satellite altimetry observations (ERS2, TOPEX/POSEIDON). One of their differences reside in their grid resolution with 0.5° and 0.125° for the GOT00.2 and FES2004 model respectively. A discussion on the accuracy of the ocean tide loading displacement corrections can be found in [Penna *et al.*, 2008]. As mentioned in [Vey *et al.*, 2002], the use of ground-based GNSS tropospheric ZPD estimates in meteorological and climate applications imposes an accurate OTL effect modelling to meet the precision and accuracy requirements requested by these applications [Dach and Dietrich, 2000; Dragert *et al.*, 2000]. The OTL effects are clearly visible on tropospheric ZPD estimates when no ocean tide model is applied. Within the test network the maximum impact on the tropospheric ZPD estimates was recorded for the site of Rabat (RABT), Morocco, with a maximal deviation of 29.34 mm (Figure 4.29, Table 4.10). We decided thus to assess the impact of the differences between the two OTL models commonly used today in GNSS: the GOT00.2 and the FES2004 models. The comparison was carried out over a 1-month period covering the 1st January 2008 to the 31st January 2008.

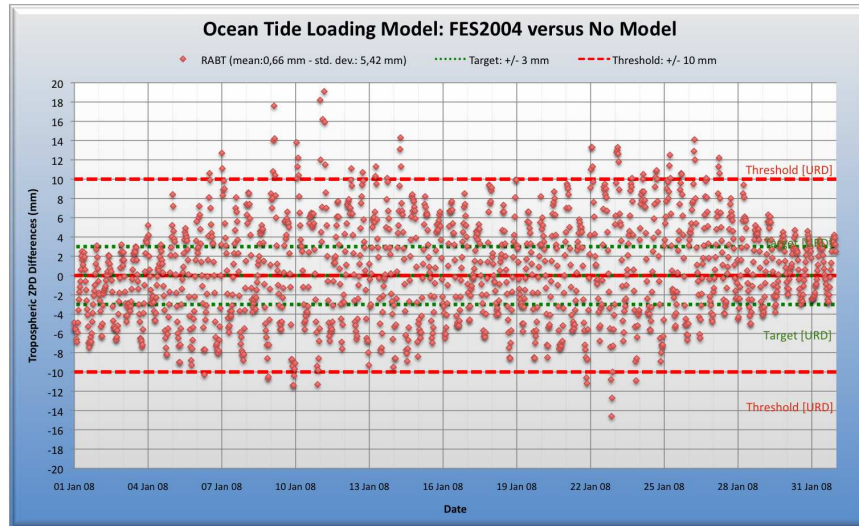


Figure 4.29: Impact of the site displacements due to the ocean tide loading (computed with the FES2004 model) on the tropospheric ZPD estimates for the site of Rabat (RABT), Morocco, during the period covering the 1st January 2008 to the 31st January 2008

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
Mean	-5.69	6.31	0.05	1.83	2.44	-0.15	4.42	0.00	79044
Std. Dev.	4.73	6.40	0.16	2.00	8.77	0.41	3.61	0.03	79044
Max. Dev.	-14.81	23.69	0.61	5.92	26.90	1.72	21.65	0.14	79044

Table 4.10: Statistics of the tropospheric ZPD differences between the solutions computed using no ocean tide loading site displacement model and the FES2004 OTL site displacement models during the period covering the 1st January 2008 to the 31st January 2008

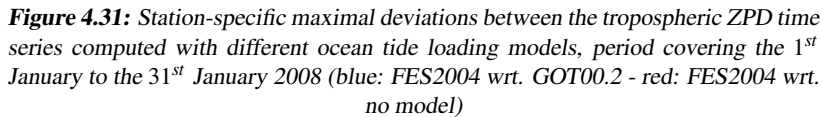
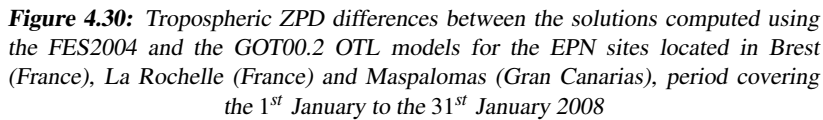
Impact on the Tropospheric ZPD Estimates

The impact on the tropospheric ZPD estimates was assessed by differencing the tropospheric ZPD obtained using the GOT00.2 model with respect to the ones obtained using the FES2400 model. For a given station, the differencing removes the signals common to both time series, leaving as residuals the impact of the differences between the two OTL models. The comparison of the tropospheric ZPD estimates obtained using the GOT00.2 model with

respect to the values obtained using the FES2004 model shows no bias but regular oscillations around zero. Their amplitudes range from 0.20 mm up to 2.50 mm. These oscillations are mainly visible at coastal sites. Examples for the coastal sites located in Brest, La Rochelle and Maspalomas are given in Figure 4.30. The tropospheric ZPD differences spectrums present a clear peak at about half a day period. In addition, the tropospheric ZPD differences show occasional peaks that reached an amplitude up to 9.20 mm (Table 4.11). The peaks suggest that the relation linking the tropospheric ZPD estimates and the OTL model might not be completely linear. This evidence is also visible when comparing Figure 4.28 and Figure 4.29, and was already reported in [Vey *et al.*, 2002]. The diurnal and sub-diurnal frequencies of the OTL model differences have a combined effect on the tropospheric ZPD and an undesired signal in the tropospheric ZPD time series not due to the atmospheric refraction is introduced. In this sensitivity test, the regular oscillations remained below the precision range requested for meteorological purposes but some peaks reached significant amplitudes (Figure 4.31), while their origin is still unknown and currently under investigation.

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
Mean	-1.53	1.22	-0.01	0.17	-0.36	-0.67	38.31	0.00	79044
Std. Dev.	1.70	0.92	0.02	0.11	2.47	3.81	83.37	0.00	79044
Max. Dev.	-7.67	2.80	-0.08	0.42	-8.84	-21.27	571.02	0.00	79044

Table 4.11: Statistics of the tropospheric ZPD differences between the solutions computed using the GOT00.2 and the FES2004 models, period covering the 1st January to the 31st January 2008



4.4.9 Orbit Products

Background and Campaign Setup

Nowadays, IGS products are available in various flavours (final, rapid, ultra-rapid, real-time - see Table 2.5 for details), differing notably by their latency and their quality (Section 2.7.2). High-precision real-time and near real-time GNSS applications, such as GNSS-meteorology, require accurate orbit models (Section 2.5.1). Since 2001, the IGS produces the *IGS Ultra-rapid orbits* (IGU), which are high-accuracy orbits generated from a weighted linear combination [Beutler *et al.*, 1995] of individual solutions provided by up to 7 independent Analysis Centres (ACs). They are provided in the *Standard Product # 3* (SP3) format [Spofford and Remondi, 1995] and includes orbits for the GPS satellites solely. The *Centre for Orbit Determination in Europe* (CODE) is one of the IGS analysis centres contributing to the IGU product. The contribution of CODE to the IGU products includes position and velocities for GPS and GLONASS satellites.

Two questions are then raised:

- Is the accuracy of the *IGS Ultra-rapid orbits* (IGU) products enough for GNSS-meteorology ? In other words, what is the impact of using the IGU instead of the IGS final or rapid products on our NRT tropospheric ZPD estimate quality ?
- Can we use the *CODE Ultra-rapid orbits* (COU) instead of the IGU products and gain thereby access to GLONASS observations for GNSS-meteorology ?

To answer these two questions, the NRT tropospheric ZPD solutions obtained using the IGU and the COU products were compared to a reference solution: the tropospheric ZPD solution obtained using the IGS final products. As a reference, the *IGS Rapid orbits* (IGR) were also included in the test. This comparison was carried out over a 15-day period covering the 1st September 2008 to the 15th September 2008.

Remark: *Real-time and near real-time GNSS applications use the predicted half-arc of the ultra-rapid orbits (Table 2.5). Because of the prediction, the precision and accuracy of the ultra-rapid orbits decreases rapidly over the time.*

After 6 to 9 hours, the precision and accuracy of the orbits is significantly worse than at the beginning of the predicted half-arc: with respect to the IGS rapid product, the 6 first predicted hours of the IGU orbits have a mean WRMS of 21.3 mm over the year 2009, while the entire 24-hour predicted arc has a WMRS of 47.3 mm [Ray, 2010]. The median values are also doubled (from 15.6 mm to 30.2 mm). The results presented hereafter simulated thus a near real-time processing using solely the first 6 hours of the predicted half-arc of the ultra-rapid orbits.

Satellite Orbit Errors

Out of the three satellite position components (radial, along-track and cross-track), the radial component is the most accurate, while the distribution of the along-track component errors is the most scattered (Figure 4.32). The along-track component accuracy is also the one that decreases the most rapidly when extending the orbit prediction up to 12 hours. Using double-difference observations in our analysis allows mitigating part of the orbit errors. This part depends on the inter-station distance (the shortest, the best) and on the orientation of the inter-station vector with respect to the orbit errors. Using the SHORT algorithm [Beutler *et al.*, 2007], which combines the nearest station observations together to produce the double-difference observations, helps reducing further the impact of the satellite errors on the production of the NRT tropospheric ZPD estimates. The radial component errors are almost removed, while the along-track component errors still might affect the tropospheric ZPD estimates [Dousa, 2008a,b]. Ambiguities are also able to absorb a significant part of the satellite orbit errors. Leaving the ambiguities float in our near real-time analysis strategy helps thus to overcome some of the deficiencies in the satellite orbit accuracy of the IGU products.

Impact on the Tropospheric ZPD Estimates

Typical examples of the agreement between the tropospheric ZPD estimated with the IGU products and with the IGS final products for the GNSS sites QAQ1, NYA1 and BRUS are shown in Figure 4.33. For a given station, the differencing removes the signals common to both time series, leaving as residuals the impact of the ultra-rapid orbit prediction on the tropospheric

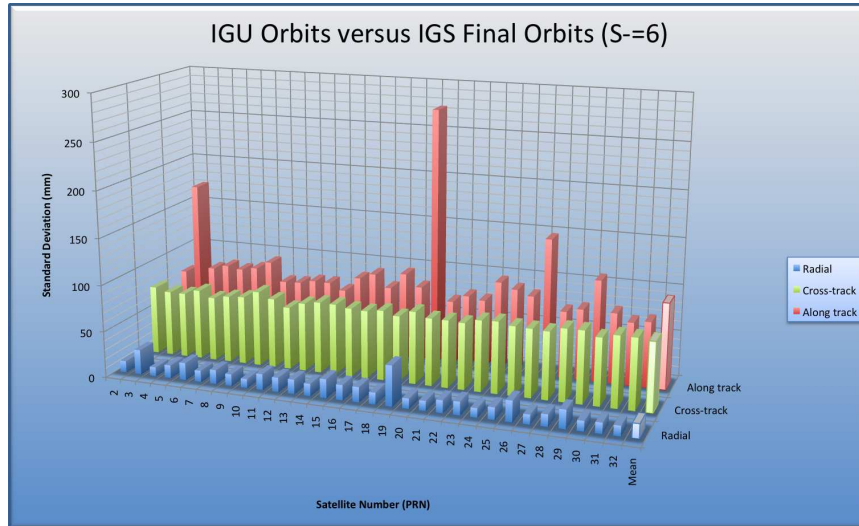


Figure 4.32: Satellite-specific standard deviation observed between the IGU and IGS final orbit models during the period covering the 1st September 2008 to the 15th September 2008

ZPD estimates. The tropospheric ZPD differences show almost no bias and relatively small standard deviations. The statistics of the tropospheric ZPD differences are summarised in Table 4.12. Averaged over the 60 GNSS stations (83167 common observations in total), the tropospheric ZPD differences show a mean bias quasi-null and a mean standard deviation of 0.70 mm. Very few discrepancies in the bias and standard deviation values are observed between the GNSS sites. The mean maximal deviation is of -1.33 mm, which is relatively small, but shows large variability according to the observation site (standard deviation of 7.08 mm) and a maximal value of 16.80 mm, which is largely above the precision threshold value specified in the URD. The variability of the mean maximal deviation emphasises the importance of the satellite-receiver geometry configuration. The maximal deviations emphasise the significant impact that reduced-accuracy orbits might have on the precision of the tropospheric ZPD estimates, even when one or a few satellites are affected (see Figure 4.33 around the 14th September 2008). Similar values are obtained when using the *CODE Ultra-rapid orbits* (COU) products, but

the mean bias and mean standard deviation are almost doubled and the mean maximal deviation almost tripled. This last result is not too unexpected as the IGU products are combined products that offer more stability and robustness against outliers and orbit mis-modelling. When using both the IGU and the COU, 99% of the near real-time tropospheric ZPD differences remain thus below the precision targeted in the URD. However, the high maximal deviation and kurtosis values indicate that the production of the NRT tropospheric ZPD shows periods of significantly reduced precision that might even exceed the precision threshold. These epochs of reduced tropospheric ZPD precision are attributed to one (or a few) satellite orbits, whose accuracy is (are) reduced but still acceptable.

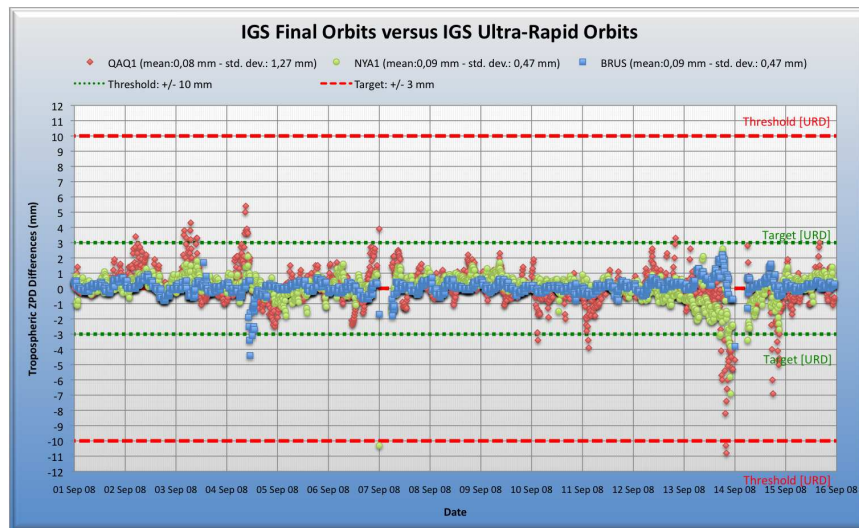


Figure 4.33: Tropospheric ZPD differences between the solutions computed using the IGU orbit products and the IGS final orbit products, period covering the 1st September 2008 to the 15th September 2008

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
IGS Rapid versus IGS Final orbit Models - Average values over the complete network									
Mean	-7.35	3.48	-1.42	1.08	-0.67	-0.38	9.42	-0.01	83167
Std. Dev.	5.55	4.24	3.43	0.56	7.45	1.26	12.48	0.04	83167
Max. Dev.	-22.15	12.82	-16.04	2.74	-15.92	-4.03	59.09	-0.12	83167
IGU versus IGS Final orbit Models - Average values over the complete network									
Mean	-5.65	4.72	0.11	0.70	-1.33	-0.56	21.65	0.01	83167
Std. Dev.	4.06	2.69	0.12	0.26	7.08	2.29	21.84	0.04	83167
Max. Dev.	-15.55	7.78	0.28	0.91	-15.47	-7.57	75.92	-0.21	83167
CODE Ultra-Rapid versus IGS Final orbit Models - Average values over the complete network									
Mean	-7.99	5.97	-0.09	1.15	-3.80	-0.68	11.54	0.00	83167
Std. Dev.	4.92	3.30	0.10	0.40	8.51	1.60	12.43	0.04	83167
Max. Dev.	-14.81	8.23	0.28	1.20	-18.93	-7.83	48.54	-0.13	83167

Table 4.12: Statistics of the tropospheric ZPD differences between the solutions computed using different orbit products, period covering the 1st September 2008 to the 15th September 2008

Satellite Exclusion based on Orbit Accuracy Codes

OAC	Formal Uncertainty Range
1	0.00 mm - 2.84 mm
2	2.85 mm - 5.66 mm
3	5.67 mm - 11.3 mm
4	11.4 mm - 22.6 mm
5	22.7 mm - 45.5 mm
6	45.6 mm - 90.5 mm
7	90.6 mm - 181 mm
8	181.1 mm - 362.0 mm
9	363.0 mm - 724.0 mm
10	725.0 mm - 1448 mm

Table 4.13: Orbit Accuracy Code (OAC) and the corresponding formal uncertainty range of the orbit

To further reduce the impact of orbit mis-modelling on the tropospheric ZPD estimates, a satellite exclusion method based on the *Orbit Accuracy Codes* (OAC) was tested. OAC provide an estimation of the orbit quality for each satellite based on the Weighted Root-Mean-Square (WRMS) of the differences among the contributing ACs compared to the average orbit. These *Orbit Accuracy Code* (OAC) are published in the header of the SP3 files and are defined as the (near) integer base-2 logarithm of the formal uncertainty of the combined orbit [Griffiths and Ray, 2009], noted here σ and expressed in millimetre, i.e.

$$\text{Orbit Accuracy Code (OAC)} = \log_2(\sigma) \quad (4.1)$$

First, satellite orbits with accuracy code of zero, i.e. for which only one analysis centre is contributing, were excluded. Then, an optimal accuracy code threshold was investigated allowing to reject satellites with reduced-accuracy orbits. During the tested period, quasi all accuracy codes in the *IGS Ultra-rapid orbits* (IGU) product ranged between 4 and 6, corresponding to an orbit accuracy between 11.4mm and 90.5mm. As shown in Table 4.14, excluding satellites, with accuracy code 7 or above, brought mostly no improvement in the precision of the tropospheric ZPD estimates. Reducing the accuracy code threshold to 6 degraded the precision of the tropospheric ZPD estimates: the standard deviation of the tropospheric ZPD differences was almost doubled compared to the use of an accuracy code threshold of 7. This was due to higher number of excluded satellite and thereby degradation in the system geometry. The accuracy code threshold value of 7 was thus retained, even if no significant improvement was observed during this particular period.

Remark: *Along the time, the IGU product accuracy has improved and the OAC contained in the SP3 files reflected this change. Today, most of the IGS ultra-rapid orbit accuracy codes are between 4 and 5. Nonetheless, current OAC are said unrealistically optimistic and are approximately constant, nearly independent of the satellite and time [Griffiths and Ray, 2009].*

Remark: *The OAC of the COU products were higher and some satellite orbits were always mis-modelled during the test period (accuracy code of 36). These satellites were excluded from our processing. OAC were also provided for the GLONASS satellite orbits, with values higher than the GPS ones. But, as for the IGU products, no optimal threshold value could be found (Table 4.14).*

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
IGU versus IGS Final orbit Models - IGS Accuracy Code Threshold: 7 - Average values over the complete network									
Mean	-5.66	4.72	0.10	0.71	-1.33	-0.60	21.59	0.01	83167
Std. Dev.	4.07	2.69	0.12	0.26	7.09	2.29	21.72	0.04	83167
Max. Dev.	-15.54	7.78	0.29	0.90	-15.57	-7.52	75.77	-0.21	83167
IGU versus IGS Final orbit Models - IGS Accuracy Code Threshold: 6 - Average values over the complete network									
Mean	-10.68	10.29	0.09	1.32	-0.52	-0.24	22.13	-0.00	83167
Std. Dev.	5.19	4.29	0.15	0.38	12.80	2.18	13.78	0.05	83167
Max. Dev.	-12.32	11.91	-0.49	0.89	22.66	-10.40	51.10	-0.26	83167
COU versus IGS Final orbit Models - IGS Accuracy Code Threshold: 12 - Average values over the complete network									
Mean	-8.58	6.89	-0.08	1.29	-3.80	-0.50	10.91	-0.00	83167
Std. Dev.	5.02	3.38	0.12	0.41	9.22	1.49	11.18	0.05	83167
Max. Dev.	-14.32	7.31	0.32	1.15	-19.02	-7.48	42.97	-0.21	83167

Table 4.14: Statistics of the tropospheric ZPD differences between the solutions computed using the different orbit products and using a satellite exclusion method based on the orbit accuracy codes, period covering the 1st September 2008 to the 15th September 2008

4.4.10 Multi-GNSS Observations

Background and Campaign Setup

While GNSS have all been designed to be self-sufficient, more and more weight has been put in the past years on their complementarities and interoperability to improve the integrity, the reliability and the performances in GNSS applications (Section 2.2). The question raised in this section is “*what are the potential benefits brought by processing multi-GNSS observations to determine tropospheric ZPD ?*” At the present time, GPS and GLONASS are the only operational GNSS available. The *Bernese GPS software* version 5.0 allows to process simultaneously GNSS observations from these two GNSS. The added-value for GNSS-meteorology of processing jointly GPS and GLONASS observations were thus investigated. Potential advantages are:

- An increased number of observations that is particularly valuable in the case of short observation session, as it is the case in our near real-time analysis

- An improved observation geometry thanks to the combination of the different satellite constellations that offers more receiver-to-satellite ray paths to better observe the Earth's atmosphere
- Indirect improvements due to the differences in the system designs, such as the ground-track repeatability and the signal structure, that offer more robustness and better strategy performances, notably in the data cleaning and the multipath mitigation

Nevertheless, the *Bernese GPS software* version 5.0 and the IGS products (Section 2.7.2) present also some deficiencies with respect to the GLONASS observations:

- When processing the carrier-phase double-difference observations (Equation 2.5), the software cannot resolve neither the GLONASS-GLONASS nor the GPS-GLONASS carrier-phase ambiguities
- The IGS final orbits for GLONASS satellites have an accuracy that can be up to 6 times worse than those for GPS satellites (Table 2.5)
- No *IGS Ultra-rapid orbits* (IGU) are available yet for the GLONASS satellites

The inclusion of GLONASS observations in the two-step analysis strategy (Section 4.3) was investigated using the 60 GNSS stations of the test network during a 2-month period covering the 1st January 2008 to the 29th February 2008. Within this network, 11 sites were equipped with a receiver capable to track simultaneously the signals from GPS and GLONASS satellites. The remaining 49 sites were equipped with GPS-only receivers and antennas. As illustrated in Figure 4.34, the impact of adding GLONASS observations was assessed successively on both steps of the analysis strategy.

Remark: *The GLONASS constellation was not complete at the time the tests were carried out: only 13 to 15 GLONASS satellites were orbiting the Earth. This low number of GLONASS satellites is expected to reduce the benefits of adding GLONASS observations.*

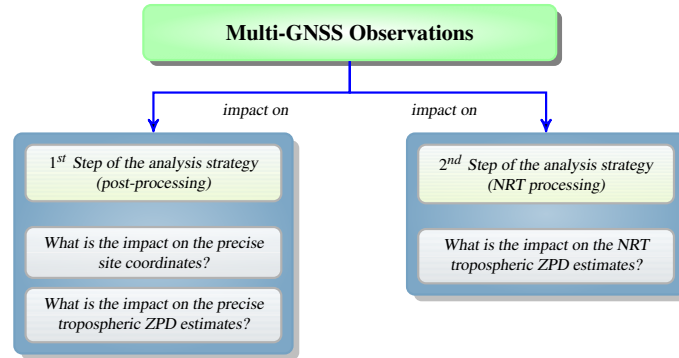


Figure 4.34: Global structure of the multi-GNSS observations sensitivity tests

Impact on the Precise Site Coordinates Determination

In a first stage, the impact of adding GLONASS observations on the site coordinate determination was assessed. As shown in Table 4.15, adding GLONASS didn't significantly improve the daily coordinate repeatability of the sites. The largest impact was observed in the vertical component for GNSS sites equipped with GPS+GLONASS receivers, except for Meewen (MEEU), Belgium, which probably take advantages from the nearby station in Eijsden (EIJ5), Netherlands, equipped with a GPS+GLONASS receiver. Moreover, since a 31-day cumulative coordinate set is used to fix the station position while estimating the NRT tropospheric ZPD estimates, the small effect on the daily coordinate is averaged out and at the end does not affect the tropospheric ZPD estimates. Indeed, the maximum difference between the coordinate repeatability of the GPS only and of the GPS+GLONASS solutions is recorded for the station Jozefoslaw (JOZ2), Poland, and is about 1.05 mm in the vertical component. According to the rule of the thumb and the discussion held in Section 4.4.3, this change in the coordinate repeatability will not impact the tropospheric ZPD estimates significantly. Nevertheless, one has to notice that a cumulative coordinate set computed using GPS+GLONASS observations might differ from the cumulative coordinate set computed with the GPS observations solely. As a consequence, fixing the station coordinate in the NRT strategy to one or the other coordinate sets could impact indirectly the tropospheric ZPD estimates (see Section 4.4.3, Figure 4.6). In the present case, the maximum coordinate difference between the GPS only and

Impact on the Post-Processed tropospheric ZPD Estimates

In a second stage, the impact of adding GLONASS observations on the post-processed tropospheric ZPD estimates was assessed. Therefore, the station positions were fixed to the cumulative coordinate set computed using GPS observations solely. The comparison was carried out for each station within the test network. For a given station, the differencing removes the common signals to both time series, leaving as residuals the impact of the additional GLONASS observations on the tropospheric ZPD estimates. The differences between the GPS only and the GPS+GLONASS tropospheric ZPD solutions are illustrated in Figure 4.36 for the sites located in Mendeleevo (MDVJ), Russian Federation, and for the co-located GNSS receivers at Cagliari (CAGL equipped with a GPS only receiver and CAGZ equipped with a GPS+GLONASS receiver), Italy. The statistics of the sensitivity test for the complete network are summarised in Table 4.16 by receiver type. As illustrated in this table, the differences show no bias (within 0.5 mm). GNSS sites equipped with GPS+GLONASS receivers undergo a slightly larger effect than the sites equipped with GPS only receivers. Nonetheless, in both cases, the tropospheric ZPD differences are significant at certain epochs (well above the precision targeted in the URD). The largest bias is observed for the station in Onsala (ONSA), Sweden, with -0.4 mm. The largest standard deviation is recorded for the station in Lindenberg (LDB2), Germany, with a value of 1.25 mm. Both sites were equipped with GPS+GLONASS receivers. In all case, the correlation factor between the GPS only and the GPS+GLONASS solutions remains above 0.99. The group of GPS receivers shows (weak to moderate) systematic under-estimation of the tropospheric ZPD (see skewness statistics) tendency due to the inclusion of GLONASS observations. Both groups of receivers present leptokurtic distribution, i.e. a sharper peak around the mean and fatter tails than a normal distribution (see kurtosis statistics values). Except at specific epochs, the effect of adding GLONASS observations remains below the precision targeted in the URD. At these specific epochs, including GLONASS observations in our analysis eliminates peaks (ranging from 1.6 mm to 19.28 mm with a mean value of 3.59 mm) present in the tropospheric ZPD time series computed using the GPS observations solely (this corresponds to the leptokurtic distribution observed).

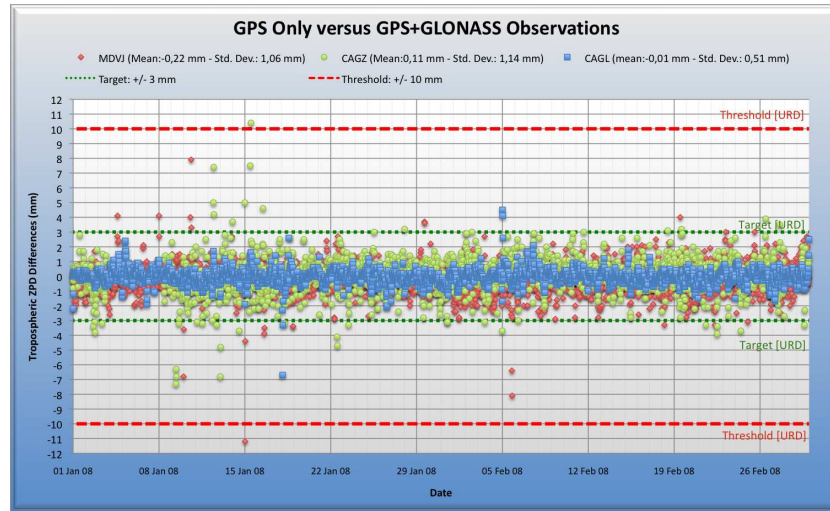


Figure 4.36: Tropospheric ZPD differences between the GPS only and the GPS+GLONASS solutions. The site of Cagliari (CAGL, in blue) is equipped with a GPS only receiver while the sites located in Mendeleevo (MDVJ, in red) and Cagliari (CAGZ, in green) are equipped with GPS+GLONASS receivers (period covering the 1st January 2008 to the 29th February 2008)

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
Statistics Averaged over the GPS Only Receivers									
Mean	-3.76	2.98	-0.04	0.41	-1.20	-0.36	20.31	0.00	122838
Std. Dev.	2.92	1.73	0.07	0.11	4.90	1.62	35.05	0.00	122838
Max. Dev	15.64	5.62	0.25	0.34	18.05	6.87	181.39	0.01	
Statistics Averaged over the GPS+GLONASS Receivers									
Mean	-7.06	6.48	-0.16	0.87	-1.07	-0.26	12.40	-0.04	31307
Std. Dev.	4.50	3.59	0.18	0.21	9.23	0.35	17.57	-0.04	31307
Max. Dev	12.44	7.22	0.33	0.39	18.21	0.83	52.73	0.01	
Statistics Averaged over All Receivers									
Mean	-4.41	3.66	-0.06	0.50	-1.17	-0.34	18.76	-0.00	154145
Std. Dev.	3.47	2.57	0.11	0.23	5.84	1.45	32.10	0.00	154145
Max. Dev.	-15.09	10.04	-0.36	0.76	-18.11	-6.89	182.94	-0.01	

Table 4.16: Statistics of the post-processed tropospheric ZPD differences between the solutions computed using GPS only and GPS+GLONASS observations for the period covering the 1st January 2008 to the 29th February 2008

Impact on the NRT tropospheric ZPD Estimates

In a final stage, the direct impact of adding GLONASS observations on the NRT tropospheric ZPD estimates is assessed. Therefore, in the NRT analysis strategy, the station coordinates are fixed to the cumulative coordinate set computed using the GPS observation solely. The statistics for the complete network are summarised in Table 4.17. As for the post-processing strategy, differencing the tropospheric ZPD time series obtained using GPS and GPS+GLONASS observations shows no bias (within 0.5 mm). The largest bias is observed for the station in Caussols (GRAS), France, with a value of 0.3 mm. The largest standard deviation is recorded for the station in Wettzell (WTZR), Germany, with a value of 0.56 mm. Again, both stations were equipped with GPS+GLONASS receivers. Compared to the post-processing analysis, the benefits of adding GLONASS observations is quasi-null: the standard deviations of the tropospheric ZPD differences are very low (in general within 0.1 mm, Table 4.17). The maximal deviations (Figure 4.37) are much below the values observed for the post-processed solutions with values usually better than the precision targeted by the GNSS-meteorology requirements.

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
Statistics Averaged over the GPS Only Receivers									
Mean	-0.66	0.46	-0.04	0.08	-0.14	-0.01	29.41	0.00	294890
Std. Dev.	0.96	0.41	0.11	0.03	1.21	3.68	105.51	0.00	294890
Max. Dev.	5.74	1.44	0.27	0.08	6.07	21.28	662.89	0.01	
Statistics Averaged over the GPS+GLONASS Receivers									
Mean	-1.24	1.21	0.02	0.15	-0.54	0.00	11.68	0.00	75093
Std. Dev.	2.05	1.92	0.16	0.14	2.40	0.88	18.39	0.00	75093
Max. Dev.	5.96	5.49	0.26	0.41	6.61	1.65	53.78	0.01	
Statistics Averaged over All Receivers									
Mean	-0.77	0.61	-0.03	0.09	-0.22	-0.01	25.93	0.00	369983
Std. Dev.	1.24	0.94	0.12	0.07	1.48	3.28	94.11	0.00	369983
Max. Dev.	-6.43	6.09	0.30	0.47	-6.93	-21.28	666.37	-0.01	

Table 4.17: Statistics of the near real-time tropospheric ZPD differences between the solutions computed using GPS only and GPS+GLONASS observations for the period covering the 1st January 2008 to the 29th February 2008

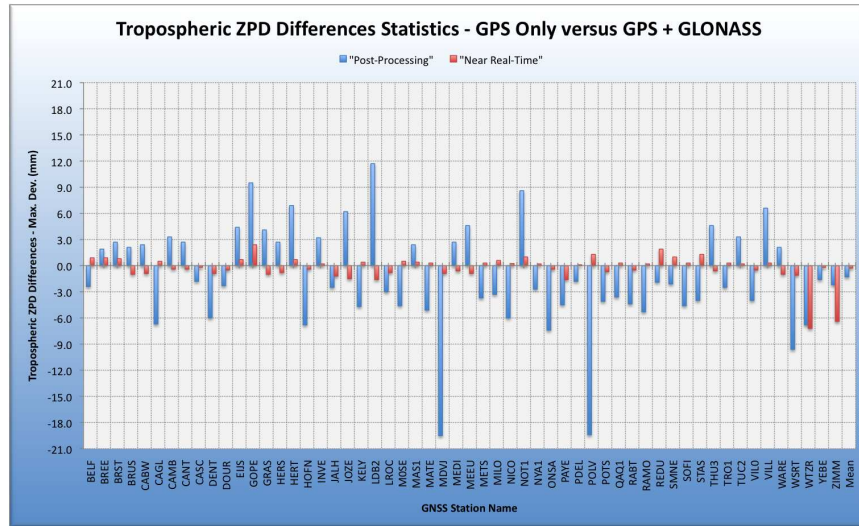


Figure 4.37: Station-specific maximal deviations of the tropospheric ZPD differences computed using GPS only and GPS+GLONASS observations for the period covering the 1st January 2008 to the 29th February 2008 (blue: post-processed solutions - red: near real-time solutions)

4.5 Summary and Conclusions

In this chapter, a 2-step analysis strategy was developed to provide the meteorologists with near real-time (NRT) tropospheric ZPD estimates from a European regional network of GNSS permanent stations to be used in operational meteorology, more specifically in *Numerical Weather Prediction* (NWP) and *nowcasting* applications (Section 4.3). This strategy was designed to satisfy a list of requirements gathered in the *User Requirements Document* (URD) [Barlag *et al.*, 2004]. Primary recommendations were determined to set up a proper network for GNSS-meteorology. Then, the sensitivity of the tropospheric ZPD estimates produced by our analysis strategy in regard to several processing options was studied and the methodology optimised accordingly (Section 4.4). The summary of the sensitivity tests can be found in Table 4.18.

Sensitivity test	Bias (*)	Standard deviation (*)	Range (*)	Maximal deviation (*)	A	P	O
Site Coordinates	0.04 ± 0.21 mm	0.09 ± 0.12 mm	0.50 mm	0.08 ± 0.57 mm	100% ▲	100% ▲	100% ▲
Relative Constraints	0.12 ± 0.10 mm	0.56 ± 0.21 mm	4.10 mm	0.06 ± 2.29 mm	100% ▲	100% ▲	80% ▼
Repetition Cycle	0.83 ± 0.77 mm	1.84 ± 0.78 mm	8.46 mm	1.65 ± 5.06 mm	100% ▲	93% ▲	43% ▼
Sequential Adjustment in Time Domain	-0.01 ± 0.06 mm	0.21 ± 0.09 mm	0.95 mm	-0.06 ± 0.60 mm	100% ▲	100% ▲	100% ▲
Reference Frame Realisation and Antenna Calibration Models	-5.51 ± 1.49 mm	1.48 ± 0.59 mm	17.21 mm	4.30 ± 12.39 mm	5% ▼	99% ▲	55% ▲
OTL Displacements	-0.01 ± 0.02 mm	0.17 ± 0.11 mm	2.75 mm	-0.36 ± 2.47 mm	100% ▲	100% ▲	77% ►
IGS Ultra-Rapid Orbits	0.11 ± 0.12 mm	0.70 ± 0.26 mm	10.37 mm	-1.33 ± 7.08 mm	100% ▲	100% ▲	32% ▼
Multi-GNSS Observations	0.02 ± 0.16 mm	0.15 ± 0.14 mm	2.45 mm	-0.54 ± 2.10 mm	100% ▲	100% ▲	83% ▼

Percentage of tropospheric ZPD estimates satisfying the sensitivity tests

▲: above 90%, ▼: between 80% and 89%, ►: between 60% and 79%, ▲: between 50% and 59%, ▼: below 49%

Table 4.18: Summary of the sensitivity tests: typical errors expected after a proper modelisation in the GNSS analysis strategy - (*) Average values ($\pm$ std. dev.) over the campaign network - A: Accuracy sensitivity, P: precision sensitivity and O: outlier sensitivity - Reference: target value of the URD

All new standards and models tested had globally a positive impact on the tropospheric ZPD estimation and were thus implemented in our 2-step analysis strategy. Some options, such as optimal values for the relative constraints and repetition cycle setup, could not be decided and need some external validations. These will be performed in Chapter 5. The need for a continuous monitoring to ensure the quality, stability, continuity and robustness necessary for our applications was emphasised. Possible improvements were also pointed out, as well as the need for further research. These concern amongst other :

Mapping Functions

The use of GNSS observations below 10° of elevation has to be considered in the future, as they might improve the quality of our tropospheric ZPD estimates. Using low elevation observations will require the use of the *Global*

Mapping Functions (GMF) or the *Vienna Mapping Functions* (VMF1) (along with their respective a priori models). These options will be available in the next version of the *Bernese GPS software* that should be released in 2010-2011.

Multi-GNSS Observations

The benefits of adding GLONASS observations in our analysis strategy was not as large as expected: it was attributed to the poor quality of the GLONASS orbits, the limited GLONASS vehicles and the small number of GPS+GLONASS receivers available at the epoch of the sensitivity test. Moreover, GLONASS orbits were often excluded from the processing because of high OAC, limiting thereby the added-value of using GLONASS observations. The differences in the results obtained between the post-processing and the near real-time tests might be attributed to the orbit quality and to the ambiguity resolution, which increased slightly the benefits brought by adding GLONASS observations in the analysis. The major contribution of adding GLONASS observations to our strategy was to improve the robustness and reliability, particularly by removing some outliers that existed in the GPS-only tropospheric ZPD solutions (Figure 4.37). Since, no *IGS Ultra-rapid orbits* (IGU) product exists today for GLONASS, the switch from GPS-only to GPS+GLONASS observations was not implemented in the near real-time step of the strategy, but well in the post-processing step. With a complete GLONASS constellation, including modernised GLONASS satellites, and GLONASS orbits of better quality, the impact on the tropospheric ZPD estimates is expected to become larger. Particularly now that the number of GPS+GLONASS receivers included in the *EUREF Permanent Network* (EPN) has largely grown (> 49 % of the stations, Section 2.7.1). The venue of Galileo should even strengthen the improvements. Processing jointly GPS+GLONASS+Galileo observations will be possible in the next version of the *Bernese GPS software* and should be re-investigated at that time.

Ambiguity Resolution

In the near real-time step of the analysis strategy, the initial carrier-phase ambiguities are left float. The main reason behind this is that the ambiguity resolution strategies implemented in the *Bernese GPS software* version 5.0

require an observation window longer than 1 hour (typically a minimum of 6 to 8 hours is necessary). Replacing the sequential adjustment in time by processing an N-hour observation window required too much computer time (to still fulfil the timeliness requirement). However, research carried out by Elmar Brockmann demonstrated that solving ambiguities in near real-time processing would improve the formal RMS of the tropospheric ZPD estimates by a factor 2.5 and that their agreement with post-processed solutions would be better by a factor 1.5 [Brockmann, 2008]. He also pointed out a possible “dry” bias of 2 mm in the ambiguity-free solutions compared to the ambiguity-fixed solutions. The improvement is to be attributed to the strong correlation between the ambiguity and tropospheric ZPD parameters. This is a field where research might still bring clear improvements to our tropospheric ZPD solutions.

The “optimised” parameters of the 2-step analysis strategy are summarised in Table 4.19 and need now to be validated in terms of GNSS-meteorology requirements.

4.5. Summary and Conclusions

Processing step	2 nd Step	1 st Step
Processing type	Near real-time	Post-processing
Software	<i>Bernese GPS software</i> version 5.0	<i>Bernese GPS software</i> version 5.0
GNSS observables		
Observation system	GPS observations only	GPS+GLONASS observations
Observation window length	1 hour	24 hours
Observation cut-off angle	3° (10° while estimating the tropospheric ZPD)	3° (10° while estimating the tropospheric ZPD)
Observable type	Ionosphere-free carrier-phase double-differences	Ionosphere-free carrier-phase double-differences
Baseline strategy	SHORT	OBS-MAX
Other model		
Reference frame realisation	IGS05	IGS05
Antenna calibration models	Absolute calibration models	Absolute calibration models
Orbit and Earth orientation parameters	IGS ultra-rapid product	IGS rapid product
Ocean tide loading model	FES2004 model	FES2004 model
Ionospheric path delay functional model		
Regional ionosphere model	No	Yes
Stochastic ionosphere model	No	Yes
Ambiguity resolution	No	Quasi Ionospheric-Free (QIF) method
Tropospheric path delay functional model		
Coordinate back-substitution	Fixed to the 31-day cumulative solution	Fixed to the 31-day cumulative solution
A priori tropospheric model	Saastamoinen-based and dry NMF	Saastamoinen-based and dry NMF
Tropospheric correction model	Estimated and wet NMF	Estimated and wet NMF
Tropospheric ZPD parameter resolution	1 parameter every 15 minutes	1 parameter every 30 minutes
Tropospheric ZPD absolute constraints	No	No
Tropospheric ZPD relative constraints	2mm	2mm
Tropospheric gradient parameter resolution	No	1 parameter every 24 hours
Tropospheric gradient parameter constraints	No	No
Sequential adjustment		
In space domain	Eleven clusters defined	Eleven clusters defined
In time domain	6-hour stacking	No

Table 4.19: Main analysis options applied to process the GNSS observations

Don't lower your expectations to meet your performance. Raise your level of performance to meet your expectations. Expect the best of yourself, and then do what is necessary to make it a reality.

Ralph Marston

5

Strategy Validation and Performances Evaluation

Summary

In this fifth chapter, the choice of the processing options made for our 2-step analysis strategy is validated and the performances of the analysis are evaluated in terms of GNSS-meteorology requirements. In that process, challenges to be faced to act as an analysis centre for operational GNSS-meteorology are emphasised.

5.1 Introduction

The sensitivity tests carried out on our 2-step analysis strategy in Section 4.4 demonstrated that the choice of several processing options might have a significant impact on the tropospheric ZPD estimate performances. In this chapter, the choice of the processing options made in Chapter 4 is validated based on the *Quality Monitoring Scheme* (QMS) presented in Section 4.3 by comparing our tropospheric products with other near real-time (NRT),

post-processed and external sources of tropospheric ZPD. Section 5.2 presents the concept of E-GVAP super-sites, which form a core network used for monitoring purposes within E-GVAP and which are extensively used in this chapter to illustrate our remarks. The performances of the 2-step analysis strategy are first evaluated in terms of coordinate repeatability scores (Section 5.3), and secondly in terms of NRT tropospheric ZPD precision (Section 5.4) and accuracy (Section 5.5). Finally, the performances with respect to the remaining GNSS-meteorology requirements and the integration within E-GVAP are discussed (Section 5.6). In that process, the challenges to be faced to act as an operational analysis centre are emphasised. Compared to the results presented in Chapter 4, the performance scores presented in this chapter are based on the operational product provided to the meteorologists in the framework of E-GVAP, not on test campaigns.

5.2 E-GVAP Super-Sites

Background

E-GVAP super-sites are GNSS sites co-located with other meteorological equipments (e.g. *radiosondes* and *water vapour radiometers*) and/or geodetic techniques (e.g. *Very Long Baseline Interferometry* and *Doppler Orbit determination and Radio-positioning Integrated on Satellite*) from which tropospheric ZPD values can be derived. They are chosen for their good geodetic qualities (coordinate repeatability, GNSS observation quality, environmental influences) and for their geographical locations, including a variety of climates and altitudes. Based on the recommendations of the E-GVAP expert team on data processing, a set of 14 super-sites was defined. They are listed in Table 5.1 and their locations are illustrated in Figure 5.1. The technique co-location allows the comparison of the ground-based GNSS tropospheric ZPD estimates against tropospheric ZPD derived from independent (meteorological or geodetic) observations or NWP models, which can serve as “ground-truth” to determine the *accuracy* of the ground-based GNSS tropospheric ZPD. This issue is addressed later in Section 5.5. Another role of the super-sites is to compare the different E-GVAP analysis centre solutions between them and consequently, to assess

the *precision* of the tropospheric ZPD estimates. This issue is discussed later in Section 5.4.3.

Site	Location	Longitude	Latitude	Receiver Type	Antenna Type
BRST	Brest (France)	355.50°	48.38°	LEICA GRX1200GGPRO	LEIAT504GG NONE
CABW	Cabauw (Holland)	4.93°	51.97°	TRIMBLE 5700	TRM41249.00 NONE
CAMB	Cambridge (England)	354.67°	50.22°	ASHTech UZ-12	ASH700936D_M SNOW
CAGL	Cagliari (Italy)	8.97°	39.14°	TRIMBLE 4700	TRM29659.00 NONE
GOPE	Pcny (Czech Republic)	14.79°	49.91°	ASHTech Z18	TPSCR3_GGD CONE
LDB2	Lindenberg (Germany)	14.12°	52.21°	JPS LEGACY	TPSCR3_GGD CONE
MOSE	Roma (Italy)	12.49°	41.89°	LEICA GRX1200GGPRO	LEIAT504GG LEIS
MEDI	Medicina (Italy)	11.65°	44.52°	TRIMBLE 4000SSI	TRM29659.00 NONE
MILO	Milan (Italy)	38.01°	12.58°	TRIMBLE 4000SSI	TRM29659.00 NONE
ONSA	Onsala (Sweden)	11.93°	57.40°	JPS E_GGD	AOAD/M_B OSOD
PAYE	Payerne (Switzerland)	6.94°	46.81°	TRIMBLE NETR5	TRM55971.00 NONE
SMNE	Seine et Marne (France)	2.43°	48.84°	LEICA GRX1200GGPRO	LEIAT504GG NONE
YEBE	Yebes (Spain)	356.91°	40.52°	TRIMBLE NETRS	TRM29659.00 NONE
ZIMM	Zimmerwald (Austria)	7.47°	46.88°	TRIMBLE NETRS	TRM29659.00 NONE

Table 5.1: List of the E-GVAP super-sites, their locations and their GNSS antenna/receiver equipments (Status: September 2009)

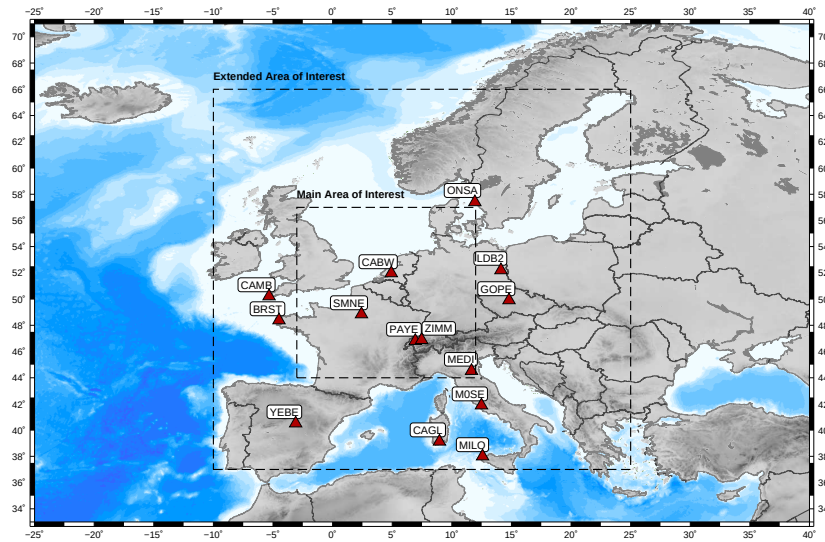


Figure 5.1: Geographical location of the E-GVAP super-sites (Status: September 2009)

Performances

Because of their importance in the solution monitoring, the E-GVAP processing expert team strongly recommends the analysis centres to include all super-sites in their routine GNSS analysis. Despite this strong recommendation, only 3 out of the 11 analysis centres include all of them in their operational analysis (status: September 2009). These analysis centres are the *Geodetic Observatory Pecny* (GOP), the *Koninklijk Nederlands Meteorologisch Instituut* (KNMI) and the *Royal Observatory of Belgium* (ROB) analysis centres. All E-GVAP super-sites (Table 5.1) are located within the extended area of interest (Section 4.4.1) defined in Chapter 4. All of them were thus included in our operational GNSS network. While they are valid for the entire network, for the sake of clarity and if not specified otherwise, the results presented in this chapter will often be illustrated using the results obtained for the E-GVAP super-sites.

Remark: *The exclusion of a super-site by an analysis centre is often related to moderate computing power, data access limitations or to the fact that the super-site is located outside the area of interest of the analysis centre.*

5.3 Performances of the Precise Coordinates

Background

During the post-processing step of the analysis strategy (Section 4.3), the daily Normal Equations (NEQ) are combined to provide cumulative solutions. The daily *coordinate outliers* are identified, then removed from the coordinate solutions (Section 4.4.3). Cleaned from these outliers, the site *coordinate repeatability* $\mathcal{R}$ provides a good indicator of the impact of coordinate errors on the tropospheric ZPD estimates for this site (Section 4.4.3). It is also an indicator of the impact of the GNSS site observation quality on the tropospheric ZPD estimates. The repeatability $\mathcal{R}$ reads

$$\mathcal{R}^c = \sqrt{\sum_{i=1}^N \frac{|X_i^c - \widehat{X}^c|^2}{N}} \quad (m) \quad (5.1)$$

- where
- c is the north, east or vertical component of the station coordinate
 - N is the number of days considered in the cumulative coordinate solution
 - X_i^c is the c^{th} component of the station coordinate of the i^{th} day in metres
 - $\hat{X}^c$ is the c^{th} component of the cumulative coordinate solution in metres

Performances

The coordinate repeatability is continuously monitored in the QMS (Section 4.3). The GNSS network processed in the post-processing analysis strategy (Section 4.3) includes today about 460 permanent stations (Figure 5.2), mainly from the GNSS observation networks mentioned in Section 2.7.1. A typical example of daily coordinate residuals (i.e. the $X_i^c - \hat{X}^c$) is illustrated in Figure 5.3. It shows the daily coordinate residuals for the E-GVAP super-site located in Onsala (ONSA), Sweden for the monthly cumulative coordinate solution from the 1st July 2009 to the 31st July 2009. The coordinate repeatabilities ($\mathcal{R}^c$) recorded for this super-site were of 1.4 mm, 1.2 mm and 3.3 mm for the north, east and vertical component respectively. It should be mentioned that the GNSS site located in Onsala is well known for the quality of its observations. Cleaned from the daily outliers and averaged over the 460 stations, the mean station coordinate repeatability during the month of July 2009 was about 1.3 mm for the horizontal components and 4.3 mm for the vertical component. During that period, the worst coordinate repeatability scores recorded reached 3.8 mm, 3.6 mm and 7.6 mm for the north, east and vertical component respectively. Using the rule of the thumb explained in Section 4.4.3 (page 4-16) and the mean and maximal repeatabilities of the vertical component given here above, we can derive the impact of coordinate errors on the tropospheric ZPD estimates: when the daily coordinate outliers are removed, using the daily site coordinates in the back-substitution procedure (Figure 4.5, Section 4.4.3) impacts the tropospheric ZPD on the order of 1.4 mm, with (exceptionally) a maximal impact up to 2.5 mm. This is within, but close to, the precision targeted in the URD. Furthermore, as shown in Section 4.4.3, using the monthly cumulative coordinate solution in the back-substitution of the site coordinates offers more precision, continuity

and robustness. Two successive sets of monthly cumulative coordinates determined by our post-processing analysis strategy only differ by a few tenths of millimetre. The daily update of the monthly coordinate solution allows thereby to not introduce any significant jump in the tropospheric ZPD estimates and to reduce the impact of the site coordinate errors to the minimum, i.e. quasi-zero in this case.

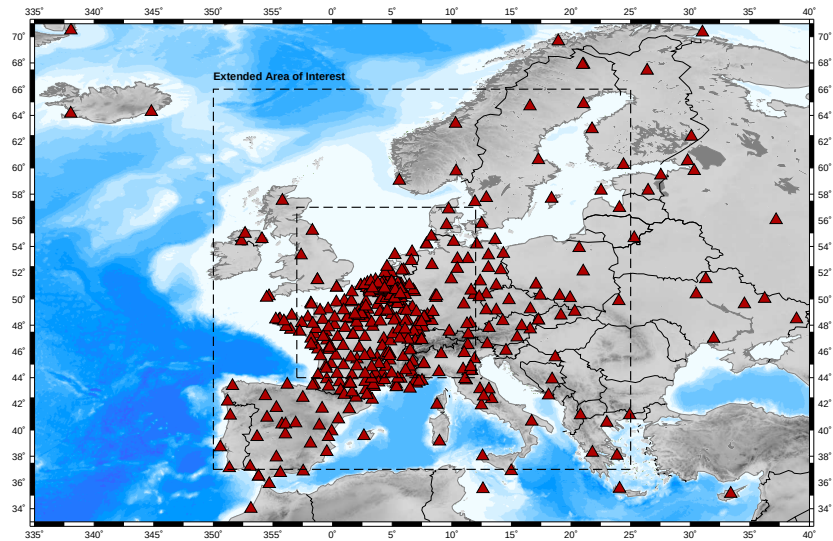


Figure 5.2: GNSS network processed in the post-processing analysis strategy to determine precise site coordinates (Status: June 2009). A few stations, notably in Greenland and in the Atlantic regions, are located outside the map region

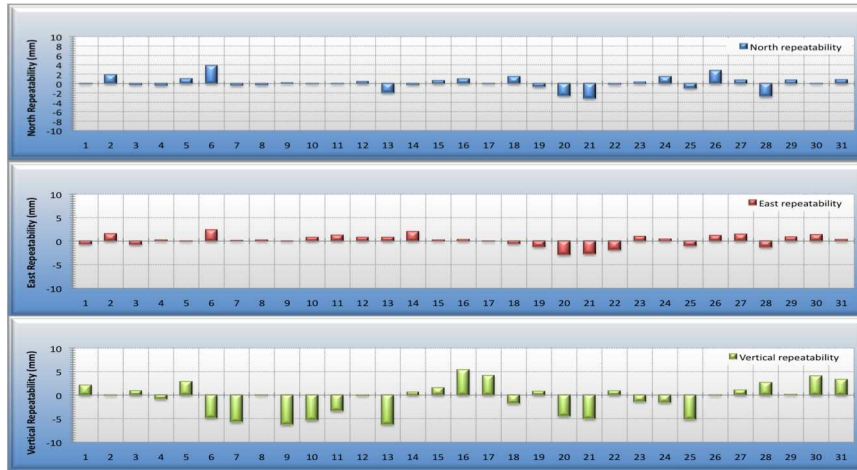
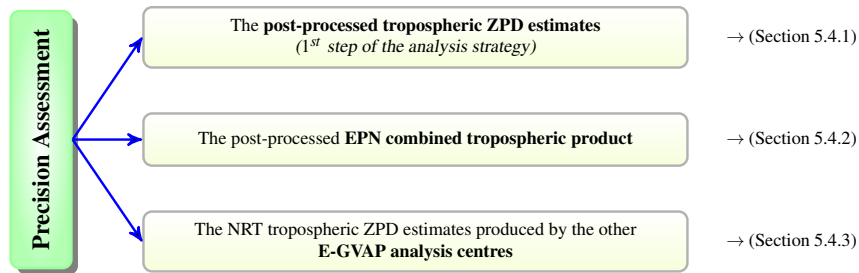


Figure 5.3: Daily coordinate residuals for the E-GVAP super-site located in Onsala (ONSA), Sweden (period covering the 1st July 2009 to the 31th July 2009 - x axis: day in the month)

5.4 Precision Assessment by Inter-GNSS Comparisons

To be of benefit to GNSS-meteorology, i.e. NWP and nowcasting applications, the NRT tropospheric ZPD estimates provided by the geodesists must reach a precision ranging from a target value of 3 mm up to a threshold value of 10 mm. To assess their precision, the NRT tropospheric ZPD estimates were compared to 3 other sources of ground-based GNSS tropospheric ZPD estimates, i.e.



5.4.1 Near Real-Time versus Post-Processed Solutions

Background

A first assessment of the precision of our NRT tropospheric ZPD estimates consists in comparing them against the tropospheric ZPD estimates obtained from our post-processing analysis. Indeed, based on a more refined processing strategy, better-quality GNSS products (e.g. orbits) and more GNSS observations, the tropospheric ZPD obtained from the post-processing can be considered as “ground-truth” to assess the precision of the NRT tropospheric ZPD solutions (Section 4.3). The comparison was carried out over a 5-month period covering the 1st January 2009 to the 31st May 2009 using the observations from the 160 GNSS stations routinely processed at that time in the framework of E-GVAP (Figure 5.4).

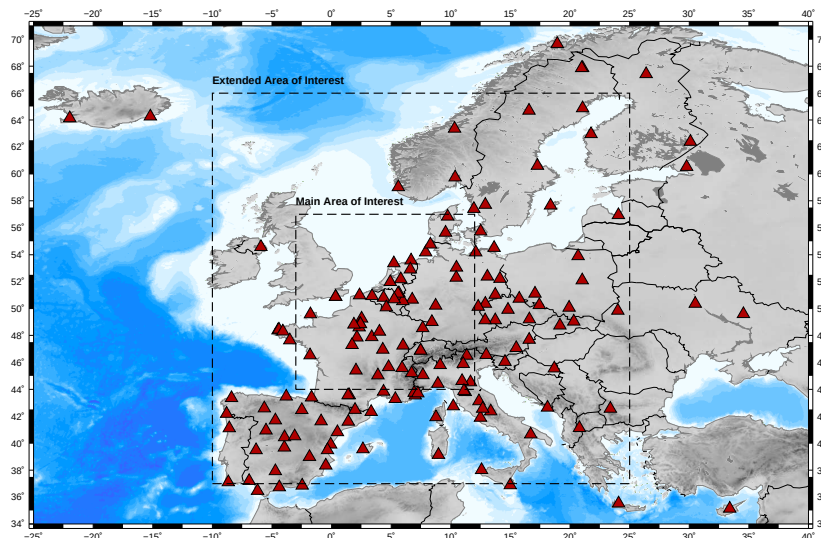


Figure 5.4: GNSS network processed in near real-time in the framework of E-GVAP (Status: June 2009). A few stations, notably in Greenland and in the Atlantic regions, are located outside the map region

Performances

An example of the agreement between the near real-time and the post-processed tropospheric ZPD solutions for the E-GVAP super-site located in Onsala (ONSA), Sweden, is given in Figure 5.5. The tropospheric ZPD differences follow a normal distribution with a bias of 1.54 mm and a standard deviation of 3.20 mm. This bias is within the tolerance level requested for GNSS-meteorology. When corrected for the bias, 66 % of the tropospheric ZPD estimates agree within the 3 mm precision level targeted in the URD and 100 % of them agree within the threshold level.

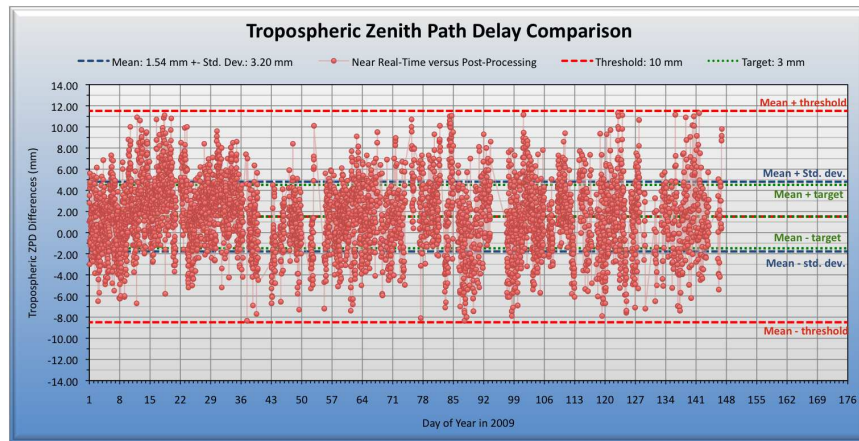


Figure 5.5: Differences between our near real-time and our post-processed tropospheric ZPD solutions for the E-GVAP super-site located in Onsala (ONSA), Sweden (period covering the 1st January 2009 to the 31st May 2009)

The statistics of the comparison for the 14 E-GVAP super-sites are summarised in Table 5.2. Averaged over the 14 E-GVAP super-sites (51750 common observations in total), the tropospheric ZPD differences follow a normal distribution (no significant skewness nor kurtosis) with a mean bias quasi-null and a mean standard deviation of 4.68 mm. Only 3 super-sites present a bias above 1 mm, with a maximal bias of 1.54 mm recorded for the E-GVAP super-site located in Onsala (ONSA), Sweden. The standard deviations range between 3.20 mm and 7.13 mm, most of them being within 5.5 mm. No linear trend is detected in the tropospheric ZPD difference time series. Extending

this analysis to the 160 stations included in the network, confirmed the aforementioned results: in average (610358 common observations in total), the tropospheric ZPD differences follow a normal distribution with a mean bias of 0.59 mm and a mean standard deviation of about 4.39 mm (Table 5.2). No significant skewness, kurtosis nor slope is observed. Site-specific biases between the NRT and the post-processed solutions are revealed but remained in all cases within the 3 mm level of precision targeted in the URD, with a maximal value of 2.97 mm (Figure 5.6). The standard deviations range from about 3 mm up to 7.13 mm, 96 % of them lying within 5.5 mm. While the correlation coefficient between the NRT and the post-processed solutions remained very high (usually above 0.99) for all sites, the tropospheric ZPD differences also emphasise occasionally peaks ('outliers') of large amplitudes for all sites, with a maximal value recorded of 21.25 mm and 95 % of them residing above the 10 mm precision threshold. A study of the geographical dependency of the site-specific biases and standard deviations (Figure 5.7 and Figure 5.8) revealed

- Larger positive biases in the northern countries, and to less extent in Spain
- Lower standard deviations in the northern countries, which might be attributed to lower content and lower variability of water vapour, specially during the northern hemisphere winter in this case
- Highest standard deviations are not geographically correlated but might be attributed to the GNSS observation quality of the site (e.g. multipath effect)

5.4. Precision Assessment by Inter-GNSS Comparisons

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
BRST	-15.50	14.70	-0.51	5.13	15.21	-0.04	3.06	0.00	3966
CABW	-10.10	12.60	1.26	3.80	-11.36	-0.07	3.01	-0.01	4477
CAGL	-16.60	15.30	-0.68	5.33	15.98	-0.03	2.92	0.00	4178
CAMB	-11.60	12.20	0.46	4.11	-12.06	-0.11	2.84	0.00	845
GOPE	-15.20	14.80	-0.30	5.16	15.10	0.01	3.02	-0.01	2736
LDB2	-20.90	21.60	0.35	7.13	-21.25	-0.12	3.08	-0.01	3784
MOSE	-14.00	12.70	-0.38	4.56	-13.62	-0.01	3.02	-0.01	3391
MEDI	-13.90	12.50	-0.70	4.45	-13.20	-0.03	2.98	-0.01	4360
MILO	-19.20	16.80	-1.25	6.03	18.05	-0.10	3.05	-0.00	4223
ONSA	-7.90	11.10	1.54	3.20	9.56	0.01	3.02	-0.01	4367
PAYE	-11.20	11.20	-0.08	3.83	11.28	0.08	2.89	-0.01	3810
SMNE	-10.90	13.00	0.86	4.05	12.14	0.10	3.06	-0.00	3875
YEBE	-13.60	14.90	0.72	4.79	-14.32	-0.03	3.03	0.01	3190
ZIMM	-11.50	12.30	0.40	3.97	-11.90	0.09	3.12	-0.01	4548
Averaged over the E-GVAP super-sites: 14 GNSS stations									
Mean	-13.72	13.98	0.12	4.68	-0.03	-0.02	3.01	-0.01	51750
Std. Dev.	3.44	2.65	0.78	0.99	14.24	0.07	0.07	0.01	51750
Max. Dev.	-7.18	7.62	1.42	2.45	-21.22	0.12	-0.17	0.02	51750
Average values over the complete network : 160 GNSS stations (rejected observations: 2.6%)									
Mean	-12.42	13.63	0.59	4.39	0.24	0.01	3.04	-0.00	610358
Std. Dev.	2.45	1.84	0.86	0.67	13.24	0.07	0.10	0.01	610358
Max. Dev.	-8.48	7.97	2.38	2.74	-21.49	-0.17	0.32	0.07	610358

Table 5.2: Statistics of the tropospheric ZPD differences between our near real-time and our post-processed solutions (period covering the 1st January 2009 to the 31st May 2009)

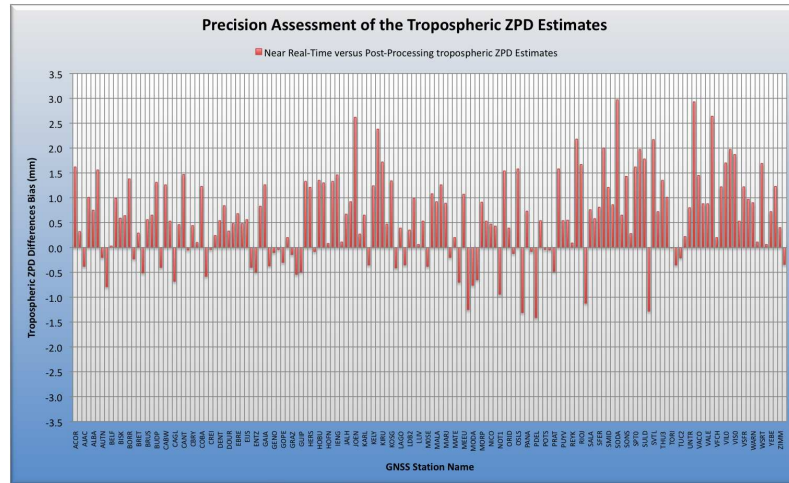


Figure 5.6: Site-specific biases between our near real-time and our post-processed tropospheric ZPD solutions (period covering the 1st January 2009 to the 31st May 2009)

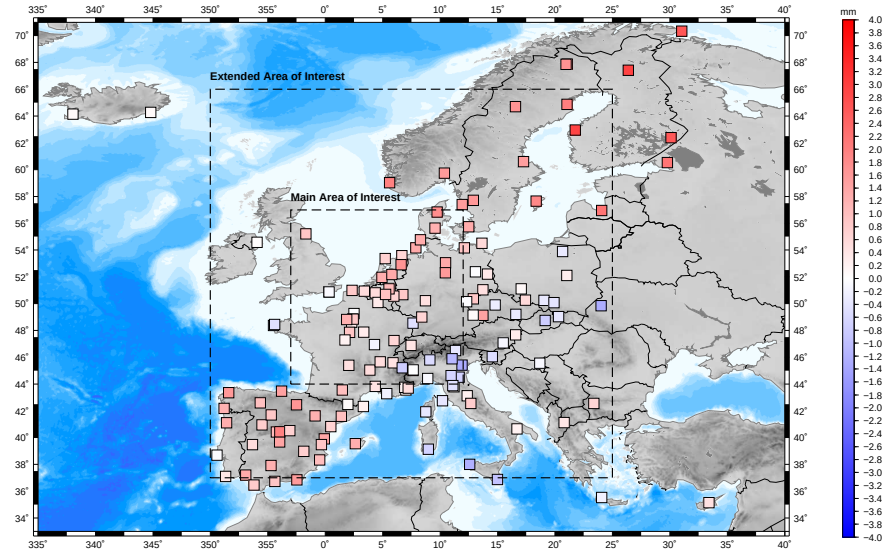


Figure 5.7: Geographical distribution of the site-specific biases obtained from the comparison between our near real-time and our post-processed solutions (period covering the 1st January 2009 to the 31st May 2009)

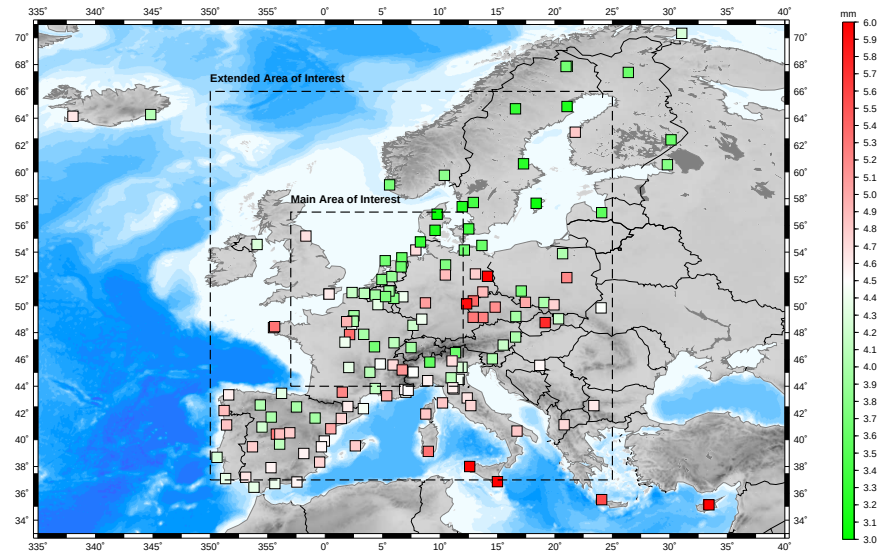


Figure 5.8: Geographical distribution of the site-specific standard deviations obtained from the comparison between our near real-time and our post-processed solutions (period covering the 1st January 2009 to the 31st May 2009)

5.4.2 The EPN Combined Tropospheric Product

Background

A second step in the assessment of the precision of our NRT tropospheric ZPD estimates was to compare them against the post-processed tropospheric ZPD estimates from the EPN combined tropospheric product. Indeed, EUREF provides a legacy tropospheric product for post-processing applications as described in [Söhne and Weber, 2002]. Basically, the EPN combined tropospheric solution is a combination of the individual tropospheric solutions provided by the 16 Local Analysis Centres (LAC) participating in EUREF. The EPN combined tropospheric solution is available since GPS week 1108 (June 2001) and each site included in the combination is at least processed by 3 LAC. The combination process allows to improve the precision of the tropospheric solution notably by improving the solution consistency, eliminating outliers and excluding analysis centre deficiencies. Currently, the weekly mean bias of the individual LAC solutions with respect to the combined solution is within the 2 mm level with nearly the same standard deviation (Figure 5.9 and Figure 5.10). According to [Söhne and Weber, 2002], it is the same order of magnitude as the biases and the standard deviations of an individual analysis centre solution with respect to the IGS troposphere combination (Table 2.5 in Section 2.7.2). This product can thus be used as a second “ground-truth” to assess the precision of our NRT tropospheric ZPD estimates. The comparison was carried out over a 5-month period covering the 1st January 2009 to the 31st May 2009 using the observations from the 139 EPN GNSS stations routinely processed in the framework of E-GVAP and available during that period. The results of this comparison were reported in [Pottiaux *et al.*, 2009].

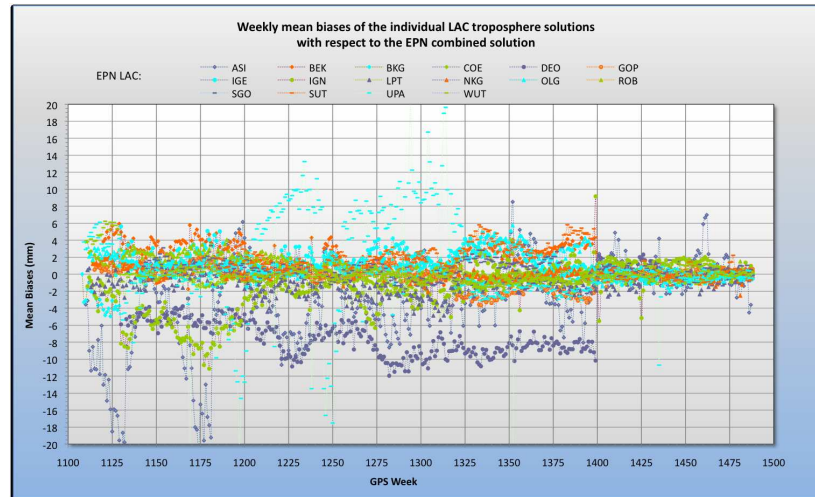


Figure 5.9: Weekly mean bias (over all stations) of the individual LAC tropospheric solutions with respect to the EPN combined tropospheric solutions
Source: [Pottiaux et al., 2009]

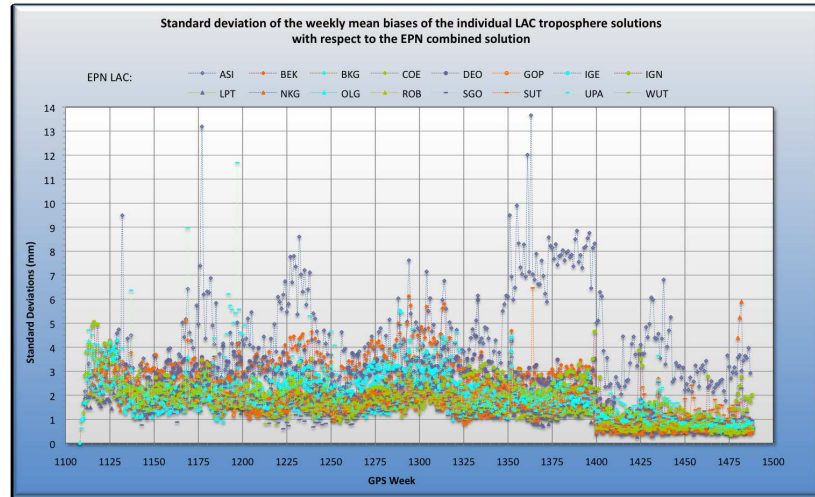


Figure 5.10: Standard deviation of the individual LAC tropospheric solutions with respect to the EPN combined tropospheric solutions
Source: [Pottiaux et al., 2009]

Performances

The statistics of this comparison for the 9 E-GVAP super-sites belonging to the EPN (Figure 2.9) are presented in Table 5.3. Averaged over the 9 super-sites (20004 common observations in total), the tropospheric ZPD differences follow a normal distribution (no significant skewness nor kurtosis) with a mean bias of -0.32 mm and a mean standard deviation of 4.83 mm . Only two super-sites present a bias above 1 mm , with a maximal bias of -1.42 mm recorded for the GNSS station located in Milan (MILO), Italy. The standard deviations range between 3.15 mm and 6.09 mm , most of them being within 5.5 mm . No linear trend is detected in the tropospheric ZPD difference time series. Moreover, results presented in Table 5.2 and Table 5.3 are highly consistent (usually within 0.5 mm in terms of bias and even less in terms of standard deviation). Extending this analysis to the 139 EPN stations included in the network, confirmed the aforementioned results: in average (305731 common observations in total), the tropospheric ZPD differences follow normal distributions with a mean bias of 0.36 mm and a mean standard deviation of 4.49 mm (Table 5.3). No significant skewness, kurtosis nor slope is observed. Station-specific biases between the NRT solutions and the EPN combined tropospheric solutions were revealed but remained in all cases within the 3 mm level of precision targeted in the URD, with a maximal value observed of 2.86 mm (Figure 5.11). The standard deviations range from 2.92 mm up to 6.69 mm , with 92.56% of them lying within the 5.5 mm level. While the correlation coefficients between the two solutions remain very high (usually above 0.99) for all sites, the tropospheric ZPD differences also emphasise occasionally peaks ('outliers') of large amplitudes for all sites, with a maximal value recorded of -19.96 mm . Concerning the geographical dependency of the station-specific biases and standard deviations, very similar results to the first precision assessment are obtained (Figure 5.12, Figure 5.13). Similar results obtained from comparisons carried out in 2008 have been reported in [Pottiaux *et al.*, 2009]. From the two firsts precision assessments, we can conclude that more than 92% of our NRT tropospheric ZPD estimates have a precision better than 5.5 mm .

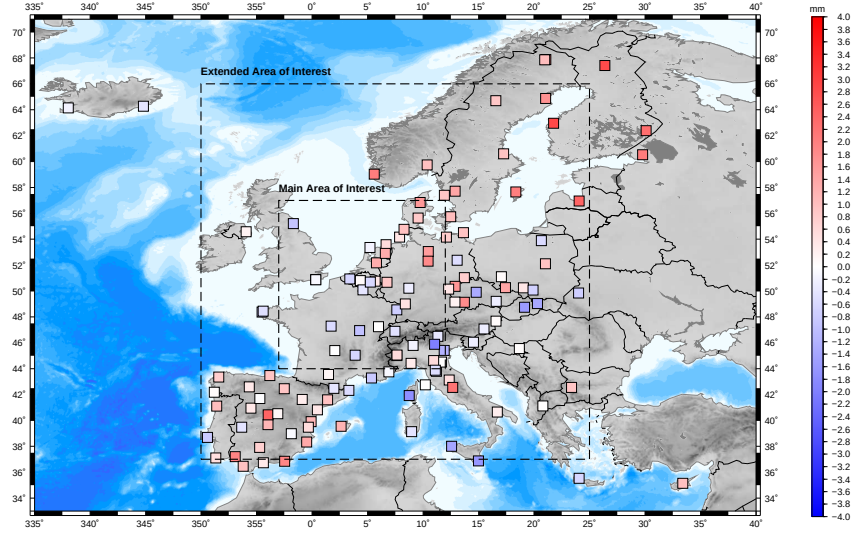


Figure 5.12: Geographical distribution of the site-specific biases obtained from the comparison between our near real-time tropospheric ZPD estimates and the EPN combined tropospheric solutions (period covering the 1st January 2009 to the 31st May 2009)

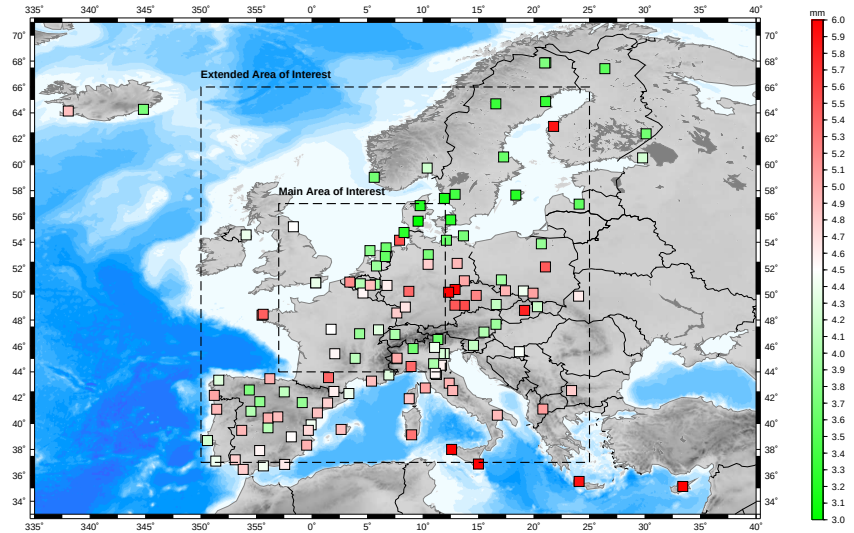


Figure 5.13: Geographical distribution of the site-specific standard deviations obtained from the comparison between our near real-time tropospheric ZPD estimates and the EPN combined tropospheric solutions (period covering the 1st January 2009 to the 31st May 2009)

5.4.3 The E-GVAP Analysis Centre Solutions

Background

In the two first comparisons (Section 5.4.1 and Section 5.4.2), the precision of the NRT tropospheric ZPD estimates was assessed with respect to post-processed tropospheric ZPD solutions, which used more refined analysis strategy, IGS products of better quality and more GNSS observations than it is possible in the NRT processing. As a final assessment, the NRT tropospheric ZPD estimates were compared to the NRT tropospheric ZPD estimates provided by the other E-GVAP analysis centres. Because no strict guidelines are imposed on the E-GVAP analysis centres, each centre is free to use its own strategy and software (Table C.1). The comparison was again carried out over the 5-month period covering the 1st January 2009 to the 31st May 2009 using the observations from the 160 GNSS stations routinely processed in the framework of E-GVAP (Figure 5.4).

Performances

The statistics of this comparison are summarised by E-GVAP analysis centre in Table 5.4. For all E-GVAP analysis centres but GFZ, the NRT tropospheric ZPD differences follow a normal distribution with quasi no bias and a standard deviations ranging from 4.53mm up to 5.60mm. No significant skewness, kurtosis nor slope is observed. The higher bias in the comparison with respect to the GFZ analysis centre reflects the use of a different analysis strategy: during that period, GFZ was still using the old IGS00 reference frame realisation and relative antenna calibration models (Section 4.4.7). The bias observed in the comparison with respect to the GFZ solution, i.e. -5.42 mm, is coherent with the mean bias induced by the switch from IGS00 to IGS05 in our analysis strategy, i.e. -5.51 mm, discussed in Section 4.4.7. In average, over all E-GVAP analysis centres and all GNSS stations (4336126 common observations in total), the mean bias recorded are of -0.21 mm and the mean standard deviation are of 4.89mm. For all GNSS sites and all analysis centres, about 62 % of the tropospheric ZPD estimates agree within the 3 mm level of precision targeted by the URD and 99 % of them agree within the threshold level, i.e. 10mm. Concerning the geographical dependency of the

station-specific biases and standard deviations, very similar results to the two previous precision assessments are obtained (Figure 5.14, Figure 5.15).

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
ROB vs. BKG	-15.21	14.94	-0.18	5.09	3.43	0.03	3.03	-0.00	354826
ROB vs. GFZ	-20.50	9.68	-5.42	5.05	2.20	0.01	2.99	0.01	1497908
ROB vs. GOP	-14.54	13.72	-0.41	4.78	-0.76	-0.00	3.03	-0.00	337038
ROB vs. KNMI	-17.23	17.95	0.33	5.91	-2.01	0.03	3.08	-0.00	207866
ROB vs. LPT	-15.52	13.73	-0.89	4.91	3.34	0.02	3.04	-0.00	349958
ROB vs. METO	-12.74	13.86	0.55	4.47	1.90	0.01	3.04	-0.01	1742148
ROB vs. SGN	-16.20	13.85	-1.17	5.03	-0.24	-0.01	3.02	0.01	1315290
Average values over the complete network and over all E-GVAP Analysis Centres but GFZ (rejected observations: 2.4%)									
Mean	-14.74	14.34	-0.21	4.89	1.30	0.01	3.04	0.00	4336126
Std. Dev.	3.10	2.73	1.47	0.84	14.79	0.08	0.10	0.06	4336126
Max. Dev.	10.06	12.06	4.19	3.58	26.65	0.39	0.45	0.88	4336126

Table 5.4: Statistics of the tropospheric ZPD differences between the different E-GVAP analysis centre solutions and our near real-time tropospheric ZPD solutions (period covering the 1st January 2009 to the 31st May 2009)

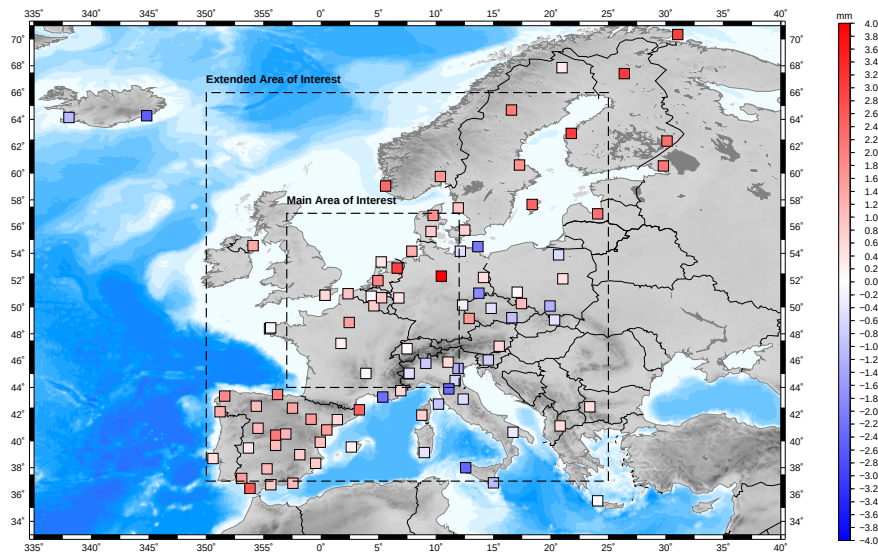


Figure 5.14: Geographical distribution of the site-specific biases obtained from the comparison between our near real-time and the E-GVAP Met office near real-time solutions (period covering the 1st January 2009 to the 31st May 2009)

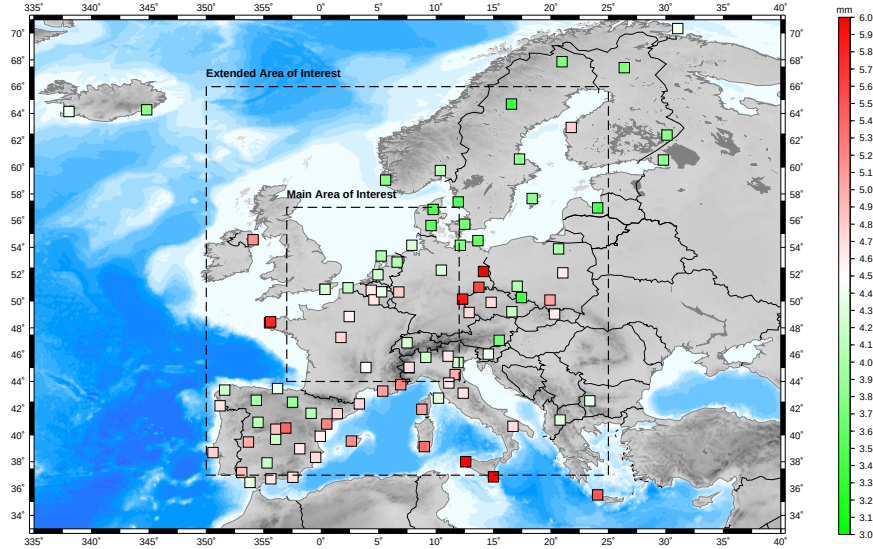
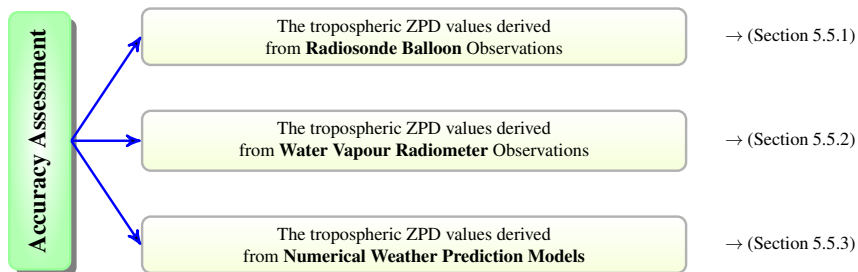


Figure 5.15: Geographical distribution of the site-specific standard deviations obtained from the comparison between our near real-time and the E-GVAP Met office near real-time solutions (period covering the 1st January 2009 to the 31st May 2009)

5.5 Accuracy Assessment by Technique Co-location

To be of benefit to GNSS-meteorology, the tropospheric ZPD estimates provided by the geodesists must reach an accuracy ranging from a target value of 3 mm up to a threshold value of 10 mm. To assess their accuracy, the NRT tropospheric ZPD estimates are compared to 3 external techniques from which tropospheric ZPD values can be computed, i.e.



5.5.1 Co-location With Radiosonde Balloons

Background

As a first step to assess their accuracy, the GNSS-based NRT tropospheric ZPD estimates were compared to tropospheric ZPD values derived from radiosonde balloon observations [Pottiaux *et al.*, 2009]. Radiosonde devices are capable of making direct in-situ measurements of air pressure, temperature and dew-point temperature while ascending through the atmosphere (Appendix E). From these in-situ measurements, hydrostatic and wet tropospheric ZPD can be obtained (Section E.2). In the context of the EUREF-EUMETNET collaboration (Appendix D), a procedure has been set up to extract the radiosonde observations from no less than 200 radiosonde launch sites within a limited grid area covering Europe and extending from 30° W to 40° E in longitude and from 25° N to 89.9° N in latitude (Figure D.3). The co-location of the GNSS sites included in our network with the radiosonde launch sites is illustrated in Figure 5.16.

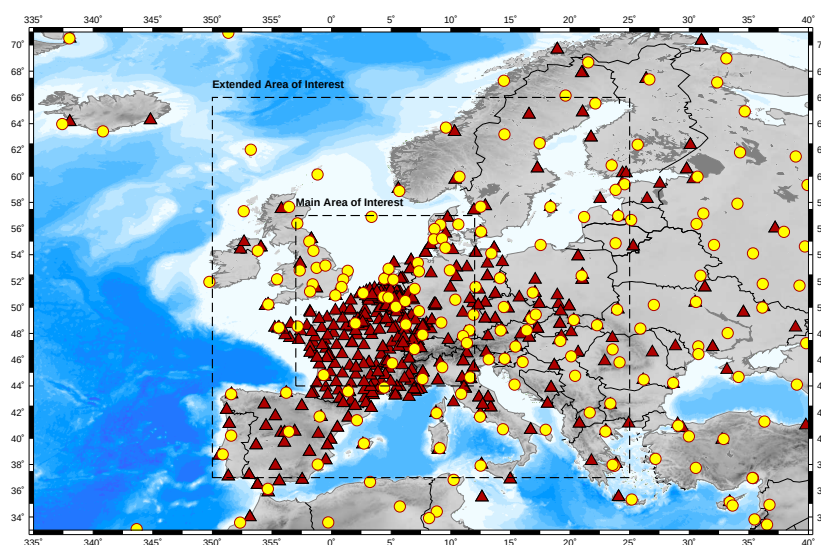


Figure 5.16: Co-location between the GNSS stations (red triangles) included in our post-processing network and the radiosonde observation launch sites (yellow dots) for which observations are made available in the framework of the EUREF-EUMETNET memorandum of understanding

In Chapter 4, we discussed the switch to the IGS05 reference frame along with the use of absolute antenna calibration models (Section 4.4.7) to adhere to the latest IGS standards. The switch influenced the site coordinates and the tropospheric ZPD estimates, introducing significant site-specific biases up to -9.53 mm in the tropospheric ZPD solutions. Nonetheless, the sensitivity tests carried out in Section 4.4.7 could not help us to decide between the two solutions in terms of accuracy. As mentioned earlier in this chapter, the assessments are based on our operational product delivered in the framework of E-GVAP. Along the time, our processing strategy changed. Moreover, because of the NRT operational nature of our product, several holes exist in our product time series. To exclude any impact of these two aspects on our results, we decided to assess the switch to the new IGS standards in terms of accuracy in two steps:

- First the switch to the new IGS standards was assessed by comparing the (post-processed) EPN combined tropospheric product (Section 5.4.2) with tropospheric ZPD values obtained from radiosonde observations. This product is obtained from a homogeneous processing and shows no hole in its time series.
- Then, the switch to the new IGS standards was assessed by comparing our NRT tropospheric ZPD estimates with tropospheric ZPD values derived from radiosonde observations

The EPN Combined Tropospheric Product

As a first step, the EPN combined tropospheric product (Section 5.4.2) was compared to tropospheric ZPD values derived from radiosonde observations. On the 1st November 2006 (GPS week 1400), all EPN Local Analysis Centres (LAC) applied the switch to the IGS05 reference frame realisation and the absolute antenna calibration models (Section 4.4.7). The time evolutions of the weekly mean bias of the individual solutions with respect to the combined solutions, as well as its standard deviation, are shown in Figure 5.9 and Figure 5.10. The impact of the strategy change (IGS05 and absolute antenna calibration models) reduced significantly the biases between the individual LAC solutions as well as their standard deviations. Currently, the weekly mean bias of the individual LAC solutions with respect to the combined solution is within the 2 mm level. The impact of the strategy

change on the EPN combined tropospheric product (in terms of accuracy) was assessed on the 4-years period covering the 1st January 2004 to the 24th March 2008. This comparison is illustrated in Figure 5.17 for the EPN twin-stations BOGI and BOGO in Borowa Gora, Poland, which are co-located with a radiosonde launch site. The differences between the radiosonde-based and the EPN combined tropospheric ZPD solutions for both EPN stations are shown in Figure 5.17. During the 2004-2008 period, the EPN stations located in Borowa Gora were equipped solely with a unique antenna type: an Ashtech ASH700936C_M for BOGI and an Ashtech ASH701945C_M for BOGO, both with SNOW radome. Over the 2.5 years preceding the strategy change, a clear bias with respect to the radiosonde-based estimations is detected. The magnitude of these biases is of -17.6 mm and -11.3 mm for the station BOGI and BOGO respectively. Higher discrepancies between the two techniques are also visible during the summer time for both stations. This is consistent with a higher water vapour content [Haase *et al.*, 2003] and held true after the processing strategy changes. Nevertheless, after a small gap at the end of 2006 due to missing radiosonde observations, the biases between the GNSS-based and the radiosonde-based tropospheric ZPD are reduced to about 1 mm for both stations. This is a clear accuracy improvement brought by the switch to the IGS05 reference frame realisation and the use of absolute antenna calibration models (Section 4.4.7). The slightly too wet values for the GNSS-based tropospheric ZPD estimates (when using the old IGS00 reference frame realisation along with the relative antenna calibration models) is an effect already mentioned in previous European projects in the area of GNSS-meteorology. Depending on the used GNSS antenna type, this bias could be further reduced, as shown in the case of BOGI and BOGO. Nevertheless, one needs to take into account the error budgets of each technique, resulting in a possible bias of more than the shown 1-2 mm tropospheric ZPD bias in the example above. The standard deviations also show a slight improvement after the strategy change of roughly 10%, but due to the different lengths of the time series before and after the change this effect still needs to be confirmed. The comparison was extended to 15 EPN sites co-located with radiosonde launch sites over the same period. The statistics of this comparison for the 15 EPN sites are summarised in Figure 5.18. The positive impact of the switch on the mean bias between the two solutions is

clearly visible for all sites, except for Ajaccio (AJAC) in Corsica and for Lviv (SULP) in Ukraine.

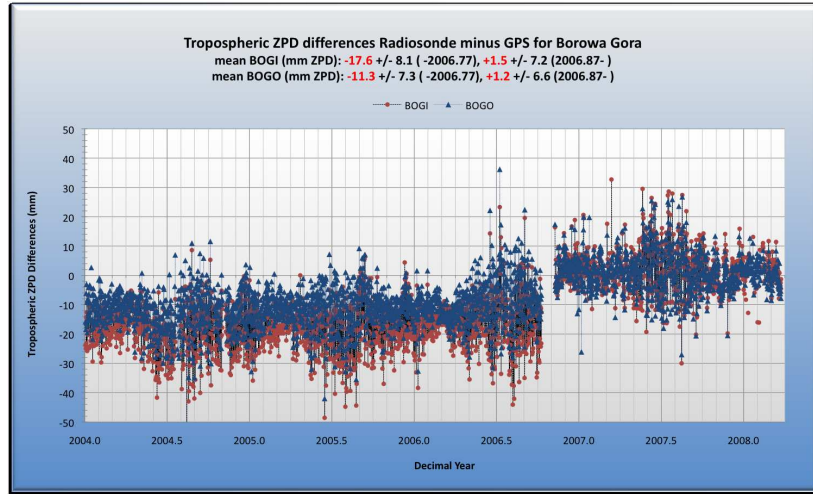


Figure 5.17: Differences between the GNSS-based and the radiosonde-based tropospheric ZPD for the EPN twin-stations located in Borowa Gora, Poland. The blue triangles represent the tropospheric ZPD of the BOGO reference station while the red dots represent those of the BOGI station

The Near Real-Time Tropospheric ZPD

To evaluate the impact of the switch to the new IGS standards on the NRT tropospheric ZPD estimates in terms of accuracy, 9 GNSS sites are located near-by radiosonde launch sites were selected. Their ground-based GNSS tropospheric ZPD estimates were compared with the tropospheric ZPD values derived from the radiosonde observations. As illustrated in Table 5.5, for all selected sites the inter-distance between the GNSS antenna and the radiosonde is less than 60km. The ground-based tropospheric ZPD time series based on the IGS00 reference frame realisation and the relative antenna calibration models were estimated for a 2-year period covering the June 2004 to the June 2006, while the ones based on the IGS05 reference frame realisation and the absolute antenna calibration models were estimated for an 8-month period covering November 2007 to June 2008. When using relative antenna calibration models, the biases and standard deviations

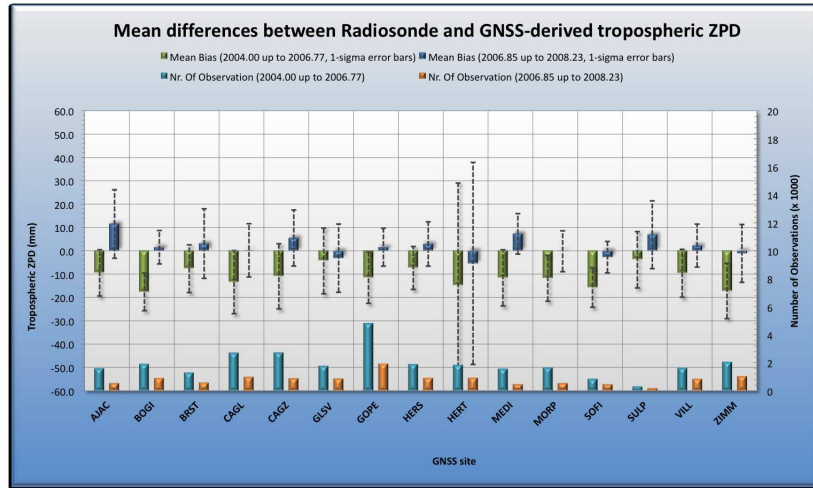


Figure 5.18: Mean biases and standard deviations of the differences between the GNSS-based and radiosonde-based tropospheric ZPD for 15 EPN stations. Since HERS and HERT are co-located, the bad agreement of HERT must be put at the account of the GNSS processing

(Table 5.5) found for the comparison between GNSS and radiosondes agree well with the results obtained by [Haase *et al.*, 2001] and [Pacione and Vespe, 2008]: the ground-based GNSS tropospheric ZPD estimates are usually a few millimetres too "wet" with respect to radiosonde observations as already pointed out for the EPN combined tropospheric product. In the dataset analysed, all radiosondes were Vaisala radiosondes except at Zimmerwald where a Meteolabor radiosonde was used. Vaisala radiosondes are well known for having a dry bias of their humidity sensor that might explain part of the biases between the two techniques (Section E.4). Also, as pointed out in [Haase *et al.*, 2001] and [Pacione and Vespe, 2008], because of their distance and height separation, the atmospheric state observed by the two techniques might be slightly different and can consequently limit the level of agreement between the two techniques. In this test, the tropospheric ZPD solutions computed using the IGS05 reference frame realisation and the absolute antenna calibration models always agree better with radiosonde observations (Table 5.5 and Figure 5.19).

Location	GNSS Station	RAOB Code	(GNSS-RAOB)		IGS00 and Relative Antenna Calibration Models				IGS05 and Absolute Antenna Calibration Models			
			Distance (km)	Height (m)	Nr. of Data	Bias (mm)	Std. Dev. (mm)	ρ	Nr. of Data	Bias (mm)	Std. Dev. (mm)	ρ
Cagliari, Italy	CAGL	16560	15	186.85	8663	6.86	11.61	0.97	4200	-0.39	10.73	0.95
Santander, Spain	CANT	08023	59	-6.69	5618	23.76	16.27	0.94	2342	5.20	9.30	0.97
Cascais, Portugal	CASC	08579	-	245.50	1959	14.22	13.56	0.90	993	1.21	9.65	0.93
Pecny, Czech Republic	GOPE	11520	29	244.55	4121	8.34	10.14	0.95	6244	2.44	9.58	0.98
Herstmonceux, U.K.	HERS	03882	4	-20.52	6096	7.10	8.41	0.98	2400	0.36	8.18	0.98
Medicina, Italy	MEDI	16144	15	0.65	4026	9.08	10.36	0.99	1665	-2.43	9.95	0.98
Villafranca, Spain	VILL	08221	32	-37.69	3670	9.68	10.97	0.96	1463	2.01	8.86	0.95
Wroclaw, Poland	WROC	12425	13	22.00	5585	11.16	8.23	0.99	2663	8.04	8.17	0.98
Zimmerwald, Switzerland	ZIMM	06610	40	416.5	8422	14.52	11.64	0.98	3235	6.12	13.08	0.97
Mean over all stations					(*) 48160	11.64	11.24	0.96	(*) 25205	2.51	9.72	0.97

Table 5.5: Comparison of near real-time ground-based GNSS tropospheric ZPD estimates with radiosonde-based tropospheric ZPD values. Tropospheric ZPD estimates obtained from GNSS analysis using the old IGS00 reference frame realisation and the relative antenna calibration models are estimated for the June 2004 - June 2006 period, while those estimated with the new IGS05 reference frame realisation and the absolute antenna calibration models are obtained from the period November 2007 - June 2008. ρ is the correlation coefficient between the GNSS and the radiosonde tropospheric ZPD time series (*) sum of all observations

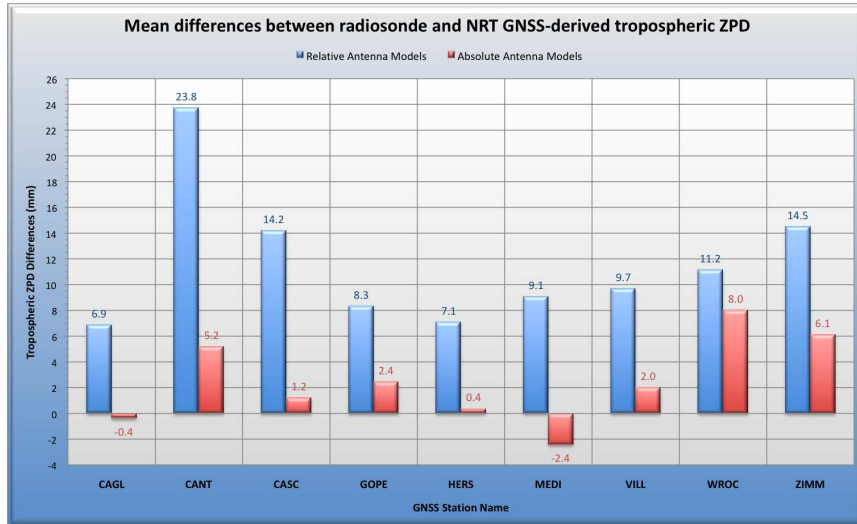


Figure 5.19: Mean biases between the GNSS-based and the radiosonde-based tropospheric ZPD time series. Tropospheric ZPD estimates obtained from the GNSS analysis using the old IGS00 reference frame realisation and relative antenna calibration models are estimated for the June 2004 - June 2006 period (blue bars), while those estimated with the new IGS05 reference frame realisation and absolute antenna calibration models are obtained for the period November 2007 - June 2008 (red bars)

5.5.2 Co-location With Water Vapour Radiometers

Background

The water vapour contained in the atmosphere behaves as a black body emitting electromagnetic waves and therefore can be observed based on radiative transfer methods as explained in [Solheim, 1993]. Water Vapour Radiometers (WVR) are instruments that observe the emissions of the atmosphere at two radio-frequencies being sensitive to the water vapour and liquid water content. From these raw measurements, the tropospheric ZPD above the observation site can be derived. Details on this technique can be found in [Westwater, 1965; Askne and Nordius, 1987; Solheim, 1993; Rosenkranz, 1998; Solheim *et al.*, 1999]. A first experience with WVR and a preliminary comparison between the GNSS-derived and the WVR-derived

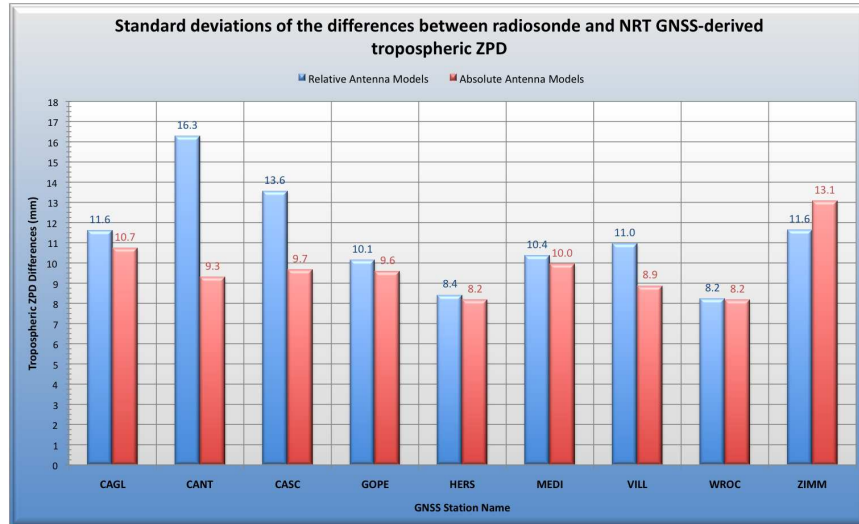


Figure 5.20: Standard deviations between the GNSS-based and the radiosonde-based tropospheric ZPD time series. Tropospheric ZPD estimates obtained from the GNSS analysis using the old IGS00 reference frame realisation and relative antenna calibration models are estimated for the June 2004 - June 2006 period (blue bars), while those estimated with the new IGS05 reference frame realisation and absolute antenna calibration models are obtained for the period November 2007 - June 2008 (red bars)

tropospheric ZPD values were published in [Pottiaux and Warnant, 2003] and [Pottiaux and Warnant, 2002] but the comparison was obtained using the old IGS00 reference frame realisation and the relative antenna calibration models. Hereafter, similar comparisons were carried out but using NRT GNSS tropospheric ZPD estimates that adhere to the new IGS standards and tropospheric ZPD values derived from the WVR co-located with the E-GVAP super-site located in Onsala (ONSA), Sweden and for a 8.5-month period covering the 1st January 2009 to mid-September 2009. Details on the Onsala WVR can be found in [Elgered and Jarlemark, 1998].

Remark: The WVR raw observations were first filtered out from 'corrupted' observations, i.e.

✎ Observations pointing too close to the Sun were removed

- ✎ Observations corrupted because of too high liquid content in the atmosphere (e.g. due to rain periods) were removed
- ✎ Observations with an elevation angle lower than 20° were filtered out since they are too noisy and contaminated by environmental influences

Performances

The agreement between the NRT GNSS tropospheric ZPD estimates and the tropospheric ZPD values derived from the WVR raw observations for the E-GVAP super-site located in Onsala (ONSA), Sweden is illustrated in Figure 5.21. The tropospheric ZPD differences follow a normal distribution (Figure 5.22) with a mean bias of -1.56 mm and a standard deviation of 4.72 mm . When corrected from this bias, 49.52% of the tropospheric ZPD estimates agree within the 3 mm level of accuracy targeted in the URD and 95.56% of them agree within the 10 mm threshold level. The statistics of this comparison are summarised in Table 5.6. No slope is detected in the tropospheric ZPD differences. The bias between the two techniques can partially be attributed to the fact that

- The cut-off elevation angle used is different for the two techniques: 10° elevation angle for the GNSS observations with respect to 20° for the WVR observations
- The WVR technique needs its own calibration procedure which is not error-free and might induce biases [Pottiaux *et al.*, 2003a], [Pottiaux *et al.*, 2003b]
- The WVR technique observes more directions per observation cycle and is thus more sensitive to water vapour distribution heterogeneities, which might explain part of the short-term variations

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
ONSA	-15.71	12.61	-1.56	4.72	14.17	0.25	3.12	0.02	18779

Table 5.6: Statistics of the differences between the ground-based GNSS near real-time tropospheric ZPD estimates and the tropospheric ZPD values derived from the WVR observations for the GNSS site located in Onsala (ONSA), Sweden (period covering the 1st January 2009 to mid-September 2009)

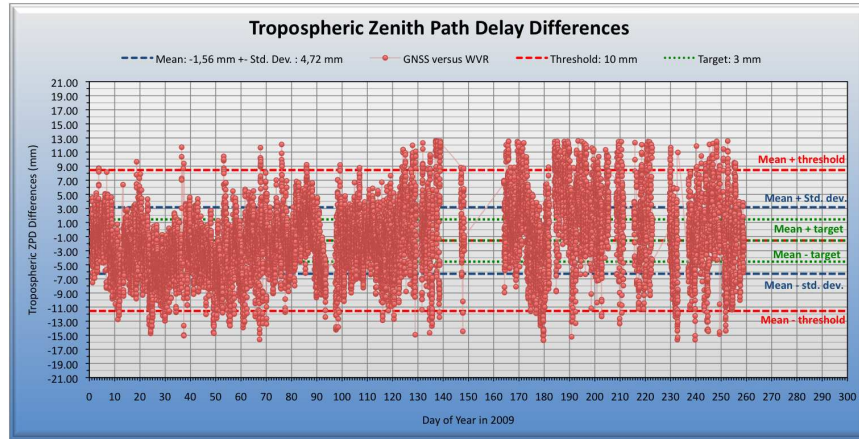


Figure 5.21: Differences between the ground-based GNSS near real-time tropospheric ZPD estimates and the tropospheric ZPD values derived from the WVR observations for the E-GVAP super-site located in Onsala (ONSA), Sweden (period covering the 1st January 2009 to mid-September 2009)

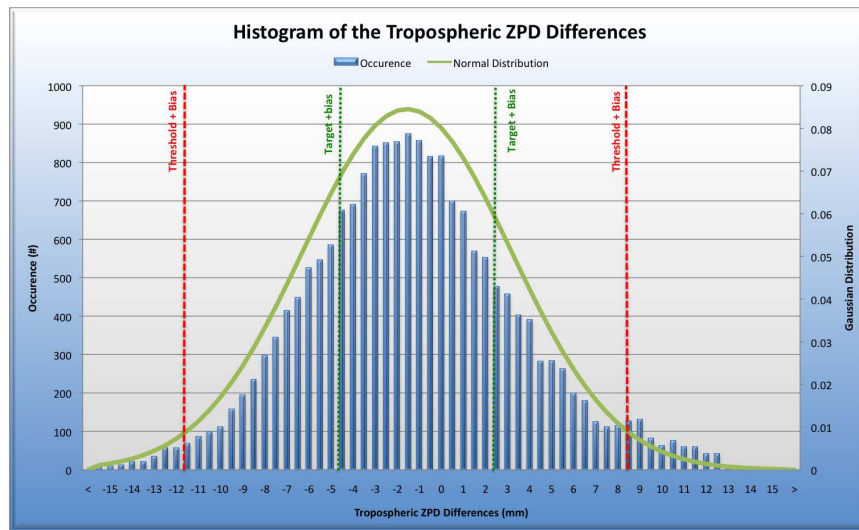


Figure 5.22: Distribution of the differences between the ground-based GNSS near real-time tropospheric ZPD estimates and the tropospheric ZPD values derived from the WVR observations for the E-GVAP super-site located in Onsala (ONSA), Sweden (period covering the 1st January 2009 to mid-September 2009)

5.5.3 Numerical Weather Prediction Models

Background

A third step to assess the accuracy of our NRT tropospheric ZPD estimates was to compare them to tropospheric ZPD values derived from *Numerical Weather Prediction* (NWP) models. The NWP model chosen for that purpose is the *High-Resolution Limited Area Model* (HIRLAM) [Unden *et al.*, 2002]. It is the same model as the one used for validation and monitoring purposes within E-GVAP [E-GVAP Web Site]. The comparison was carried out in two steps:

- First, a *short-term comparison* was carried out over a 7-day period covering the 15th March 2008 to the 21st March 2008 using the observations from all E-GVAP super-sites
- Then, a *long-term comparison* was carried out over a 5-month period covering the 1st January 2009 to the 31st May 2009 using the observations from the 160 GNSS stations routinely processed in the framework of E-GVAP

Short-term Performances

The statistics of the short-term comparison for the 12 E-GVAP super-sites available during that period are summarised in Table 5.7. The comparison reveals a mean bias over all super-sites of 0.80mm and a mean standard deviation of 7.70mm. During that period, the Italian station at Medecina (MEDI) presented a higher bias, which might be attributed to unreliable GNSS observations. High scattering of the daily coordinates residuals with outliers of up to 2cm were observed at that time in the homogenous reprocessing of the EPN [Kenyeris *et al.*, 2009]. The same comparison carried out at different epochs revealed a lower bias for the GNSS station of MEDI with for example a 7-days bias of 1.24mm for the period covering the 20th November 2008 to the 26th November 2008. The standard deviations presented in Table 5.7 are slightly above the precision of the ground-based GNSS NRT tropospheric ZPD estimates (Section 5.4) but remain in all cases within the accuracy threshold specified in the URD. The same analysis was carried out for the other E-GVAP analysis centre solutions (Figure 5.24). The mean biases (averaged over all E-GVAP super-sites) reveal to be analysis-centre specific (because of the different GNSS networks and analysis strategies) but close. Note the

negative bias for GFZ and NGAA, which can be attributed to the *Precise Point Positioning* (PPP) method used by these analysis centres. All other analysis centres use a network approach (double-differences). The standard deviations are very similar (about 7 mm), except for the ASI and the NGAA analysis centres which use another processing software and analysis strategy (Table C.1). The higher values of the standard deviations compared to the values obtained in the precision assessments might be attributed (to a certain extend) to the HIRLAM-derived tropospheric ZPD uncertainties. These results have been reported in [Pottiaux, 2008].

	Number of Observations	Mean (mm)	Std. Dev. (mm)
BRST	49	1.00	5.61
CABW	54	-0.35	7.11
CAGL	54	0.25	7.05
CAMB	54	1.77	7.29
GOPE	54	-1.46	9.78
LDB2	54	1.35	7.54
M0SE	51	3.99	9.01
MEDI	54	5.49	7.92
PAYE	32	0.85	7.28
SMNE	49	-1.64	6.63
YEBE	54	-0.28	8.39
ZIMM	54	-1.32	8.84
Average values over the complete network : 12 GNSS stations			
Bias	613	0.80	7.70
Std. Dev.	613	2.17	1.15
Max. Dev.	613	4.69	-2.09

Table 5.7: Biases and standard deviations of the differences between the ground-based GNSS near real-time tropospheric ZPD estimates and the HIRLAM-derived tropospheric ZPD values (period covering the 15th March 2008 to the 21st March 2008)

Long-term Performances

The comparison proposed here above has the advantage to quickly evidence accuracy problem for a specific station and/or analysis centre and is therefore suitable for a continuous monitoring of the accuracy. Nevertheless, to emphasise systematic biases in the NRT tropospheric ZPD estimates a comparison over a longer period, i.e. a 5-month period, was also carried out.

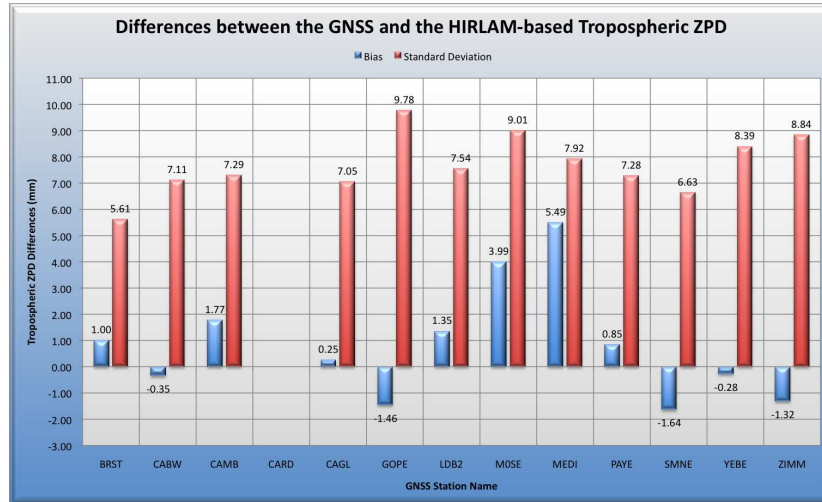


Figure 5.23: Biases and standard deviations of the differences between the ground-based GNSS near real-time tropospheric ZPD estimates and the HIRLAM-derived tropospheric ZPD values for each E-GVAP super-sites (period covering the 15th March 2008 to the 21st March 2008)

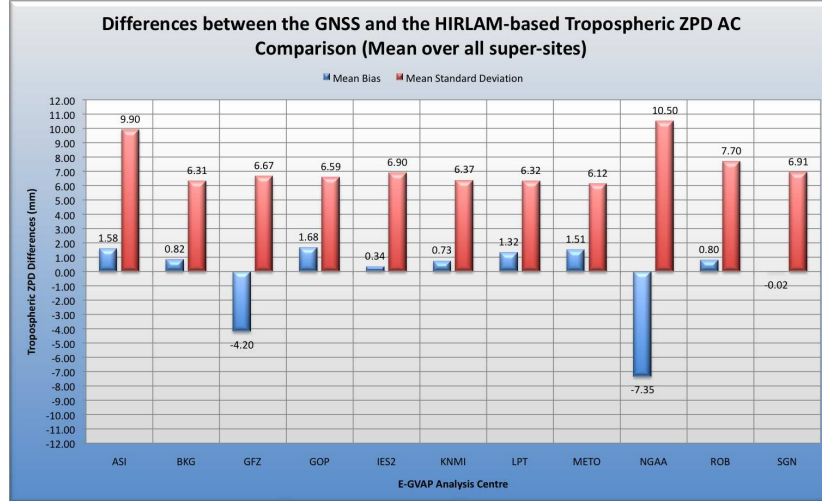


Figure 5.24: Mean Biases and standard deviations (averaged over all E-GVAP super-sites) for each E-GVAP analysis centre solutions (period covering the 15th March 2008 to the 21st March 2008)

A typical example of the agreement between the GNSS-derived and the NWP model derived tropospheric ZPD values for the E-GVAP super-site of Onsala (ONSA), Sweden, is given in Figure 5.25. The tropospheric ZPD differences follow a normal distribution (Figure 5.26) with a mean bias of 3.05 mm and a standard deviation of 6.15 mm. When corrected for the bias, 34.55 % of the tropospheric ZPD values agree within the 3 mm precision level targeted in the URD and 86.65 % of them agree within the threshold level.

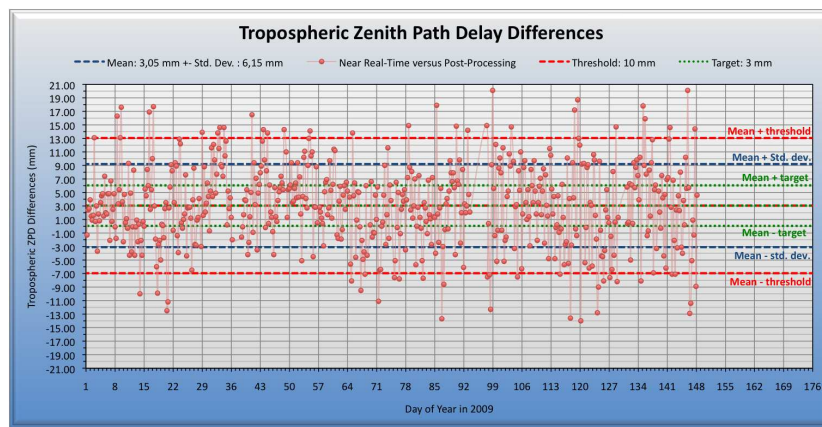


Figure 5.25: Differences between the GNSS-derived and the HIRLAM-derived tropospheric ZPD values for the E-GVAP super-site located in Onsala (ONSA), Sweden (period covering the 1st January 2009 to the 31th May 2009)

The statistics of the comparison for the 14 E-GVAP super-sites are summarised in Table 5.8. Averaged over all super-sites (7020 common observations in total), the tropospheric ZPD differences follow a normal distribution (no significant skewness nor kurtosis) with a mean bias of 2.72 mm and a mean standard deviation of 8.59 mm. The maximal bias is recorded for the E-GVAP super-site located in Medicina (MEDI), Italy, with a value of 6.65 mm. The maximal standard deviation is recorded for another Italian station located in Milan (MILO) with a value of 10.70 mm. Extending the analysis to the complete network (168 GNSS stations), confirmed the aforementioned results: in average (84793 common observations in total), the tropospheric ZPD differences follow a normal distribution with a mean bias of 2.14 mm and a mean standard deviation of 8.46 mm (Table 5.8). No significant skewness nor kurtosis is detected. Site-specific biases between the GNSS-derived and the

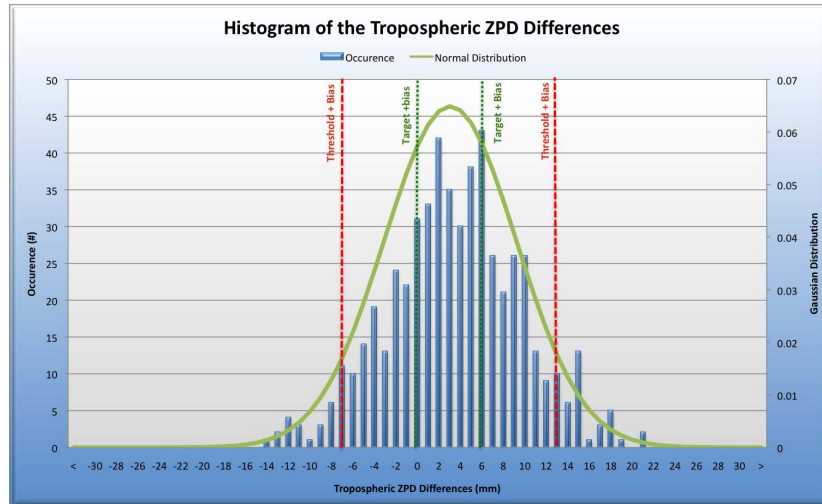


Figure 5.26: Distribution of the differences between the GNSS-derived and the HIRLAM-derived tropospheric ZPD values for the E-GVAP super-site located in Onsala (ONSA), Sweden (period covering the 1st January 2009 to the 31th May 2009)

HIRLAM-derived tropospheric ZPD are seen but remain in all cases within the 10mm level of accuracy (threshold) specified in the URD with a maximal value of 7.57mm (Figure 5.27). The site-specific standard deviations range from 4.03mm up to 14.58mm, 78% of them being within 10mm and 95% being within 12mm. The tropospheric ZPD differences also occasionally emphasise peaks ("outliers") of large amplitudes for all sites, with a maximal value of about 39mm recorded for the GNSS site located in Modane (MODA), France.

	Min (mm)	Max (mm)	Bias (mm)	Std. Dev. (mm)	Max. Dev. (mm)	Skewness	Kurtosis	Slope	Sample Count
BRST	-24.50	28.90	2.10	9.01	26.80	-0.02	3.29	-4.03	527
CABW	-17.00	19.00	0.72	6.71	18.28	-0.15	2.83	-1.94	548
CAGL	-24.50	28.90	3.03	9.31	-27.53	-0.02	2.93	7.81	502
CAMB	-23.30	21.10	1.95	8.49	-25.25	-0.23	2.85	1.05	192
GOPE	-20.60	27.60	3.06	8.30	24.54	-0.20	3.41	-4.89	436
LDB2	-24.60	28.10	1.52	9.04	26.58	0.14	2.97	2.50	544
MOSE	-24.50	33.60	5.17	9.90	-29.67	-0.15	3.08	-2.12	515
MEDI	-20.40	35.80	6.65	10.30	29.15	-0.12	2.87	-3.30	557
MILO	-27.10	33.90	4.11	10.70	-31.21	0.21	3.25	9.04	525
ONSA	-14.00	20.10	3.05	6.15	-17.05	-0.03	3.03	-2.47	547
PAYE	-23.50	24.20	0.34	8.02	23.86	-0.17	3.13	-4.50	551
SMNE	-20.20	25.40	2.77	8.03	-22.97	-0.11	3.35	0.94	529
YEBE	-20.50	24.70	3.97	8.17	-24.47	-0.11	2.97	1.03	488
ZIMM	-24.30	21.60	-0.31	8.17	-23.99	-0.40	3.24	-11.87	559
Average over the E-GVAP Super-sites : 14 GNSS Sites									
Mean	-22.07	26.64	2.72	8.59	-3.78	-0.10	3.09	-0.91	7020
Std. Dev.	3.38	5.12	1.82	1.21	25.10	0.15	0.19	5.12	7020
Max. Dev.	8.07	9.16	3.93	-2.45	32.93	0.31	0.32	-10.96	7020
Average values over the complete network : 168 GNSS Sites (rejected observations: 1.89%)									
Mean	-22.09	26.20	2.14	8.46	0.81	-0.07	3.10	-0.91	84793
Std. Dev.	5.69	6.19	2.15	1.91	25.32	0.14	0.20	8.12	84793
Max. Dev.	-23.81	19.70	-5.65	6.12	-43.84	-0.71	0.73	38.83	84793

Table 5.8: Statistics of the differences between the ground-based GNSS near real-time tropospheric ZPD estimates and the HIRLAM-derived tropospheric ZPD values (period covering the 1st January 2009 to the 31st May 2009)

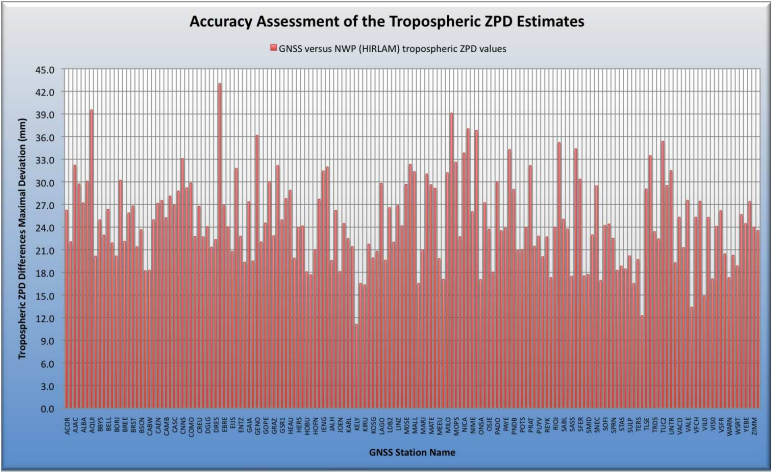


Figure 5.27: Site-specific biases obtained from the comparison between the GNSS-derived and the HIRLAM-derived tropospheric ZPD values (period covering the 1st January 2009 to the 31st May 2009)

5.6 Integration within E-GVAP

In Section 5.4 and Section 5.5, the production of the NRT tropospheric ZPD estimates was validated in terms of *precision* and *accuracy*. To act as an analysis centre and to provide the meteorologists with NRT tropospheric ZPD estimates for operational NWP and nowcasting applications, requirements in terms of *repetition cycle*, *horizontal domain*, *spatial resolution* and *timeliness* must also be reached. Several technical aspects (computing power limitation, internet bandwidth, heavy parallelisation of the code, storage limits, redundancy of the source of information...) presently limit our capability to improve the service provided by our analysis strategy. They act on both the Local Data Centre (Section 4.4.2) and the analysis strategy itself. They limit the size of the network, the number of GNSS stations, the timeliness of our solutions but also the quality of the NRT tropospheric estimates (e.g. because only batches of 1 hour of observations can be processed to comply with the timeliness limit). The keywords for a GNSS-meteorology service are fast, stable and robust. No single point of failure is tolerated and the availability of all GNSS station observations must be ensured. This is achieved by retrieving the data from redundant number of external data centres. The dataflow must also be *very fast*. In this context, the computer power and Internet bandwidth/speed are the principal limitations. A backup server must also be foreseen to take over the service in case the primary server fails. The timeliness is directly linked to the computing power available and is ensured by a heavy parallelisation of the code, an optimisation according to the server specifications and a limitation in the number of GNSS stations included in our processing. A good balance between the *repetition cycle*, the *horizontal domain*, the *spatial resolution*, the *timeliness* and the computer resources must thus be found.

5.6.1 Repetition Cycle

Background

For NWP applications, the *repetition cycle* requirement ranges from a target value of 15 min up to a threshold value of 90 min (Table 4.1). The impact

of changing the repetition cycle on the quality of the NRT tropospheric ZPD estimates was studied in Section 4.4.5 (page 4-36). We have seen that all repetition cycles between 10 min and 60 min could be applied successfully and that proper *relative constraints* on the NRT tropospheric ZPD estimates needed to be set up specifically for the chosen *repetition cycle* of 15 min. Finally, we saw that dephasing phenomena between NRT tropospheric ZPD time series (Figure 4.21 and Figure 4.24) might appear when using different repetition cycles. A low repetition cycle helps to reduce the dephasing phenomena.

Performance

In a network solution, the augmentation of the repetition cycle increases significantly the number of unknown parameters to be estimated and the size of the Normal Equations (NEQ). For an operational service processing a large number of GNSS stations, the 10 min repetition cycle increases the processing time considerably with respect to the 15 min repetition cycle. The current *repetition cycle* applied to all GNSS stations within our network supports thus the 15 min value targeted in the URD, allowing us to process a few GNSS stations more than with the 10 min repetition cycle. The epochs of tropospheric ZPD estimations are equidistant, except for the last estimate which is advanced by 1 min to avoid simultaneous values (from the current and next hour), which cannot (yet) be properly handled by (certain) NWP models.

5.6.2 Horizontal Domain and Spatial Resolution

The Horizontal Domain: a Joint Effort

The *spatial domain* targeted in E-GVAP covers the whole Europe, for which the main source of GNSS observations is the EPN. Over the past years, the EPN was continuously densified (from 154 stations in 2004 to 223 stations in 2009) and today 93.2% of the EPN stations provide also hourly RINEX files. As illustrated in Figure 5.28, thanks to the EPN densification, our operational GNSS network could be progressively extended and densified to improve its *horizontal domain* and its *spatial resolution*. Nevertheless, with a mean inter-station distance of solely 225 km, the EPN does not allow to achieve by itself the targeted spatial resolution in Europe: only 10% of

the stations are separated by less than 100km and solely 2% of them by less than the 30km target. A *spatial resolution* better than 100km can only be reached by focusing on narrower regions and when using regional and national densifications of the EPN. Because of moderate computing power, a single GNSS analysis centre cannot achieve the targeted spatial resolution on a European level: a joint effort of all geodetic agencies participating in E-GVAP is necessary. All E-GVAP analysis centres are thus strongly encouraged to focus and to process GNSS observations from densification networks when available. Moreover, even in narrower regions, the 30km target remains difficult to achieve since regional and national densification networks are designed with typical inter-station distances of about 60km to 100km. But finally, as a joint effort, all E-GVAP analysis centres together provide an observation network having a mean *spatial resolution* of about 59.59km, 26.71% (respectively 94.68%) of the inter-station distances being below the 30km (respectively 100km) requirement. However, certain European areas remain less densely covered.

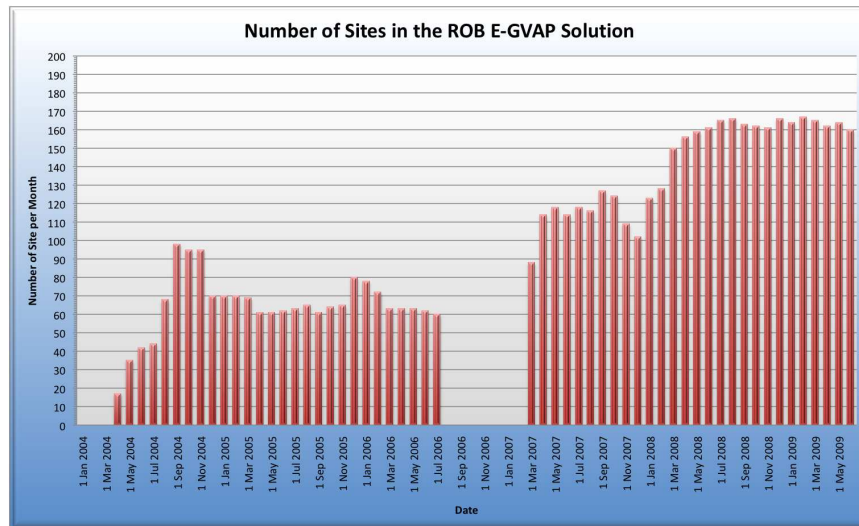


Figure 5.28: Number of sites per month included in the ROB tropospheric ZPD solutions and provided to the meteorologists since April 2004

Performances

As shown in Figure 5.28, at the beginning of the ROB analysis centre activities, our analysis centre included mainly a few EPN and IGS sites. In 2006, a nominal network configuration was reached, including 69 stations. In the current status (Figure 5.4), the majority of the EPN sites providing hourly observations are processed. The remaining sites have usually been excluded because of poor data availability, because of high latency (with respect to the timeliness requirement discussed in the next section), because of poor observation quality or because they are located outside the extended area of interest (Section 4.4.1, Figure 4.3). A few stations outside this region (notably in Greenland and in the Atlantic regions) have been added mainly to improve the solution within the area of interest (border effects, including long baselines... see Section 4.4). In addition, the network was augmented by GNSS sites from national networks to improve the *spatial resolution* within the region of interest. It includes notably stations from the German GREF, the Netherlands AGRS.NL and the French RGP networks. The density of the latter has remarkably increased over the past years (from 60 sites in November 2004 to 187 sites in June 2009) and as of June 2009, 38% of the RGP stations are included in our processing, bringing the total number of stations to about 200 (as on January 2010). It represents about 1/7 of the number of unique sites processed by the 11 E-GVAP analysis centres. Including sites from these densification networks allows to increase to 23% (resp. 5%) the percentage of inter-station distances below 100km (resp. 30km). With a mean spatial resolution of about 180km, our operational GNSS network remains nevertheless by itself not dense enough to detect fine tropospheric structures related to water vapour distribution (precipitation cells, snow fall, thunderstorms...) as we will see later in Chapter 6.

5.6.3 Timeliness

Background

The *timeliness* requirement targets 30min, with a threshold limit of 90min above which the NRT tropospheric ZPD estimates may have a marginal use (Section 4.2). A *timeliness* value of 30min also allows the NRT tropospheric

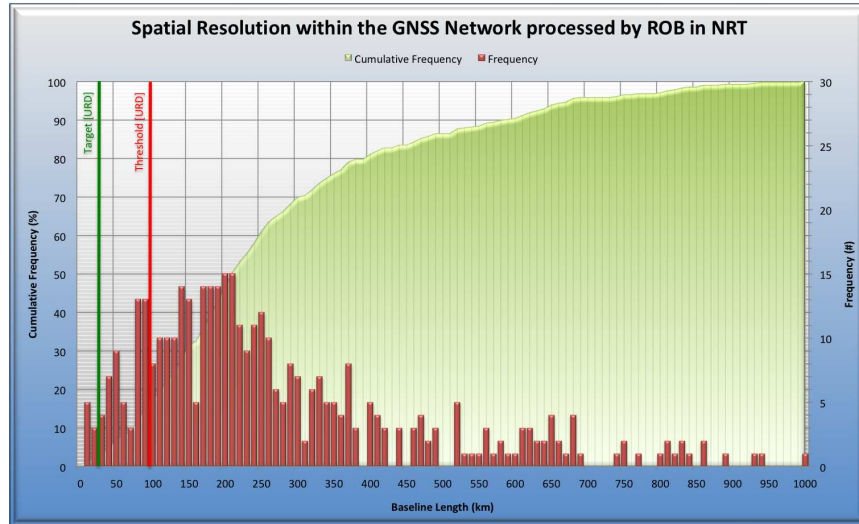


Figure 5.29: Distribution of the inter-station distances (red bars) within the network used for the near real-time tropospheric ZPD estimation and the corresponding cumulative distribution (green area) - (Status: June 2009)

ZPD estimates to be used in nowcasting applications. According to our initial objectives (Chapter 4), we target thus in this work to collect all GNSS data and products, process them and provide the meteorologists with at least 95 % of the NRT tropospheric ZPD estimates within 30 min. This timeliness limit imposes thus a very tight data management and processing schedule on the analysis centres. In this context, the GNSS data availability and the computing power play notably a major role: a good balance between the time spent for all GNSS observations to be available for download, the observation processing time and the timeliness must be found. To reach the targeted timeliness, a monitoring of the GNSS observation latency was first carried out.

Monitoring of the Observation Latency

The last years, along with its densification, a remarkable effort has been done within the EPN to reduce the hourly RINEX file latency. Monthly EPN data latency statistics are published on the EPN Central Bureau web site [EPNCB Web Site]. Today, about 68 % and 85 % of the EPN RINEX files are usable for GNSS-meteorology with a latency below 5 min and 10 min respectively.

Unfortunately, not all GNSS networks perform as good as the EPN. For instance, only about 19 % and 32 % of the RGP RINEX files have a latency below 5 min and 10 min respectively. Increasing the latency to 15 min allows only to download between 50 % and 75 % of the RGP RINEX files depending on the epoch. It is better but still not sufficient for GNSS-meteorology, which requires a stable dataflow and a short RINEX file latency. Monitoring the *data latency* allowed us to optimise the GNSS observation download and to exclude stations of which the latency was always too high (e.g. the availability of the RINEX file of the EPN station located in Hoefn, HOFN, Iceland, at the OLG regional data centre, Figure 5.30, OLG regional data centre) or that showed sporadic problems in the data delivery (e.g. the minimum latency of the RINEX file of the same station, around the day of the year 130 for all data centres, Figure 5.31). It also clearly shows the need for redundant data centres from which the GNSS observations are collected to ensure the minimum latency and the highest possible availability rate. Therefore, the near real-time data flow of the RINEX files is designed for redundancy (Figure 5.32), including for example both the primary and the secondary EPN Regional Data Centres (RDC). The download is split in different batches according to the data centre. Each batch starts at a different epoch chosen in function of the typical latency of the GNSS observation files for this specific data centre. Finally, for a given data centre, the download is parallelised (several files are downloaded at the same time) to reduce the download time at its minimal value.

Performances

Because of the large amount of RINEX files to be downloaded each hour and because of their very different latency scores following the GNSS site and the data centre, the download procedure was sequentialised according to the data centre, then parallelised within the scope of each of the 11 data centres. As illustrated in Figure 5.33, the first download procedure is started at 10 min past the full hour and the last download procedure ends about 7 min later. The analysis strategy can thus be started at 17 min past the full hour, leaving about 12 min for the processing of the GNSS observations using the *Bernese GPS software* and 1 min to transform the output in the COST-716 format [COST-716, 2003] and to upload of the NRT tropospheric ZPD estimates to the E-GVAP data hub. The remaining 30 min are notably dedicated to the

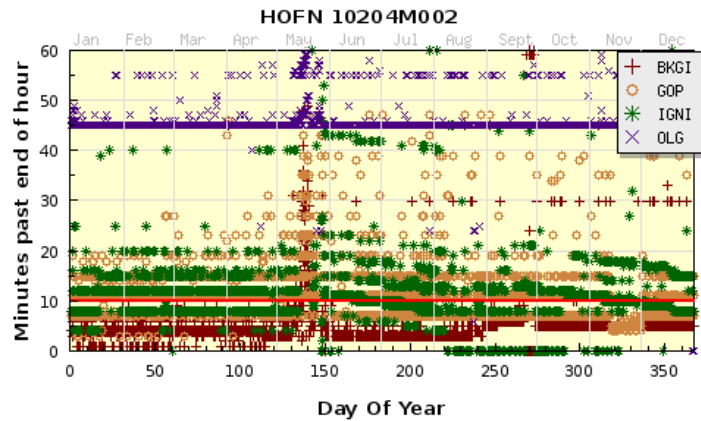


Figure 5.30: Hourly RINEX file latency during 2008 for the EPN station located in Hoefn (HOFN), Iceland for the different IGS and EPN data centres
Source: EPNCB Web Site

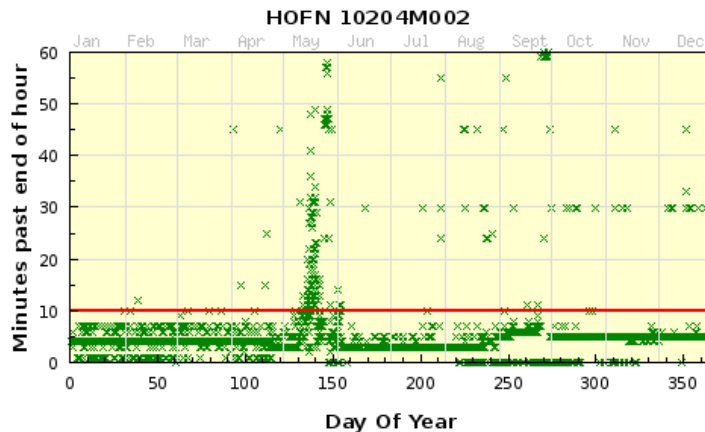


Figure 5.31: Hourly RINEX file minimum latency during 2008 for the EPN station located in Hoefn (HOFN), Iceland for the different IGS and EPN data centres
Source: EPNCB Web Site

quality monitoring of the solution (Section 4.3 pp. 4-10). The timeliness depends strongly on the number of stations included in the processed network, mainly because of the *sequential adjustment in time step* (NEQ stacking, Section 4.4.6), which is not parallelised in the *Bernese GPS software*. All

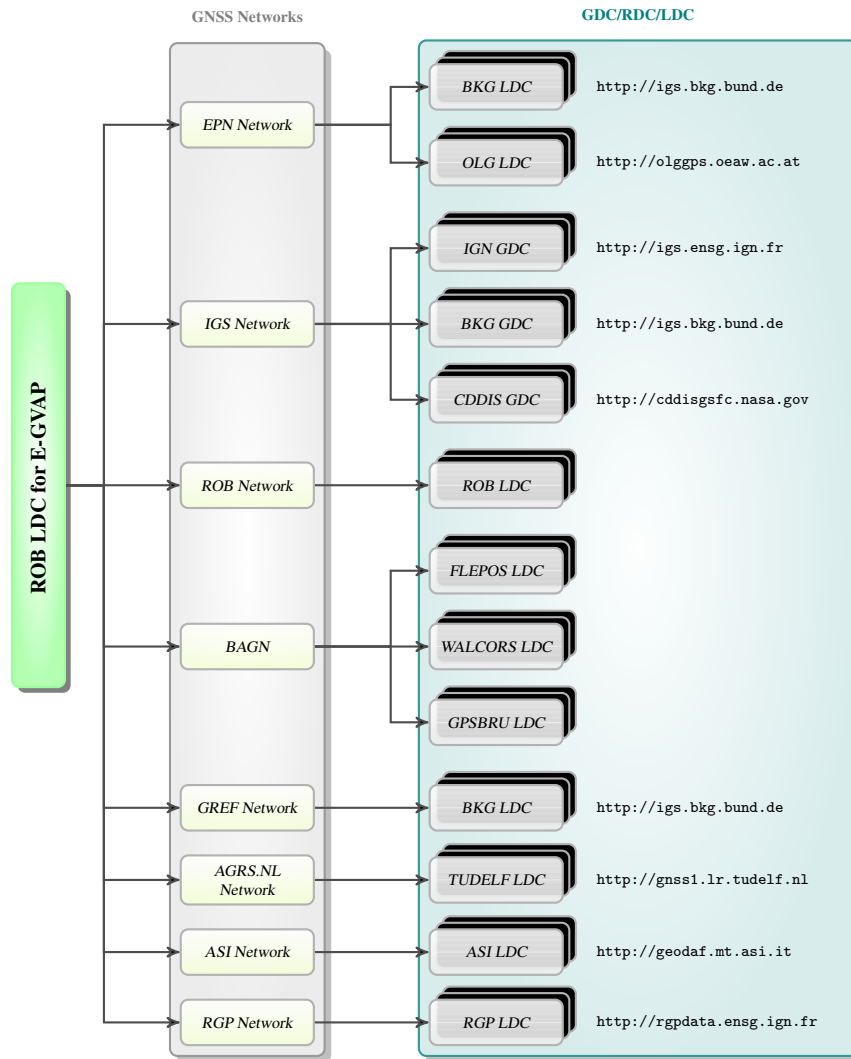


Figure 5.32: Near real-time RINEX dataflow setup in the framework of E-GVAP

other steps have been heavily parallelised and optimised using e.g. a *sequential adjustment in space* (combination of cluster solutions, Section 4.4.4). To meet the 30 min *timeliness* requirement, a good balance has been found between the number of GNSS sites, the extension of the network and the time needed for the processing. The histogram of the timeliness of the NRT tropospheric ZPD

solutions for 1 week is illustrated in Figure 5.34. The red bars represent the percentage of solutions provided in 1-minute bins and the green line represents the cumulative histogram. The E-GVAP timeliness requirement is completely fulfilled with a reliability score above 99 %. Today, more GNSS stations are included in our network to improve the spatial resolution of our solutions. As a consequence, the timeliness of our solutions has slightly grown above the 30 min target. Nonetheless, it remains within 45 min and 80 % of our solutions have still a timeliness within the 30 min target (Status: October 2009).

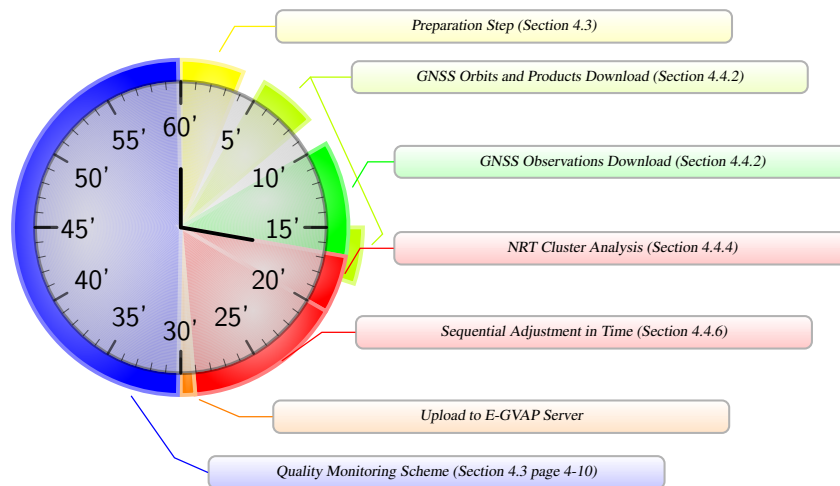


Figure 5.33: Time schedule of the near real-time analysis strategy

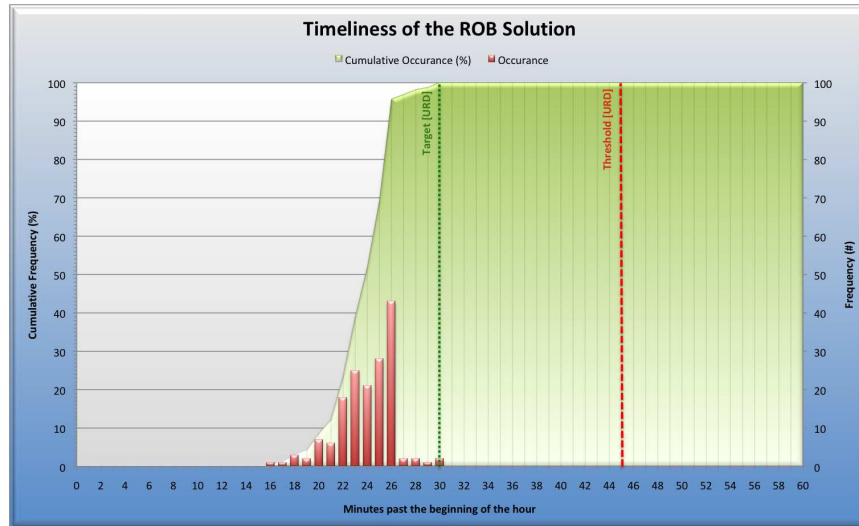


Figure 5.34: Timeliness of the near real-time tropospheric ZPD estimate solutions (red bars) and the corresponding cumulative histogram (green line) (period covering the 24th April 2008 to the 1st May 2008)

5.7 Conclusions and Perspectives

In this chapter, the performances of our 2-step analysis strategy were validated with respect to the latest GNSS-meteorology requirements presented in Section 4.2. All aspects of the URD were addressed using the operational product delivered to our E-GVAP partners, i.e. the *horizontal domain*, the *spatial resolution*, the *repetition cycle* and the *timeliness* with as focal point the assessment of the *precision* and the *accuracy* of the NRT tropospheric ZPD estimates. We demonstrated that our analysis strategy provides NRT tropospheric ZPD estimates for a regional network of GNSS stations covering the whole of Europe that adhere to all GNSS-meteorology requirements except the spatial resolution, which must be reached as a joint effort of all the geodetic partners acting within E-GVAP. This network contains at the moment about 200 GNSS stations, most of them being EPN and IGS sites. The NRT tropospheric ZPD estimate performances are summarised in Table 5.9. Particularly, the strategy developed proved to deliver NRT

tropospheric ZPD estimates with a precision of about 5 mm and an accuracy slightly higher. We also showed that space remains for improvements. An important perspective is to continue to improve the precision and accuracy achieved in the determination of the NRT tropospheric ZPD estimates. In this context, Elmar Brockmann from swisstopo pointed out that resolving the ambiguities in near real-time is essential and that the agreement with the post-processed solutions will be thereby 1.5 better [Brockmann, 2008]. Techniques for ambiguity resolution using short session GNSS observations should be investigated and the corresponding necessary computing power evaluated. Also, improvements in the automatic detection of outliers, misbehaving stations and satellites clearly need to be investigated to improve the precision and accuracy of our solutions. A second important perspective focuses on the horizontal domain and the spatial resolution. Adding new E-GVAP super-sites for monitoring purposes, notably the EKOFISK oilrig GNSS sites offshore Norway, is presently under investigation within E-GVAP. As their GNSS observations will become freely available to the E-GVAP community, these new super-sites will be included in our analysis. As we will see in the next chapter, including more GNSS sites from regional and national densification networks is necessary to improve our contribution to GNSS-meteorology by accessing small-scale tropospheric structures. Including new GNSS sites from the French RGP (Figure 2.11), the Netherlands AGRL.NL, the German SAPOS, the U.K. OS net (Figure 2.13) and more particularly from the Belgian AGN (Figure 2.10) should thus be investigated in the future. But in this context, using a ionosphere-free double-difference carrier-phase observations in a network approach seemed to have reached its limits in terms of processing time and computing power requirements. To keep our timeliness, or even more to decrease it for nowcasting applications, while increasing the number of stations processed will require more computing power but also a deep structural adaptation of the analysis strategy such as the switch to a *Precise Point Positioning* (PPP) approach. Nonetheless, a PPP approach also has its own limitations, which will express mainly in terms of reduced precision and accuracy. This is notably due to using IGU clocks of poor quality [Dousa, 2008a,b]. Some E-GVAP members recommended to the IGS workshop held in Miami 2008 to increase the frequency update of the IGS orbit and clock products. But it wasn't accepted yet, since it

represents a heavy load on the IGS analysis centres. A possible work-around would be to produce our own orbits and clocks, at least until the IGS produces reliable high-frequency ultra-rapid clocks. Finally, a complete automation of the quality monitoring scheme (Section 4.3) to ensure a stable and reliable service of quality to the meteorologists would be desirable. In this context, the EUREF-EUMETNET collaboration (Appendix D) provides today the necessary meteorological information to assess continuously the accuracy performances of our product. Moreover, the associated meteorological database will be enriched in the future with other observation techniques such as WVR data that will complement the current radiosonde observations offer. The Memorandum of Understanding (MoU) will thus permit soon a continuous and automatic monitoring of the accuracy performance by the geodesist using at least three techniques: radiosonde observations, water vapour radiometers and numerical weather prediction models. The long-term availability will moreover allow us to detect bias, trends and signals in the NRT tropospheric ZPD time series, for studying the long-term interaction with the reference frame realisation and the potential use of the tropospheric ZPD estimates in climate applications.

5.7. Conclusions and Perspectives

Sensitivity test	Targeted value			Threshold value		
	Criterion	Score		Criterion	Score	
Horizontal Domain	Europe to Regional	100 %	▲	Europe to Regional	100 %	▲
Spatial Resolution	< 30 km	5 %	▼	< 100 km	23 %	▼
Repetition Cycle	15 min	100 %	▲	60 min	100 %	▲
Timeliness	< 30 min	80 %	▼	< 90 min	100 %	▲
Precision	3 mm	~ 2 %	▼	10 mm	~ 99.9 %	▲
Absolute accuracy	3 mm	~ 85 %	▼	10 mm	~ 99.9 %	▲

Percentage of tropospheric ZPD estimates satisfying the requirement tests

▲ : above 90 %, ▼ : between 80 % and 89 %, ► : between 60 % and 79 %, ▲ : between 50 % and 59 %, ▼ : below 49 %

(a) Summary of the E-GVAP requirement validations

Precision tests	Bias (mm)	Std. dev. (mm)	Range (mm)	Max. dev. (mm)	Target value scores			Threshold value scores		
					A	P	O	A	P	O
NRT vs. POST (*)	0.59 ± 0.86 mm	4.39 ± 0.67 mm	26.15 mm	0.24 ± 13.24 mm	~ 100 % ▲	~ 2.0 % ▼	~ 100 % ▲	~ 100 % ▲	~ 100 % ▲	~ 100 % ▼
NRT vs. EUREF (*)	0.36 ± 0.99 mm	4.49 ± 0.74 mm	26.54 mm	1.47 ± 13.47 mm	~ 100 % ▲	~ 2.2 % ▼	~ 100 % ▲	~ 100 % ▲	~ 100 % ▲	~ 100 % ▼
NRT vs. E-GVAP (*)	-0.21 ± 1.47 mm	4.89 ± 0.84 mm	29.08 mm	1.30 ± 14.79 mm	~ 95.6 % ▲	~ 1.2 % ▼	~ 100 % ▲	~ 100 % ▲	~ 100 % ▲	~ 100 % ▼

Percentage of tropospheric ZPD estimates satisfying the assessment tests

▲ : above 90 %, ▼ : between 80 % and 89 %, ► : between 60 % and 79 %, ▲ : between 50 % and 59 %, ▼ : below 49 %

(b) Summary of the precision assessments

Accuracy tests	Bias (mm)	Std. dev. (mm)	Range (mm)	Max. dev. (mm)	Target value scores			Threshold value scores		
					A	P	O	A	P	O
NRT vs. RAOB (*)	2.51 ± 3.36 mm	9.72 ± 1.50 mm	-	-	~ 50 % ▲	~ 0 % ▼	~ 98.7 % ▲	~ 57.4 % ▲	~ 57.4 % ▲	~ 57.4 % ▼
NRT vs. WVR	-1.56 mm	4.72 mm	28.32 mm	14.17 mm	~ 100 % ▲	~ 0 % ▼	~ 100 % ▲	~ 100 % ▲	~ 100 % ▲	~ 100 % ▼
NRT vs. HIRLAM (*) (**)	2.14 ± 2.15 mm	8.46 ± 1.91 mm	48.29 mm	0.81 ± 25.32 mm	~ 64 % ►	~ 0 % ▼	~ 100 % ▲	~ 100 % ▲	~ 79 % ►	~ 79 % ▼

Percentage of tropospheric ZPD estimates satisfying the assessment tests

▲ : above 90 %, ▼ : between 80 % and 89 %, ► : between 60 % and 79 %, ▲ : between 50 % and 59 %, ▼ : below 49 %

(c) Summary of the accuracy assessments

Table 5.9: Summary of the validation and performance evaluation
(*) Averaged values over the campaign network, (**) Long-term comparisons

*The trouble with weather forecasting is that
it's right too often for us to ignore it and
wrong too often for us to rely on it.*

Patrick Young

6

GNSS Densification Networks and Meteorological Applications: Accessing Fine Mesoscale Tropospheric Structures For Nowcasting Applications

Summary

This sixth chapter investigates the potential benefits brought by processing observations from GNSS densification networks to access fine mesoscale tropospheric structures for nowcasting applications. Therefore, the GNSS and meteorological observations recorded during a severe multi-cellular thunderstorm event that occurred in Belgium on the 29th June 2005 were analysed.

6.1 Introduction

For a long time, radiosonde observations remained the major operational source of upper-air water vapour information used for weather forecasting.

This technique is expensive and does not offer sufficient resolution for weather forecasting, neither in space (Figure D.3) nor in time (Section E.1). Because of its temporal and spatial resolution, the European radiosonde network (Figure D.3) cannot provide information about atmospheric structures, whose scales are smaller than the synoptic scale (Section F.1.1). GNSS is a good candidate to replace or complement the radiosonde observations by providing valuable information on the tropospheric water vapour field. Indeed, GNSS proved to deliver high-quality water vapour information (Section 5.4 and Section 5.5) with a much higher resolution, in space and in time, while keeping low-cost operation. As a consequence, the high-resolution water vapour measurements provided by GNSS are likely to have a large impact on forecasting rapidly developing systems such as thunderstorms [Mazany *et al.*, 2002; de Haan, 2002; de Haan *et al.*, 2004; de Haan, 2006]. In addition, GNSS, contrary to some meteorological sources of information like satellite imagery, is an all-weather observing system and does not depend for example on the cloud coverage. In this chapter, the potential benefits of using observations from GNSS densification networks to access fine mesoscale tropospheric structures (meso-beta and meso-gamma scales, see Section F.1.1) are investigated, more particularly during meteorological events such as heavy rainfalls, thunderstorms or severe snowfalls. We demonstrate that using GNSS observations from European regional networks allows to detect only large mesoscale patterns in the tropospheric refractivity field and that the use of GNSS densification networks is mandatory to observe the fine tropospheric structures. To prove this assertion, the meteorological and GNSS observations gathered during a day of complex weather conditions were analysed: a severe multi-cellular storm that occurred in Belgium on the 29th June 2005.

6.2 GNSS Networks and Analysis Methodology

Mesoscale Structures and Network Considerations

As mentioned in the preface, the troposphere is the seat of all *hydrometeors* (such as rain, hail and snow) and meteorological phenomena. The associated tropospheric refractivity field is thus made up of structures evolving at various temporal and spatial scales. Variations in the hydrostatic refractivity field are

directly related to variations in the total ground pressure field (Equation 3.6). These pressure variations are mainly linked with synoptic and large mesoscale phenomena such as weather fronts and cyclogenesis and therefore, evolve slowly in time (over several hours) and stretch over large spatial scale (typically several hundreds of kilometres, Section 3.2.4). Because of their spatial and temporal characteristics, such structures and the related phenomena would have to be detected using typical GNSS-meteorology regional networks with inter-station distances down to about 100km. The latter distance was thus fixed as threshold value for the spatial resolution in the *User Requirements Document* (URD) [Barlag *et al.*, 2004]. If the hydrostatic part accounts for about 90% of the total refractivity field (Section 3.2.4), the wet component presents much 'faster' variations in both the space and the time domain. In addition, the amplitude of its variations are about two to three times those in the hydrostatic refractivity field (Figure 3.2, Figure 3.3). Structures in the wet refractivity field are associated with the partial pressure of water vapour field (Equation 3.6). They are thus tightly linked with finer mesoscale meteorological phenomena such as convection, rain, hail or thunderstorms, which evolve much quicker, affect narrower regions (from a few km up to 100km) and which might therefore hardly be detected with such regional GNSS networks. To test this later assertion, two sets of GNSS stations were defined: a European regional core network and its Belgian densification.

The European Regional Core Network

The *European regional core network* consists of about 85 EPN stations, complemented by the 7 GNSS permanent stations operated by the *Royal Observatory of Belgium* (ROB). This network extends over a large area in Europe (from 27° N to 70° N in latitude and from 22° W to 30° E in longitude), satisfying the horizontal domain requirement. It also includes several long baselines (over 1000km) to ensure good estimates of the absolute tropospheric ZPD (Section 4.4.1). The GNSS stations from the *core network* available on the 29th June 2005 are illustrated in Figure 6.1. Within this *European regional core network*, the ROB GNSS stations (blue dots) are separated by about 60km to 80km, which is better than the spatial resolution threshold specified in the URD. According to the remarks made above, this

network is expected to provide sufficient information on the medium and large mesoscale tropospheric structures evolving above Belgium.

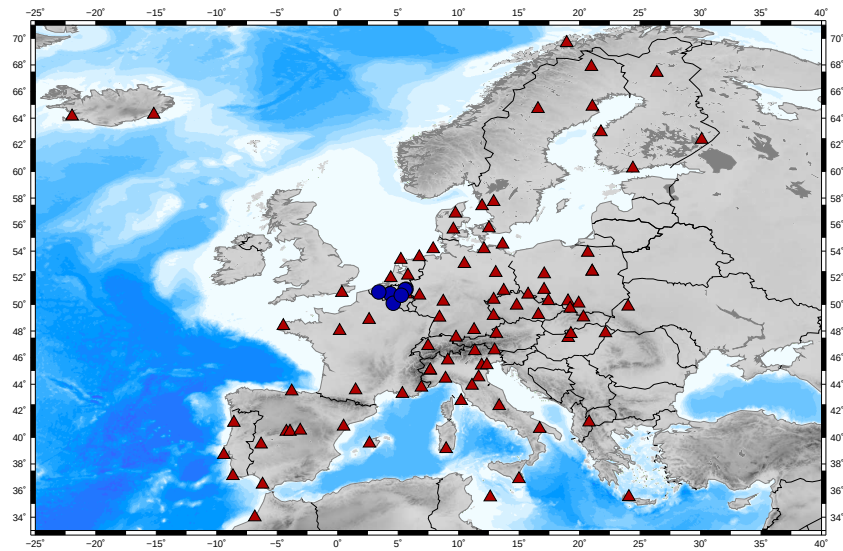


Figure 6.1: GNSS stations of the European regional core network available on the 29th June 2005 (blue dots: the ROB permanent stations - red triangles: the other EPN permanent stations). A few stations, notably in Greenland and in the Atlantic regions, are located outside the map region

The Belgian Active Geodetic Network

In addition to the 7 GNSS stations operated by ROB, 63 other permanent stations from the *Belgian Active Geodetic Network* (BAGN) operated by the 3 regions exist in Belgium (Section 2.7.1). In total, 70 permanent GNSS stations cover the country uniformly with typical inter-station distances of 25km in the north of Belgium (Flanders) and 35km in the south of Belgium (Wallonia). Some sites are even only a few kilometres apart from each other such as those of Saint-Gilles (GILL) and Brussels (BRUS), which are separated by only 4km. The European regional core network was thus densified using the 63 GNSS stations from the Belgian AGN. Hereafter, the network composed by the 63 permanent AGN stations and the 7 ROB GNSS stations is referred to as the *Belgian densification network*. The GNSS stations

from the Belgian densification network available on the 29th June 2005 are illustrated in Figure 6.2.

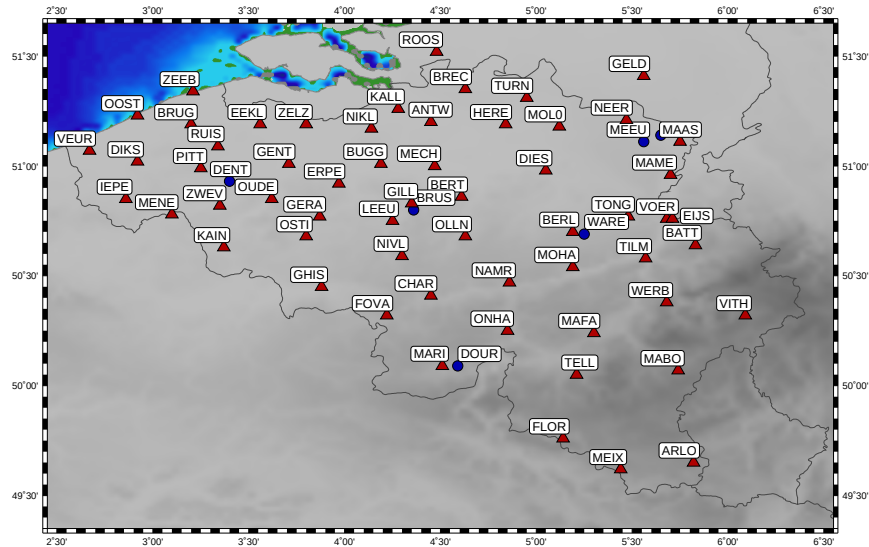


Figure 6.2: GNSS stations of the Belgian densification network available on the 29th June 2005 (blue dots: the ROB permanent stations - red triangles: the Belgian Active Geodetic Network stations)

Analysis Methodology

The GNSS observations were processed using the 2-step analysis strategy developed in Chapter 4. This strategy satisfies all GNSS-meteorology requirements for *Numerical Weather Prediction* (NWP) and *nowcasting* applications, but the spatial resolution. The spatial resolution limitation, emphasised in Section 5.6.2, only concerns the European coverage. When focusing on Belgium, the ROB permanent network already overcomes this limitation. Processing GNSS observations from the Belgian AGN achieves the spatial resolution targeted in the URD. The tropospheric ZPD estimated by the post-processing analysis strategy were used to fully evaluate the potential benefits brought by the Belgian AGN densification. The IGS final orbits (Section 2.7.2) were used, kept fixed, and bad satellites or stations were excluded. The IGS products corresponding to that epoch were computed using the IGS00 reference frame realisation and relative antenna models

(Section 4.4.7). To ensure consistency, it was necessary to use also the IGS00 reference frame realisation and the relative antenna calibration models to process our GNSS observations. On the 29th June 2005, only a few GLONASS satellites were providing observations and the quality of the GLONASS IGS orbit products was relatively poor at that time. Only GPS observations were thus processed. Precise coordinates were determined for all sites based on a cumulative solution of the last 31 days preceding the 29th June 2005 (Section 4.3). The cumulative solution was then used to fix the site coordinates in the back-substitution procedure (Section 4.4.3) while estimating the tropospheric ZPD parameters. The main processing options used are summarised in Table 6.1. The benefits of using GNSS densification networks for meteorological applications, more particularly *nowcasting* applications, was investigated based on the exploitation of the Belgian AGN on top of the European regional core network. The GNSS observation analysis was thus carried out two times:

- The first time, the analysis was carried out using the GNSS observations from the European regional core network solely (i.e. the EPN, the IGS and the ROB GNSS stations)
- The second time, the GNSS observations from the Belgian AGN were added on top of those of the European regional core network

Processing options	Value
Processing type	Post-processing
Software	<i>Bernese GPS software</i>
GNSS observables	
Observation system	GPS observations only
Number of GNSS stations	150 stations (90 EPN/IGS stations + 70 ROB/BAGN stations)
Observation window length	24 hours
Observation cut-off angle	3° (10° while estimating the tropospheric ZPD parameters)
Observable type	Ionosphere-free carrier-phase double-differences
Baseline strategy	OBS-MAX
Other model	
Reference frame realisation	IGS00
Antenna models	Relative models
Orbit and Earth orientation parameters	IGS final products (GPS only, IGS00 reference frame, relative antenna models)
Ocean tide loading model	GOT00.2 model
Ionospheric path delay functional model	
Regional ionosphere model	Yes
Stochastic ionosphere model	Yes
Ambiguity resolution	Quasi Ionospheric-Free (QIF) method
Tropospheric path delay functional model	
Coordinate back-substitution	Fixed to the 31-day cumulative solution
A priori tropospheric model	Saastamoinen-based and dry NMF
Tropospheric correction model	Estimated and wet NMF
Parameter resolution	1 parameter every 30 minutes
Absolute constraints	No
Relative constraints	2mm
Tropospheric gradient parameter resolution	1 parameter every 24 hours
Tropospheric gradient parameter constraints	No
Sequential adjustment	
In space domain	Yes
In time domain	No

Table 6.1: Main analysis options applied to process the GNSS observations

6.3 The 29th June 2005 Multi-Cellular Thunderstorm

6.3.1 Meteorological Observations and Infrastructure

To understand the ongoing meteorological phenomena and to analyse the water vapour information obtained from GNSS observations, meteorological observations from several techniques were gathered. It includes notably radiosonde observations, synoptic observations, lightning strike records, Meteosat and weather radar images. Details on these techniques can be found in Appendix D, Appendix E and Appendix F.

6.3.2 General Weather Conditions

With the arrival of continental air masses associated with an anticyclone centred over France, Belgium experienced a heat-wave between the 17th June 2005 and the 28th June 2005 with daily maximal temperatures above 25°C and 4 scorching days with maxima above 30°C. On the 28th June 2005, the isobaric and frontal analysis chart at 18:00 UTC showed a typical cyclone in its early stage of occlusion located offshore of south-west U.K. (Figure 6.3a). Pressure values of 1007hPa were observed in the centre of the low-pressure system. The weather conditions observed in the next hours can be split into 3 main phases:

Phase I

The advection of unstable maritime air from south-west supported the development of thunderstorms on the incoming pre-frontal convergence line followed by clear sky and a sunny forenoon

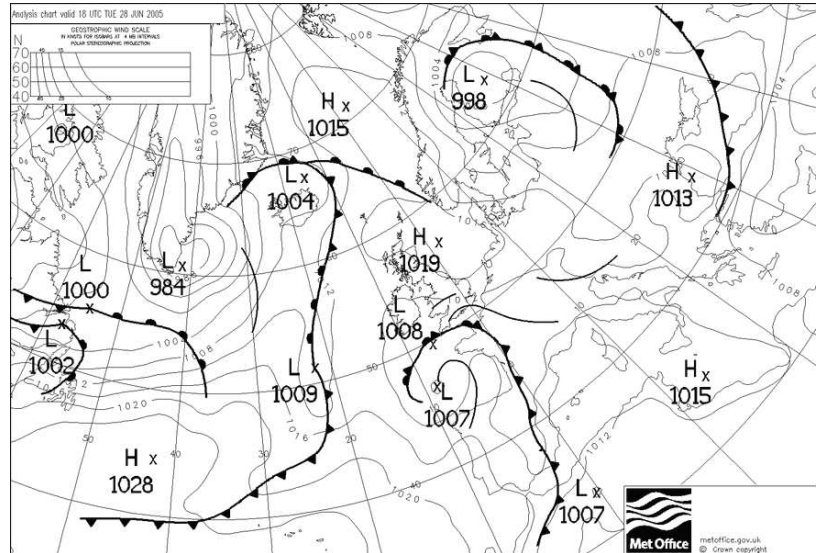
Phase II

The development of a severe multi-cellular thunderstorm during the afternoon

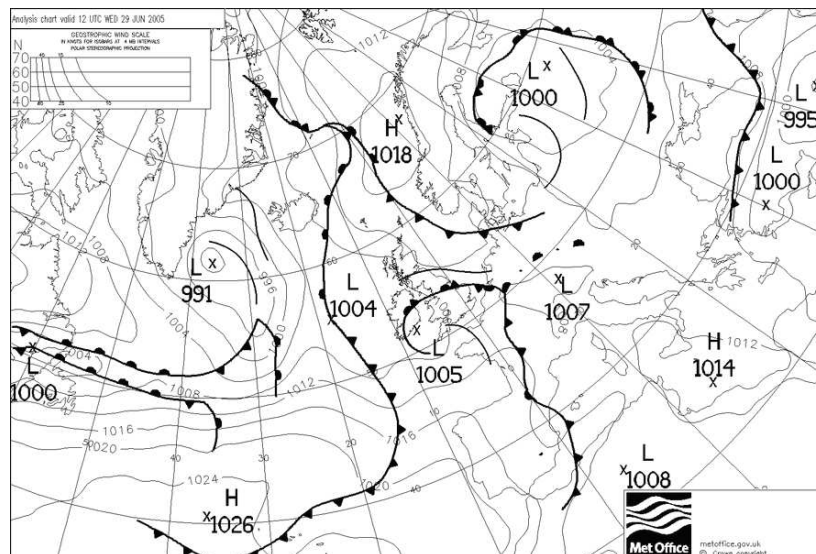
Phase III

The end of the thunderstorm period, leaving place for a large precipitation band

6.3. The 29th June 2005 Multi-Cellular Thunderstorm



(a) Isobaric and frontal analysis chart of the 28th June 2005 at 18:00 UTC



(b) Isobaric and frontal analysis chart of the 29th June 2005 at 12:00 UTC

Figure 6.3: General weather conditions between the 28th June 2005 and the 29th June 2005 - © Crown copyright 2005, the Met. Office

6.4 Accessing Fine Mesoscale Tropospheric Structures

6.4.1 Tropospheric ZPD Reduction

Nowcasters are primarily interested in a (qualitative) short-term prediction of the spatial and temporal water vapour distribution (Section 4.2). To better describe the water vapour behaviour and the associated tropospheric structures, the tropospheric ZPD estimates were thus first converted to *Integrated Water Vapour* (IWV) values. The IWV is the integral of the water vapour density along the vertical column of the neutral atmosphere (Section E.2.3). The IWV corresponds roughly to the tropospheric ZWD divided by 6.5 (Section E.2.4). The conversion of the tropospheric ZPD estimates to IWV values removed the hydrostatic part of the tropospheric path delay and, thereby, the associated orographic signal. The conversion was carried out according to the data reduction scheme illustrated in Figure 6.4 and used synoptic observations (Section D.3) provided by the *Koninklijk Nederlands Meteorologisch Instituut* (KNMI). The *Mean Sea Level* (MSL) tropospheric ZHD field over Belgium reconstructed using the synoptic observations of the 29th June 2005 at 12:00 UTC is illustrated in Figure 6.5. Despite the severity of the evolving meteorological phenomena, the spatial gradients in the hydrostatic tropospheric path delay remained quite low (maximum a few millimetres through the whole country).

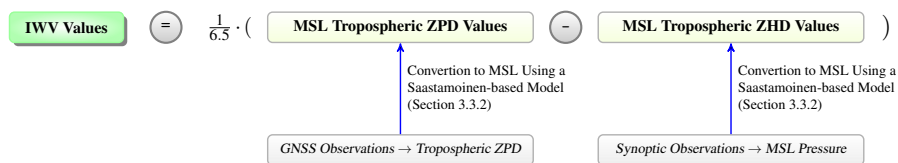


Figure 6.4: Data reduction scheme applied to transform the tropospheric ZPD estimates to IWV values

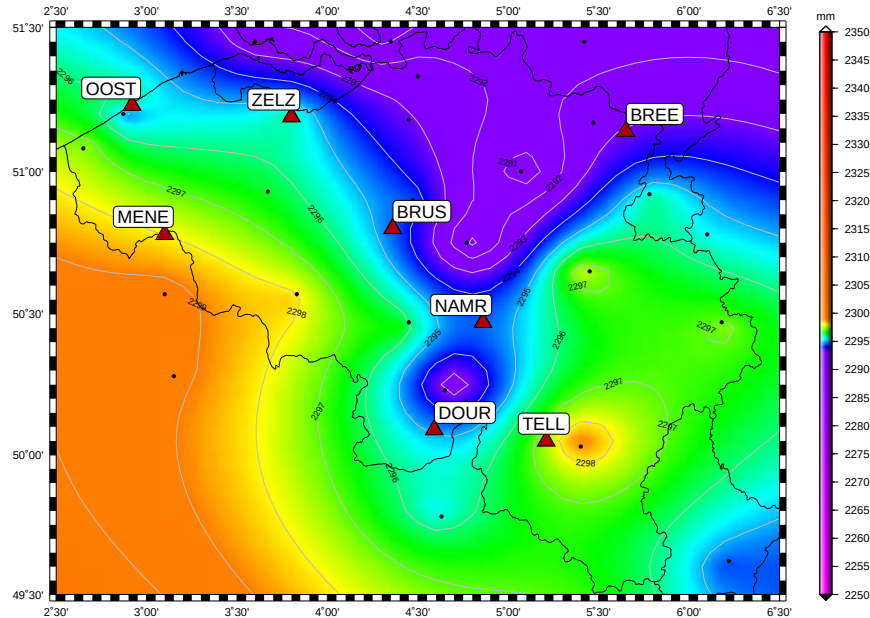


Figure 6.5: Mean sea level tropospheric ZHD field over Belgium reconstructed from synoptic observations using a Saastamoinen-based a priori model.
Reference epoch: 29th June 2005 at 12:00 UTC

6.4.2 Time Series Analysis

The IWV time series for a few Belgian GNSS stations are illustrated in Figure 6.6 along with the rainfall rate recorded by the closest meteorological station. The station locations are shown in Figure 6.5. The number of lightning strikes recorded with the *Surveillance et Alerte Foudre par Interférométrie Radioélectrique* (SAFIR) system [Wessels, 1998; Holleman, 2003] in the last 30 min in a neighborhood of 20 km around the station are also represented.

Phase I: The Two First Thundery Bursts

During the afternoon and the evening of the 28th June 2005, the IWV shows the increase of the water vapour content associated with the advection of unstable maritime air from the south-west, which supported the development of thunderstorms on the incoming pre-frontal convergence line. This is

particularly clear in the IWV time series of Bree (BREE), with a sharp rise of about 10 mm of IWV in solely 3 hours during the evening of the 28th June 2005. From 21:00 UTC on, lightning and thunders were recorded in the south of the country but no rain was observed. Then, *two successive thundery bursts of rain* happened:

- ✎ The first one around 22:15 UTC brought up to 14 mm of rain in half an hour.
- ✎ The second burst, lighter, did occur a couple of hours later (around midnight) and brought up to 5 mm of rain.

No direct correlation with the amount of precipitation could be emphasised. However, all time series show an increase of IWV during the afternoon of the 28th June 2005. In the next hours, the cold front associated with this cyclone moved up from south-west of France towards Belgium and the Netherlands, and the thundery period was followed by clear sky and a sunny forenoon. On the 29th June 2005, all time series show high IWV values, with a mean around 33.57 mm. A maximal IWV value of 38.53 mm is recorded in the GNSS station located in Namur (NAMR), south-east of Brussels. Such IWV values are unusually high compared to the typical water vapour content generally observed in Belgium (Figure 3.3).

Phase II: The Afternoon Multi-Cellular Thunderstorm

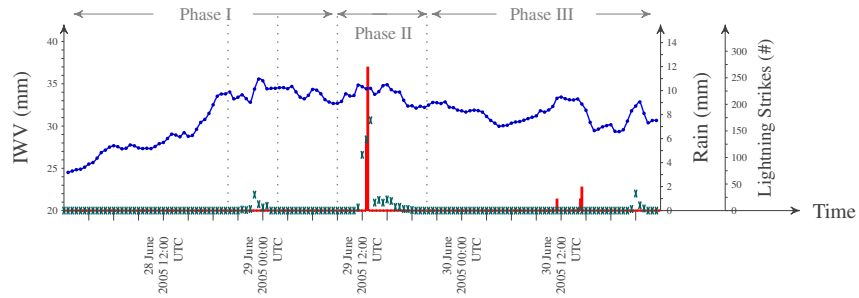
During the cyclogenesis, the occlusion of the cold front moved towards Belgium and a new warm front appeared, starting from the occlusion point in Belgium (Figure 6.3b). At that time, the country became the seat of highly unstable air masses bringing a lot of precipitation. At 12:00 UTC most of Belgium was still cloud-free. During the next hours, a huge convective cell, visible in the Meteosat composite images (see Section F.2.5 and Figure F.3 for more details), developed rapidly over Belgium. At 16:00 UTC, the country was completely covered by a convective cloud with frozen top. Clouds with frozen tops are often in tight relationship with precipitation cells. The instability was checked using the *Boyden Index* (BI) derived from radiosonde observations collected on the 29th June 2005 around Belgium (see Section F.2.4 for details). The higher the value of BI, the greater the risk of thunderstorms: values exceeding 96 indicate severe thunderstorm activity [Schmeits *et al.*, 2005]. All

of them indicated a risk of severe thunderstorms with values between 96.4 and 97.8 (Table F.2). Both, the BI values and the Meteosat images give insights on a probable thunderstorm but no real 'picture' on the evolving meteorological phenomena. This instability is also visible in the IWV time series: during the 29th June 2005, the IWV time series varied over 11 mm and emphasised quick variations of significant amplitudes (up to 3 mm between successive estimations, i.e. 30 min).

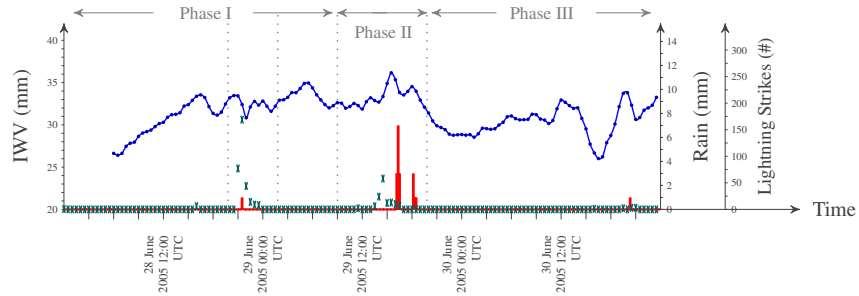
Several severe thundery outbreaks followed between 12:00 UTC and 17:00 UTC, bringing torrential precipitations, strong gusts of wind (about 110 km/h) and bulky hail in numerous parts of the country. A maximum temperature of 31 °C and top rainfall accumulation of 61 mm were recorded in Gosselies, Belgium. This is nearly the 67.4 mm monthly rainfall accumulation given by the seasonal average for the month of June for the country. The strongest thundery outbreaks occurred in the centre of the country. A drop of about 10 °C linked to a fall of 2-3 cm diameter hail was reported in Uccle, Belgium. Similar hail fall was recorded in Aalst (about 20 km north-west of Brussels). A large number of lightning impacts has been observed in Belgium on that day. During only the night between the 28th June 2005 and the 29th June 2005, 60.000 cloud-to-cloud lightning and 18.000 ground impacts have been recorded by the SAFIR system.

Phase III: The Large Precipitation Band

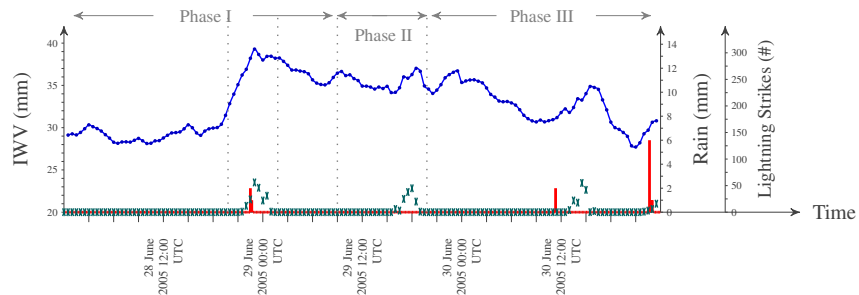
At the end of the afternoon (starting from 16:15 UTC), the thundery cells leaved room to a large precipitation band covering almost all the country. Rain slowly moved out Belgium by the northeast during the evening and remained until midnight. Rain eased off past midnight with the frontal zone moving over the Netherlands.



(a) GNSS station located in Brussels

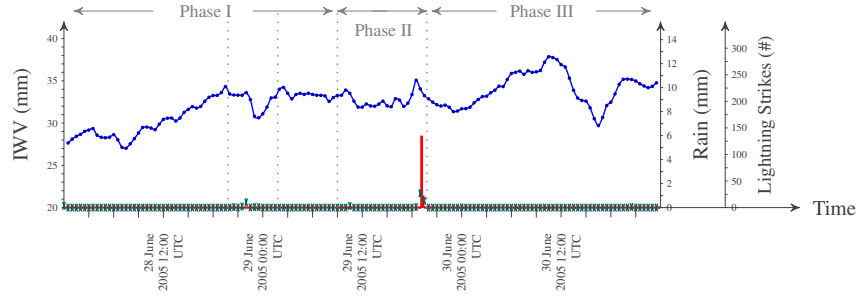


(b) GNSS station located in Dourbes

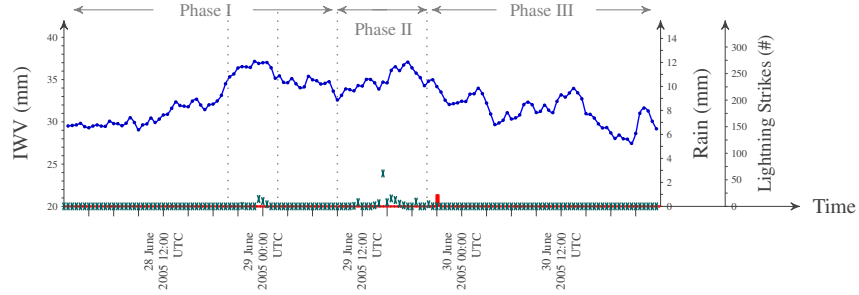


(c) GNSS station located in Bree

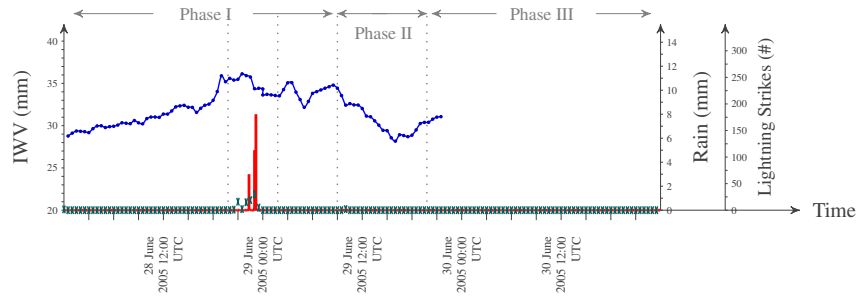
Figure 6.6: IWV time series computed from GNSS observations at several Belgian stations between the 28th June 2005 and the 30th June 2005 (blue curve) along with the precipitation rate recorded by the nearby meteorological station (red bars) and the number of lightning strikes (green crosses) observed in the last 30 min



(d) GNSS station located in Menen

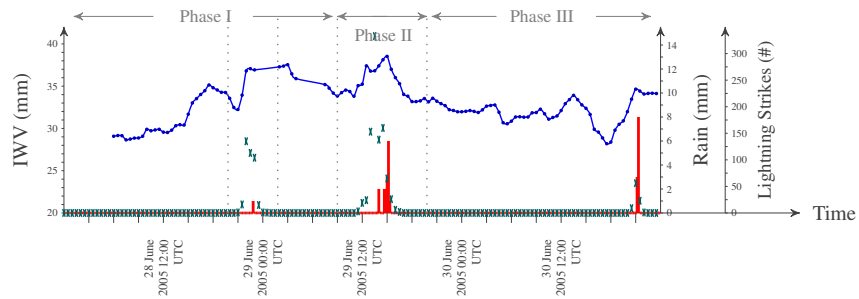


(e) GNSS station located in Zelzate

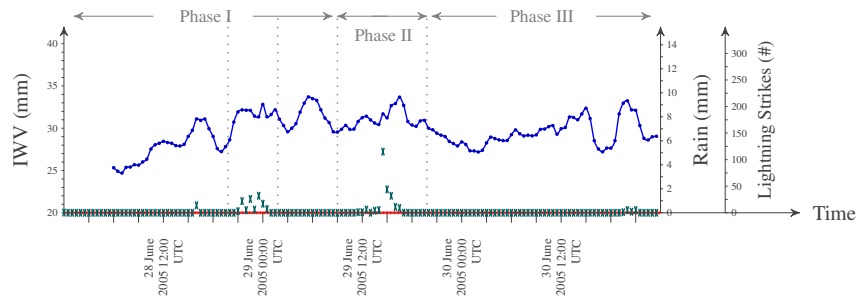


(f) GNSS station located in Oostende

Figure 6.6: IWV time series computed from GNSS observations at several Belgian stations between the 28th June 2005 and the 30th June 2005 (blue curve) along with the precipitation rate recorded by the nearby meteorological station (red bars) and the number of lightning strikes (green crosses) observed in the last 30 min



(g) GNSS station located in Namur



(h) GNSS station located in Tellin

Figure 6.6: IWV time series computed from GNSS observations at several Belgian stations between the 28th June 2005 and the 30th June 2005 (blue curve) along with the precipitation rate recorded by the nearby meteorological station (red bars) and the number of lightning strikes (green crosses) observed in the last 30 min

Impact of Heavy Rainfall on the IWV Time Series

Heavy and downpour rainfall might significantly affect the propagation of GNSS signals [Solheim, 1993; Solheim *et al.*, 1999; Walpersdorf, 2010; Brenot *et al.*, 2006] and their signals should appear in the tropospheric ZPD estimates and thereby in the IWV values. According to [Solheim *et al.*, 1999], drizzle and steady rain ($10 - 15 \text{ mm/h}$) should have a impact on the (slant) radio-wave propagation below 1 mm of IWV. Heavy rainfall, such as those associated with the thundery cells evolving in this case, have much higher rainfall rate (here about $70 - 100 \text{ mm/h}$) and should impact the radio-wave propagation by up to several millimetres (in IWV units). However, no clear impact of these heavy rain cells can be seen in the IWV time series presented in Figure 6.6. Several reasons can be raised to explain this fact:

- Regions where very high rainfall rates are observed are quite narrow (usually a few *km* of diameter). Because of the azimuth symmetry hypothesis imposed on the tropospheric ZPD (Section 3.3), the tropospheric ZPD quantity is a spatially integrated quantity and consequently the impact of such narrow high rainfall rate cells on the estimated tropospheric ZPD is averaged out.
- The high rainfall rate period does not necessary impacts the complete GNSS observation period from which a specific tropospheric ZPD is estimated. Because the tropospheric ZPD is a time-integrated quantity, the impact of high rainfall rate cells on the tropospheric ZPD estimates is also averaged out.
- In addition, relative constraints (Section 4.4.5, page 4-32) are imposed to the tropospheric ZPD to not vary "too much" from one epoch to another. The 2 mm relative constraints set up to process our GNSS observations might have been too strong to let the tropospheric ZPD varies according to the signal induced by these high rainfall rate cells. This should be investigated in the future.
- Last but not least, the GNSS data cleaning, which is based on the post-fit residuals to eliminate outliers in the ionosphere-free carrier-phase double-difference observations. The maximal post-fit residual of 6 mm allowed in the data cleaning usually performs very well. However, under these particular meteorological conditions, it is not so adequate: Figure 6.7 illustrates the post-fit residuals over the Dentergem-Waremme baseline during the 29th June 2005. During the stormy period of the afternoon, the post-fit residuals before the data cleaning (red dots) show a high variability, probably related to the thundery precipitations. The figure also clearly emphasises a high number of rejected observations after the data cleaning (e.g. between 12:30 UTC

and 15:00 UTC). The data cleaning has more than probably also removed the necessary information to let the high rainfall rate cells play a (significant) role in the IWV time series.

In conclusion, the analysis strategy should be revisited in the future to better take into account such "extreme" meteorological events.

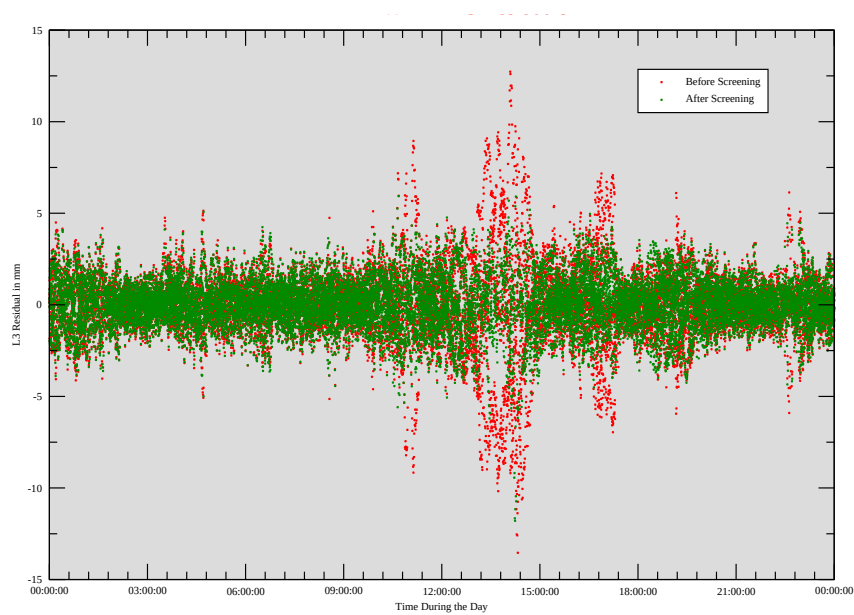


Figure 6.7: Ionosphere-free carrier-phase double-difference post-fit residuals before (red dots) and after (green dots) data cleaning for the baseline Dentergem-Waremme during the 29th June 2005

IWV Gradients Analysis

More information is expected to be retrieved from the analysis of the IWV horizontal gradients. The first step in that direction is to compare the IWV time series recorded by nearby GNSS stations and to derive the "horizontal gradients" (IWV differences) between the stations, epoch by epoch. To get horizontal gradient values representative of the fine structure, GNSS observations from very close stations should be considered. Therefore, the GNSS observations from the Belgian densification network were used. Hereafter, that analysis is shown in the neighbourhood of Brussels (BRUS), region where hail falls were recorded. Three other GNSS stations were chosen in this area: they are located in Bertem (BERT, 19.23 km north-east of BRUS), Burghout (BUGG, 26.07 km north-west of BRUS) and Nivelles (NIVL, 23.95 km south of BRUS). The corresponding IWV horizontal gradients are represented in Figure 6.8. The two thundery bursts that happened in the evening of the 28th June 2005 (phase I) are clearly visible in the beginning of the time series with IWV gradients up to 0.8 mm/km. However, the most striking event visible in the time series occurs between 12:30 UTC and 16:00 UTC with a maximal IWV gradient of about 2.4 mm/km (peak to peak) recorded between the GNSS stations in Brussels and Bertem and corresponds to the multi-cellular thunderstorm (phase II). It is up to 5 times the IWV gradient recorded (over the same time period) during the rest of the day.

Conclusions

Even if some patterns related to the evolving multi-cellular thunderstorm might be emphasised in the IWV time series and in the IWV horizontal gradient time series, they provide no information on the spatial extension of the mesoscale structures and solely a few insights on their spatial and time evolution. This latter information is of course of uttermost importance for nowcasters and a 2-D IWV field reconstruction method was thus investigated. The analysis of IWV time series and IWV gradient time series are not however without interest: setting up an IWV horizontal gradient threshold might for example help in the automatic detection and classification of severe meteorological events.

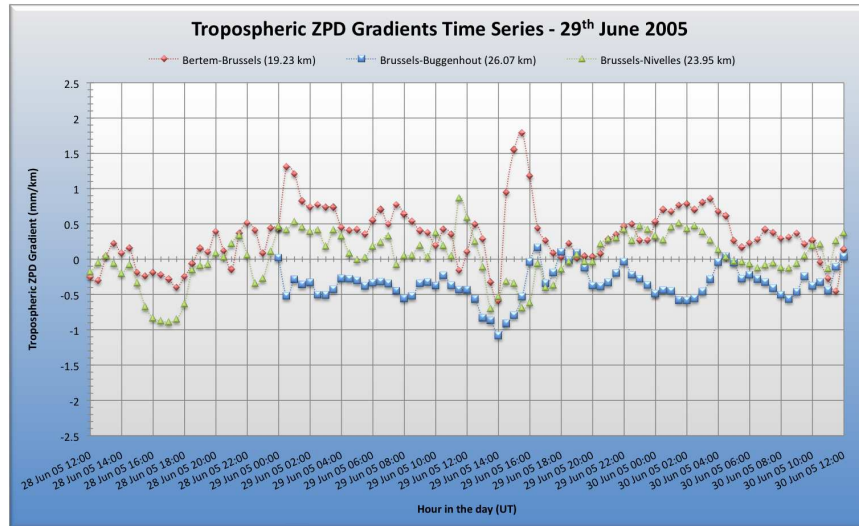


Figure 6.8: Tropospheric ZPD gradient time series observed around Brussels during the stormy day

6.4.3 Gridding Method

To detect the fine mesoscale structures in the troposphere, and to determine their spatial and time evolution, the IWV values obtained from our GNSS analysis were gridded using the *Generic Mapping Tool* (GMT) [Wessel and Smith, 2008] to represent the IWV field over Belgium. Two gridding methods were evaluated: the *Delaunay triangulation* and the *surface gridding* methods. The first method, the *Delaunay triangulation*, represents the IWV field as a union of planar triangular facets. The algorithm connects the IWV values to give the most equilateral triangulation possible [Watson, 1982]. The main advantage of this method is that no interpolation between the IWV observations is done and consequently no artefact is introduced in the IWV maps. The disadvantage is that the corresponding map is not differentiable and doesn't fit well with the physical proprieties of the actual water vapour spatial distribution, particularly if the inter-station distances are large compared to the characteristic distance of the significant variations in the reconstructed field. For this reason, a second method of reconstruction was investigated: the

“*surface gridding*“ method that uses a higher order (smooth and differentiable) interpolation between the “randomly-spaced“ IWV observations. In this algorithm, the IWV field, which is denoted here by $\mathcal{W}(x,y)$, is the surface obtained by solving the following equation

$$(1 - \mathcal{T}) \cdot \Delta^2 \mathcal{W}(x,y) + \mathcal{T} \cdot \Delta \mathcal{W}(x,y) = 0 \quad (6.1)$$

with

$$\begin{aligned} \mathcal{W} : \quad \mathbb{Q} \subset \mathbb{R}^2 &\longmapsto \mathbb{R} \\ (x,y) &\longmapsto \mathcal{W}(x,y) \end{aligned} \quad (6.2)$$

- where
- x is the latitude in degree
 - y is the longitude in degree
 - $\mathcal{T} \in [0, 1]$ is the *surface tension factor*
 - Δ is the Laplacian operator
 - $\mathbb{Q} \subset \mathbb{R}^2$ is the *gridding domain*

Gridding Domain and Grid Resolution

The *gridding domain* $\mathbb{Q}$ was chosen rectangular and covered from 49.5° N up to 51.5° N in latitude and from 2.5° E up to 6.5° E in longitude. It covers thus completely Belgium and its direct surroundings. All IWV values obtained from the GNSS observations were used and served as boundary conditions to reduce the border effects within the country. In the rest of the text (unless specified otherwise), we only consider the reconstructed IWV field over Belgium, even if the complete gridding domain $\mathbb{Q}$ is represented. The *grid resolution* used in the reconstruction problem was defined as a 0.1° in longitude $\times$ 0.05° in latitude resolution. This corresponds to a grid of about 5.6 km in longitude by 5.6 km in latitude covering uniformly Belgium. It also meets the spatial resolution criterion targeted for nowcasting applications and between $1/2$ to $1/4$ of the thundery cell size evolving in the observed phenomena.

Surface Tension Parameter

In the reconstruction method, the surface tension parameter $\mathcal{T}$ can be adjusted between a “minimum curvature” solution ($\mathcal{T} = 0$, most smooth surface possible) and an approximation of the triangulation solution ($\mathcal{T} = 1$). According to [Smith and Wessel, 1990], the minimum curvature can cause undesired oscillations and false local maxima or minima. Going for a minimum curvature solution can thus introduce artefacts in the IWV field reconstructed and is therefore not recommended. Hereafter, IWV fields reconstructed using different $\mathcal{T}$ values (Figure 6.9) are compared to assess the impact of the surface tension factor on the reconstructed tropospheric ZPD field. The minimum curvature gives indeed a solution very different compared to all other solutions tested and therefore was not adopted (Figure 6.9). The IWV fields reconstructed using the different surface tension parameters are also compared to weather radar images. From this qualitative comparison, the IWV field reconstructed using a surface tension parameter $\mathcal{T} = 0.5$ matches the best with the weather radar images. Because high-resolution (raw) data from weather radar were not accessible, no quantitative analysis was carried out. Moreover, the IWV field reconstructed using a surface tension parameter $\mathcal{T} = 0.5$ shows a bias (over the complete $\mathbb{Q}$ domain) with respect to the one reconstructed with $\mathcal{T} = 0.75$ by about -0.028 mm (in IWV units). The variability in time (standard deviation) of this bias is ± 0.057 mm and can thus be considered constant (Figure 6.10c). The variability in space (standard deviation) between the two grids remains below 0.19 ± 0.051 mm (IWV units). Similar values are obtained for $\mathcal{T} = 0.25$, although with an inversion of the sign for the bias (Figure 6.10b). Between 16:00 UTC and 19:00 UTC, the IWV grids reconstructed with the different surface tension parameters slightly diverge from each other (visible bulge in the bias and standard deviation time series). At this epoch, the thundery cells merged into a large precipitation band covering almost the whole country. The median of the IWV differences remains however mostly unaffected, indicating thereby that the bias is caused by local phenomena. Nonetheless, the IWV grid differences, reconstructed with surface tension parameter values between 0.25 and 0.75, remain far below the precision and accuracy targeted for nowcasting applications. From this test, we can conclude that this reconstruction method reaches a precision and an

accuracy within the millimetre level (in IWV unit). It can thus be considered sufficient for our needs.

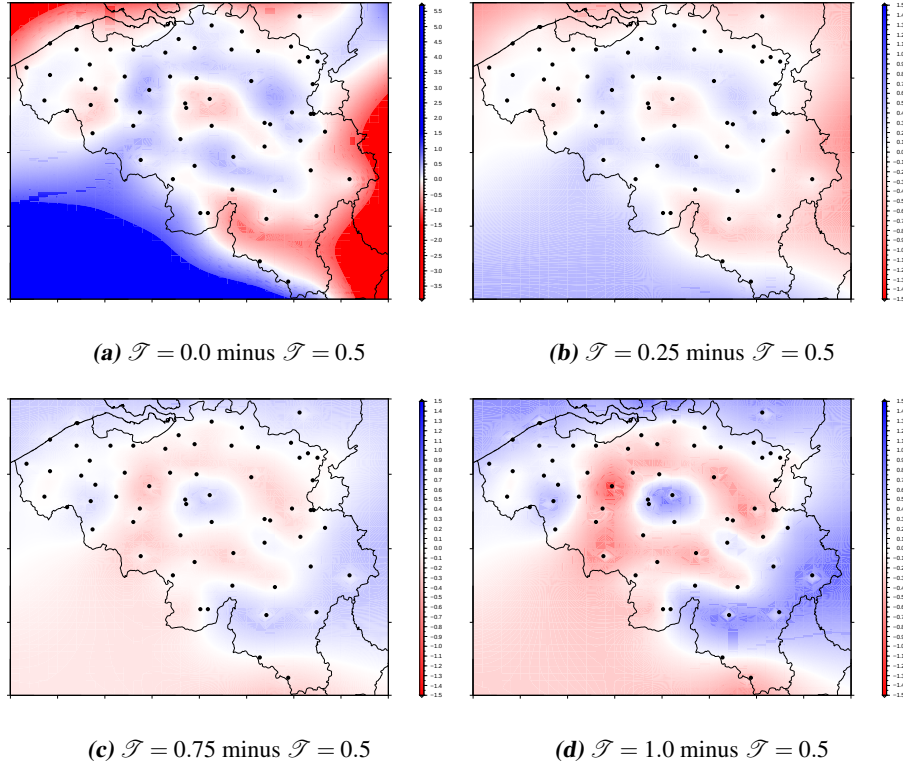


Figure 6.9: 2-D grid differences (in millimetre) between the IWV fields reconstructed using the surface gridding method and different surface tension values (surface tension value used as reference: $\mathcal{T} = 0.5$ - reference epoch: 13:30 UTC). Note the different y-axis scale for Figure 6.9a

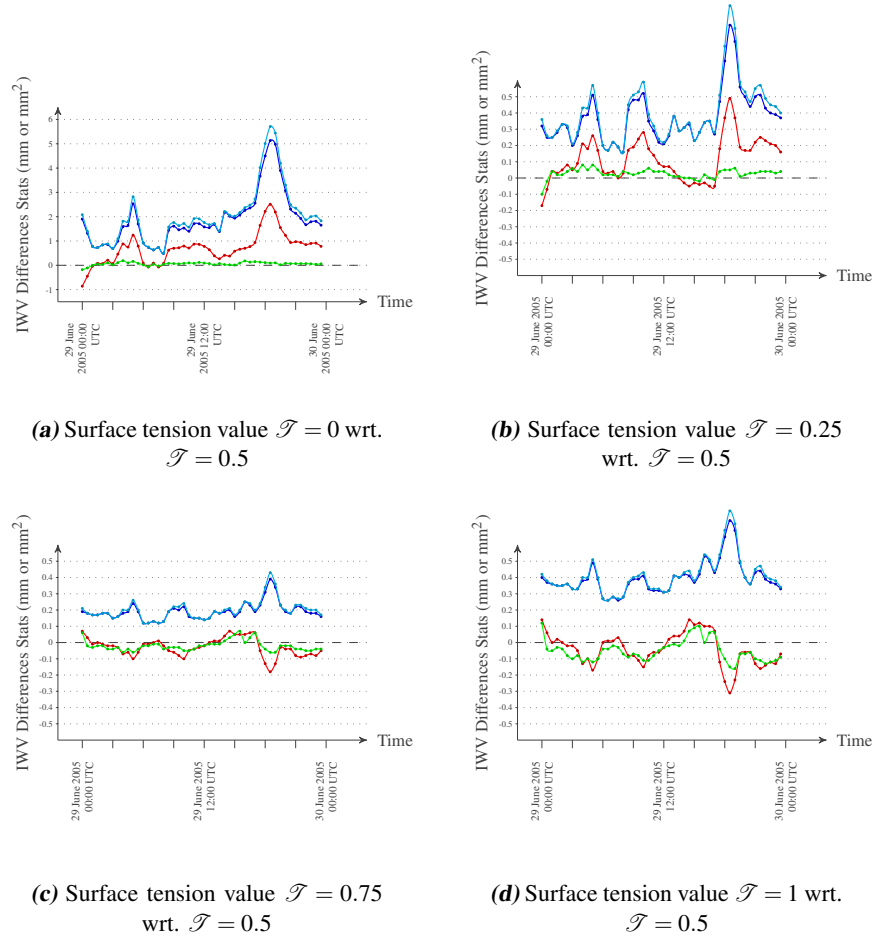


Figure 6.10: Bias (red curve), median (green curve), standard deviation (blue curve) and RMS (cyan curve) time series of the differences between the IWV fields reconstructed using the surface gridding method and different surface tension values. Note the different y-axis scale for Figure 6.10a

6.4.4 Location and Spatial Extension of the IWV Structures

Weather radars emit directional pulses of X/C/S-band microwave radiations and record the returned signal scattered by hydrometeors to locate and to estimate the intensity of precipitation zones, calculate their motions, determine their types (rain, snow, hail) and forecast their evolutions based on the Rayleigh scattering theory (Section F.2.2). In the present case, the 5-min images from the Belgian weather radars located in Wideumont and Zaventem and operated respectively by the *Royal Meteorological Institute of Belgium* (RMI) and *Belgocontrol* were gathered. The weather radar observations were analysed during the thunderstorm day to determine the location, scale and motion of the precipitation cells. The two sets of IWV fields (one obtained using GNSS observations from the European regional core network solely, the other using also the observations from the Belgian densification network) were compared to these weather radar images to assess qualitatively the IWV reconstruction and the benefits brought by the Belgian densification network. The comparison was carried out for each IWV grid reconstructed, i.e. every 30 minutes, to analyse the spatial and time evolution of the water vapour structures revealed in the IWV fields. Hereafter, this analysis is illustrated by a few examples chosen in each of the 3 phases of the analysed weather event.

Remark: *As already stated before, the 2-D IWV grid contains information almost only about atmospheric water vapour, not about precipitation. However, the water vapour distribution might be indirectly linked to precipitations. Similarities, as well as differences, are thus expected between the 2-D IWV grids and the weather radar images.*

Phase I: The Two First Thundery Bursts

During the night between the 28th June 2005 and the 29th June 2005, the weather radar images show light to moderate reflectivity values over nearly the whole country (Figure 6.11). They show the precipitations associated with the incoming pre-frontal convergence line propagating towards the north-east. The precipitation rates determined by the radars reach 10 mm/h to 15 mm/h. A few moderate thundery cells are visible, such as the one in the neighbourhood of Wideumont (Figure 6.11c), with precipitation rates of 25 mm/h to 50 mm/h. This period corresponds to the second thundery burst described in Section 6.4.2. The 2-D IWV fields reconstructed with and without the Belgian densification network are illustrated in Figure 6.12 for the 29th June 2005 at 00:00 UTC. The IWV field reconstructed with solely the GNSS observations from the European regional core network mainly shows the IWV level associated with the pre-frontal convergence line followed by (somewhat) dryer air. This corresponds to the information contained the 1-D IWV time series (Figure 6.6). The IWV field reconstructed using the GNSS observations from the Belgian densification network shows additional finer mesoscale structures. It shows notably an "isolated" zone of high water vapour content located in the north of Wideumont that could have feed the thundery precipitation cells evolving in that region between 23:30 UTC and 00:00 UTC (Figure 6.11b and Figure 6.11c). Because the advantages of using the Belgian densification network observations are even more pronounced in the next phase, we illustrate hereafter these results using the Belgian densification network solely.

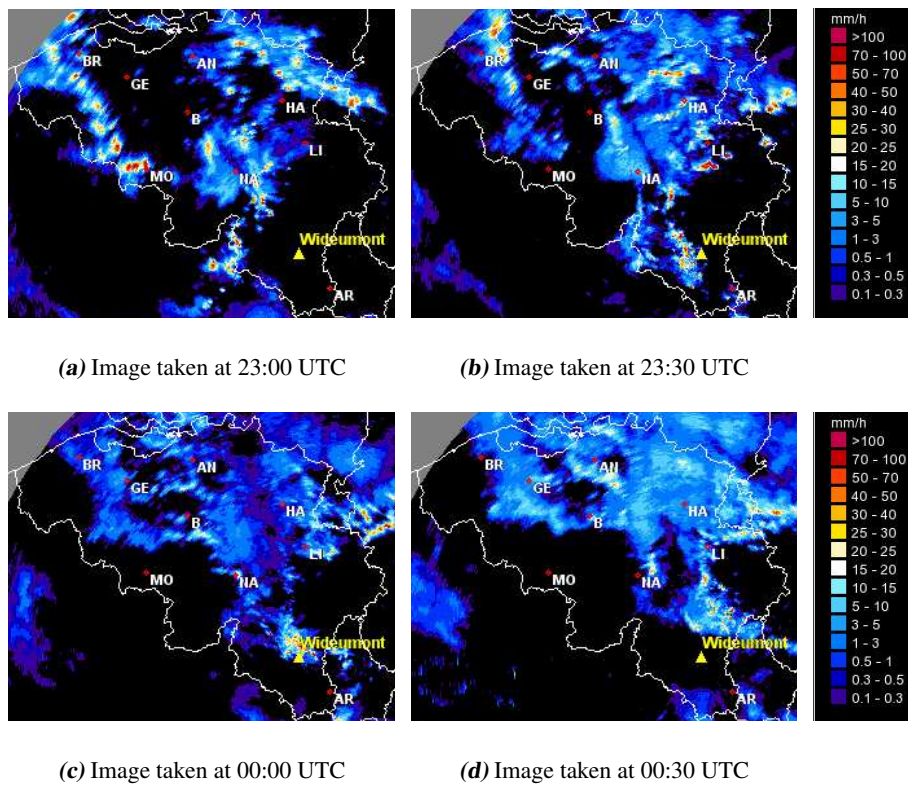


Figure 6.11: Weather rada images taken during the night between the 28th and the 29th June 2005. The colour scale (from blue to red) represents the strength of the Doppler echo reflected by the hydrometeors: the redder, the more intense

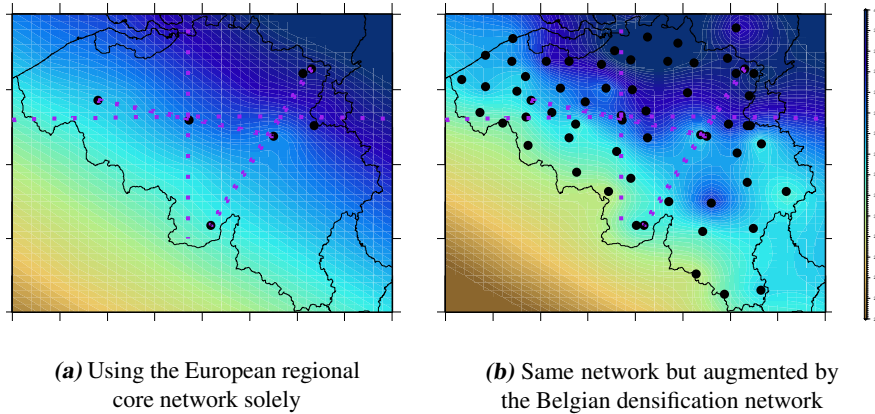


Figure 6.12: IWV fields reconstructed from GNSS observations during the first thundery burst that occurred in Belgium (night between the 28th and the 29th June 2005 at 00:00 UTC - the vertical scales correspond to IWV values in millimetres)

Phase II: The Afternoon Multi-Cellular Thunderstorm

After a sunny forenoon, several thundery outbreaks followed between 12:00 UTC and 17:00 UTC (Section 6.4.2). Weather radar images show severe thundery cells (high reflectivity zones) emerging from 12:00 UTC onwards (Figure 6.13a and Figure 6.13b). The thundery precipitation cells are appearing, moving and disappearing very quickly (sometimes within 15 min). The precipitation cells extend generally over a diameter of 5 km to 20 km and the precipitation rates recorded within these cells reach the 70 mm/h to 100 mm/h level. The IWV fields reconstructed using GNSS observations are illustrated in Figure 6.14a and Figure 6.14b, and the corresponding weather radar images in Figure 6.13a and Figure 6.13b respectively. The IWV fields reconstructed using the Belgian densification network show interesting features, as the dry incursion in centre of the country and propagating from the region of Nivelles (NIVL, at 12:30 UTC, Figure 6.14a) towards the Brussels's region (BRUS at 13:30 UTC, Figure 6.14b). This dry region is the region where severe hail falls were reported (Section 6.3.2) and is associated with a sharp drop of 10°C, visible in the temperature records of Uccle, Belgium. The propagation of GNSS signals are even less sensitive to hail (ice droplets) than to heavy rainfall [Solheim *et al.*, 1999]. The amplitude of the IWV differences between the dryer zone and its surroundings cannot be explained by the propagation

delay induced by hail. This dryer zone might rather be explained by a decrease in the water vapour content indirectly related to the hail (transformation of water vapour into ice and drop in the temperature). The dryer zone inclusion is slightly visible in the IWV time series of Brussels (Figure 6.6a) and lasts for only about 1 hour. This clearly emphasises the capability to access the fine (water vapour) mesoscale structures using GNSS observations, even when these structures only last for a very short time (here about 15 min to 30 min). Nonetheless, special attention must be paid to the dephasing phenomena coming from the integration effect of the GNSS analysis. This could be improved in the future by increasing the repetition cycle of the IWV. Between 16:00 UTC and 16:30 UTC, larger precipitation structures started to appear, while a few severe thunderstorm regions still emerged, notably in the neighbourhood of Wideumont and near the French border (Figure 6.13c and Figure 6.13d). These thundery regions are visible in the IWV fields reconstructed with the Belgian densification network as regions of very high IWV levels (Figure 6.14c and Figure 6.14d), one in the neighbourhood of Gent (GENT) and one another near the Dutch border.

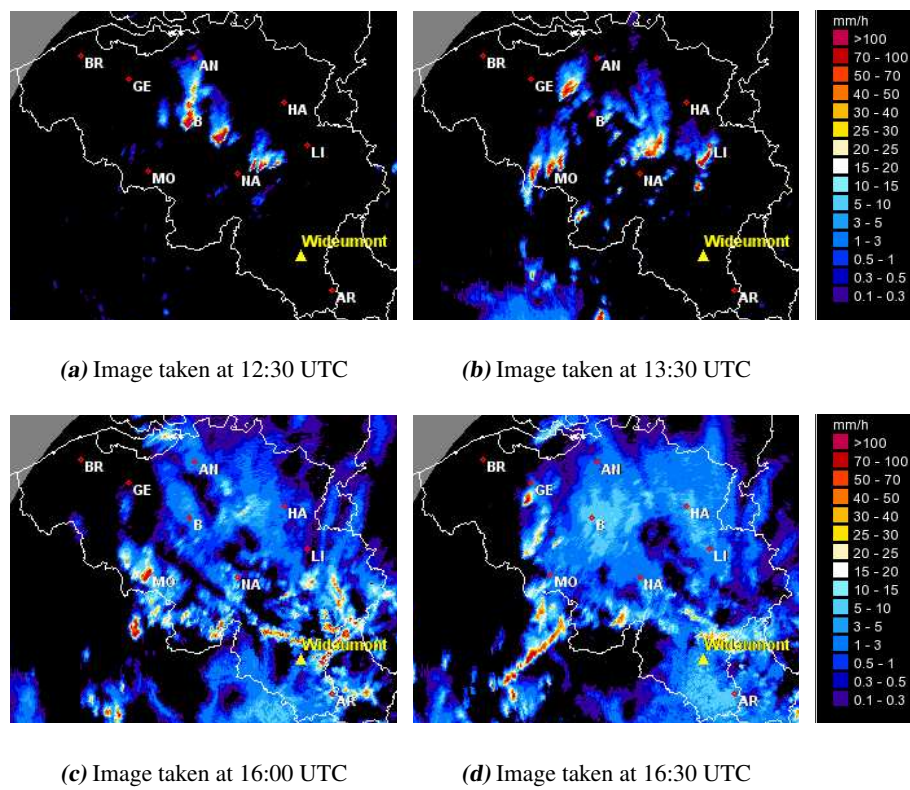


Figure 6.13: Weather radar images taken at 12:30 UTC, 13:30 UTC, 16:00 UTC and 16:30 UTC during the 29th June 2005.

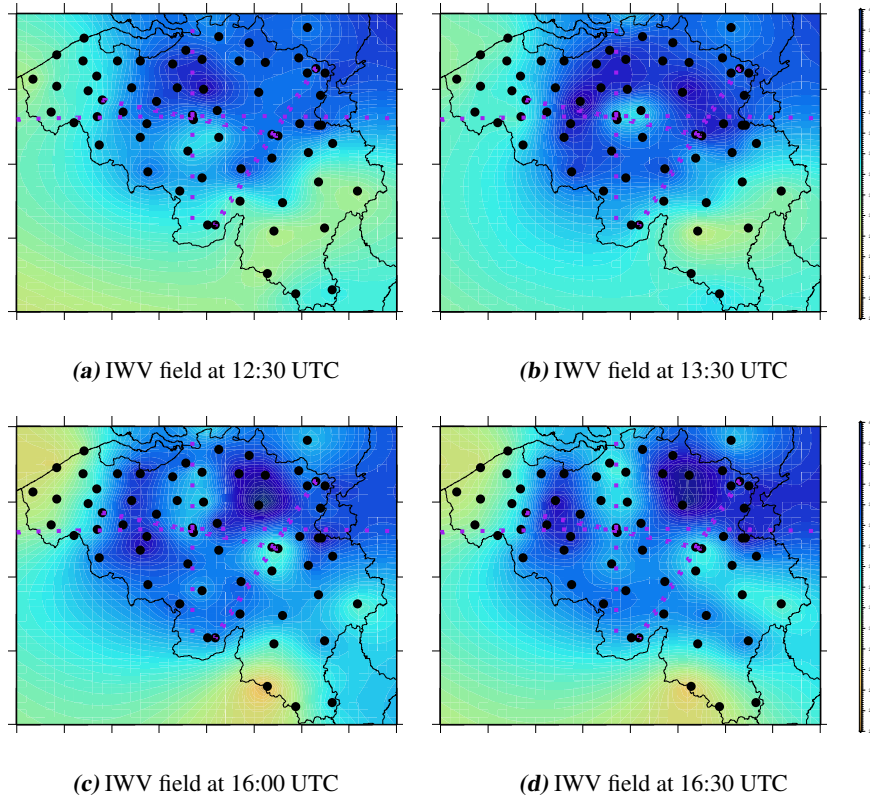
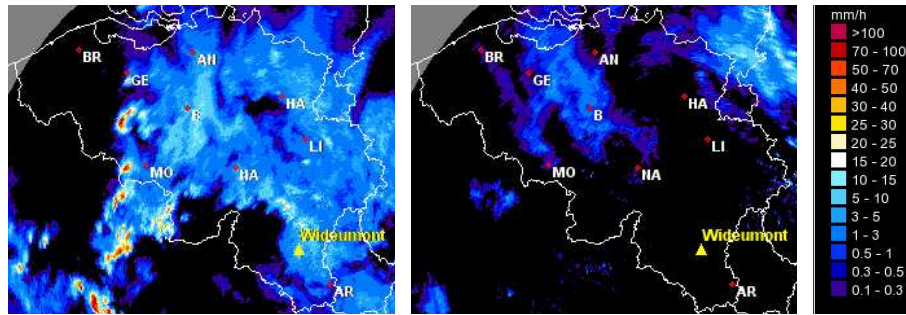


Figure 6.14: IWV fields reconstructed using GNSS observations from the European regional core network augmented by the Belgian densification network on the 29th June 2005 at 12:30 UTC, 13:30 UTC, 16:00 UTC and 16:30 UTC (the vertical scales correspond to IWV values in millimetres)

Phase III: The Large Precipitation Band

At the end of the afternoon (between 17:00 UTC and 18:00 UTC), the thundery cells leaved space to a large precipitation band covering almost completely the country and moving towards the northeast. The weather radar image illustrated in Figure 6.15a shows this band in the form of a large cloud of light to moderate refractivity corresponding to precipitation rate of 3 mm/h to 15 mm/h. Even in such conditions, the IWV grid reconstructed using the Belgian densification network shows interesting fine structures in the water vapour field that are missing in the IWV field reconstructed without the network densification (Figure 6.16). During the evening, the rain moved out Belgium by the north-east (Figure 6.15b).



(a) Image taken at 17:00 UTC

(b) Image taken at 22:00 UTC

Figure 6.15: Weather radar images taken during the 29th June 2005. The colour scale (from blue to red) represents the strength of the Doppler echo reflected by the hydrometeors: the redder, the more intense

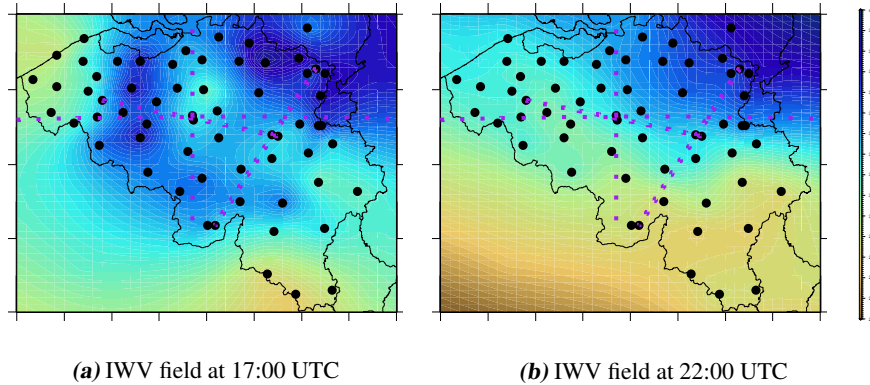


Figure 6.16: IWV fields reconstructed from GNSS observations on the 29th June 2005 at 17:00 UTC and 22:00 UTC (the vertical scales correspond to IWV values in millimetres)

6.4.5 Quantitative Analysis

Section 6.4.4 demonstrated that the location and the motion of the fine mesoscale tropospheric water vapour structures associated with the thundery precipitation cells are well revealed by the IWV field reconstructed using the Belgian densification network, while they are almost completely missing when using the observations from the European regional core network solely. In nowcasting applications, forecasters are not only interested in the location and motion of the atmospheric structures but also in the amplitude of the horizontal gradients observed in the water vapour field. In this section, the improvements achieved in the IWV field reconstruction brought by the Belgian AGN densification are thus assessed quantitatively. Therefore, 4 along-track IWV profiles through the country were determined and analysed:

- A North-South profile passing by Brussels (BRUS), Belgium
- A West-East profile passing by Brussels
- A Bree-Dourbes (BREE-DOUR) profile, which is more or less the direction of the propagation of the weather front associated with the thunderstorms
- A Dentergem-Waremme (DENT-WARE) profile, which is more or less perpendicular to the direction of the propagation of the weather front associated with the thunderstorms

As can be seen in Figure 6.17, the 4 along-track profiles extracted at 13:30 UTC from the IWV grids reconstructed using the observations from the Belgian densification network show significant differences compared to the IWV field reconstructed using the observations from the European regional core network solely. While the IWV differences in the direction of the front propagation (Bree-Dourbes profile, Figure 6.17b) remain moderately low (within 2 mm), the differences in the 3 other directions reach significant values up to 4.77 mm (e.g. Dentergem-Waremme profile, Figure 6.17a). To assess the amplitude of the IWV differences between the two fields globally over Belgium, IWV values obtained with and without the Belgian densification network observations were differentiated at each grid point. The two IWV grids present an average bias of 0.15 mm and the spatial variability of their differences (standard deviation) reaches up to 2.03 mm. The maximal discrepancy is recorded between the GNSS sites located in Brussels (BRUS) and Erpe Mere (ERPE) with a value of 5.47 mm. This analysis was carried out for the complete day and the corresponding bias and standard deviation time series are illustrated in Figure 6.18. In average over the day, the IWV field reconstructed with the Belgian densification network observations is slightly dryer by about 0.30 mm, compared to the one using the observation from the European regional core network solely. The average variability in space (standard deviation) between the two IWV fields is of about 1.66 mm.

The amplitude of the signal recorded in the IWV field differences reach up to 5 times the sensitivity targeted for nowcasting applications. It is well above the precision and accuracy achieved by our GNSS analysis method (Section 5.4 and Section 5.5) and by the gridding method (Section 6.4.3).

Again, a higher bias is observed between 15:00 and 20:00 UTC. Nonetheless, in this case the median of the IWV differences shows a similar behaviour to the bias, meaning that the bias concerns a larger area in the country. This can be explained by the lack of GNSS stations in the south of the country when considering the European regional core network solely. At that time, the weather radar images emphasise no reflectivity cell in the south of the country and the corresponding IWV values in that region are much lower than in the remaining part of the country. This cannot be rendered when using the core network solely.

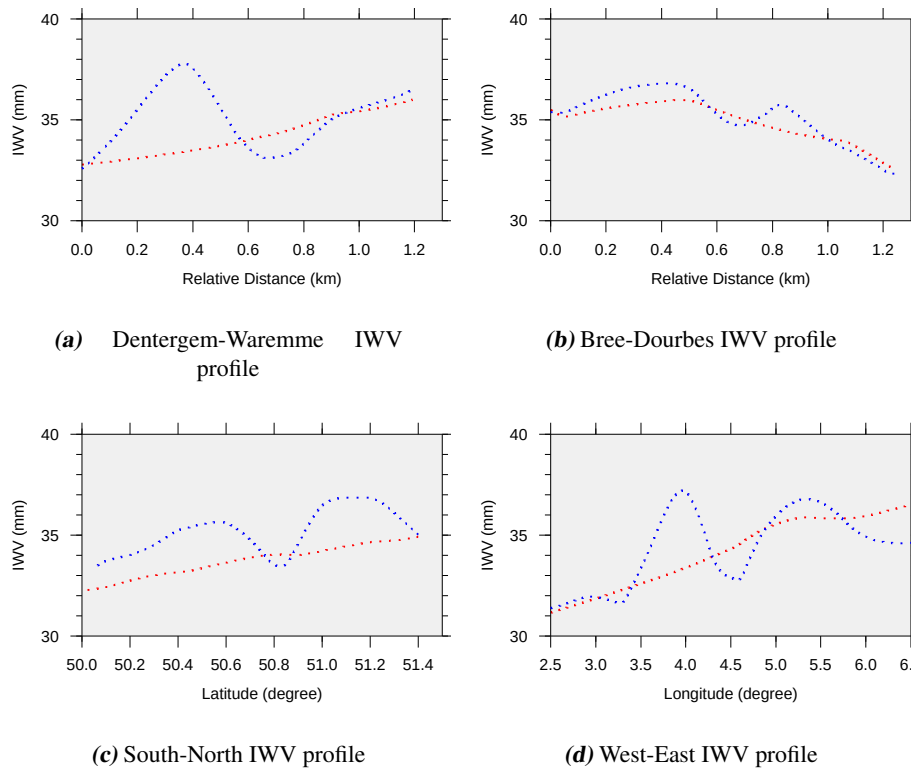


Figure 6.17: Four along-track profiles extracted from the IWV field reconstruction at 13:30 UTC (red curve: using the European regional core network solely - blue curve: using the Belgian densification network)

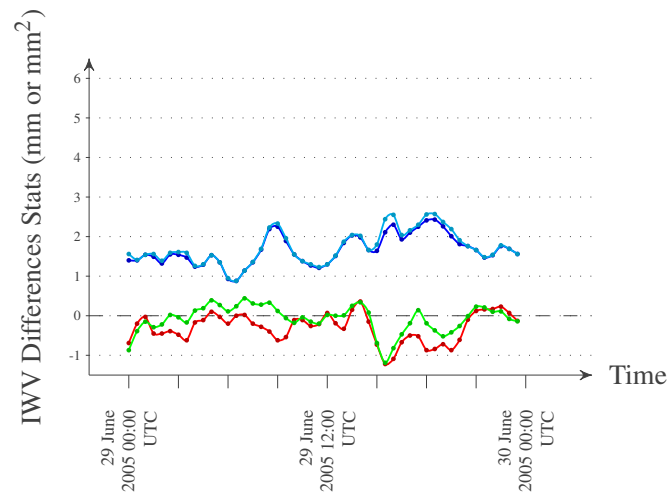


Figure 6.18: Bias and standard deviation time series of the differences between the IWV fields reconstructed with and without the Belgian Active Geodetic Network (BAGN)

6.5 Discussion, Limitations and Conclusions

In this chapter, the detection and the monitoring of the fine mesoscale water vapour structures in the troposphere using GNSS observations was investigated. These fine structures are usually associated with meso-beta and meso-gamma scale meteorological phenomena such as severe rainfall, snowfall, hail fall and thunderstorms. Therefore, a day of complex weather conditions associated with a severe multi-cellular thunderstorm that occurred in Belgium on the 29th June 2005 was analysed. The tropospheric ZPD estimated from the GNSS observation processing were reduced to IWV values, then gridded to reconstruct the 2-D IWV field over the country. The analysis of the 2-D IWV field proved that using European regional networks with inter-station distances of about 100 km only allow to access the large mesoscale structures in the water vapour field, linked with phenomena such as weather fronts and cyclogenesis. It also proved that using GNSS observations from densification networks, such as the Belgian AGN, is mandatory to detect the fine mesoscale structures in the troposphere linked to the thunderstorm cells. In the latter case, the 2-D IWV field allowed to determine the location, the spatial extension and the evolution (both in space and in time) of tropospheric water vapour structures associated with the thundery cells. The benefits brought by the Belgian AGN for nowcasting applications was quantified: differences up to 5.84 mm were revealed between the IWV grids reconstructed with and without the Belgian densification network. This is well above the precision and accuracy targets specified in the URD for *nowcasting* applications. Using the Belgian densification network, GNSS can provide 2-D images of the water vapour distribution with high spatial and temporal resolution. The results presented here proved that a synergetic use of GNSS and meteorological observations might help in forecasting rapidly developing systems such as thunderstorms. Some improvements can however still be envisaged:

Analysis Strategy and GNSS Networks

Analysing nowadays nowcasting cases would allow to apply the latest state-of-the-art strategy options (e.g. the IGS05 reference frame realisation, absolute antenna calibration models, GLONASS observations and improved

orbit products), improving thereby the precision and the accuracy of the 2-D IWV field reconstructed. Observations from much more GNSS stations are also available today. A densification of the network using more stations from the French RGP, the UK OS net, the German SAPOS and the Dutch networks (Section 2.7.1) would greatly reduce the possibility of border effects within the gridding domain. It would also probably allow to extend the gridding domain and thereby, to monitor the water vapour structures over a larger region and over a longer time, although with less performances due to the increase of inter-station distances outside Belgium. Finally, an operational usage of GNSS tropospheric ZPD estimates for nowcasting applications requires the use of the near real-time step of the analysis strategy. It would increase the tropospheric ZPD repetition cycle down to 10 or 15 min and, thereby, improve both the 1-D and 2-D IWV analysis and finally reduce the possibility of dephasing phenomena (Section 5.6.1).

Gridding Method

The surface gridding method used to reconstruct the IWV maps showed a reasonable precision and accuracy, although some limitations were pointed out. The different reconstruction schemes investigated differed by up to 10 – 20 % of the observed signal in the IWV field reconstructed. Although it is not of a problem when analysing moderate and severe weather conditions, it might be a problem when faint water vapour structures are to be studied. The interpolation method also presumes the IWV data contain no error. Actually, this hypothesis is not true: the GNSS tropospheric ZPD estimates, as well as the pressure grid obtained from the synoptic observations, are contaminated with errors. Even if these errors proved to be small with respect to the signal observed in the current reconstructed IWV field, a better reconstruction method would take into consideration these errors. More sophisticated reconstruction methods would provide an added-value for studying faint water vapour structures. The variational technique presented in [de Haan, 2008] is such a method and a good candidate to improve further the gridding reconstruction in the future. The use of a pressure field from NWP models can also be investigated to densify, complement or replace the pressure data to be gridded and thereby, improving the resulting tropospheric ZHD field.

Validation and Synergy

High-rate weather radar raw data can be used to improve the validation of the location and motion of the water vapour structures in the GNSS IWV field. The precipitation rate offered by these data can also be used to determine if a specific zone of high IWV level is linked to a precipitation area or rather serves as water vapour tank to feed further thundery cells. IWV field obtained from NWP models such as HIRLAM can also be compared to the GNSS IWV field to either validate the precision and accuracy of the method and/or to emphasise deficiencies in the weather prediction model.

Slant Path Delay (SPD) and Tomography

The use of the Belgian densification network observations would certainly be of further benefit to meteorology by producing *Slant Path Delay* (SPD) to be used within a 3-D reconstruction method (tomography), such as the one presented in [de Haan, 2008].

We have a habit in writing articles published in scientific journals to make the work as finished as possible, to cover up all the tracks, to not worry about the blind alleys or describe how you had the wrong idea first, and so on. So there isn't any place to publish, in a dignified manner, what you actually did in order to get to do the work.

Richard Feynman, American physicist, Nobel
Lecture, 1966



Summary, Outlook and Recommendations

7.1 Summary and Conclusions

The primary objective of our research was to develop a state-of-the-art analysis strategy to provide ground-based GNSS near real-time (NRT) tropospheric ZPD from a regional network of European permanent stations, to be used in operational meteorology, more particularly in *Numerical Weather Prediction* (NWP) models and *nowcasting* applications. To reach this goal, we set up a 2-step GNSS analysis strategy based on the *Bernese GPS software*. To meet all requirements imposed on GNSS-meteorology (repetition cycle, horizontal domain, spatial resolution, timeliness, precision and accuracy), we studied the sensitivity of our strategy in regard to several processing options. In that process, we identified several processing options, such as the antenna calibration models or the relative constraints imposed on the tropospheric ZPD estimates, for which change in their setup affect the NRT tropospheric ZPD above the precision and accuracy levels targeted for GNSS-meteorology. The methodology was optimised according to the results obtained from these sensitivity studies, and then the performances of our strategy were assessed. These assessments showed that our NRT tropospheric

ZPD estimates adhere to all GNSS-meteorology requirements, except the spatial resolution which must be reached as a joint effort of all the geodetic partners providing the tropospheric ZPD. Particularly, we compared our NRT tropospheric ZPD to other GNSS-sources of tropospheric ZPD, as well as to similar quantities provided by independent “techniques” (radiosondes, water vapour radiometers, NWP model data). It proved that our analysis strategy delivers NRT tropospheric ZPD estimates with a precision of about 5 mm and slightly better accuracy (about 64 % of the estimates have an accuracy better than 3 mm, all are within the threshold value). It is of sufficient quality for operational meteorology and our secondary objective could thus be achieved: we set up an operational analysis centre at ROB to provide the meteorologists with NRT tropospheric ZPD estimates. Today, this operational analysis centre is one of the analysis centres participating in the *EUMETNET EIG GNSS Water Vapour Program II* (E-GVAP II). Since the beginning of this service, the network was regularly (spatially) extended and densified. Today, it covers the whole of Europe and includes about 200 GNSS permanent stations. The reliability score of our NRT tropospheric ZPD solutions lies above 99 %, and 80 % (resp. 100 %) of our solutions have a timeliness less than 30 minutes (resp. 45 minutes). The NRT tropospheric ZPD estimates provided by ROB are recognised as valuable and enter the assimilation process in several meteorological agencies participating in E-GVAP II, such as the *Danish Meteorological Institute* (DMI), the *Koninklijk Nederlands Meteorologisch Instituut* (KNMI), Meteo France and the U.K. Met Office.

Finally, we demonstrated that 2-D GNSS water vapour maps can be of benefit to short-term weather forecasting. We showed that fine mesoscale tropospheric structures like those linked to severe weather phenomena, such as heavy rainfall and thunderstorms, can only be detected when using GNSS observations from densification networks, such as the *Belgian Active Geodetic Network* (BAGN). The added-value brought by the network densification was quantified: differences of up to 5.84 mm of IWV (i.e. about 38 mm of tropospheric ZPD) were revealed between the fields reconstructed with and without the Belgian AGN. This is well above the 1 mm precision targeted for nowcasting. Our results also indicated that a synergetic use of 2-D water vapour maps derived from ground-based GNSS observations in conjunction with more traditional remote sensing instruments, such as weather radar or

satellite water vapour images, is potentially very useful for forecasting rapidly developing systems such as thunderstorms.

7.2 Outlook and Recommendations

Although our 2-step analysis strategy satisfies all requirements imposed on GNSS-meteorology, possible improvements were identified, as well as the need for further research. They mainly concern the implementation of an ambiguity resolution technique in the near real-time step of the strategy, the use of a NWP tropospheric a priori model and mapping functions (along with a lower observation cut-off angle) and the processing of multi-GNSS observations. These improvements will affect the tropospheric solutions in terms of precision, accuracy, robustness and reliability. Most of them will be studied as soon as the new version of the *Bernese GPS software* is issued, i.e. in 2010-2011.

Multi-GNSS Observations

Concerning the benefits of processing multi-GNSS observations for meteorology, we only studied the inclusion of GLONASS observations. The tests carried out revealed quite limited improvements in the NRT tropospheric ZPD estimates. They mainly resided in terms of the robustness and the reliability of our solutions, eliminating outliers in the tropospheric ZPD time series. This limited added-value was attributed to the poor quality of the GLONASS orbits and to the limited number of available GLONASS satellites at the time of the tests. Processing data from more recent periods should produce more added-values because of the better quality of the orbits and the increased number of available GLONASS satellites. The number of receivers, recording both GPS and GLONASS signals, has also dramatically increased since then. In the (near) future, processing new and modernised multi-GNSS observations will increase the number of observations using new and improved signals. Part of the limitations residing in the *Bernese GPS software* and in the IGS orbits will also be eliminated. Processing jointly GPS, GLONASS and

Galileo is thus expected to improve the production of our NRT tropospheric ZPD estimates in terms of precision, accuracy and reliability.

Quality Monitoring

The *Quality Monitoring System* (QMS) used to check the production of our NRT tropospheric ZPD partly relies on the observations available in the framework of the EUREF-EUMETNET memorandum of understanding (MoU). Unfortunately, the external sources of information used in Chapter 5 to validate our strategy, are not all available in near real-time through automated access. For example, this is the case for the Water Vapour Radiometer (WVR) observations and for the HIRLAM-derived tropospheric ZPD data. Consequently, an important part of the monitoring is still done manually. Continuous access to these data might be requested in the framework of E-GVAP to resolve this issue. In the future, the QMS should thus be revisited and improved to provide a fully automatic monitoring. Additional procedures should also be implemented. As an example, new procedures should check that at least 7 days of daily precise coordinates are used to compute the cumulative solution for this station. Any faulty station should be excluded from the NRT analysis strategy, as its coordinate quality might be of unsatisfactory precision or accuracy to provide valuable tropospheric ZPD estimates. These new procedures should also ensure that, for each station, at least 4 hours of continuously estimated tropospheric ZPD exist before providing the meteorologists with any NRT tropospheric ZPD information for this specific station. Moreover, the QMS should also be re-thought in synergy with the upcoming “active monitoring” which will be developed within E-GVAP II. In that framework, and in an ideal case, the QMS should ensure a complete redundancy as well as a comprehensive crosscheck of the E-GVAP II quality monitoring procedures.

Horizontal Domain and Spatial Resolution

The thesis demonstrated that including more GNSS sites from regional and national densification networks is necessary to improve our contribution to GNSS-meteorology by accessing fine mesoscale tropospheric structures. New GNSS sites, particularly from the Belgian AGN, should thus be added in the

future. This will improve our spatial resolution for NWP applications, but also strengthen our contribution to future nowcasting applications, notably in Belgium. But in that context, our NRT analysis strategy seems to have reached its limits in terms of processing time and computing power requirements. Deep structural changes in the near real-time step of the strategy, or even a switch to a *Precise Point Positioning* (PPP) approach, might be required to solve this issue.

Sub-hourly Processing and Nowcasting

Until now, our NRT tropospheric ZPD are estimated on an hourly basis. However, to be useful for (operational) nowcasting applications, e.g. to help in the analysis of rapidly developing systems such as thunderstorms, the 2-D water vapour maps obtained from the GNSS analysis have to be presented to the forecaster with a shorter timeliness. To achieve that, sub-hourly GNSS data processing, e.g. every 15 minutes, has to be investigated. The hourly RINEX observation files used until now will have to be replaced by a real-time data transfer system, such as NTRIP, and deep structural changes will certainly have to be applied to the strategy (network size reduction, PPP approach...). At the present time, the dissemination of sub-hourly solutions within E-GVAP is not possible, but is under discussion. It should become operational by the end of 2010, or early 2011 at the latest. A first E-GVAP analysis centre, the *Koninklijk Nederlands Meteorologisch Instituut* (KNMI), has already developed a test solution (KNM1), processing data from about 38 GNSS stations in 15-min batches.

Slant Path Delay (SPD) and Tomography

Nowcasting applications would also take advantage from using *Slant Path Delay* (SPD) estimates along with a 3-D reconstruction method (tomography) such as the one proposed in [de Haan, 2008]. This is particularly true in Belgium because of the small inter-station distances in the Belgian AGN. Unfortunately, the *Bernese GPS software* is not able to directly provide the SPD information. However, some work has already been done in that direction and could be adapted to our analysis strategy to produce SPD observations [de

Haan, 2002]. Both, the production of SPD observations and a tomography method could be investigated in the future.

Climate Applications

As the major greenhouse gas, the atmospheric water vapour plays an important role in climate models and in the global warming process [Desbois and Roca, 2000; Elgered *et al.*, 2007]. In that context, a GNSS analysis strategy to provide post-processing tropospheric ZPD estimates for climate applications could be investigated. This analysis strategy should provide tropospheric ZPD with the highest precision and accuracy, but also ensure the (long-term) stability of the estimates. Therefore, a reprocessing of the historical GNSS data using an homogeneous (fixed and consistent) strategy should be considered. The strategy should apply the latest state-of-the-art standards to a global GNSS network and use the re-processed IGS products. In this perspective, a project such as E-GVAP could be established and might be of benefit to climate models.

*"Au bout de tout savoir et de tout accroissement
de notre savoir, il n'y a pas un point final, mais
un point d'interrogation."*



Prix Nobel de littérature, 1946
Herman Hesse

List of Appendices

*People will realise that software is not a
product; you use it to build a product*

Linus Torvalds



The Bernese GPS Software

Summary

This appendix briefly discusses, in the context of the near real-time step of our analysis strategy, how the Least-Squares (LSQ) method is applied in the Bernese GPS software to estimate the unknown parameters.

A.1 Introduction

The *Bernese GPS software* [Beutler *et al.*, 2007] is a software developed by the Astronomical Institute, University of Berne, that analyses (PRN-code and carrier-phase) GNSS observations for high-precision applications such as reference frame realisation, crustal deformation and atmosphere monitoring. In its current version 5.0, both active *Global Navigation Satellite Systems* (GNSS) are supported: the American GPS and the Russian GLONASS (Section 2.2). However, our Near Real-Time (NRT) analysis strategy uses (until now) solely GPS satellite signals (see Chapter 4 for details). In the

Bernese GPS software, parameter estimation is based on a Gauss-Markov model of full rank and Least-Squares (LSQ) estimation.

A.2 Least-Squares Adjustment

According to [Beutler *et al.*, 2007], in the Gauss-Markov model of full rank [Kock, 1988], the observation equations given in Section 2.6 can be written as

$$\vec{y} + \vec{v} = \mathbf{A} \cdot \vec{p} \quad (\text{A.1})$$

with

$$E(\vec{v}) = 0 \quad \text{and} \quad D(\vec{v}) = D(\vec{y}) = \sigma^2 P^{-1}$$

- where
- n is the number of observations
 - u is the number of unknowns
 - $E(\cdot)$ is the operator of expectation
 - $D(\cdot)$ is the operator of dispersion
 - P is a $n \times n$ positive definite weight matrix
 - σ^2 is the variance of unit weight (variance factor)

The principle of LSQ estimation in the Gauss-Markov model consists in minimising the sum of the squared residuals¹, i.e. the minimisation of the following quadratic form:

$$\Omega(\vec{p}) = \frac{1}{\sigma^2} (\vec{y} - A\vec{p})^T P (\vec{y} - A\vec{p}) \quad (\text{A.2})$$

The introduction of this condition is necessary to leads us from an ambiguous system of equations (Equation A.1) to an unambiguous Normal Equation (NEQ) system for the determination of $\vec{p}$, which expresses as

$$(A^T P A) \hat{\vec{p}} = A^T P \vec{y} \quad \text{or} \quad N \hat{\vec{p}} = \vec{b} \quad (\text{A.3})$$

where $\hat{\vec{p}}$ is the vector of estimated unknowns, $\vec{b} = A^T P \vec{y}$ and N is the normal equation matrix. A complete mathematical description of this method, as applied in the *Bernese GPS software*, can be found in [Brockmann, 1996].

During the processing the last hour of GNSS observations in our NRT analysis strategy, we can describe each term of Equation A.1 as follow:

The observations $\vec{y}$ are the ionosphere-free carrier-phase double-difference observables (Equation 2.11) corrected from all computable effects such as the geometrical distance (using satellite orbit products and a priori station coordinates), geophysical effects (e.g. station displacements due to the solid Earth's tides and the ocean tide loading), an a priori tropospheric model (an a priori hydrostatic model and its associated dry mapping function) and the antenna calibration models. During the processing of the GPS observations from the last hour, we use ionosphere-free carrier-phase double-difference (DDL3) observations recorded at a 30-sec sampling rate by a network of 194 GNSS stations. With about 8 GPS satellite visible in each station and 193 independent baselines, one hour of GPS raw observations provide us with about 185000 DDL3 observations.

¹The residuals are the differences between observed values and values obtained by back-substituting parameter estimations in models

The unknowns $\vec{p}$ are the parameters to be estimated, such as the coordinates of the stations, the carrier-phase ambiguities, the site-specific tropospheric parameters and possibly the horizontal tropospheric gradients. During the processing of the GPS observations from the last hour, we estimate 1 tropospheric Zenith Path delay (ZPD) value each 15 min per station along with the coordinates of the station and the carrier-phase ambiguities.

The design matrix A is a matrix of partial derivative coefficients linking the observations to the parameters to be estimated. In the present case, these coefficients are for example representative of the ionosphere-free linear combination and of the wet mapping function coefficients.

Observation-unknown balance: Table A.1 summarises the (theoretical) balance between the available observations and the unknown parameters to be estimated. About 3104 unknowns have to be estimated based on about 185280 ionosphere-free carrier-phase double-difference observations. File Outline A.2.1 illustrates a real case. It reveals a lower number of observations (144592), due notably to data cleaning, but also a few more parameters to be estimated (3350) due to additional carrier-phase ambiguities set up (e.g. in case of cycle slips and data gaps).

Observations	Unknown Parameters		
	Coordinates	Tropospheric ZPD	Ambiguities
120 obs./ (station+satellite) * 193 baselines * 8 satellites	3 param./station * 194 stations -	5 param./station * 194 stations -	1 param./ (station+satellite) * 194 stations * 8 satellites
	~ 582 param.	~ 970 param.	~ 1552 param.
~ 185280 obs.	~ 3104 param.		

Table A.1: Balance between the observations and the parameters to be estimated when processing a single hour of GPS observations

File Outline A.2.1 (Sample of parameter estimation summary file content - 7th May 2010 - Hour 1).

FN10127I.OUT Rms: 0.9 , # fil.: 194 , # obs.: 144592 , # par.: 3350 (DOY: 127) Max.
correction in a: 0.00 +- 0.00 for sat.: 0

A.3 Sequential Least-Squares Adjustment

The results obtained for the Least-Squares adjustment using all observations in one step is the same as splitting up the Least-Squares adjustment in different parts and combining the individual results in a latter step [Brockmann, 1996]. This is the principle applied in the sequential Least-Squares adjustment in time (Section 4.4.6) when combining the last 6-hour NEQ in our near real-time analysis strategy. In a first step, each hourly NEQ system is solved independently:

$$\vec{y}_i + \vec{v}_i = A_i \vec{p}_i + O_i \vec{\gamma}_i \quad \text{with} \quad D(\vec{y}_i) = \sigma_i^2 P_i^{-1} \quad \text{and} \quad i = 1, \dots, N \quad (\text{A.4})$$

where the parameter types $\vec{\gamma}_i$ are only relevant for the individual observation series. The O_i matrices are the design matrices associated to the $\vec{\gamma}_i$ parameter types. In a second step, an estimation for $\vec{p}$ is derived from the individual estimations $\vec{p}_i$ by setting up new pseudo-observation equations that read

$$\vec{p}_i + v_{i,new} = I \vec{p} \quad (\text{A.5})$$

The interpretation of these pseudo-observation equations is easy: each individual estimation is introduced as a new observation using the associated covariance matrix as the corresponding weight matrix. Detailed mathematical expressions of the sequential adjustment is given in [Brockmann, 1996].

Observation-unknown balance: Table A.2 summarises the (theoretical) balance between the available observations and the parameters to be estimated in the 6-NEQ stacking step of the near real-time analysis strategy. During the session combination (NEQ stacking), a back-substitution of the station's coordinates by a cumulative solution takes place, leaving the carrier-phase ambiguities and the tropospheric ZPD as only unknowns. About 16224 unknown parameters have to be estimated based on about 1192000 observations. File Outline A.3.1 illustrates a real case. It reveals a lower number of observations (851717), due notably to data cleaning, for more or less the expected number of parameters to be estimated (16126).

Observations	Unknown Parameters		
	Coordinates	Tropospheric ZPD	Ambiguities
720 obs./((station+satellite) * 207 baselines * 8 satellites	Back-substituted 0 param.	30 param./station * 208 stations -	6 param. /((station+satellite) * 208 stations * 8 satellites
		~ 6240 param.	~ 9984 param.
~ 1192320 obs.	~ 16224 param.		

Table A.2: Balance between the observations and the parameters to be estimated during the 6-hour NEQ stacking

File Outline A.3.1 (Sample of parameter estimation summary file content - 7th May 2010 - Hour 1).

AT10127I.OUT Rms: 0.9 , # fil.: 1181 , # obs.: 851717 , # par.: 16126 (DOY: 127)
Max. correction in a: 0.00 +- 0.00 for sat.: 0

A.4 Absolute and Relative Constraints

Applying a priori constraints to an unknown parameter in the NEQ system corresponds to incorporate information about this parameter of the form

$$\vec{w} + \vec{v}_w = H\vec{p} \quad \text{with} \quad D(\vec{v}_w) = D(\vec{w}) = \sigma^2 P_w^{-1} \quad (\text{A.6})$$

- where
- ✎ H is a $r \times u$ constraints matrix of given coefficients
 - ✎ r is the number of constraining equations, with $r < u$
 - ✎ $\vec{w}$ is a $r \times 1$ vector of known constants
 - ✎ $\vec{v}_w$ is a $r \times 1$ residual vector
 - ✎ P_w is the $r \times r$ dispersion matrix of the constraining equations

We can interpret the a priori constraints (Equation A.6) as additional fictitious observations (also called “pseudo- observations”). Taking into consideration these pseudo-observations, the observation equations can be written as

$$\begin{bmatrix} \vec{y} \\ \vec{w} \end{bmatrix} + \begin{bmatrix} \vec{v}_y \\ \vec{v}_w \end{bmatrix} = \begin{bmatrix} A \\ H \end{bmatrix} \vec{p} \quad \text{with} \quad D\left(\begin{bmatrix} \vec{y} \\ \vec{w} \end{bmatrix}\right) = \sigma^2 \begin{bmatrix} P^{-1} & 0 \\ 0 & P_w^{-1} \end{bmatrix} \quad (\text{A.7})$$

with the associated normal equation system

$$(A^T P A + H^T P_w H) \hat{\vec{p}} = A^T P \vec{y} + H^T P_w \vec{w} \quad (\text{A.8})$$

In a Least-Squares adjustment, the estimated parameters can be constrained to their a priori values by constraining the parameter improvement to a specific value: this is referred to as *absolute constraints* (see Section 4.4.5 for more details). It is also possible to constrain the time evolution of a parameter: this is referred to as *relative constraints* (see Section 4.4.5 for more details). Table A.3 summarises the structure of the different matrices and vectors acting in Equation A.6 in the case of absolute and relative constraints.

Constraints	$H\vec{p} = \vec{w} + \vec{v}_w$	H	$\vec{w}$	P_w
Absolute	$p_i = 0 + v_{w,i}$	$H_i = [0, \dots, 0, 1, 0, \dots, 0]$	$w_i = 0$	$\text{diag}(\frac{\sigma_p^2}{\sigma_{abs}^2})$
Relative	$p_i - p_{i+1} = 0 + v_{w,i}$	$H_i = [0, \dots, 0, 1, -1, 0, \dots, 0]$	$w_i = 0$	$\text{diag}(\frac{\sigma_p^2}{\sigma_{rel}^2})$

Table A.3: Formulation of the absolute and relative constraints in the normal equation system

In the final stage of our NRT analysis strategy, the last 6-hour NEQ are stacked and relative constraints are imposed on the tropospheric ZPD parameters (see Section 4.3, Section 4.4.5 and Section 4.4.6 for details). For a given station A , the pseudo-observation equations express conditions in the form

$$ZPD_A(t_i) - ZPD_A(t_{i+1}) = 0 \quad (\text{A.9})$$

where t_i and t_{i+1} are two successive epochs of parameter estimation.

For each station, 1 pseudo-observation equation for each estimated tropospheric ZPD is set up (except for the last one). For the 208 stations and the 6-hour observation windows, a total of about 6032 pseudo-observation equations are thus added.

*Do not put your faith in what statistics say
until you have carefully considered what they
do not say.*

William W. Watt

B

Fundamentals of Statistics

Summary

*This appendix exposes the basic notions of statistics used in the thesis
to avoid any ambiguity on their definition or meaning.*

B.1 Normal Distribution

In probability theory and statistics, the *normal distribution* is a continuous probability distribution that describes a random variable X that clusters around a mean or average value. The graph associated with the *Probability Density Function* (PDF) is bell-shaped, with a peak at the mean value μ (Figure B.1). In Science, the normal distribution is usually referred to as the *Gaussian distribution* and it is often used for studying measurement errors. The *Probability Density Function* (PDF) of the normal distribution $\mathcal{N}(\mu, \sigma)$ reads

$$\begin{aligned}\mathcal{N}(\mu, \sigma) : \mathbb{R} &\mapsto \mathbb{R}^+ \\ x &\mapsto \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right)\end{aligned}\quad (\text{B.1})$$

where $\mu \in \mathbb{R}$ is the mean or average value (i.e. the expected value)
 $\sigma^2 \in \mathbb{R}^+$ is the variance

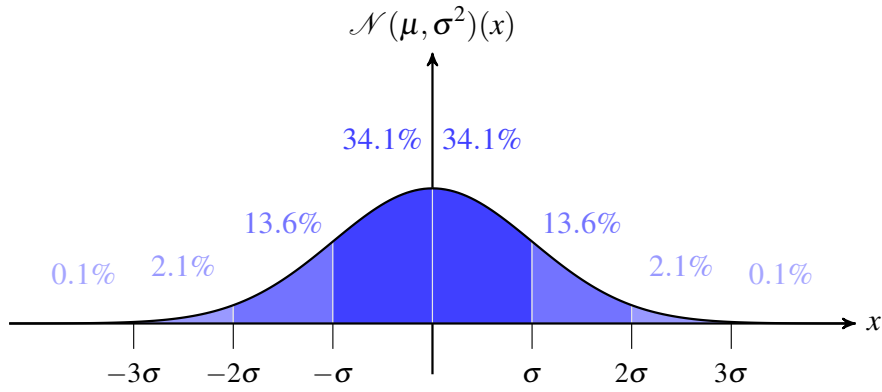


Figure B.1: Normal Probability Distribution Function (PDF)
of mean $\mu = 0$ and $\sigma = 1$

B.2 Mean, Standard Deviation and Confidence Intervals

The *standard deviation*, abbreviated here by *std. dev.*, of a statistical population or of a probability distribution is the square-root of its variance σ^2 . The standard deviation is widely used to measure the variability or dispersion of the population around the mean. In the case of a discrete variable X with mean value μ , taking random values from a finite data set $(x_1, \dots, x_N)$, which each values having the same probability, estimators of the mean and standard deviation read respectively

$$\hat{\mu} = \sum_{i=1}^N \frac{x_i}{N} \quad (\text{B.2})$$

$$\hat{\sigma} = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \hat{\mu})^2} \quad (\text{B.3})$$

The Central Limit Theorem

The *Central Limit Theorem* (CLT) states that the distribution of a sum of many independent, identically distributed random variables tends toward a normal distribution. Based on a normal distribution hypothesis, in addition to express the variability of a population around the mean value, the standard deviation is commonly used to measure the *Confidence Intervals* (CI) in statistical conclusions. In such case, about 68 % of the values observed are within $1 \cdot \sigma$ of the mean, about 95 % of these values are within $2 \cdot \sigma$ and about 99.7 % lie within $3 \cdot \sigma$ (Table B.1). This rule is usually referred to as the empiric rule of the $3 \cdot \sigma$.

CI	% within CI
$0.6745 \cdot \sigma$	50.00 %
$1 \cdot \sigma$	68.27 %
$1.645 \cdot \sigma$	90.00 %
$1.960 \cdot \sigma$	95.00 %
$2 \cdot \sigma$	95.45 %
$2.576 \cdot \sigma$	99.00 %
$3 \cdot \sigma$	99.73 %
$4 \cdot \sigma$	99.99 %

Table B.1: Percentage of observed values within a certain Confidence Interval (CI)

B.3 K^{th} Moment

In the case of a discrete variable X , with mean μ , taking random values from a finite data set $(x_1, \dots, x_N)$, each having the same probability, an estimator of the k^{th} moment is given by

$$\mu_k = \sum_{i=1}^N \frac{(x_i - \hat{\mu})^k}{N} \quad (\text{B.4})$$

where x_i is the i^{th} observed value of the discrete variable X , $\hat{\mu}$ is the value of the sample mean estimator and N the sample size.

B.4 Skewness

The *skewness* is a measure of the *asymmetry* or *lopsidedness* of the probability distribution of a real-valued random variable. The skewness is defined as the third (standardised) moment of the PDF and reads

$$\gamma_1 = \frac{\mu_3}{\sigma^3} \quad (\text{B.5})$$

where μ_3 is the third moment of the PDF. In the case of a discrete variable X , with mean μ , taking random values from a finite data set $(x_1, \dots, x_N)$, each having the same probability, an estimator of the *skewness* is given by

$$\hat{g}_1 = \frac{\frac{1}{N} \cdot \sum_{i=1}^N (x_i - \hat{\mu})^3}{\left(\frac{1}{N} \cdot \sum_{i=1}^N (x_i - \hat{\mu})^2\right)^{\frac{3}{2}}} \quad (\text{B.6})$$

where x_i is the i^{th} observed value of the discrete variable X and $\hat{\mu}$ is the value of the sample mean estimator. Many simplistic models assume a normal distribution, i.e. symmetry around the mean of the sample, which has a skewness of zero. In reality, data points are not perfectly symmetric, so an understanding of the skewness of a data set indicates where deviations from the mean are going to be positive or negative. A negative skewness reveals a longer left tail corresponding to the mass of the distribution concentrated more right of the mean. A positive skewness reveals a longer tail on the right, corresponding to a distribution concentrated on the left of the mean. Examples of distributions having positive and negative skewness are given in Figure B.2.

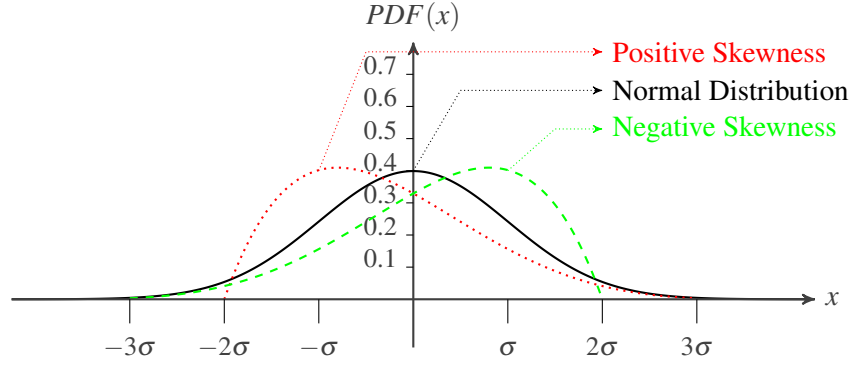


Figure B.2: Example of Probability Distribution Functions (PDF) having positive skewness (red curve) and negative skewness (green curve). In reference (black curve), the normal distribution (mean $\mu = 0$ and $\sigma = 1$) having zero skewness is drawn

B.5 Kurtosis

The *kurtosis* is a measure of the “peakiness” of the probability distribution of a real-valued random variable. The kurtosis is defined as the fourth standardised moment around the mean. It reads thus as the fourth moment divided by the square of the variance of the PDF, i.e.

$$\gamma_2 = \frac{\mu_4}{\sigma^4} \quad (\text{B.7})$$

In the case of a discrete variable X , which mean is μ , taking random values from a finite data set $(x_1, \dots, x_N)$, each having the same probability, an estimator of the *kurtosis* is given by

$$\hat{g}_2 = \frac{\frac{1}{N} \cdot \sum_{i=1}^N (x_i - \hat{\mu})^4}{\left(\frac{1}{N} \cdot \sum_{i=1}^N (x_i - \hat{\mu})^2 \right)^2} \quad (\text{B.8})$$

where x_i is the i^{th} observed value of the discrete variable X and $\hat{\mu}$ is the value of the sample mean estimator. Distributions with kurtosis equal to 3, such as the normal distribution, are called *mesokurtic*. Distribution with a kurtosis value

greater than 3 are called *leptokurtic*. They present a sharper peak and fatter tails around the mean. Distributions with a kurtosis value below 3 are called *platykurtic*. They present a more rounded peak with wider “shoulders” around the mean. Examples of *leptokurtic* and *platykurtic* distributions are given in Figure B.3.

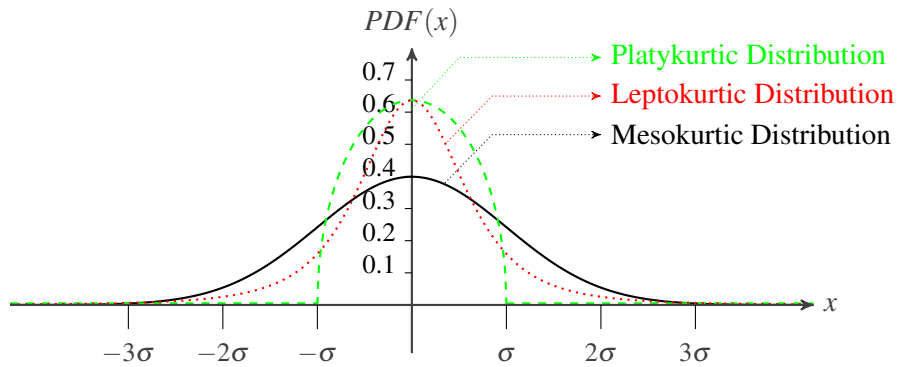
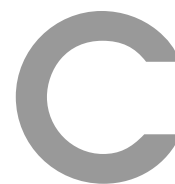


Figure B.3: Examples of mesokurtic (black curve), leptokurtic (red curve) and platykurtic (green curve) Probability Distribution Functions (PDF) of mean $\mu = 0$ and $\sigma = 1$



The EUMETNET EIG GNSS Water Vapour Program II

Summary

The appendix gathers some information on the EUMETNET EIG GNSS Water Vapour Program II (E-GVAP II) analysis centres and their analysis strategies.

C.1 Introduction

During the last decade, several European initiatives started to promote the use of ground-based GNSS tropospheric Zenith Path Delays (ZPD) in meteorology and climatology. These initiatives were joint ventures of geodesists and meteorologists aiming to stimulate the collaboration between their two communities at both the European and the national level. In 2005, the people involved in such projects decided to continue their activities within the *Network of European Meteorological Services* (EUMETNET) [EUMETNET Web Site] and to make operational meteorology benefit from GNSS

tropospheric ZPD estimates. Therefore, they started the *EUMETNET GPS Water Vapour Program* (E-GVAP) [E-GVAP Web Site]. The follow-up of the E-GVAP activities was ensured with the E-GVAP II project that started in April 2009.

C.2 E-GVAP Analysis Centres

Within E-GVAP the geodetic community plays an important role by operating 11 GNSS data analysis centres, which provide on a European scale ground-based GNSS ZPD estimates in near real-time to their EUMETNET partners for data assimilation in operational meteorology [Vedel, 2007]. These analysis centres are operated by

- ✎ The *Agenzia Spaziale Italiana* (ASI), which provides the ASI_ solution
- ✎ The *Bundesamt für Kartographie und Geodäsie* (BKG), which provides the BKG_ solution
- ✎ The *GeoForschungsZentrum* (GFZ) Potsdam, which provides the GFZ_ solution
- ✎ The *Geodetic Observatory Pecný* (GOP), which provides the GOP_ solution
- ✎ The *Spanish Instituto Geográfico Nacional* (IGE), which provides the IGE_ solution
- ✎ The *Koninklijk Nederlands Meteorologisch Instituut* (KNMI), which provides the KNMI solution
- ✎ The *swisstopo* (LPT), which provides the LPT_ solution
- ✎ The *U.K. Met Office* (METO), which provides the METO solution
- ✎ The *Nordic GNSS Analysis Centre* (NGAA), which provides the NGAA solution
- ✎ The *Royal Observatory of Belgium* (ROB), which provides the ROB_ solution
- ✎ The *French IGN service of geodesy* (SGN), which provides the SGN_ solution

C.3 E-GVAP Analysis Centre Strategies

No strict guidelines are imposed on the E-GVAP analysis centres. The analysis strategy of each analysis centre slightly differs from the other notably in terms of GNSS network and processing options, or even in term of GNSS processing software. An overview of their processing schemes is provided in Table C.1.

ASI_	BKG_	GFZ_	GOP_	IGE_	KNMI	LPT_	METO	NGAA	ROB_	SGN_
Software and Approach										
GIPSY ver. 4.04	BSW ver. 5.0	EPOS.P ver. 2.0	BSW ver. 5.0	BSW ver. 5.0	BSW ver. 5.0	BSW ver.5.0+	BSW ver. 5.0	GIPSY n.a.	BSW ver. 5.0	BSW ver. 5.0
NET	NET	PPP	NET	NET	NET	NET	NET	PPP	NET	NET
Orbits, Clocks and Earth Orientation Parameters										
IGU	IGSP24	GFZ calculated	IGU	IGU	IGU	IGU	IGU	NGAA calculated	IGU	IGU
Antenna Calibration Models										
Absolute	Absolute	Relative	Absolute	Absolute	Absolute	Absolute	Absolute	Absolute	Absolute	Absolute
Ocean Tide Loading Model										
FES2004	n.a.	Pagatakis	FES2004	FES2004	n.a.	FES2004	FES2004	FES2004	FES2004	FES2004
Relative Constraints										
10 mm	n.a.	Random walk	15 mm	1 mm	n.a.	Loose	1 mm	Random walk	2 mm	10 mm
Bernese Normal Equation File Window										
24 hours	n.a.	n.a.	12 hours	12 hours	n.a.	8 hours	5 hours	n.a.	6 hours	5 hours
Number of GNSS Sites Processed										
76	95	317	73	97	47	95	212	380	211	189
Number of E-GVAP Super-Sites Included (total: 14 sites)										
12	7	9	14	9	14	13	11	9	14	13
Repetition Cycle										
15 min	60 min	15 min	60 min	15 min	15 min	60 min	15 min	5 min	15 min	15 min

Table C.1: Strategies applied by the different E-GVAP analysis centres
Source: [E-GVAP Web Site] - April 2009
N.A.: information not available

*Two are better than one, because they
have a good return for their work: If one
falls down, his friend can help him up.
But pity the man who falls and has no
one to help him up! Though one may be
overpowered, two can defend themselves.
A cord of three strands is not quickly
broken.*

King Solomon



The EUREF-EUMETNET Memorandum of Understanding

Summary

This appendix briefly exposes the origin and the terms of the memorandum of understanding signed by EUREF and EUMETNET. We explain the practical and technical aspects of this memorandum in the framework of which several sources of meteorological observations used in this thesis are accessed. More details on the content of this appendix can be found in [EUREF-EUMETNET-2007] and [Pottiaux et al., 2009].

D.1 Introduction

During the EUREF Symposium 2007 held in London, a memorandum of understanding (MoU) was signed between EUREF and EUMETNET with the goal to increase synergies and collaborations between the geodetic and

meteorological communities and to facilitate the data exchange between the two parties [EUREF-EUMETNET-2007]. Indeed, both communities would benefit from sharing their expertise and their infrastructures: on one hand, the *EUMETNET GPS Water Vapour Program* (E-GVAP) [E-GVAP Web Site], which is a program running under the aegis of the *Network of European Meteorological Services* (EUMETNET) [EUMETNET Web Site], aims at establishing a European observing system for delivering near real-time (NRT) ground-based GNSS tropospheric Zenith Path Delay (ZPD) estimates for *Numerical Weather Prediction* (NWP) and *nowcasting* applications (Section 4.2). In that context, meteorologists need continued access to GNSS raw data and products. On the other hand, EUREF, which is the reference frame sub-commission for Europe of the *International Association of Geodesy* (IAG) [IAG Web Site], maintains the *EUREF Permanent Network* (EPN, Figure 2.9). EUREF also determines the coordinates of the continuously observing EPN GNSS stations to maintain the *European Terrestrial Reference System* (ETRS89). To improve its GNSS data processing and to validate its GNSS-derived products, EUREF needs access to meteorological observations from all over Europe. In the context of the MoU, EUMETNET recently granted EUREF with a free access to meteorological observations provided by national meteorological agencies member of EUMETNET. In [Pottiaux *et al.*, 2009], the status of the EUREF-EUMETNET collaboration is reviewed and the potential benefits of using the meteorological observations to validate the GNSS data processing and their derived products are outlined from the geodetic point of view. The practical and technical aspects of this collaboration, in the framework of which several sources of meteorological observations used in this thesis are accessed, are summarised hereafter.

D.2 The Meteorological Database

The meteorological database set up by EUMETNET in the context of the EUREF-EUMETNET collaboration is based on the already existing e-infrastructure of E-GVAP. The free FTP access to the database is granted provided that a standard “condition of use” form (stating that the data will be used for non-commercial applications solely) is signed. For this purpose,

the EUMETNET contact person is the E-GVAP program manager Henrik Vedel. Since June 2008, access to synoptic data (Section D.3) and radiosonde observations (Section D.4) has been provided to EUREF members through the meteorological database. For the time being, the database is updated daily and the latency of the meteorological observations is roughly 1 day. In the future, other types of observations, such as output from the short-range forecasting system *High-Resolution Limited Area Model* (HIRLAM) [Uden *et al.*, 2002] (Section D.5), will be added to the database. More frequent updates of the database and a reduction of the latencies are also foreseen to fill the needs of user applications.

Directory structure of the meteorological database:

```

‘‘http://ftp.metoffice.gov.uk’’
├── archive
├── met ..... SYNOPTIC FILES (synop_YYYYMMDD_knmi.dat.gz)
│   ├── rs
│   │   ├── past
│   │   │   ├── YYYYMM PAST RADIOSONDE FILES (?????.YYYYMM.gz)
│   │   │   └── recent
│   │   │       ├── YYYYMM ..... RECENT RADIOSONDE FILES
│   │   │       │   (?????.YYYYMM.gz)
│   │   └── hirlam
│   │       ├── dmi
│   │       │   ├── YYYYMM ..... HIRLAM FILES

```

where  YYYY is the 4-char year

 MM is the 2-char month

D.3 Synoptic Observations

The first type of meteorological data that has been made available through the MoU was the synoptic observations. Synoptic observations gather hourly surface records of pressure, mean sea-level pressure, temperature and dew-point temperature. All observations related to a specific day are included in a unique file within the database, which contains data from more than 1280 meteorological stations in Europe. A sample of a synoptic file content is given hereafter (File Outline D.3.1). Examples of the temperature and the mean sea-level pressure fields reconstructed from the synoptic observations are shown in Figure D.1 and Figure D.2. From these ground meteorological measurements, a tropospheric Zenith Hydrostatic path Delay (ZHD) field, as it is used in Chapter 6 might notably be reconstructed (Section 6.4.1).

File Outline D.3.1 (Sample of synoptic file content - 29th September 2009).

```
EGVAP METv1.0 source : KNMI-RTWNDB
WMONo YYYYMMDDHHmm lat (deg) lon (deg) MSLht(m) P(hPa) Pmsl Temp(K) DewT(K)
01001 200909290000 70.93000 -8.67000 10.000 1008.5 1009.7 275.9 272.0
01001 200909290100 70.93000 -8.67000 10.000 1008.7 1009.9 276.2 272.2
01001 200909290200 70.93000 -8.67000 10.000 1008.6 1009.8 276.3 272.5
01001 200909290300 70.93000 -8.67000 10.000 1008.4 1009.6 276.2 270.9
01001 200909290400 70.93000 -8.67000 10.000 1008.2 1009.4 276.1 270.5
01001 200909290500 70.93000 -8.67000 10.000 1007.6 1008.8 276.0 270.2
01001 200909290600 70.93000 -8.67000 10.000 1007.3 1008.5 276.0 271.2
01001 200909290700 70.93000 -8.67000 10.000 1007.3 1008.5 275.7 271.2
01001 200909290800 70.93000 -8.67000 10.000 1007.5 1008.7 275.5 270.8
01001 200909290900 70.93000 -8.67000 10.000 1007.7 1008.9 275.5 270.3
01001 200909291000 70.93000 -8.67000 10.000 1007.9 1009.1 275.7 269.8
01001 200909291100 70.93000 -8.67000 10.000 1007.7 1008.9 275.6 270.2
01001 200909291200 70.93000 -8.67000 10.000 1007.6 1008.8 275.4 270.2
01001 200909291300 70.93000 -8.67000 10.000 1007.6 1008.8 275.4 269.8
01001 200909291400 70.93000 -8.67000 10.000 1007.5 1008.7 275.3 270.5
...
```

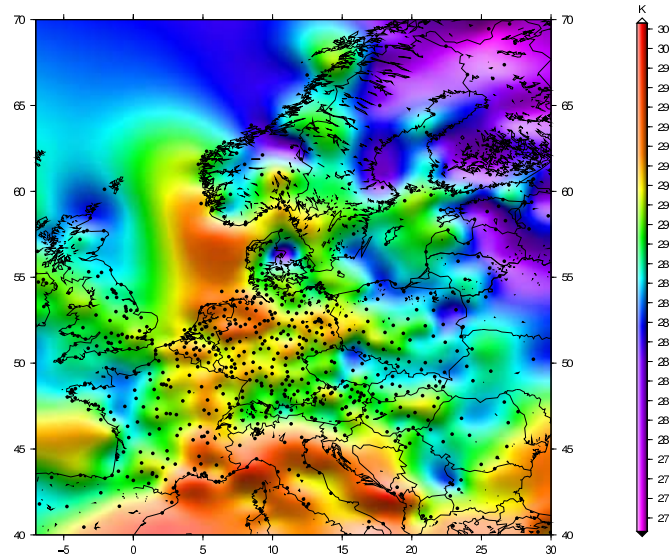


Figure D.1: Temperature field reconstructed from the 1280 synoptic observations recorded on the 29th July 2008 at 00:00 UTC (synoptic observation sites are indicated by black dots)

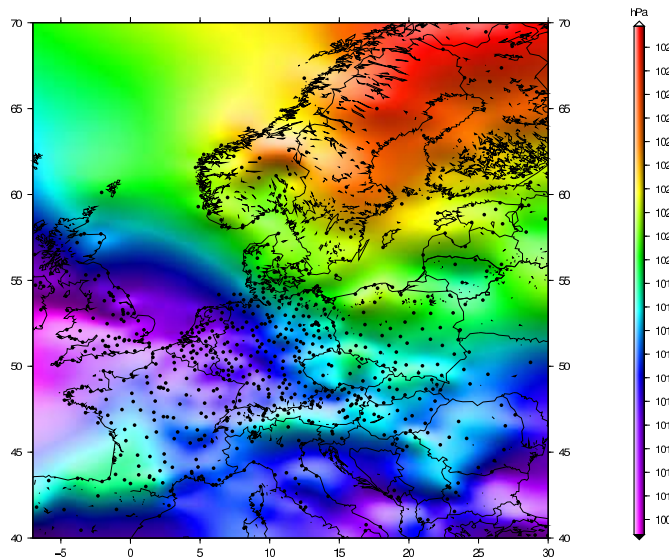


Figure D.2: Mean sea-level pressure field reconstructed from the 1280 synoptic observations recorded on the 29th July 2008 at 00:00 UTC (synoptic observation sites are indicated by black dots)

D.4 Radiosonde Observations

National meteorological agencies provide the *World Meteorological Organisation* (WMO) [WMO Web Site] with radiosonde observations via the *Global Telecommunication System* (GTS) [GTS Web Site]. As explained in Appendix E, hydrostatic and wet tropospheric ZPD values can be computed. In the context of the EUREF-EUMETNET collaboration, a procedure has been set up to extract the radiosonde observations from the GTS database (and additional national radiosonde data which are missing in the GTS database) within a limited grid area covering Europe and extending from 30° W to 40° E in longitude and from 25° N to 89.9° N in latitude. Again, all radiosonde observations related to a specific day are included in a unique file, which contains observations from more than 200 radiosonde launch sites in this European grid (Figure D.3). An example of a radiosonde file is given hereafter (File Outline D.4.1). Radiosonde observations have been used in this work to detect deficiencies in our GNSS analysis strategy and to assess the accuracy of the ground-based GNSS tropospheric ZPD estimates (Section 5.5.1). More details on radiosondes are given in Appendix E.

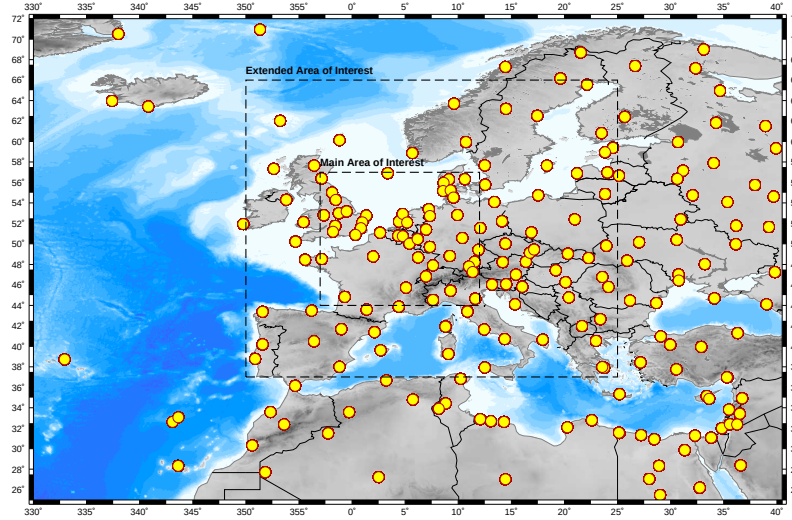


Figure D.3: Geographical location of the radiosonde launch sites available in the meteorological database in the frame of the EUREF-EUMETNET collaboration

File Outline D.4.1 (Example of radiosonde file content - 27th September 2009).

```

# NO  JAN MAYEN
1001  70.93  -8.67    9. 42  2009  9 27  0  0
98100.00    90.00  274.40  270.70  0.32399E-02
97900.00   250.00  275.60  270.60  0.32230E-02
92500.00   4730.00  271.90  268.70  0.29540E-02
85000.00  11280.00  266.50  264.00  0.21716E-02
82200.00  13810.00  264.30  263.40  0.20932E-02
76000.00  19720.00  260.10  259.90  0.16111E-02
70000.00  25830.00  255.70  249.70  0.69178E-03
69800.00  26020.00  255.50  249.50  0.68013E-03
65800.00  30320.00  252.30  245.30  0.47663E-03
61200.00  35520.00  247.70  243.90  0.42938E-03
57100.00  40410.00  243.50  236.50  0.21446E-03
50600.00  48720.00  235.70  231.60  0.13487E-03
50000.00  49520.00  235.30  231.00  0.12755E-03
41700.00  61630.00  229.50  215.50  0.24036E-04
40000.00  64430.00  227.70  216.70  0.28601E-04
38400.00  67020.00  225.90  216.90  0.30017E-04
33200.00  76420.00  224.50  207.50  0.10071E-04
30000.00  83060.00  229.30  198.30  0.30790E-05
26800.00  90550.00  235.10  197.10  0.30321E-05
25000.00  95320.00  234.30  197.30  0.33265E-05
20000.00 110130.00  230.30  194.30  0.24925E-05
15300.00  -9999.00  228.50  193.50  0.28143E-05
15000.00 129150.00  229.30  193.30  0.28005E-05
13800.00  -9999.00  231.90  194.90  0.40384E-05
12100.00  -9999.00  226.70  191.70  0.26039E-05
10000.00 155730.00  226.30  191.30  0.29368E-05
9490.00  -9999.00  227.50  192.50  0.38175E-05
7000.00 178870.00  224.50  190.50  0.36072E-05
6410.00  -9999.00  221.50  188.50  0.27234E-05
5620.00  -9999.00  222.90  188.90  0.33716E-05
5000.00 200350.00  219.90  186.90  0.26023E-05
4190.00  -9999.00  216.50  184.50  0.19593E-05
3690.00  -9999.00  219.10  186.10  0.30379E-05
3380.00  -9999.00  214.50  183.50  0.19868E-05
3090.00  -9999.00  216.90  184.90  0.28669E-05
3000.00 232220.00  216.10  184.10  0.25349E-05
2720.00  -9999.00  214.90  183.90  0.26666E-05
2550.00  -9999.00  218.30  186.30  0.45219E-05
2120.00  -9999.00  214.50  183.50  0.31676E-05
2000.00 257420.00  214.30  183.30  0.32303E-05
1700.00  -9999.00  212.30  181.30  0.25683E-05
1540.00  -9999.00  216.50  184.50  0.53307E-05

```

D.5 Numerical Weather Prediction Model Data

Numerical Weather Prediction (NWP) is an initial value problem: provided an estimate of the atmospheric state, the model simulates the atmospheric state at latter times. The determination of the initial state is referred to as the *data analysis* or *data assimilation*. The predicted states at latter times are called the *analysis*. The NWP problem is a under-estimated problem and auxiliary information are necessary. Usually, data from short-term NWP forecasts are used. These data are called *background* or *first guess field*. Modern data assimilation combines many, widely different types of observations and the *background* field to produce the atmospheric state at latter times. GNSS observations are one of them. During the assimilation process, a quality control of the observations is performed. It evaluates notably the deviation between the observations and the expectation based on a short-term forecast (*background field*) while taking into account the statistical description of the errors in both, the forecast field and the observations. The values of the deviation between the GNSS tropospheric observations and the background field (O-B analysis) have been used in this work to detect the deficiencies in our GNSS analysis strategy and to assess the accuracy of the ground-based GNSS tropospheric ZPD estimates Section 5.5.3. The *High-Resolution Limited Area Model* (HIRLAM) [Unden *et al.*, 2002] is one of the NWP models running in Europe. It runs in different setup flavours, according to the meteorological institute running the model. It runs notably at the *Koninklijk Nederlands Meteorologisch Instituut* (KNMI) and the *Danish Meteorological Institute* (DMI). As an example, at the KNMI, HIRLAM is run operationally every 6 hours to forecast the weather of the next 48 hours. The model assimilates synoptic observations such as wind, temperature and humidity from radiosondes and surface wind and temperature records to analyse the initial state of the atmosphere. No GNSS data are assimilated yet. The previous 6-hour forecast is used as *background field* information and the boundary conditions are retrieved from the *European Centre for Medium-Range Weather Forecasting* (ECMWF) forecast fields.

File Outline D.5.1 (Sample of O-B analysis file content - 30th September 2008).

```

0070
Data from NWP HIRLAM derived at DMI
51.45960 11.98050 128.98600 106.34582
2008 09 30 00
24
0 0 2.3692 0.1022 15.9278 99628.71 2.3750 0.1006 15.6625 99951.91 283.16 0.6490E-02
1 0 2.3679 0.1000 15.5251 99671.61 2.3756 0.1018 15.8191 99929.86 282.37 0.6430E-02
2 0 2.3674 0.0995 15.4227 99667.13 2.3758 0.1028 15.9568 99896.90 281.93 0.6315E-02
3 0 2.3662 0.0993 15.3940 99620.41 2.3741 0.1016 15.7659 99869.32 281.74 0.6251E-02
4 0 2.3615 0.0959 14.8388 99565.98 2.3691 0.0977 15.1309 99822.50 281.22 0.6078E-02
5 0 2.3581 0.0934 14.4184 99524.88 2.3657 0.0954 14.7496 99773.09 280.81 0.5922E-02
6 0 2.3623 0.0981 15.1457 99505.36 2.3698 0.0998 15.4297 99760.40 281.62 0.6116E-02
7 0 2.3718 0.1083 16.6951 99474.30 2.3791 0.1095 16.9036 99740.52 282.43 0.6200E-02
8 0 2.3766 0.1152 17.7774 99377.84 2.3833 0.1154 17.8031 99666.59 283.68 0.6237E-02
9 0 2.3791 0.1188 18.3231 99333.72 2.3859 0.1190 18.3429 99625.19 284.68 0.6413E-02
10 0 2.3798 0.1201 18.5297 99307.62 2.3866 0.1203 18.5537 99598.10 285.25 0.6729E-02
11 0 2.3827 0.1245 19.2476 99240.89 2.3886 0.1232 19.0231 99559.14 284.98 0.6878E-02
12 0 2.3850 0.1251 19.2932 99311.95 2.3941 0.1295 20.0174 99522.91 284.49 0.6929E-02
13 0 2.3880 0.1312 20.2531 99179.45 2.3960 0.1334 20.6147 99434.03 284.12 0.6952E-02
14 0 2.3866 0.1321 20.4012 99075.29 2.3948 0.1348 20.8320 99322.42 283.85 0.6919E-02
15 0 2.3856 0.1316 20.3086 99058.59 2.3946 0.1355 20.9562 99281.42 283.73 0.6886E-02
16 0 2.3846 0.1322 20.4235 98983.96 2.3935 0.1361 21.0599 99207.70 283.54 0.6849E-02
17 0 2.3822 0.1319 20.3708 98893.87 2.3915 0.1364 21.1196 99105.45 283.36 0.6794E-02
18 0 2.3847 0.1357 20.9924 98836.19 2.3936 0.1394 21.5944 99066.13 283.87 0.7170E-02
19 0 2.3877 0.1409 21.8358 98738.33 2.3943 0.1409 21.8161 99032.27 283.61 0.7123E-02
20 0 2.3853 0.1409 21.8460 98631.77 2.3913 0.1400 21.6778 98940.22 283.52 0.7040E-02
21 0 2.3798 0.1371 21.2383 98560.96 2.3879 0.1394 21.6178 98813.51 283.56 0.7032E-02
22 0 2.3792 0.1385 21.5081 98471.38 2.3865 0.1395 21.6655 98746.29 283.75 0.7071E-02
23 0 2.3754 0.1362 21.1610 98405.07 2.3831 0.1379 21.4394 98666.48 283.71 0.7120E-02
...

```


There are no such things as applied sciences, only applications of science.

Louis Pasteur (1822-1895)



Tropospheric Path Delays From Radiosonde Observations

Summary

This appendix familiarises the reader with the radiosonde balloon technique (system design, raw in-situ measurements) and exposes the method used in this work to derive tropospheric path delay information from the raw in-situ measurements recorded by the radiosonde device. Finally, the method is illustrated by assessing the long-term behaviour of the tropospheric path delay over Belgium using radiosonde observations.

E.1 Introduction

Despite its major inconveniences (poor spatial coverage, cost and instrumental biases), the *radiosonde* balloon technique remains world-wide the main source of upper-air atmospheric water vapour information used by the meteorologists in their operational models. It is also the main source of in-situ atmospheric measurements that allows the computation of tropospheric path delays.

Therefore, this technique is used to assess the accuracy of the tropospheric Zenith Path Delays (ZPD) obtained from ground-based GNSS observations (Section 5.5.1). *Radiosondes* are small, light weight instrument platforms suspended from a helium-filled balloon equipped with radio transmitting capabilities. These devices are capable of making direct in-situ measurements of air temperature, relative humidity and pressure while ascending through the atmosphere. When released at the ground, the apparatus rises through the atmosphere at roughly 5 m/s and terminates its ascent at an altitude of about 30km after a usual time of more than one hour [Vedel *et al.*, 2001]. The radiosonde package can be equipped with a radar reflector that permits radio-direction finding antenna equipments located at the ground station to determine the elevation and the azimuth of the balloon during its ascent. These elevation and azimuth information are then converted into wind speed and wind direction at various levels in the atmosphere. The in-situ observations are transmitted to the ground station in real-time by means of the radio-transmitter. At the ground station, the received information is processed at some fixed time interval along with the elevation and azimuth of the balloon when available. Nominally, meteorological institutes launch balloons at 00:00 and 12:00 UTC, but launches are also often carried out at 06:00 and 18:00 UTC. The radiosonde observations describe thus the vertical profile of temperature, relative humidity, wind direction and wind speed as a function of pressure and height from the ground surface to the altitude where the sounding is terminated (Figure E.1).

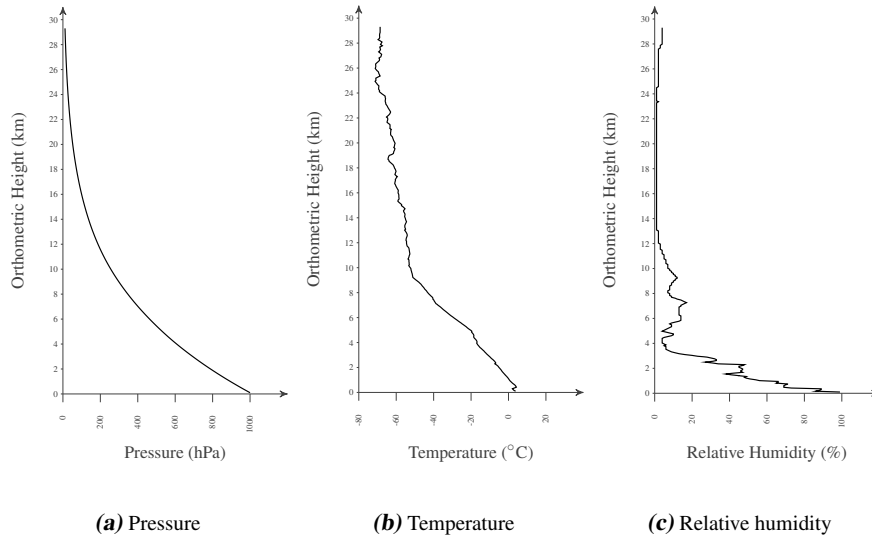


Figure E.1: Raw in-situ measurement profiles observed by a radiosonde sounding carried out at 00:00 UTC on the 1st December 2003 in Uccle, Belgium

E.2 Tropospheric Path Delays Derived From Radiosonde Profiles

The primary observables of the radiosondes, i.e. the pressure, temperature and relative humidity, recorded during the ascent of the balloon can be used to compute the dry and wet refractivity index (Section 3.2.1) profiles along the path followed by the balloon. These refractivity index profiles can be used, in turn, to infer the corresponding hydrostatic and wet tropospheric path delays (Section 3.2.3) at the height of the GNSS stations. In the frame of this work, a program has been written to process the radiosonde in-situ raw observations and to compute these tropospheric path delays. Later, a dedicated software was provided to the geodesists in the context of the EUREF-EUMETNET collaboration (Appendix D) by the E-GVAP program manager, Henrik Vedel, to compare GNSS and radiosonde-based tropospheric ZPD. Results from both software were compared and showed a good agreement.

E.2.1 Refractivity Index Profiles

The first step to infer the tropospheric path delays is to derive the *refractivity index profiles* from the raw in-situ measurements taken by the radiosonde device. The developments introduced in Chapter 3 demonstrated that the hydrostatic and wet refractivity indices (noted here as N_{hydro} and N_{wet} respectively) can be expressed as function of the altitude z as

$$N_{hydro}(z) = k_1 \cdot R_d \cdot \rho_{tot}(z) \quad (E.1)$$

and

$$N_{wet}(z) = \left(k_2 - \frac{R_d}{R_v} \cdot k_1 + \frac{k_3}{T(z)} \right) \cdot \frac{e(z)}{T(z)} \quad (E.2)$$

- where
- ✎ z is the orthometric height in metres
 - ✎ ρ_{tot} is the total density of the air in $kg \cdot m^{-3}$
 - ✎ R_d and R_v are the dry and wet gas constants respectively in $m^2 \cdot s^{-2} \cdot K^{-1}$
 - ✎ T is the ambient temperature of the air in Kelvin
 - ✎ e the water vapour partial pressure in hPa

The k_i (for $i \in 1, 2, 3$) are empirically determined constants quantifying the refractivity of the lower neutral atmosphere for radio-waves in the GNSS frequency range (Section 3.2.1). The uncertainties of their values may contribute to the uncertainty of the tropospheric Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD) values at the millimetre level. Example of values for the k_i constants are given in Table 3.1. We used here those from [Bevis *et al.*, 1994].

E.2.2 Tropospheric Hydrostatic Path Delays

Using the expression of the *hydrostatic refractivity index* given in Equation E.1, the expression of the tropospheric Zenith Hydrostatic Delay (ZHD) given in Equation 3.13 can be reformulated, with a slightly different notation, as

$$ZHD = 10^{-6} \cdot \int_{z_{site}}^{z_{top}} k_1 \cdot R_d \cdot \rho_{tot}(z) \cdot dz \quad (\text{m}) \quad (\text{E.3})$$

where z is the orthometric height in metres

z_{site} is the orthometric height of the radiosonde launch site in metres

z_{top} is the orthometric height of the top of the atmosphere in metres

Under the assumption of local hydrostatic equilibrium, $dP = -\rho_{tot}(z) \cdot g \cdot dz$ and the tropospheric ZHD reads

$$ZHD = 10^{-6} \cdot \int_{P_{top}}^{P_{site}} k_1 \cdot \frac{R_d}{g} \cdot dP \quad (\text{m}) \quad (\text{E.4})$$

where g is the local vertical acceleration due to gravity and non inertial forces.

Ellipsoidal and Orthometric Heights

When comparing GNSS and radiosonde derived tropospheric ZPD, the height of both the radiosonde and the GNSS station must be expressed in the same system: the orthometric height. Therefore, the ellipsoidal GNSS station heights are transformed into orthometric heights using the new *Earth Gravitational Model 2008* (EGM2008) geoid from the U.S. *National Geospatial intelligence Agency* (NGA) [Pavlis *et al.*, 2008]. The exact accuracy of this model is not yet well established. Nevertheless, it is expected to have an accuracy better than 10cm and consequently, errors from using the EGM2008 model should impact the tropospheric ZPD by less than 0.5 mm.

Variations of g with Height

When using Equation E.4 to determine the tropospheric ZHD, it is important to include the variations of g with height. Indeed, these variations correspond to using the proper geometric height in Equation E.3 rather than the geopotential heights commonly used in meteorology, see [Vedel, 2000] for details. According to [Vedel *et al.*, 2001], the effect of not including these variations in Equation E.4 is about -5 mm in tropospheric ZPD for a station at mid-latitude. The variations in the value of g across the Earth's surface is about 0.5% due to latitude plus a change of roughly 0.003% per 100m of altitude. An approximate value of g at a given latitude Φ and height H above the mean sea level geoid may be calculated from the formula

$$g(\Phi, H) = g_0 \cdot (1 + A \cdot \sin^2(\Phi) + B \cdot \sin^2(2\Phi)) - C \cdot H \quad (\text{m} \cdot \text{s}^{-2}) \quad (\text{E.5})$$

where $g_0 = 9.780318 (\text{m} \cdot \text{s}^{-2})$

$A = 0.0053024$

$B = 0.0000059$

$C = 3.086 \cdot 10^{-6} (\text{s}^{-2})$

Φ is the latitude in degree

H is the altitude in metres above the mean sea level (orthometric height)

The uncertainty in the value of g obtained using this equation is generally less than ± 5 parts in 10^5 .

Contribution From Above the Radiosonde Profile

The contribution to the integral in Equation E.4 from above 80km is negligible, thus the lower limit of the integral P_{top} can safely be set to zero [Vedel *et al.*, 2001]. Nonetheless, the contribution of the hydrostatic refractivity to the tropospheric ZHD from the top of the radiosonde profile up to about 80km is significant and cannot be neglected. Therefore, [Vedel *et al.*, 2001] derived an expression to account for the contribution of the dry delay from the top of

the known profile and further up. This expression is based on the assumptions of hydrostatic equilibrium and of the temperature being constant upwards the top of the known profile. If we note r the distance to the centre of the Earth, this expression reads

$$\Delta ZHD = 10^{-6} \cdot \frac{k_1 \cdot R_d \cdot P_1}{g_1} \cdot \left\{ 1 + 2 \left(\frac{R_d \cdot T_1}{r_1 \cdot g_1} \right) + 2 \left(\frac{R_d \cdot T_1}{r_1 \cdot g_1} \right)^2 \right\} \quad (\text{m}) \quad (\text{E.6})$$

where T_1 , g_1 , r_1 and P_1 are the values at the top of the known profile. A value of g_1 can be derived using the procedure used in [Vedel, 2000].

E.2.3 Integrated Water Vapour

The *Integrated Water Vapour* (IWV) is defined as the integral of the water vapour density along the vertical column of the neutral atmosphere and reads

$$IWV = \int_{z_{site}}^{z_{top}} \rho_v(z) \cdot dz \quad (\text{kg} \cdot \text{m}^{-2}) \quad (\text{E.7})$$

where the same notations as in Equation E.3 have been used and where ρ_v is the water vapour density in $\text{kg} \cdot \text{m}^{-3}$. The water vapour density at altitude z can be expressed as a function of the raw in-situ radiosonde observations as followed

$$\rho_v(z) = U(z) \cdot e_s(z) \cdot \frac{1}{R_v \cdot T(z)} \quad (\text{kg} \cdot \text{m}^{-3}) \quad (\text{E.8})$$

where U is the relative humidity in percent and e_s the saturation water vapour pressure in hPa. The saturation water vapour pressure e_s has to be decomposed into “raw in-situ radiosonde observations” using the *Clausius-Clapeyron equation*, which can be rewritten as

$$e_s(z) = e_{s_0} \cdot \exp \left[\frac{L_v}{R_v} \cdot \left(\frac{1}{T_0} - \frac{1}{T(z)} \right) \right] \quad (\text{hPa}) \quad (\text{E.9})$$

- where
-  e_s is the saturation water vapour pressure in hPa
 -  $e_{s_0} = 6.11 \text{ hPa}$
 -  R_v is the specific gas constant for water vapour in $\text{m}^2 \cdot \text{s}^{-2} \cdot \text{K}^{-1}$
 -  T is the temperature in degree Kelvin
 -  $T_0 = 273 \text{ K}$
 -  L_v is the specific warmth of water vapour and can be computed using
 $L_v = (3.14001 - 0.00234 \cdot T(z)) \cdot 10^6 \quad \text{J} \cdot \text{kg}^{-1}$

This decomposition leads to the final expression of the IWV:

$$IWV = \int_{z_{site}}^{z_{top}} \alpha(z) \cdot \exp[\beta(z)] \cdot dz \quad (\text{kg} \cdot \text{m}^{-2}) \quad (\text{E.10})$$

where

$$\alpha(z) = \frac{U(z) \cdot e_{s_0}}{R_v \cdot T(z)}$$

and

$$\beta(z) = \frac{(3.14001 - 0.00234 \cdot T(z)) \cdot 10^6}{R_v} \cdot \left(\frac{1}{T_0} - \frac{1}{T(z)} \right)$$

E.2.4 $Q(T_m)$ Factor

The $Q(T_m)$ parameter is defined as the factor that relates the tropospheric ZWD and the IWV. The relation reads

$$ZWD = Q(T_m) \cdot IWV \quad (\text{m}) \quad (\text{E.11})$$

where T_m is the weighted mean temperature of the atmosphere along the integration path and is defined as

$$T_m = \frac{\int_{z_{site}}^{z_{top}} \frac{e(z)}{T(z)} \cdot dz}{\int_{z_{site}}^{z_{top}} \frac{e(z)}{T^2(z)} \cdot dz} \quad (\text{K}) \quad (\text{E.12})$$

According to [Baltink *et al.*, 2002], we have

$$Q(T_m) = 10^{-3} \cdot R_v \left\{ \frac{k_3}{T_m} + k_2 - \frac{R_d}{R_v} \cdot k_1 \right\} \quad (\text{m} \cdot \text{K}^{-1}) \quad (\text{E.13})$$

where the linear relation $T_m = 0.72 \cdot T_s + 70.2$ (m/K) from [Bevis *et al.*, 1992] is commonly applied, although it is well known that the relation between T_m and T_s is seasonally and location dependent [Ross and Rosenfeld, 1997]. A approximate value of $Q(T_m)$ is about 6.5 m/K.

E.2.5 Tropospheric Non-Hydrostatic Path Delays

Using the expression of the *wet refractivity index* given in Equation E.2, the expression of the tropospheric ZWD given in Equation 3.14 can be reformulated, with a slightly different notation, as

$$ZWD = 10^{-6} \cdot \int_{z_{site}}^{z_{top}} \left(k_2 - \frac{R_d}{R_v} \cdot k_1 + \frac{k_3}{T(z)} \right) \cdot \frac{e(z)}{T(z)} \cdot dz \quad (\text{m}) \quad (\text{E.14})$$

Using the relationship $e(z) = e_s(z) \cdot U(z)/100$ (hPa) and the same decomposition as in Section E.2.3, it leads us to the final expression

$$ZWD = 10^{-6} \cdot \int_{z_{site}}^{z_{top}} \alpha(z) \cdot \exp[\beta(z)] \cdot dz \quad (\text{m}) \quad (\text{E.15})$$

where

$$\alpha(z) = \left(k_2 - \frac{R_d}{R_v} \cdot k_1 + \frac{k_3}{T(z)} \right) \cdot \frac{RH(z)}{100} \cdot e_{s_0}$$

and

$$\beta(z) = \frac{(3.14001 - 0.00234 \cdot T(z)) \cdot 10^6}{R_v} \cdot \left(\frac{1}{T_0} - \frac{1}{T(z)} \right)$$

Contribution From Above the Radiosonde Profile

The contribution of the wet refractivity to the tropospheric ZWD from above the top of a standard radiosonde profile (i.e. typically 30km) is negligible. Therefore, no correction term was applied, contrary to the hydrostatic term.

E.3 Exploitation of the Radiosonde Database

In the context of the EUREF-EUMETNET collaboration (Appendix D), we accessed the radiosonde observations from the European network made available by the Memorandum of Understanding (MoU) (Section D.4). This database was used to compute tropospheric ZPD throughout Europe and to validate the GNSS analysis strategy developed in Chapter 4 (see Section 5.5 for details). We also used radiosonde observations from the *Royal Meteorological Institute of Belgium* (RMI): between the 1st January 1990 and the 1st November 2003, the RMI carried out systematic radiosonde launches twice a day (one at 00:00 UTC and one at 12:00 UTC) on the site of Uccle, Belgium. The radiosonde launch site of Uccle is located a few tens of metres away from the IGS GNSS station of Brussels. Observations from this 13 years database were used to characterise the order of magnitude, the seasonal and long-term trends in the hydrostatic and non-hydrostatic tropospheric path delays over Belgium (centre of the area of interest). Figure E.2 and Figure E.3 illustrate the hydrostatic and wet tropospheric path delays computed from Equation E.4 and Equation E.15 for the site of Uccle over 13 years. A clear annual variation of the tropospheric ZWD is visible with a maximum average of about 16 cm in the summer and a minimum average of about 7 cm in the winter. The hydrostatic

delay reveals an invert pattern with a minimum average of about 2.28 m in the summer and a maximum average of about 2.31 m in the winter. The reasons for these annual variations are well known from the meteorologists: in the case of the tropospheric ZWD, these variations are mainly due to the annual variations of the temperatures giving more humid air in the summer and drier air in the winter. In the case of the tropospheric ZHD, these variations are mainly due to the low-pressure trend in winter. Diurnal patterns are also visible: the tropospheric ZWD time series recorded at noon present more variability compared to the one recorded during the night. This pattern is also visible in the standard deviations obtained from the comparison between the GNSS and radiosonde-based tropospheric ZWD, when analysing separately the night and day radiosonde launches. The higher variability at noon is due to the impact of the solar radiation on the radiosonde device, inducing a bias in the humidity sensor. This effect is even stronger during the summertime compared to the wintertime. For the tropospheric ZHD, mostly no diurnal variations can be emphasised.

Remark: *The variability (range) of the tropospheric ZWD is about 2 to 3 times the one of the tropospheric ZHD.*

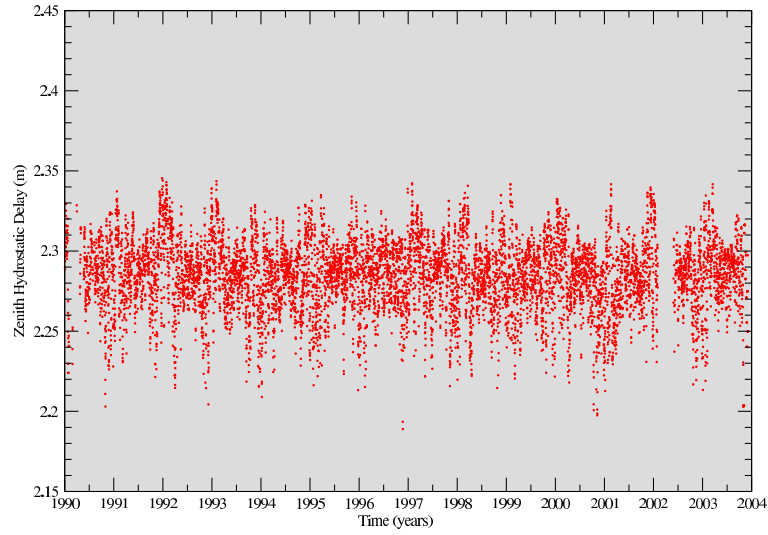


Figure E.2: Tropospheric Zenith Hydrostatic Delay (ZHD) time series computed from the radiosonde observations recorded in Uccle, Belgium between 1990 and 2004

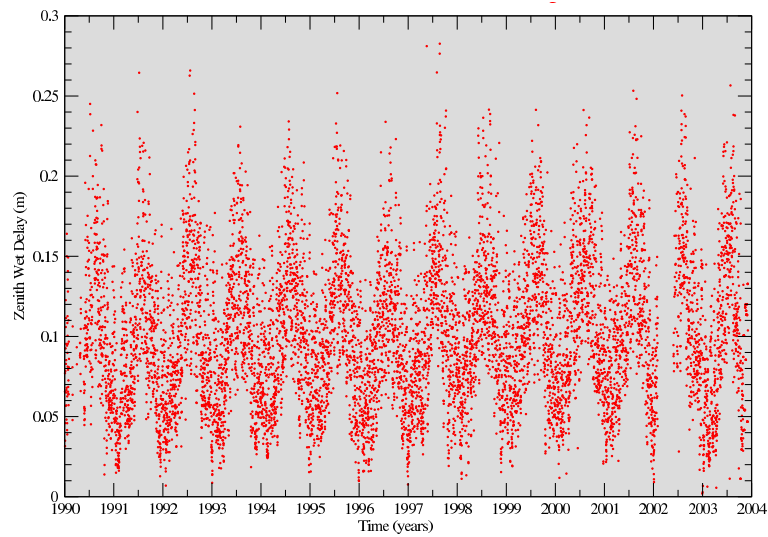


Figure E.3: Tropospheric Zenith Wet Delay (ZWD) time series computed from the radiosonde observations recorded in Uccle, Belgium between 1990 and 2004

E.4 Technique Limitation

Radiosonde balloons can be launched in almost all type of weather conditions. Nevertheless, severe weather, such as thunderstorms, may cause instrument failure or radio interferences. Moreover, soundings during severe weather may be representative of only a small (unstable) air portion, rather than the complete troposphere state above the observation launch site. In addition, as any technique, radiosonde devices may suffer from problems such as incomplete sounding or abnormal observation records. Another potential problem is the different performances of the various setups encountered in practice: sensor-dependent biases may be introduced and thereby, uncertainties in the studies for which the data are used and may, for instance, make the assessment of long-term effects difficult. For example, the widely used RS-80 Vaisala radiosondes present a well-known dry bias of the humidity sensor and has been discussed in [Wang *et al.*, 2002; Turner *et al.*, 2003] and [Vömel *et al.*, 2007]. Therefore, to reach the highest degree of accuracy in the comparisons against the radiosonde observations, the device model, the possible biases of the sensors, the altitude difference and the collocation distance between the techniques should be taken into account. Nevertheless, as far as we are aware of these limitations, radiosonde observations remains a good technique to validate the GNSS-based tropospheric ZPD: the resolution and reproducibility of the raw in-situ measurements announced by the manufacturers (see Table E.1 for typical technical specification values) allows to retrieve the tropospheric ZPD values with a few millimetre of (theoretical) precision and accuracy.

Observation	Captor	Measuring Range	Resolution	Reproducibility
Pressure	BAROCAP@ capacitive aneroid	from 1060 hPa up to 3 hPa	0.1 hPa	0.5 hPa
Temperature	THERMOCAP@ capacitive bead	from +60 °C up to −90 °C	0.1 °C	≤ 0.3 °C
Relative Humidity	HUMICAP@ thin film capacitor	from 0 % up to 100 %	1 %	< 3 %

Table E.1: Vaisala RS80 technical specifications.

Source: the British Atmospheric Data Centre (BADC) web site, [RS-80, 1996]

*La météorologie c'est l'art de prévoir ce
qui change tout le temps.*

Francis Blanche et Pierre Dac



Fundamental Notions of Meteorology

Summary

This appendix summarises a few fundamental notions of meteorology used in this thesis. It also gathers some information about the meteorological techniques and observations used in Chapter 6.

F.1 Terminology

F.1.1 Scales in Meteorology

Meteorological phenomena evolve at various horizontal scales in the troposphere. The two scales used in this thesis are the *synoptic scale* and the *mesoscale*. The synoptic scale (also known as large scale or *cyclonic scale*) has a horizontal length scale on the order of 1000km or more. The *mesoscale* concerns phenomena, which horizontal length scale are between 2km and the

synoptic scale. Orlanski proposed a division of mesoscale meteorology into 3 sub-classes [Orlanski, 1975]:

- The *meso-gamma scale*, from 2km to 20km, also known as *storm-scale* and dealing with phenomena like thunderstorm and convection
- The *meso-beta scale*, from 20km to 200km, dealing with phenomena like sea breezes and snow storms
- The *meso-alpha scale*, from 200km to 2000km, dealing with fronts, squall lines, mesoscale convective systems (MCS) and tropical cyclones at the edge of synoptic scale

F.1.2 Multi-cellular Storms

Multi-cellular thunderstorms are storms that have some organised structure, making their lifetime longer. Multi-cellular storms consist of several cells of storms, which occur one after another: each cell has a lifetime of 30min to 40min, typically. In severe multi-cellular storms, there are usually several cells active at any one time. Lightning is a good indication of an active thunderstorm cell.

F.2 Meteorological Observations and Techniques

F.2.1 Surface Weather Map Analysis

The *surface weather map analysis* allows to identify and locate the large-scale features of the sea level pressure field and surface fronts. Isobars reveal how rapidly the pressure varies with the distance in the horizontal direction but it is also useful to visualise the near surface wind regimes: the winds tend to be parallel to the isobars, with low pressure to the left of the wind flow in the northern hemisphere. A slight cross-isobar deflection of the winds towards the low pressure is often seen. Additionally, when isobars are packed more closely, the wind speed tends to be greater. An example of a surface weather map analysis is given in Figure F.1.

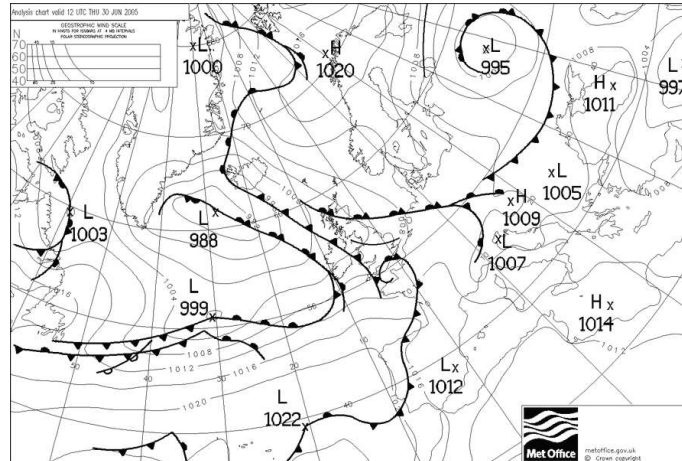


Figure F.1: Surface weather map analysis on the 30th June 2005, 12:00 UTC
© Crown copyright 2005, the Met. Office

High and low pressures centres are indicated with a large block H and L respectively, together with the estimated value of the central pressure. The map include also the *frontal analysis*. A front is defined as the transition zone between air masses having dissimilar thermal and moisture proprieties. Usually, these transitional zones are classified according to their movement and represented as in Table F.1

	Front type	Specifications
1	① Cold Front	A front where cold air replaces warm air
2	② Warm Front	A front where warm air replaces cold air
3	③ Occluded front	A front where the cold front has overtaken and merged with a warm front
4	④ Stationary front	A front with little lateral movement

Table F.1: Nomenclature of the weather fronts

F.2.2 Weather Radars

Weather radars are primary used in short-term weather forecasting applications. They emit directional pulses of X/C/S-band microwave radiations (about 5.6GHz/5 cm for the C-Band) and record the returned signal scattered by hydrometeors to locate and to estimate the intensity of precipitation zones, calculate their motions, determine their types (rain, snow, hail) and to forecast their evolutions based on the Rayleigh scattering theory [Atlas, 1990; Doviak and Zrnic, 1993]. The time elapsed between the emission of the pulses and the reception of the atmospheric echoes is converted into distance measurements. The intensity of the atmospheric echoes is converted to the so-called radar reflectivity $\mathcal{Z}$ using the equations for Rayleigh scattering [Atlas, 1990]. The Rayleigh equations are valid when the wavelength of the radar is much larger than the diameter of the scatters (maximum 6 mm for rain). In that case, the radar reflectivity strongly depends (to the sixth power) on the diameter of the rain droplets. The radar reflectivity is a good measure for the strength of the convection (up-drafts) and the amount of condensed moisture in the atmosphere. From the three-dimensional scans, pseudoCAPPI images (that is horizontal cross sections of radar reflectivity at constant altitude) are produced with a target height of 800m above antenna level and a horizontal resolution of 2.4km. Radar reflectivity values are converted to rainfall intensities $\mathcal{R}$ using the relationship of Marshall and Palmer [1948]:

$$\mathcal{Z} = 200 \cdot \mathcal{R}^{1.6} \quad (\text{F.1})$$

with the radar reflectivity $\mathcal{Z}$ in mm^6/m^3 and rainfall rate $\mathcal{R}$ in mm/h . Weather radar usually measure up to a typical distance of 200km, while a realistic estimation of the precipitation rate is usually only possible below 100km. In Europe, about 100 weather radars are operational and participate to the European program OPERA [European Program OPERA Web Site]. Among them, two Belgian C-Band weather radars: one located in Wideumont (49.915° N, 5.505° E), installed in 2001 and operated by the *Royal Meteorological Institute of Belgium* (RMI) and one located in Zaventem (50.901° N, 4.451° E), installed in 2003 and operated by Belgocontrol.

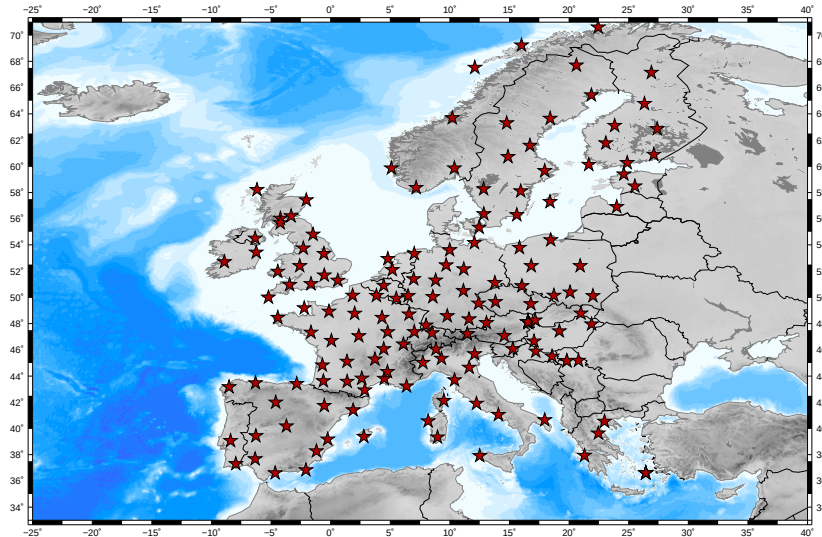


Figure F.2: European network of weather radars. The location of the radars were obtained from the European Program OPERA Web Site

F.2.3 Système d'Alerte Foudre par Interférométrie Radioélectrique (SAFIR)

The “*Système d'Alerte Foudre par Interférométrie Radioélectrique*” (SAFIR) is a lightning detection system [Wessels, 1998; Holleman, 2003]. The location of the lightning strikes is performed by triangulation from a network of antennas in the VHF band (typically between 108MHz and 118MHz). It allows the real-time detection of lightning activity with a location accuracy of about 1km and a time resolution of about $100\mu s$. The antenna are complemented with capacitive electrical antennas, which allows to discriminate between intra-cloud and cloud-to-ground lightning activity.

F.2.4 Stability Indices and Boyden Index

Stability indices have been developed in meteorology to illustrate the potential for convection within an air mass based on radiosonde or model-derived sounding. The values of these stability indices are compared to some statistical thresholds differentiating e.g. non-thunderstorm and thunderstorm cases. The *Boyden Index* (BI) is one of them [Boyden, 1963]. It has been developed to allow a diagnosis of frontal thunderstorms and is expressed as

$$BI = 0.1 \cdot (z_{700} - z_{1000}) - T_{700} - 200 \quad (\text{F.2})$$

- where
-  z is the geopotential height in metres
 -  z_{700} and z_{1000} are the geopotential height in metres at 700hPa and 1000hPa respectively
 -  T_{700} is the temperature in degree Celcius at the geopotential height corresponding to 700hPa

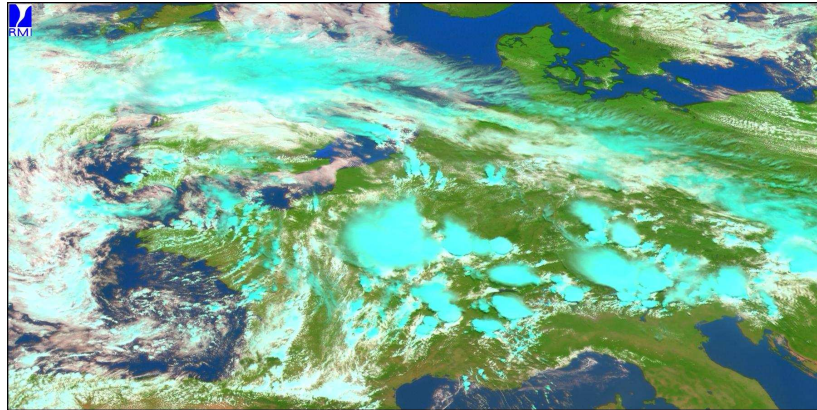
The factor 200 is used to bring the absolute value of BI close to a range from 90 to 100. Since the index doesn't contain any surface temperature information, there is little variation between continental and maritime air masses. The diurnal variation is also small. The higher the value of BI, the greater the risk of thunderstorms: values exceeding 96 indicate severe thunderstorm activity [Schmeits *et al.*, 2005]. Examples of BI for the 29th June 2005 is given in Table F.2.

City, country	Lat.	Long.	Alt.	Epoch	BI
1. De Bilt, The Netherlands	52.10°	5.18°	4 m	12:00 UTC	96.5
2. Herstmonceux, United Kingdom	50.9°	0.32°	54 m	12:00 UTC	96.5
3. Essen, Germany	51.60°	7.15°	65 m	00:00 UTC	97.0
				12:00 UTC	96.4
4. Idar-Oberstein, Germany	49.70°	7.33°	377 m	12:00 UTC	97.1
5. Saint-Hubert, Belgium	50.03°	5.40°	563 m	06:00 UTC	97.8

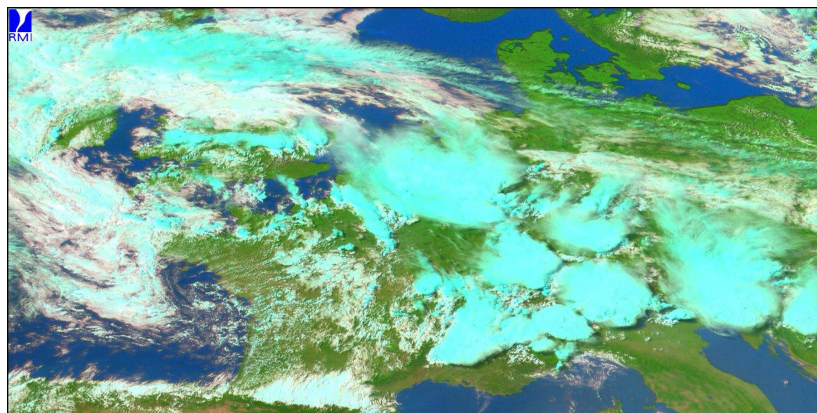
Table F.2: Boyden Index (BI) for some European cities around Belgium on the 29th June 2005

F.2.5 Meteosat Composite Images

Meteosat Second Generation (MSG) composite images are taken by the *Spinning Enhanced Visible and InfraRed Imager* (SEVIRI). The SEVIRI instrument is a 12 channels radiometer onboard MSG delivering daylight images of the weather pattern with a resolution of 3 km. More details on the instrument can be found in [Pasternak *et al.*, 1994]. The composite images of Figure F.3b are taken in the visible and near infrared channels, which are characteristic of the water vapour and ice respectively. Frozen cloud tops indicated by the light blue zones in the MSG composite images are often in tight relationship with precipitation cells. On the 29th June 2005, the MSG composite images confirmed the instability in Belgium (Section F.2.5): at 12:00 UTC most of Belgium was still cloud-free. During the next hours, a huge convective cell developed rapidly over Belgium and at 16:00 UTC the country was completely covered by a convective cloud with frozen top.



(a) Composite images taken on the 29th June 2005 at 12:00 UTC



(b) Composite images taken on the 29th June 2005 at 16:00 UTC

Figure F.3: Meteosat-8 composite images taken on the 29th June 2005 at 16:00 UTC by the SEVIRI instrument in the visible and near infrared wavelengths (on the courtesy of RMI)

Personal Peer-Review Bibliography

Personal Peer-Review Publications

Pottiaux, E.. 2009.

GNSS near real-time Zenith Path Delay estimation at ROB: methodology, quality monitoring and performance evaluation.

Bulletin of Geodesy and Geomatics, LXVIII(2):125–146.

Pottiaux, E. and Warnant, R.. 2002.

Quality assessment of GPS Integrated Water Vapor estimations using Water Vapor Radiometer observations.

GPS Solutions, 6(1-2):11–17.

Pottiaux, E., Brockmann, E., Soehne, W., and Bruyninx, C.. 2009.

The EUREF-EUMETNET collaboration: First experiences and potential benefits.

Bulletin of Geodesy and Geomatics, LXVIII(3).

Warnant, R. and Pottiaux, E.. 2000.

The increase of the ionospheric activity as measured by GPS.

Earth, Planets, and Space, 52:1055–1060.

Bibliography

Bibliography

ALADIN Web Site.

The ALADIN Numerical Weather Prediction Project.
<http://www.cnrm.meteo.fr/aladin/spip.php?page=sommaire>.

Altamimi, Z., Collilieux, X., Legrand, J., Garayt, B., and Boucher, C. 2007.

ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters.
Journal of Geophysical Research (Solid Earth), 112(B11):9401–+.

Askne, J. and Nordius, H. 1987.

Estimation of tropospheric delay for microwaves from surface weather data.
Radio Science, 22:379–386.

Atlas, D. 1990.

Radar in Meteorology: Battan Memorial and 40th Anniversary Radar Meteorology Conference.
American Meteorological Society.
AMS code RADMET.

Baltink, H. K., van der Marel, H., and van der Hoeven, A. G. A. 2002.

Integrated atmospheric water vapor estimates from a regional GPS network.
Journal of Geophysical Research (Atmospheres), 107:4025–+.

Barlag, S., de Haan, S., and Offiler, D. 2004.

User Requirements Document, TOUGH Deliverable D15 Report, version 1.0.
Technical report.
http://web.dmi.dk/pub/tough/deliverables/tough_urd_10.pdf.

Baueršima, I. 1983.

NAVSTAR/Global Positioning System (GPS), II., Mitteilungen der Satelliten-Beobachtungsstation Zimmerwald, Nr. 10, Astronomical Institute, University of Berne.

Bean, B. R. and Dutton, E. J. 1966.

Radio meteorology.
Monograph, 92.

Berg, H. 1948.

Allgemeine Meteorologie: Einführung in die Physik der Atmosphäre.
Duemmler, Bonn, Germany.

Beutler, G. 1995.

Development of the IGS.
Technical report, International GPS Service, IGS 1994 Annual Report, 3-9, Ed. J. F. Zumberge, R. Liu, R. E. Neilan.

- Beutler, G., Kouba, J., and Springer, T. 1995.**
Combining the orbits of the IGS Analysis Centers.
Bulletin Geodesique, 69:200–222.
- Beutler, G., Bock, H., Dach, R., Fridez, P., Gäde, A., Hugentobler, U., Jäggi, A., Meindl, M., Mervart, L., Prange, L., Schaer, S., Springer, T., Urschl, C., and Walser, P. 2007.**
Bernese GPS Software Version 5.0.
Astronomical Institute, University of Bern.
- Bevis, M., Businger, S., Herring, T. A., Rocken, C., Anthes, R. A., and Ware, R. H. 1992.**
GPS Meteorology: Remote Sensing of Atmospheric Water Vapor Using the Global Positioning System.
Journal of Geophysical Research, 97(15):787–801.
- Bevis, M., Businger, S., Chiswell, S., Herring, T. A., Anthes, R. A., Rocken, C., and Ware, R. H. 1994.**
GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water.
Journal of Applied Meteorology, 33(3):379–386.
- Bishop, G. J., Klobuchar, J. A., and Doherty, P. H. 1985.**
Multipath effects on the determination of absolute ionospheric time delay from GPS signals.
Radio Science, 20:388–396.
- Boehm, J. and Schuh, H. 2003.**
Vienna Mapping Functions.
In *Proceedings of the 16th Working Meeting on European VLBI for Geodesy and Astronomy*, pages 131–143. verslag des Bundesamtes für Kartographie und Geodäsie.
- Boehm, J. and Schuh, H. 2004.**
Vienna mapping functions in VLBI analyses.
Geophysical Research Letters, 31(1):1603–+.
- Boehm, J., Niell, A. E., Schuh, H., Tesmer, V., and Tregoning, P. 2006.**
Mapping functions for atmospheric delay modelling in GNSS analysis.
In *Proceedings of the IGS Analysis Workshop, Darmstadt, 2006*.
- Boehm, J., Werl, B., and Schuh, H. 2006.**
Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data.
Journal of Geophysical Research (Solid Earth), 111(B10):2406–+.
- Boehm, J., Heinkelmann, R., and Schuh, H. 2007.**
Short Note: A global model of pressure and temperature for geodetic applications.
Journal of Geodesy, 81(10):679–683.
- Botton, S., Duquenne, F., Egels, Y., Even, M., and Willis, P. 1997.**
GPS: localisation et navigation.
Conseil National de l’Information Geographique - Groupe de Positionnement Statique et Dynamique, Edition Herms, Paris.
- Boudouris, G. 1963.**
On the index of refraction of air, the absorption and dispersion of centimeter waves by gases.
Journal of Res. Natl. Bur. Stand., 67D:631–684.

Boyden, C. J.. 1963.

A simple instability index for use as a synoptic parameter.
Met. Mag., (92):198–210.

Brenot, H., Ducrocq, V., Walpersdorf, A., Champollion, C., and Caumont, O.. 2006.

GPS zenith delay sensitivity evaluated from high-resolution numerical weather prediction simulations of the 8-9 September 2002 flash flood over southeastern France.
J. Geophys. Res., 111:15105.

Brockmann, E.. 1996.

Combination of Solutions For Geodetic and Geodynamic Applications of the Global Positioning System (GPS).
Ph.D. thesis, Astronomy Institute, University of Bern.

Brockmann, E.. 2008.

Swisstopo (LPT) E-GVAP Report.
Presentation at the E-GVAP Joint Expert Team Meeting.

Bruyninx, C.. 2004.

The EUREF Permanent Network: a multi-disciplinary network serving surveyors as well as scientists.
GeoInformatics, 7:32–35.

Bruyninx, C., Altamimi, Z., Boucher, C., Brockmann, E., Caporali, A., Gurtner, W., Habrich, H., Hornik, H., Ihde, J., Kenyeres, A., Mäkinen, J., Stangl, G., Marel, H., Simek, J., Söhne, W., Torres, J., and Weber, G.. 2009.

The European Reference Frame: Maintenance and Products.
Geodetic Reference Frames, pages 131–136.

Businger, S., Chiswell, S. R., Bevis, M., Duan, J., Anthes, R. A., Rocken, C., Ware, R. H., Exner, M., Vanhove, T., and Solheim, F. S.. 1996.

The Promise of GPS in Atmospheric Monitoring.
Bulletin of the American Meteorological Society, 77:5–18.

CBSWG. 1996.

CBS Working Group on Satellites. Second Session, 15-19 April 1996, Final Report.

Chao, C. C.. 1974.

The troposphere calibration model for Mariner Mars 1971.
Technical Report 32 - 1587, Jet Propulsion Laboratory, Pasadena, California.

COMPASS FOC.

<http://www.insidegnss.com/node/1152>.

COSMO Web Site.

COSMO Numerical Weather Prediction Project.
<http://www.meteosuisse.admin.ch/web/en/weather/models/cosmo.html>.

COST-716. 2003.

Format specification for COST-716 processed GPS data, Version 2.0a..
Technical report, COST-716.

Bibliography

COST-716 Members. 2004.

COST716: Exploitation of Ground-Based GPS for Operational Numerical Weather Prediction and Climate Applications. Final Report.
Technical report, COST.

Crane, R. K.. 1976.

In Methods of Experimental Physics, volume 12B.
Chapter: "Refraction effects in the neutral atmosphere".
Academic Press, New York, ed. m.l. meeks edition.

Dach, R. and Dietrich, R.. 2000.

Influence of the ocean loading effect on GPS derived precipitable water vapor.
Geophysical Research Letters, 27(18):2953–2956.

Davis, J. L., Herring, T. A., Shapiro, I. I., Rogers, A. E. E., and Elgered, G.. 1985.

Geodesy by radio interferometry - Effects of atmospheric modeling errors on estimates of baseline length.
Radio Science, 20(6):1593–1607.

Davis, J. L., Elgered, G., Niell, A. E., and Kuehn, C. E.. 1993.

Ground-based measurement of gradients in the "wet" radio refractivity of air.
Radio Science, 28(6):1003–1018.

de Haan, S.. 2002.

Comparison of GPS slant delay measurements to a numerical model: case study of a cold front passage.
Physics and Chemistry of the Earth, 27(4-5):317–322.

de Haan, S.. 2006.

Measuring Atmospheric Stability with GPS.
Journal of Applied Meteorology and Climatology, 45:467–475.

de Haan, S.. 2008.

Meteorological applications of a surface network of Global Positioning System receivers..
Ph.D. thesis, Wageningen Universiteit.

de Haan, S., Barlag, S., Klein Baltink, H., Debie, F., and van der Marel, H.. 2004.

Synergetic Use of GPS Water Vapor and Meteosat Images for Synoptic Weather Forecasting.
Journal of Applied Meteorology, 43:514–518.

Debye, P. J. W.. 1929.

Polar molecules.
Dover, New York.

Dejong, C. D.. 1991.

GPS: Satellite orbits and atmospheric effects.
NASA STI/Recon Technical Report N, 92:14097–+.

Desbois, M. and Roca, R.. 2000.

Integrated water content and Climate change.
In proceeding of the COST-716 symposium, Oslo.

Dousa, J.. 2008a.

Case study for the IGS ultra-rapid orbit requirements.
Poster presented at the IGS Analysis Centre Workshop 2008, Miami, Florida, USA.

- Dousa, J.. 2008b.**
Case study for the IGS ultra-rapid orbit requirements.
Presentation at the IGS Analysis Workshop 2008, Miami, U.S.A.
- Doviak, R. J. and Zrnic, D. S.. 1993.**
Doppler Radar and Weather Observations.
Dover Publications.
Second Edition.
- Dow, J. M., Neilan, R. E., and Rizos, C.. 2009.**
The International GNSS Service in a changing landscape of Global Navigation Satellite Systems.
Journal of Geodesy, 83(3-4):191–198.
- Dragert, H., James, T. S., and Lambert, A.. 2000.**
Ocean loading corrections for continuous GPS: A case study at the Canadian coastal site Holberg.
Geophysical Research Letters, 27(14):2045–2048.
- Duan, J., Bevis, M., Fang, P., Bock, Y., Chiswell, S., Businger, S., Rocken, C., Solheim, F., van Hove, T., Ware, R., McClusky, S., Herring, T. A., and King, R. W.. 1996.**
GPS Meteorology: Direct Estimation of the Absolute Value of Precipitable Water.
Journal of Applied Meteorology, 35(6):830–838.
- E-GVAP Web Site.**
<http://egvap.dmi.dk>.
- Eanes, R. J.. 1994.**
Diurnal and semidiurnal tides from TOPEX/POSEIDON altimetry.
Eos Trans. AGU, 75(16):108.
- Eanes, R. and Bettadpur, S. V.. 1995.**
The CSR 3.0 global ocean tide model.
- Egbert, G. D., Bennett, A. F., and Foreman, M. G. G.. 1994.**
TOPEX/POSEIDON tides estimated using a global inverse model.
Journal of Geophysical Research, 99(C12):24821–24852.
- Elgered, G.. 1993.**
Atmospheric Remote Sensing by Microwave Radiometer.
Chapter: “Tropospheric radio-path delay from ground-based microwave radiometry”, pages 218–258.
M.A. Janssen (Edt.), Wiley & Sons, Inc.
- Elgered, G. and Jarlemark, P. O. J.. 1998.**
Ground-based microwave radiometry and long-term observations of atmospheric water vapor.
Radio Science, 33(3):707–718.
- Elgered, G., Davis, J. L., Herring, T. A., and Shapiro, I. I.. 1991.**
Geodesy by radio interferometry - Water vapor radiometry for estimation of the wet delay.
Journal of Geophysical Research, 96(B4):6541–6555.
- Elgered, G., Nilsson, T., and Willén, U.. 2007.**
Assessment of Using GNSS for the monitoring of the atmospheric water vapour content over long time scales.
In *proceedings of the 1st colloquium on the scientific and fundamental aspects of the GALILEO program, Toulouse, October 2007.*

Bibliography

EPNCB Web Site.

<http://epncb.oma.be>.

Eresmaa, R. and Järvinen, H.. 2006.

An observation operator for ground-based GPS slant delays.
Tellus Series A, 58:131–140.

Essen, L. and Froome, K. D.. 1963.

13th International Geodesy Association, General Assembly.
Bull. Geod., 70:390.

Estefan, J. A. and Sovers, O. J.. 1994.

A comparative survey of current and proposed tropospheric refraction-delay models for DSN radio metric data calibration.
Technical report.

EUMETNET Web Site.

<http://www.eumetnet.org>.

EUREF-EUMETNET-2007.

The EUREF-EUMETNET Memorandum of Understanding.
http://www.euref-iaig.net/documentation/OtherDocuments/EUREF_EUMETNET_MoU.pdf.

European Program OPERA Web Site.

European Program OPERA.
<http://www.knmi.nl/opera/>.

Ferland, R.. 2006.

Proposed IGS05 Realization.
IGSMail-5447.

FLEPOS Web Site.

FLEPOS Web Site.
<http://www.agiv.be/gis/diensten/flepos/?catid=9>.

GALILEO-ICD. 2006.

GALILEO Interface Control Document.
<http://www.galileoic.org/la/files/Galileo%20S%20SIS%20ICD%20230506.pdf>.

Gendt, G.. 2006.

IGS switch to absolute antenna model and ITRF2005.
IGSMail-5438, IGS Central Bureau, Pasadena.

GENERX1.

Septentrio GENERX1 receiver specifications.
http://www.septentrio.com/products_generx1.htm.

Georgiadou, Y. and Kleusberg, A.. 1988.

On carrier signal multipath effects in relative GPS Positioning.
Manuscripta Geodaetica, 13:172–179.

GLONASS Almanacs.

<http://www.glonass-ianc.rsa.ru/pls/htmldb/f?p=202:21:14637162736231801312::N0::>.

GLONASS Constellation Status.

<http://www.glonass-ianc.rsa.ru/pls/htmldb/f?p=202:20:13355669450982240959::N0>.

GLONASS-ICD. 2002.

GLONASS Interface Control Document.

http://www.glonass-ianc.rsa.ru/i/glonass/ICD02_e.pdf.
ICD02_e.

GPS Broadcast Quality.

<http://gge.unb.ca/gauss/htdocs/grads/orbit>.

GPS Constellation Status.

<ftp://tycho.usno.navy.mil/pub/gps/gpstd.txt>.

GPS-ICD. 1993.

GPS Interface Control Document.

ARINC Research Corporation.

ICD-GPS-200C.

GPS Yuma Almanacs.

<http://www.navcen.uscg.gov/GPS/almanacs.htm>.

GPSBru Web Site.

GPSBru.

<http://ign.be/agn/FR/FR1.shtm>.

Griffiths, J. and Ray, J. R. 2009.

On the precision and accuracy of IGS orbits.

Journal of Geodesy, 83:277–287.

GTS Web Site.

Global Telecommunication System Web Site.

<http://www.wmo.ch/pages/prog/www/TEM/XGTS/gts.html>.

Haase, J., Calais, E., Talaya, J., Rius, A., Vespe, F., Santangelo, R., Huang, X., Davila, J. M., Ge, M., Cucurull, L., Flores, A., Sciarretta, C., Pacione, R., Boccolari, M., Pugnaghi, S., Vedel, H., Mogensen, K., Yang, X., and Garate, J. 2001.

The contributions of the MAGIC project to the COST 716 objectives of assessing the operational potential of ground-based GPS meteorology on an international scale.

Physics and Chemistry of the Earth, 26(issues 6-8):433–437.

Haase, J., Ge, M., Vedel, H., and Calais, E. 2003.

Accuracy and Variability of GPS Tropospheric Delay Measurements of Water Vapor in the Western Mediterranean.

Journal of Applied Meteorology, 42(11):1547–1568.

Hall, M. P. 1979.

Effects of the troposphere on radio communication.

Peter Peregrinus LTD on behalf of the Institution of Electrical Engineers.

Hartmann, G. K. and Leitingner, R. 1984.

Range errors due to ionospheric and tropospheric effects for signal frequencies above 100 MHz.

Bulletin Géodésique, 58(2):109 – 136.

Bibliography

Herring, T. A.. 1992.

Modeling atmospheric delays in the analysis of space geodetic data.

In **Munk, J. D. and Spoelstra, T.**, editors, *Symposium on Refraction of Transatmospheric Signals in Geodesy*, 36, pages 157–164. Netherlands Geodetic Commission, Delft.

Holleman, I.. 2003.

SAFIR beeldproduct voor real-time gebruik.

Technical report, Koninklijk Nederlands Meteorologisch Instituut.

http://www.knmi.nl/publications/fulltexts/ir_safir_def_copy1.pdf.

Hopfield, H. S.. 1969a.

Approximation to the tropospheric range correction.

Applied Physics Laboratory, pages 572 – 569.

Silver Spring, Md., 12. November, S1A-572-69, 4 pp.

Hopfield, H. S.. 1969b.

Two-Quartic Tropospheric Refractivity Profile for Correcting Satellite Data.

Journal of Geophysical Research, 74(18):4487–4499.

Hopfield, H. S.. 1971a.

Tropospheric effect on electromagnetically measured range: Prediction from surface weather data.

Radio Science, 6(3):357–367.

Hopfield, H. S.. 1971b.

Tropospheric range error at the zenith.

In *Proceedings of the Fourteenth Plenary Meeting of the Committee on Space Research, Seattle, Washington, 17 June-2 July*, page 31.

Hopfield, H. S.. 1978.

Tropospheric correction of electro-magnetic ranging signals to a satellite: Study of parameters.

In **Richardus, P.**, editor, *Proceedings of International Symposium on Electromagnetic Distance Measurement and the Influence of Atmospheric Refraction, Wageningen, The Netherlands, 23-28 May 1977*, pages 205–215.

Houghton, J. T.. 1986.

The physics of atmospheres.

Hugentobler, U.. 2005.

Models in GNSS Data Analysis.

Presentation at the COMET'05 symposium, November, London.

IAG Web Site.

<http://www.iag-aig.org/>.

IERS Conventions Update.

Online Update of the IERS Conventions 2003.

<http://tai.bipm.org/iers/convupdt/convupdt.html>.

Ifadis, I. M.. 1992.

The excess propagation path of radio waves: Study of the influence of the atmospheric parameters on its elevation dependence.

Survey Review - Directorate of Overseas Surveys, 31(243):289–298.

IGS Analysis Centre Web Site.

<http://acc.igs.org>.

IGS Antenna Files.

General information on the IGS antenna files.

ftp://igscb.jpl.nasa.gov/igscb/station/general/antenna_README.pdf.

IGS Central Bureau.

<http://igscb.jpl.nasa.gov>.

Janes, H. W., Langley, R. B., and Newby, S. P. 1989.

A comparison of several models for the prediction of tropospheric propagation delay.

In *Proceedings of the Fifth International Geodetic Symposium on Satellite Positioning, DMA, NGS, Las Cruces, N. Mex.*, volume II, pages 777–788. Physical Science Laboratory, New Mexico State University, Las Cruces, N. Mex.

Janes, H. W., Langley, R. B., and Newby, S. P. 1991.

Analysis of tropospheric delay prediction models - Comparisons with ray-tracing and implications for GPS relative positioning.

Bulletin Géodésique, 65:151–161.

Järvinen, H., Eresmaa, R., Vedel, H., Salonen, K., Niemelä, S., and de Vries, J. 2007.

A variational data assimilation system for ground-based GPS slant delays.

Quarterly Journal of the Royal Meteorological Society, 133:969–980.

Jupp, A. 2006.

Met Office assimilation results.

TOUGH Deliverable D48.

Danish Meteorological Institute.

Kaplan, E. D. and Hegarty, C. J., editors. 2005.

Understanding GPS Principles and Applications.

Artech House Mobile Communication Series. Artech House Publisher.

Kenyeres, A., Legrand, J., Figurski, M., Bruyninx, C., Kaminski, P., and Habrich, H. 2009.

Homogenous Reprocessing of the EPN : First Experiences and Comparisons.

Bulletin of Geodesy and Geomatics, 3:207–218.

Kleijer, F. 2004.

Troposphere Modeling and Filtering for Precise GPS Leveling.

Ph.D. thesis, University of Technology, Delft.

Kock, K. R. 1988.

Parameter estimation and hypothesis testing in minear models.

Springer, Berlin Heidelberg New York.

Kouba, J. 1979.

Improvements in Canadian Geodetic Doppler Programs.

In *Geodetic Symposium on Satellite Doppler Positioning*, pages 63–+.

Kouba, J. 2008.

A Guide to Using International GNSS Service (IGS) Products.

Bibliography

Kouba, J., Mireault, Y., and Lahaye, F. 1995.

1994 IGS Orbit/Clock Combination and Evaluation.

Technical report, International GPS Service, IGS 1994 Annual Report, 70-90, Ed. J. F. Zumberge, R. Liu, R. E. Neilan.

Lambert 2008.

Lambert 2008 Coordinate System.

<http://www.ngi.be/FR/FR2-1-7.shtm>.

Le Provost, C., Genco, M. L., Lyard, F., Vincent, P., and Canceil, P. 1994.

Spectroscopy of the world ocean tides from a finite element hydrodynamic model.

Journal of Geophysical Research, 99(C12):24777–24798.

Le Provost, C., Lyard, F., Molines, J. M., Genco, M. L., and Rabilloud, F. 1998.

A hydrodynamic ocean tide model improved by assimilating a satellite altimeter-derived data set.

Journal of Geophysical Research, 103(C3):5513–5530.

Lefèvre, F., Lyard, F. H., and Le Provost, C. 2000.

FES98: A new global tide finite element solution independent of altimetry.

Geophysical Research Letters, 27:2717–2720.

Leick, A. 1990.

GPS Satellite Surveying.

John Wiley & Sons.

Leick, A. 1995.

GPS Satellite Surveying.

John Wiley & Sons.

Leick, A. 2004.

GPS Satellite Surveying.

John Wiley & Sons.

Lienen, S. 1997.

Hochpräzise Positionierung über grosse Entfernungen und in Echtzeit mit dem Global Positioning System.

Technical report, Deutsche Geodätische Kommission.

Liu, J. 2003.

Implementation and Analysis of GPS Ambiguity Resolution Strategies in Single and Multiple Reference Station Scenarios.

Master's thesis, University of Calgary.

Lyard, F., Lefevre, F., Letellier, T., and Francis, O. 2006.

Modelling the global ocean tides: modern insights from FES2004.

Ocean Dynamics, 56(5-6):394–415.

MacMillan, D. S. 1995.

Atmospheric gradients from very long baseline interferometry observations.

Geophysical Research Letters, 22(9):1041–1044.

Mader, G. L. 1999a.

GPS Antenna Calibration at the National Geodetic Survey.

GPS Solutions, 3(1):50–58.

Mader, G. L..

GPS Antenna Calibration at the National Geodetic Survey.
<http://www.ngs.noaa.gov/ANTCAL/images/summary.html>.

Marini, J. W.. 1972.

Correction of satellite tracking data for an arbitrary tropospheric profile.
Radio Science, 7(2):223–231.

Marshall, J. S. and Palmer, W. M.. 1948.

The Distribution of Raindrops with Size.
Journal of Atmospheric Sciences, 5(4):165–166.

Matsumoto, K., Takanezawa, T., and Ooe, M.. 2000.

Ocean Tide Models Developed by Assimilating TOPEX/POSEIDON Altimeter Data into Hydrodynamical Model: A Global Model and a Regional Model Around Japan.
Journal of Oceanography, 56:567–581.

Mazany, R. A., Businger, S., Gutman, S. I., and Roeder, W.. 2002.

A Lightning Prediction Index that Utilizes GPS Integrated Precipitable Water Vapor.
Weather and Forecasting, 17(5):1034–1047.

McCarthy, D. D. and Petit, G.. 2004.

IERS Conventions (2003).
Technical report.

Meindl, M., Schaer, S., Hugentobler, U., and Beutler, G.. 2004.

Tropospheric Gradient Estimation at CODE: Results from Global Solutions, in Applications of GPS Remote Sensing to Meteorology and Related Fields.
Journal of the Meteorological Society of Japan, 82(1B):331 – 338.

Mendes, V. B. and Langley, R. B.. 1994.

A comprehensive analysis of mapping functions used in modelling tropospheric propagation delay in space geodetic data.
In *KIS94, Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, Banff, Alberta 30 August - 2 september, The University of Calgary, Calgary, Alberta, Canada*, pages 87–98.

Menge, F., Seeber, G., Voelksen, C., Wuebbena, G., and Schmitz, M.. 1998.

Results of absolute field calibration of GPS antenna PCV.
In *Proc ION-GPS98, Nashville*, pages 31–38.

Mervart, L.. 1995a.

Ambiguity resolution techniques in geodetic and geodynamic applications of the Global Positioning System..
Ph.D. thesis, Astronomical Institute, University of Berne.

Mervart, L.. 1995b.

Ambiguity resolution techniques in geodetic and geodynamic applications of the Global Positioning System.
Geod.-Geophys. Arb. Schweiz, 53.

Bibliography

Mueller, I. I. and Zerbini, S.. 1989.

The interdisciplinary role of space geodesy; Proceedings of the International Workshop, Erice, Italy, July 23-29, 1988.
Lecture Notes in Earth Sciences, Berlin Springer Verlag, 22.

NGS Web Site.

<http://www.ngs.noaa.gov/ANTCAL/>.

Niell, A. E.. 1996.

Global mapping functions for the atmosphere delay at radio wavelengths.
Journal of Geophysical Research, 101:3227–3246.

Niell, A. E.. 2000.

Improved atmospheric mapping functions for VLBI and GPS.
Earth, Planets, and Space, 52:699–702.

Orlanski, I.. 1975.

A rational subdivision of scales for atmospheric processes.
Bulletin of the American Meteorological Society, 56(5):527–530.

OTL Provider Web Site.

Ocean Tide Loading Provider Web Site.
<http://www.oso.chalmers.se/~loading/>.

Owens, J. C.. 1967.

Optical refractive index of air: dependence on pressure, temperature, and composition.
Applied Optics, 6(1):51–58.

Pacione, R. and Vespe, F.. 2008.

Comparative Studies for the Assessment of the Quality of Near-Real-Time GPS-Derived Atmospheric Parameters.
Journal of Atmospheric and Oceanic Technology, 25(5):701–714.

Pasternak, F., Lorsignol, J., and Wolff, L.. 1994.

Spinning enhanced visible and infrared imager (SEVIRI): the new imager for METEOSAT second generation.
In **M. G. Cerutti-Maori & P. Roussel**, editor, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 2209 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pages 86–94.

Pavlis, N. K., Holmes, S. A., Kenyon, S. C., and Factor, J. K.. 2008.

An Earth Gravitational Model to Degree 2160: EGM2008.
presented at the EGU General Assembly 2008 Vienna, Austria, April 13-18, 2008.

Penna, N. T., Bos, M. S., Baker, T. F., and Scherneck, H.. 2008.

Assessing the accuracy of predicted ocean tide loading displacement values.
Journal of Geodesy, 82(12):893–907.

POLARX3.

Septentrio POLARX3 receiver specifications.
http://www.septentrio.com/products_polarx3.htm.

POLARX3G.

Septentrio POLARX3G receiver specifications.
http://www.septentrio.com/products_polarx3G.htm.

Poli, P., Moll, P., Rabier, F., Desroziers, G., Chapnik, B., Berre, L., Healy, S. B., Andersson, E., and El Guelai, F. 2007.

Forecast impact studies of zenith total delay data from European near real-time GPS stations in Météo France 4DVAR.
Journal of Geophysical Research (Atmospheres), 112(D11):6114–+.

Pottiaux, E.. 2008.

The Belgian Contribution to the EUMETNET GPS Water Vapour Program (E-GVAP): New Developments and Applications.
Poster presented at the EGU Symposium in Vienna, Austria, 2008.

Pottiaux, E. and Warnant, R.. 2002.

Quality assessment of GPS Integrated Water Vapor estimations using Water Vapor Radiometer observations.
GPS Solutions, 6(1-2):11–17.

Pottiaux, E. and Warnant, R.. 2003.

First experiences with a water vapor radiometer at the Royal Observatory of Belgium.
In *Proceedings of the EUREF Symposium, Ponta Delgada - Azorian Island*, pages 351–354. EUREF, Bayerischen Kommission für die Internationale Erdmessung, Astronomisch - Geodätische Arbeiten.

Pottiaux, E., Becker, M., Bürki, B., Gyger, R., Häfele, P., Plötz, C., Schlüter, W., Schwarz, W., Somieski, A., and Warnant, R.. 2003a.

Poster presented at the EGS - AGU - EUG Joint Assembly held in Nice, France, 6 - 11 April 2003.

Pottiaux, E., Becker, M., Bürki, B., Gyger, R., Häfele, P., Plötz, C., Schlüter, W., Schwarz, W., Somieski, A., and Warnant, R.. 2003b.

Calibration and quality assessment of water vapor radiometer observations using radiosonde, GPS and VLBI.
Poster presented at the EGS - AGU - EUG Joint Assembly held in Nice, France, 6 - 11 April 2003.

Pottiaux, E., Brockmann, E., Soehne, W., and Bruyninx, C.. 2009.

The EUREF-EUMETNET collaboration: First experiences and potential benefits.
Bulletin of Geodesy and Geomatics, LXVIII(3).

Ray, J.. 2010.

[IGSMail-6053]: status of the IGS orbit products.
IGS Electronic Mail.

Ray, J. and Griffiths, J.. 2008.

Overview of IGS Products and Analysis Center Modeling.
Presented at the IGS 2008 Workshop, Miami Beach, Florida, 2-6 June 2008.

Ray, R. D.. 1999.

A Global Ocean Tide Model From TOPEX/POSEIDON Altimetry: GOT99.2.
Technical report, NASA Technical Memorandum 209478.
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19990089548_1999150788.pdf.

Bibliography

ROB GNSS Web Site.

The GNSS Web Site from the Royal Observatory of Belgium.
<http://www.gnss.be>.

Rocken, C.. 2004.

An Introduction to Ground Based GPS Meteorology.
Presentation of the NCAR GPS Meteorology Colloquium, June 20 - July 2, 2004, Boulder, Colorado.

Rocken, C., Ware, R., Van Hove, T., Solheim, F., Alber, C., Johnson, J., Bevis, M., and Businger, S.. 1993.

Sensing atmospheric water vapor with the Global Positioning System.
Geophysical Research Letters, 20:2631–2634.

Rocken, C., Hove, T. V., Johnson, J., Solheim, F., Ware, R., Bevis, M., Chiswell, S., and Businger, S.. 1995.

GPS/STORM - GPS Sensing of Atmospheric Water Vapor for Meteorology.
Journal of Atmospheric and Oceanic Technology, 12:468–+.

Rosenkranz, P. W.. 1998.

Water vapor microwave continuum absorption: a comparison of measurements and models.
Radio Science, 33:919–928.

Ross, R. J. and Rosenfeld, S.. 1997.

Estimating mean weighted temperature of the atmosphere for Global Positioning System applications.
Journal of Geophysical Research, 102(D18):21719–21730.

Rothacher, M., Springer, T. A., Schaer, S., and Beutler, G.. 1998.

Processing Strategies for Regional GPS Networks.
In **Brunner**, editor, *Proceedings of the IAG General Assembly in Rio, September 3-9, 1997*, 118.
Springer Verlag.

RS-80. 1996.

RS80 Radiosondes.
Technical report.
Ref. A571en, Vaisala Oy, Finland.

Rüeger, J. M.. 2002.

Refractive Index Formulae for Radio Waves.
In *Proceedings of the FIG XXII International Congress, Washington, D. C. USA, April 19-26*.

Saastamoinen, J.. 1972.

Atmospheric correction for troposphere and stratosphere in radio ranging of satellites. The Use of Artificial Satellites for Geodesy.
In *Papers presented at the Third International Symposium on The Use of Artificial Satellites for Geodesy*, Eds. S. W. Henriksen, A. Mancini, B. H. Chovitz, AGU, AIAA, NOAA, U.S.ATC, Washington, D. C., 15-17 April 1971, American Geophysical Union, Washington, D. C., *Geophysical monograph 15*, volume 15, pages 247 – 251.

Saastamoinen, J.. 1973.

Contributions to the theory of atmospheric refraction. Introduction to practical computation of astronomical refraction.
Bulletin G od sique, 105, 106, and 107:279 – 298, 383 – 397 and 13 – 34.
In three parts.

- Santerre, R.. 1991.**
Impact of GPS satellite sky distribution.
Manuscript of Geodesy, 16:28–53.
- Schmeits, M. J., Kok, K. J., and Vogelezang, D. H. P. 2005.**
Probabilistic Forecasting of (Severe) Thunderstorms in the Netherlands Using Model Output Statistics.
Weather and Forecasting, 20(2):134–148.
- Schmid, R., Steigenberger, P., Gendt, G., Ge, M., and Rothacher, M. 2007.**
Generation of a consistent absolute phase-center correction model for GPS receiver and satellite antennas.
Journal of Geodesy, 81(12):781–798.
- Schupler, B., Allshouse, R., and T.A., C. 1994.**
Signal characteristics of GPS user antennas.
Journal of the Institute of Navigation, 41:277–295.
- Schwiderski, E. W. 1980.**
On Charting Global Ocean Tides.
Reviews of Geophysics, 18(1):243–268.
- Sleewaegen, J.-M. 1999.**
Modeling, Quality Analysis and Management of GPS data: an Instrumental Approach.
Ph.D. thesis, Faculté des Sciences Appliquées, Service Electronique Microélectronique Télécommunications, Université Libre de Bruxelles.
- Smith, E. K. and Weintraub, S. 1953.**
The constants in the equation of atmospheric refractive index at radio frequencies.
In *Proceedings of the Institut of Radio Engineers*, volume 41, pages 1035–1037.
- Smith, W. H. F. and Wessel, P. 1990.**
Gridding with continuous curvature splines in tension.
Geophysics, 55(3):293–305.
- Solheim, F. S. 1993.**
Use of Pointed Water Vapor Radiometer Observations to Improve Vertical GPS Surveying Accuracy..
Ph.D. thesis, Department of Physics, University of Colorado, Boulder.
- Solheim, F. S., Vivekanandan, J., Ware, R. H., and Rocken, C. 1999.**
Propagation delays induced in GPS signals by dry air, water vapor, hydrometeors, and other particulates.
Journal of Geophysical Research, 104(D8):9663–9670.
- Spilker, J. J. 1996.**
Global Positioning System Theory and Applications, volume 163.
Chapter: “GPS Signal Structure and Theoretical Performance”, pages 57–119.
B. W. Parkinson and J. J. Spilker, Progress in Astronautics and Aeronautics.
- Spilker, J. J., Jr. 1978.**
GPS signal structure and performance characteristics.
Navigation Journal of ION, 25(2):121–146.
- Spofford, P. and Remondi, B. 1995.**
The National Geodetic Survey standard GPS Format SP3.
NOAA, National Geodetic Survey.

Steigenberger, P., Boehm, J., and Tesmer, V. 2009.

Comparison of GMF/GPT with VMF1/ECMWF and implications for atmospheric loading.
Journal of Geodesy, 83(10):943–951.

Söhne, W. and Weber, G.. 2002.

EUREF Permanent Network Special Project - Status Report.
In *Report on the Symposium of the IAG Subcommission for Europe (EUREF), Ponta Delgada, 05-08 June 2002, Mitteilungen des Bundesamtes für Kartographie und Geodäsie*, volume 29, pages 85–90.

Teunissen, P. J. G. and Kleusberg, A. 1998.

GPS for Geodesy.
Springer, 2nd edition edition.

Thayer, G. D. 1974.

An improved equation for the radio refractive index of air.
Radio Science, 9(10):803–807.

TOUGH Web Site.

<http://tough.dmi.dk>.

Treuhaft, R. N. and Lanyi, G. E.. 1987.

The effect of the dynamic wet troposphere on radio interferometric measurements.
Radio Science, 22(2):251 – 265.

Turner, D. D., Lesht, B. M., Clough, S. A., Liljegren, J. C., Revercomb, H. E., and Tobin, D. C.. 2003.

Dry Bias and Variability in Vaisala RS80-H Radiosondes: The ARM Experience.
Journal of Atmospheric and Oceanic Technology, 20(1):117–132.

Unden, P., Rontu, L., Järvinen, H., Lynch, P., Calvo, J., Cats, G., Cuxart, J., Eerola, K., Fortelius, C., Garcia-Moya, J. A., Jones, C., Lenderlink, G., McDonald, A., McGrath, R., Navascues, B., Nielsen, N. W., Degaard, V., Rodriguez, E., Rummukainen, M., Room, R., Sattler, K., Sass, B. H., Savijarvi, H., Schreur, B. W., Sigg, R., The, H., and Tijn, A. 2002.

HIRLAM-5 Scientific Documentation.

Uppala, S. M., Kallberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D. C., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Berg, L. V. D., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., McNally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J. 2005.

The ERA-40 re-analysis.
Quarterly Journal of the Royal Meteorological Society, 131(612):2961–3012.

van der Marel, H. and Gündlich, B.. 2006.

Development of models for use of slant delays, slant delay retrieval and multipath mapping software.
TOUGH Deliverable D33.
Danish Meteorological Institute.

Vedel, H.. 2000.

Conversion of WGS84 geometric heights to NWP model HIRLAM geopotential heights.
Technical report, Danish Meteorological Institute.
DMI scientific rapport 00-04.

- Vedel, H.. 2007.**
EUREF E-GVAP MoU and Status of E-GVAP.
presentation at the EUREF Symposium, London, 6-9 June, 2007.
- Vedel, H. and Sattler, K.. 2006.**
Deliverable D41: Impact study of assimilation of GPS slant delays.
Technical report, Danish Meteorological Institute.
- Vedel, H., Mogensen, K. S., and Huang, X.. 2001.**
Calculation of zenith delays from meteorological data comparison of NWP model, radiosonde and GPS delays.
Physics and Chemistry of the Earth A, 26(6-8):497–502.
- Vey, S., Calais, E., Llubes, M., Florsch, N., Woppelmann, G., Hinderer, J., Amalvict, M., Lalancette, M. F., Simon, B., Duquenne, F., and Haase, J. S.. 2002.**
GPS measurements of ocean loading and its impact on zenith tropospheric delay estimates: a case study in Brittany, France.
Journal of Geodesy, 76(8):419–427.
- Vey, S., Dietrich, R., Fritsche, M., Rülke, A., Rothacher, M., and Steigenberger, P.. 2006.**
Influence of mapping function parameters on global GPS network analyses: Comparisons between NMF and IMF.
Geophysical Research Letter, 33(1):1814–+.
- Voet, P.. 2008.**
Presentation at the EUREF Symposium 2008, June 2008, Brussels, Belgium.
- Vömel, H., Selkirk, H., Miloshevich, L., Valverde-Canossa, J., Valdés, J., Kyrö, E., Kivi, R., Stolz, W., Peng, G., and Diaz, J. A.. 2007.**
Radiation Dry Bias of the Vaisala RS92 Humidity Sensor.
Journal of Atmospheric and Oceanic Technology, 24:953–+.
- WALCORS Web Site.**
WALCORS Web Site.
<http://gps.wallonie.be/>.
- Walpersdorf, A.. 2010.**
De la méthodologie GPS à la mesure de la déformation actuelle.
Mémoire présenté pour obtenir le diplôme d’Habilitation à Diriger des Recherches de l’Université Joseph Fourier - Grenoble I.
- Wang, J., Cole, H. L., Carlson, D. J., Miller, E. R., Beierle, K., Paukkunen, A., and Laine, T. K.. 2002.**
Corrections of Humidity Measurement Errors from the Vaisala RS80 Radiosonde-Application to TOGA COARE Data.
Journal of Atmospheric and Oceanic Technology, 19(7):981–1002.
- Warnant, R. and Pottiaux, E.. 2000.**
The increase of the ionospheric activity as measured by GPS.
Earth, Planets, and Space, 52:1055–1060.
- Watson, D.. 1982.**
Acord: automatic contouring of raw data.
Computers and Geosciences, 8:97–101.

Bibliography

Wessel, P. and Smith, W. H. F. 2008.

The Generic Mapping Tools.

Wessels, H. 1998.

Evaluation of Radio Interferometry Lightning Positioning System.

Technical report, Het Koninklijk Nederlands Meteorologisch Instituut.

Scientific Report WR-98-04.

[Http://www.knmi.nl/bibliotheek/knmipubWR/WR98-04.pdf](http://www.knmi.nl/bibliotheek/knmipubWR/WR98-04.pdf).

Westwater, E. 1965.

Ground-based passive probing using the microwave spectrum of oxygen.

Radio Science, 69D:1201– 1211.

WMO Web Site.

World Meteorological Organisation Web Site.

http://www.wmo.int/pages/index_en.html.

List of Acronyms

List of Acronyms

AGIV	<i>Agentschap voor Geografische Informatie Vlaanderen</i>
AGN	<i>Active Geodetic Network</i>
APC	<i>Antenna Phase Centre</i>
APCV	<i>Antenna Phase Centre Variations</i>
APCE	<i>Antenna Phase Centre Eccentricity</i>
APCO	<i>Antenna Phase Centre Offset</i>
ARP	<i>Antenna Reference Point</i>
AS	<i>Anti-Spoofing</i>
ASI	<i>Agenzia Spaziale Italiana</i>
BADC	<i>The British Atmospheric Data Centre</i>
BKG	<i>Bundesamt für Kartographie und Geodäsie</i>
bps	<i>bits per second</i>
C/A	<i>Coarse/Acquisition</i>
CDMA	<i>Code Division Multiple Access</i>
CNES	<i>Centre National d'Etudes Spatiale</i>
CODE	<i>GPS analysis centre of the IGS at the Astronomical Institute of the University of Berne, Switzerland</i>
CORS	<i>Continuous Operating GNSS Reference Stations</i>
COST-716	<i>COST Action 716: Exploitation of ground-based GPS for climate and numerical weather prediction applications</i>
COU	<i>Code Ultra-rapid orbits</i>
dB	<i>Decibels</i>
DD	<i>Double-Difference</i>
DGPS	<i>Differential GPS</i>
DMA	<i>Defence Mapping Agency</i>
DoD	<i>Department of Defence</i>
DOY	<i>Day of year</i>
EC	<i>European Commission</i>
E-GVAP	<i>The EUMETNET GPS water VApour Programme</i>
EPN	<i>EUREF Permanent Network</i>
ETRF	<i>European Terrestrial Reference Frame</i>
ETRS	<i>European Terrestrial Reference System</i>

List of Acronyms (*Continued ...*)

EU	<i>European Union</i>
EUREF	<i>EUropean REference Frame</i>
FDMA	<i>Frequency Division Multiple Access</i>
FLEPOS	<i>FLEmish POSitioning Service</i>
FOC	<i>Full Operational Capability</i>
GFZ	<i>GeoForschungsZentrum Postdam</i>
GIOVE	<i>Galileo-In-Orbit Validation Element</i>
GLONASS	<i>GLObal'naya NAVigatsionnaya Sputnikovaya Sistema</i>
GMF	<i>Global Mapping Function</i>
GMT	<i>Generic Mapping Tool</i>
GNSS	<i>Global Navigation Satellite Systems</i>
GOP	<i>Geodetic Observatory Pecny</i>
GPS	<i>Global Positioning System</i>
GPSBru	<i>Part of the Belgian AGN belonging to the Brussels region</i>
GPT	<i>Global Pressure Temperature model</i>
GREF	<i>German Geodetic REference</i>
GST	<i>Galileo System Time</i>
HIRLAM	<i>HIgh Resolution Limited Area Model</i>
HP-code	<i>High-Precision code</i>
IAG	<i>International Association of Geodesy</i>
ICD	<i>Interface Control Document</i>
IERS	<i>International Earth Rotation Service</i>
IGE	<i>Spanish Instituto Geográfico Nacional</i>
IGR	<i>IGS rapid orbits</i>
IGS	<i>International GNSS Service for Geodynamic</i>
IGU	<i>IGS ultra-rapid orbits</i>
IPWV	<i>Integrated Precipitable Water Vapour</i>
ITRF	<i>International Terrestrial Reference Frame</i>
IVS	<i>International VLBI Service</i>
IWV	<i>Integrated Water Vapour</i>
JPL	<i>Jet Propulsion Laboratory</i>
KNMI	<i>Koninklijk Nederlands Meteorologisch Instituut</i>

List of Acronyms (Continued ...)

LAC	<i>Local Analysis Centre</i>
LDC	<i>Local Data Centre</i>
LPT	<i>Swisstopo</i>
LSE	<i>Least-Squares Estimation</i>
LSQ	<i>Least-Squares</i>
METO	<i>U.K. Met Office</i>
MHz	<i>Megahertz</i>
MoU	<i>Memorandum of Understanding</i>
MSL	<i>Mean Sea Level</i>
NASA	<i>National Aeronautics and Space Administration</i>
NAV	<i>NAVigation message</i>
NEQ	<i>Normal EQUation</i>
NGAA	<i>Nordic GNSS Analysis Centre</i>
NMA	<i>National Mapping Agencies</i>
NMF	<i>New Mapping Function</i>
NMS	<i>National Meteorological Services</i>
NRT	<i>Near Real-Time</i>
NWP	<i>Numerical Weather Prediction</i>
OAC	<i>Orbit Accuracy Code</i>
OS	<i>Ordnance Survey</i>
OS net	<i>Ordnance Survey network</i>
P-code	<i>Precision code</i>
PCV	<i>Phase Centre Variation</i>
PCE	<i>Phase Centre Eccentricity</i>
PCO	<i>Phase Centre Offset</i>
PPP	<i>Precise Point Positioning</i>
PPS	<i>Precise Positioning Service</i>
PRN (Codes)	<i>Pseudo-Random Noise (Codes)</i>
P(Y)	<i>Precise or (Y) code</i>
QMS	<i>Quality Monitoring Scheme</i>
RAOB	<i>Radiosonde Observation</i>
RDC	<i>Regional Data Centre</i>

List of Acronyms (*Continued ...*)

RF	<i>Radio Frequency</i>
RGP	<i>Réseau GPS Permanent</i>
RINEX	<i>Receiver INdependent Exchange (format)</i>
RMI	<i>Royal Meteorological Institute of Belgium</i>
RMS	<i>Root Mean Square</i>
ROB	<i>Royal Observatory of Belgium</i>
RTE	<i>Radiative Transfer Equation</i>
RTK	<i>Real-Time Kinematic</i>
S/N	<i>Signal-to-Noise Ratio</i>
SA	<i>Selective Availability</i>
SAPOS	<i>SATellite POSitioning Service</i>
SD	<i>Single-Difference</i>
SGN	<i>French IGN service of geodesy</i>
SP-code	<i>Standard Precision code</i>
SPS	<i>Standard Positioning Service</i>
SPT	<i>Standard Pressure Temperature (model)</i>
STD	<i>Slant Total (tropospheric) Delay</i>
S.U.	<i>Soviet Union</i>
SV	<i>Satellite Vehicle</i>
TEC	<i>Total Electron Content</i>
TOUGH	<i>Targeting Optimal Use of GPS Humidity</i>
TRANSIT	<i>The Navy Navigation Satellite System</i>
URD	<i>User Requirement Document</i>
U.S.	<i>United States of America</i>
USNO	<i>U.S. Naval Observatory</i>
UT	<i>Universal Time</i>
UTC (USNO)	<i>Coordinated Universal Time (as represented by the United States Naval Observatory)</i>
USDoD	<i>United States Department of defence</i>
VLBI	<i>Very Long Base Interferometry</i>
VMF	<i>Vienna Mapping Function</i>
WALCORS	<i>WALloon Continuously Operating Reference Stations</i>

List of Acronyms (*Continued ...*)

WGS84	<i>World Geodetic System 1984</i>
WMO	<i>World Meteorological Organisation</i>
wrt.	<i>With respect to</i>
WVR	<i>Water vapour Radiometre</i>
ZD	<i>Zero-Difference</i>
ZDD	<i>Zenith Dry Delay</i>
ZHD	<i>Zenith Hydrostatic Delay</i>
ZND	<i>Zenith Neutral Delay</i>
ZPD	<i>Zenith Path Delay</i>
ZWD	<i>Zenith Wet Delay</i>

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