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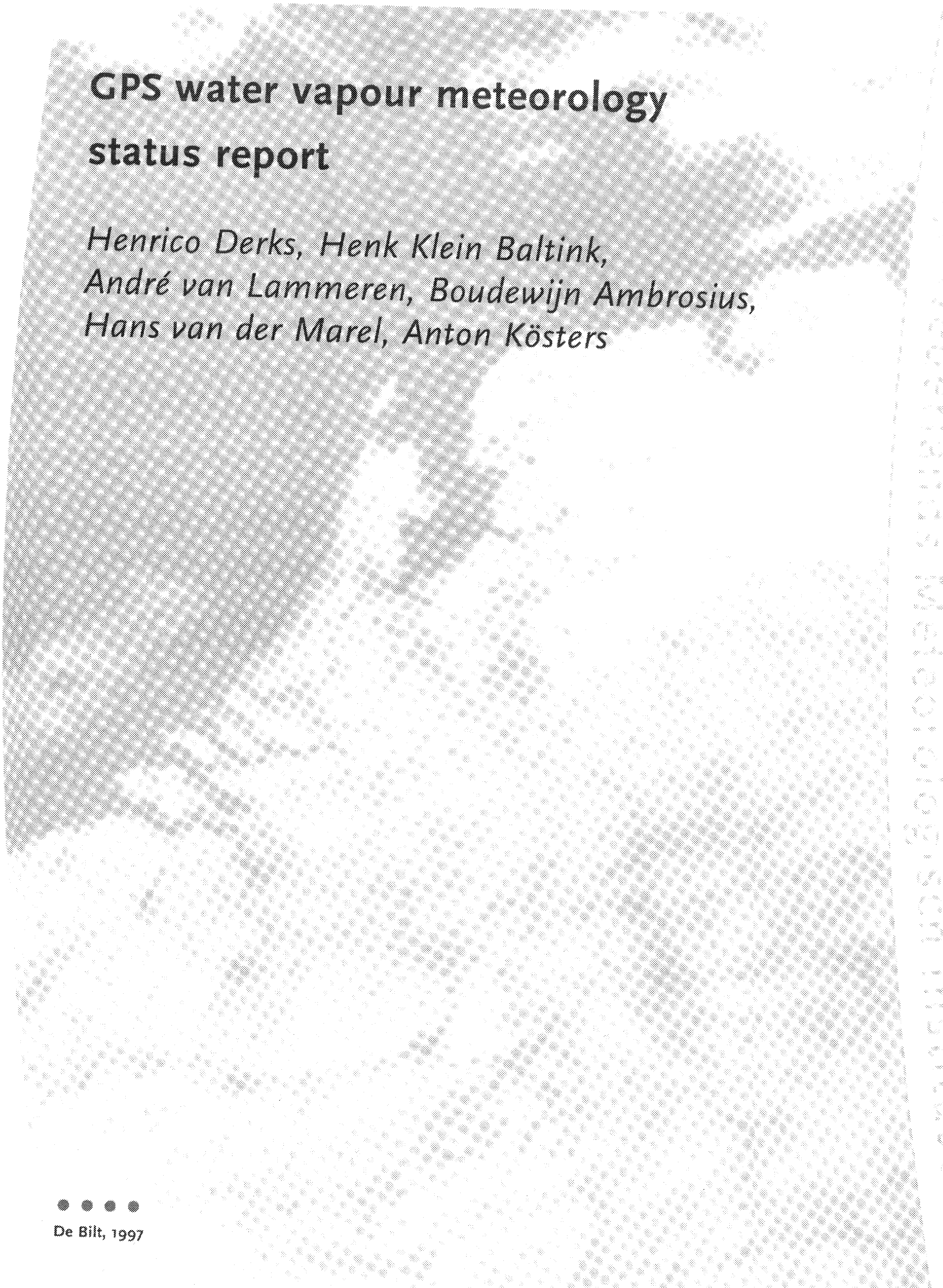

GPS water vapour meteorology status report

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De Bilt, 1997

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GPS Water Vapour Meteorology

Status Report

BCRS Project 1.1/AP-01

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Abstract

Microwave radio signals transmitted by GPS satellites are refracted by the atmosphere as they propagate to the Earth surface. This delay, regarded as a nuisance parameter by geodesists, is directly related to the amount of water vapour in the atmosphere, and hence is a product of considerable value for meteorologists. Measurement of atmospheric water vapour by Earth based GPS receivers was demonstrated in various international projects during the last few years. The accuracy of the GPS water vapour estimates proved to be within 1-2 mm IPWV compared to radiosonde and water vapour radiometer (WVR) data.

Recently the regional GPS infrastructure is extended to a network of 5 operational reference stations (AGRS-NL) equally distributed across the Netherlands. This network fits the requirements for regional GPS water vapour estimation perfectly. Meteorologists have shown their interest to use the GPS water vapour estimations for climatological studies and they are working on the assimilation of this data within the numerical weather forecasting programs. For this latter purpose, the GPS data will have to be processed within near real-time.

This document is the first progress report of a study carried out in the framework of the BCRS Project on *GPS Water Vapour Meteorology*. Participating institutes are the Royal Netherlands Meteorological Institute (KNMI), Faculty of Aerospace Engineering and Faculty of Geodetic Engineering of Delft University of Technology (DUT), and the Survey Department of RWS. The infrastructure for GPS water vapour estimation selected for the duration of the project is described in this report. First analysis of intercomparison of WVR, radiosondes and GPS water vapour measurements during experimental campaigns is presented as well.

Parallel to the acquisition and validation of GPS water vapour estimations, the problem areas in real-time GPS water vapour estimation are investigated further. These problem areas include the availability of accurate GPS satellite orbit information and the real-time GPS data acquisition. Additionally, the assimilation of GPS water vapour estimates in meteorological models needs to be further investigated.

Contents

List of Acronyms and Symbols

AGRS-NL	Active GPS Reference System Netherlands
BALTEX	Baltic Sea Experiment
BCRS	Beleids Commissie Remote Sensing
BUFR	Binary Universal Form for Representation
C/A	Coarse Acquisition
CBI	Compressed Binary format
CC	Computing Centre
CDDIS	Crustal Dynamics Data Information System
CISC	Consejo Superior de Investigaciones Cientificas
CLARA	Clouds And Radiation project
CODE	Centre for Orbit Determination Europe
DUT	Delft University of Technology
ECMWF	European Centre for Medium range Weather Forecasts
GCM	General Circulation Model
GAS	GPS Analysis Software
GPS	Global Positioning System
GTS	Global Telecommunications System
GSI	Geographical Survey Institute of Japan
HIRLAM	High Resolution Limited Area Model
IESSG	Institute of Engineering Surveying and Space Geodesy
IGS	International GPS Service for Geodynamics
IGS/AC	IGS Analysis Centre
ITRF	International Terrestrial Reference Frame
IPWV	Integrated Precipitable Water Vapour
JMA	Japanese Meteorological Agency
JPL	Jet Propulsion Laboratory
KNMI	Koninklijk Nederlands Meteorologisch Instituut
LAM	Limited Area Model
LES	Large Eddy Simulation
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NEQ	Normal Equation
NOAA	National Oceanic and Atmospheric Administration
NOAA/FSL	NOAA Forecast Systems Laboratory
NWP	Numerical Weather Prediction
OSO	Onsala Space Observatory
RACMO	Regional Atmospheric Climate Model
RINEX	Receiver Independent Exchange format
RS	Reference Station

SMHI	Swedish Meteorological and Hydrological Institute
TZD	Tropospheric Zenith Delay
VLBI	Very Long Baseline Interferometry
UCAR	University Corporation for Atmospheric Research
UNAVCO	University Navstar Consortium
WAVEFRONT	Water Vapour Experiment For Regional Operational Network Trials
WMO	World Meteorological Organisation
WVR	Water Vapour Radiometer
ZHD	Zenith Hydrostatic Delay
ZWD	Zenith Wet Delay

E	Elevation angle
e_s	Water vapour saturation pressure
f_1	Frequency of carrier wave L1
f_2	Frequency of carrier wave L2
g_m	Mean gravity
H	Height above mean sea level
k_1,k_2,k_3	Physical constants
$L1$	Primary carrier wave
$L2$	Secondary carrier wave
N	Total refractivity
N_w	Refractivity of wet part of the atmosphere
P	Pressure
P_d	Partial pressure of dry constituents of the air
P_s	Surface pressure
P_{sea}	Pressure at mean sea level
P_v	Partial water vapour pressure
R_d	Specific gas constant of dry air
R_v	Specific gas constant of water vapour
RH	Relative humidity
RH_{sea}	Relative humidity at mean sea level
Δs_{zd}	total zenith delay
Δs_{zhd}	zenith hydrostatic delay
Δs_{zwd}	zenith wet delay
T	Temperature
T_m	Weighted mean temperature of wet part of atmosphere
T_s	Surface temperature
T_{sea}	Temperature at mean sea level

Π	Constant of proportionality
ϕ_{if}	Ionospheric free carrier phase
ϕ_1	Phase of primary carrier wave L1
ϕ_2	Phase of secondary carrier wave L2
ρ	Air density
ρ_w	Water density
ρ_v	Water vapour density

Chapter 1

Introduction

Water vapour is one of the most important constituents of the atmosphere as moisture and latent heat are transported through the water vapour phase. Besides that, water vapour is the most important greenhouse gas. Accurate, dense and frequent sampling of water vapour, is obviously of great use for climatological research as well as operational weather forecasting. Currently water vapour is measured using radiosondes and ground or space based water vapour radiometers. Radiosondes produce an accurate measurement of the water vapour profile, but the temporal and spatial resolution is rather poor. Ground based radiometers experience problems during periods of rain fall and space based radiometers can be degraded in the presence of clouds. Besides these limitations, all systems involve considerable costs.

Over the past few years, a new technique to measure integrated water vapour (IWV) has been developed. This technique is based on the estimation of the tropospheric delay time of GPS signals. The delay, regarded as a nuisance parameter by geodesists, can be directly related to the amount of water vapour in the atmosphere, and hence is a product of considerable value for meteorologists. Furthermore, ground based GPS water vapour estimation is not affected by rain fall and clouds, and can therefore be called an 'all-weather' system. As it takes minor effort to obtain GPS water vapour estimates from the existing GPS infrastructure, and since the temporal and spatial resolution are higher than of the current techniques used, GPS water vapour estimation is a valuable complement.

This document is the first progress report of a study carried out in the framework of the BCRS Project on *GPS Water Vapour Meteorology*. The objectives of the project are:

- to set up an infrastructure for the acquisition, storage and processing of GPS-IWV data
- to make an assessment of the accuracy of GPS-IWV data
- to investigate the usefulness of GPS-IWV data for weather forecast models and climate research
- to study the feasibility of real-time processing of GPS-IWV data

Participating institutes are the Survey Department of RWS (RWS-MD), Faculty of Aerospace Engineering and Faculty of Geodetic Engineering of Delft University of Technology (DUT), and the Royal Netherlands Meteorological Institute (KNMI).

This report will cover the following aspects. First of all, the basic theory behind the GPS water vapour estimation technique will be discussed in Chapter 2.

In Chapter 3 a review on the previous and current investigations in this field is presented. This includes a discussion about the accuracy with which the GPS-IWV data can be recovered and the possibilities for real-time processing of GPS data for this purpose. In the Netherlands an infrastructure for the acquisition of GPS data already exists and has recently been extended to 5 operational stations. The background of this network and its current status is presented in Chapter 4. Next, in Chapter 5, an overview is given of the data requirements defined by the potential future users of the GPS water vapour estimates, *i.e.* the meteorological services.

At present DUT is already involved in the routine analysis of GPS data. This work is primarily aimed at the maintenance of a European reference network and at deformation analysis. The applications could be extended to GPS-IWV estimation however. This requires some additional work though, such as collecting pressure and temperature measurements and extracting the GPS-IWV from the daily processing. For this project an infrastructure has been defined which will reach completion during the first half of 1997. Chapter 6 gives a description of this infrastructure. Implications of near real-time GPS water vapour estimation are discussed in this chapter as well. Finally, Chapter 7 presents some preliminary conclusions and recommendations.

Chapter 2

GPS Water Vapour Estimation Technique

As the GPS radio signals propagate through the Earth's atmosphere, they are being delayed and refracted by the gases composing the atmosphere. The atmospheric delay can be divided in two contributions: a delay caused by the ionised part of the atmosphere, called the ionospheric delay, and a delay caused by the neutral part of the atmosphere. The latter contribution is often denoted as the tropospheric delay. This notation is slightly incorrect hiding other constituents of the neutral atmosphere like the stratosphere. However the dominant contribution of the troposphere explains the notation.

The ionospheric delay is dispersive, *i.e.* frequency dependent, and can therefore be determined by observing both the frequencies transmitted by the GPS satellites. Regarding the carrier phase observable ϕ, the ionospheric delay can largely be eliminated by simply combining both frequencies observed:

$$\phi_{if} = \phi_1 - \frac{f_1}{f_2} \cdot \phi_2 \tag{2.1}$$

where ϕ_{if} is the ionospheric free carrier phase, ϕ_1 is the phase of the primary carrier (L1) with frequency f_1 and ϕ_2 is the phase of the secondary carrier (L2) with frequency f_2. By using equation 2.1 the first order term of the ionospheric delay is eliminated, without reference to observations recorded by other receivers in the network. The third order effect, although being small, can be significant at lower elevations under certain circumstances.

The tropospheric delay is less simple to eliminate. The troposphere delays the GPS signals by causing them to 'bend' and retard as they pass through the tropospheric part of the atmosphere. This delay is strongly dependent upon the refractivity of the atmosphere, which is in turn dependent upon the distribution of the dry air and water vapour along the signal path. As a result, the tropospheric delay is separated in a part which is called the hydrostatic delay and a so-called wet delay.

Using the three-term formula for the total refractivity N of moist air we can derive an accurate expression for the total tropospheric zenith delay. The total refractivity is defined by [*Smith and Weintraub*, 1953; *Boudouris*, 1963]:

$$N = k_1 \frac{P_d}{T} + k_2 \frac{P_v}{T} + k_3 \frac{P_v}{T^2} \tag{2.2}$$

Here T is the temperature in K, P_d is the partial pressure of the dry constituents of the air and P_v is the partial water vapour pressure, both in hPa. k_1, k_2 and

k_3 are constants related to the refractivity of moist air. These constants can be determined by direct measurements made using microwave cavities. In this study, the experimental values derived by *Boudouris* [1963] are used:

$$\begin{aligned} k_1 &= 77.593 \pm 0.08 && KhPa^{-1} \\ k_2 &= 72 \pm 10 && KhPa^{-1} \\ k_3 &= (3.754 \pm 0.03)10^5 && K^2hPa^{-1} \end{aligned}$$

The total zenith delay Δs_{zd} is defined as:

$$\Delta s_{zd} = 10^{-6} \int_s N(z)dz \tag{2.3}$$

The refractivity is integrated along the vertical signal path s. Δs_{zd} is given in m, z is the vertical coordinate in m. The integration requires knowledge of the profiles of both the wet and dry constituents of the atmosphere, the mixing ratio of which is highly variable [*Davis et al.*, 1985]. Rewriting the first two terms in 2.2 using the equation of state $R\rho = P/T$, we are able to create a term that is independent of this mixing ratio:

$$k_1 \frac{P_d}{T} + k_2 \frac{P_v}{T} = k_1 R_d \rho_d + k_2 R_v \rho_v = k_1 R_d \rho + k_2' \frac{P_v}{T} \tag{2.4}$$

where k_2' is equal to

$$k_2' = k_2 - \frac{R_d}{R_v} k_1 \tag{2.5}$$

R_d and R_v are the specific gas constants of dry and wet air respectively. By using equation 2.4 the expression for the total refractivity is transformed to

$$N = k_1 R_d \rho + k_2' \frac{P_v}{T} + k_3 \frac{P_v}{T^2} \tag{2.6}$$

As the first term in equation 2.6 is only dependent on the total density, and not on the wet/dry mixing ratio, this term can be integrated applying the condition that hydrostatic equilibrium is satisfied,

$$\frac{dP}{dz} = -\rho(z)g(z) \tag{2.7}$$

where $g(z)$ is the acceleration due to gravity at the vertical coordinate z in ms^{-2} and $P(z)$ is the total pressure in hPa. Integrating equation 2.7, we obtain

$$P_s = g_m \int_s \rho(z)dz \tag{2.8}$$

where

$$g_m = \frac{\int_s \rho(z)g(z)dz}{\int_s \rho(z)dz} \tag{2.9}$$

This term can be approximated quite accurately using [*Saastamoinen*, 1972]:

$$g_m = 9.784 \cdot (1 - 0.00266 \cos 2\lambda - 0.00028H) = 9.784 \cdot f(\lambda, H) \tag{2.10}$$

$f(\lambda, H)$ is used to model the variation of the gravitational acceleration, where λ is the latitude and H the height of the station above the mean sea level in km.

Denoting the result of the integration of the first term as the zenith hydrostatic delay (ZHD) Δs_{zhd}, we find that

$$\Delta s_{zhd} = 10^{-6}[k_1 R_d g_m^{-1}]P_s \tag{2.11}$$

Combining all the constants in equation 2.11 along with their uncertainties results in [*Elgered*, 1993]:

$$\Delta s_{zhd} = (0.0022768 \pm 0.0000024)\frac{P_s}{f(\lambda, H)} \tag{2.12}$$

The two terms that remain from equation 2.6 are *wet* terms:

$$N_w = \frac{P_v}{T}\left[\frac{k_3}{T} + k_2'\right] \tag{2.13}$$

Hence the zenith wet delay (ZWD) Δs_{zwd} is defined by

$$\Delta s_{zwd} = 10^{-6}\int_s N_w dz = 10^{-6}\int_s \frac{P_v}{T}\left[\frac{k_3}{T} + k_2'\right] dz \tag{2.14}$$

Introducing a "mean temperature" T_m

$$T_m = \frac{\int \frac{P_v}{T} dz}{\int \frac{P_v}{T^2} dz} \tag{2.15}$$

equation 2.14 can be written as

$$\Delta s_{zwd} = 10^{-6}[k_3 + k_2' T_m]\int_s \frac{P_v}{T^2} dz \tag{2.16}$$

Using equation 2.15 and the equation of state, this formula can be rewritten to

$$\Delta s_{zwd} = 10^{-6} R_v \left[\frac{k_3}{T_m} + k_2'\right]\int_s \rho_v dz \tag{2.17}$$

The last term of this equation is denoted as the integrated water vapour IWV:

$$IWV = \int_s \rho_v dz \tag{2.18}$$

IWV is given in kgm^{-2}. The amount of water vapour present in the vertical column can also be represented by the integrated precipitable water vapour IPWV, which is the height of an equivalent column of liquid water:

$$IPWV = \frac{1}{\rho_w}\int \rho_v dz \tag{2.19}$$

ρ_w is the density of liquid water which is equal to 10^3 kgm^{-3} and hence we find that 1 kgm^{-2} IWV is equivalent to 1 mm IPWV. Furthermore, the term in front of the integral in equation 2.17 is denoted as the inverse of the *constant of proportionality* Π:

$$\Pi^{-1} = 10^{-6} R_v \left[\frac{k_3}{T_m} + k_2'\right] \tag{2.20}$$

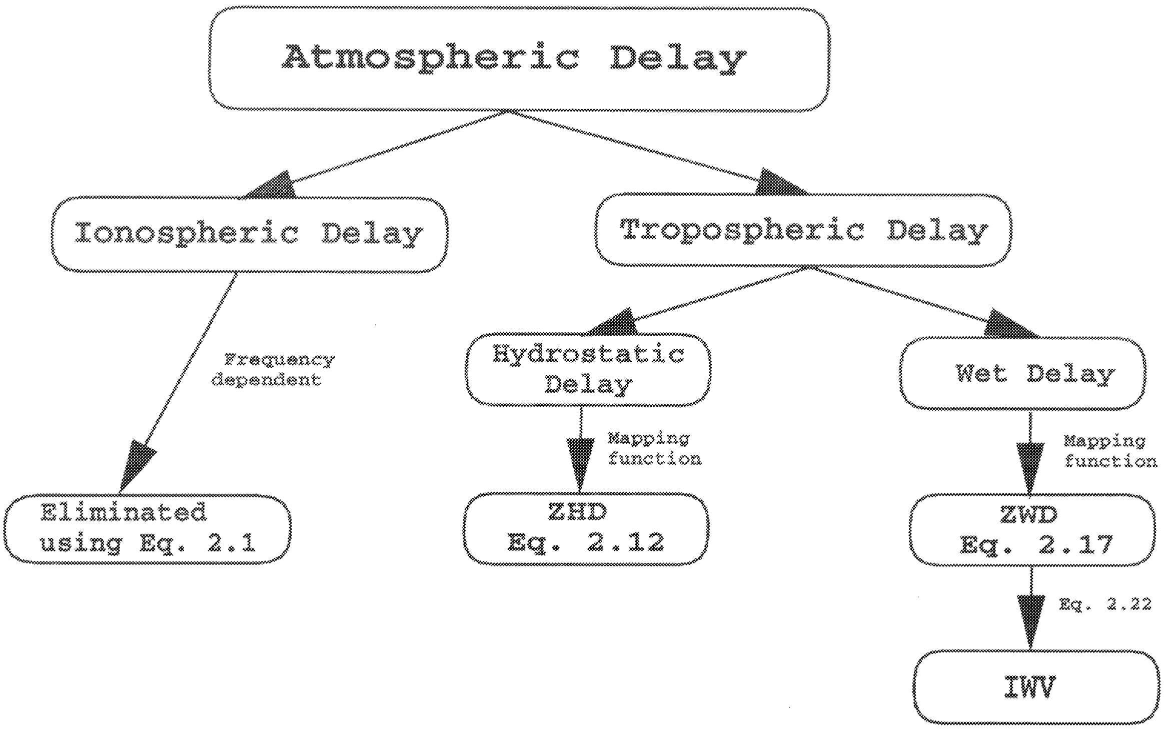

Figure 2.1 Modelling of the atmospheric delay.

Factor Π is approximately 0.15 m^3kg^{-1}, but varies with location, elevation and season by as much as 20%. Π can be determined to about 2% when computed as a function of surface temperature, using an approximation for T_m by *Bevis et al.* [1992]:

$$T_m = 70.2 + 0.72\,T_s \tag{2.21}$$

This regression is based on a large number of radiosonde launches over a 2-yr interval from 13 stations in the United States. The rms scatter about this regression is 4.7 K, corresponding to a relative error of less than 2%.

As can be seen from equation 2.16, surface meteorological measurements are not sufficient for the computation of ZWD. Combining equations 2.17, 2.18 and 2.20 we find a simple relation between ZWD and IWV:

$$IWV = \Pi \cdot ZWD \approx 0.15 \cdot ZWD \tag{2.22}$$

Zenith delays (*i.e.* both wet and hydrostatic) can be mapped to the elevation angles of observation by use of mapping functions. The most simple mapping function is the direct projection from the zenith onto the line of sight given by $1/\sin E$, where E is the elevation angle of the satellite. More sophisticated mapping functions are given by *Lanyi* [1984] or *Seeber* [1993]. Fig. 2.1 shows the way the atmospheric delay can be modelled for the GPS observations.

Traditionally, the effects on GPS signals due to the atmosphere have been solved for as computational unknowns within GPS data analysis, in order to obtain ever more precise GPS positions. Signal delays due to the ionosphere are solved for using relation 2.1. An a priori value for the tropospheric delay is provided by meteorological models based upon surface meteorological data [*Hopfield*, 1971; *Saastamoinen*, 1972] or by location and use of a standard atmosphere. In the latter case, the meteorological data is replaced by formulas which vary with height only [*Rothacher and Mervart*, 1996]:

$$\begin{aligned} P &= P_{sea}(1 - 2.26 \cdot 10^{-5} \cdot H)^{5.225} \\ T &= T_{sea} - 0.0065 \cdot H \\ RH &= RH_{sea}\, e^{-6.396 \cdot 10^{-4} \cdot H} \end{aligned} \tag{2.23}$$

P_{sea}, T_{sea} and RH_{sea} are the air pressure, the temperature and the relative humidity at mean sea level respectively, and H is the height above mean sea level in m. Once the total tropospheric delay has been determined, the hydrostatic component can be modelled and removed using equation 2.12, leaving an accurate estimate of the wet delay. The GPS data processing selected for this project, is discussed in Section 6.3.

The IPWV derived from GPS data analysis, can easily be compared to other data sources. Radiosonde measurements *e.g.*, supply temperature and humidity profiles of the vertical column, which can be used to compute IPWV using equation 2.19. The water vapour density ρ_v can be derived from the temperature and relative humidity profiles measured by the radiosondes:

$$\rho_v = 7.223 \cdot e_s \cdot \frac{RH}{100} \cdot \frac{300}{T} \tag{2.24}$$

e_s is the water vapour saturation pressure in hPa which is defined by Magnus:

$$e_s = 6.1070 \cdot e^{\frac{17.38(T-273.16)}{T-34.16}} \tag{2.25}$$

With the temperature T ranging from 233 K to 313 K this relation is within 0.01 hPa of the World Meteorological Organisation (WMO) standard [*Van Westrhenen*, 1993].

Also water vapour radiometers (WVRs) can be used to derive the amount of water vapour in the vertical column. With a radiometer, brightness temperatures at two or more frequencies are measured. From these measurements it is possible to derive the integrated liquid water and water vapour content of the vertical column, using special algorithms. The most simple algorithms contain linear combinations of the atmospheric attenuations at the frequencies measured.

Radiometer measurements and radiosonde launches were conducted within the framework of the CLARA[1] campaign in Delft, where a GPS receiver is located as well. Therefore validation of the GPS-IPWV estimates for station Delft, is carried out over the time intervals covered by the CLARA campaign. The radiometer measurements are performed by the Telecommunications Division of Eindhoven University of Technology (EUT). The radiometer, owned by ESTEC, measures the brightness temperatures at 21.3 GHz and 31.7 GHz. During the last CLARA campaign, a second radiometer was used, which was bought by the Radiocommunications Group of EUT with funding of the Dutch Technology Foundation (STW). This radiometer measures the brightness temperatures at three frequencies just above 50 GHz, in order to obtain temperature profile information.

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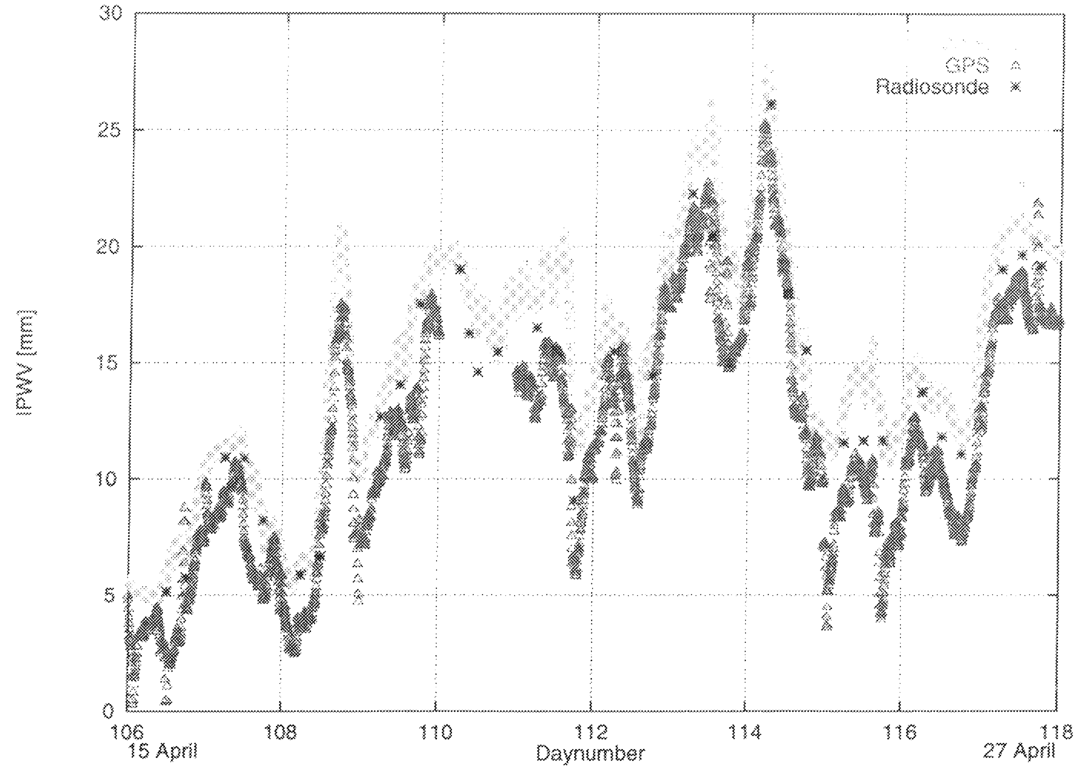
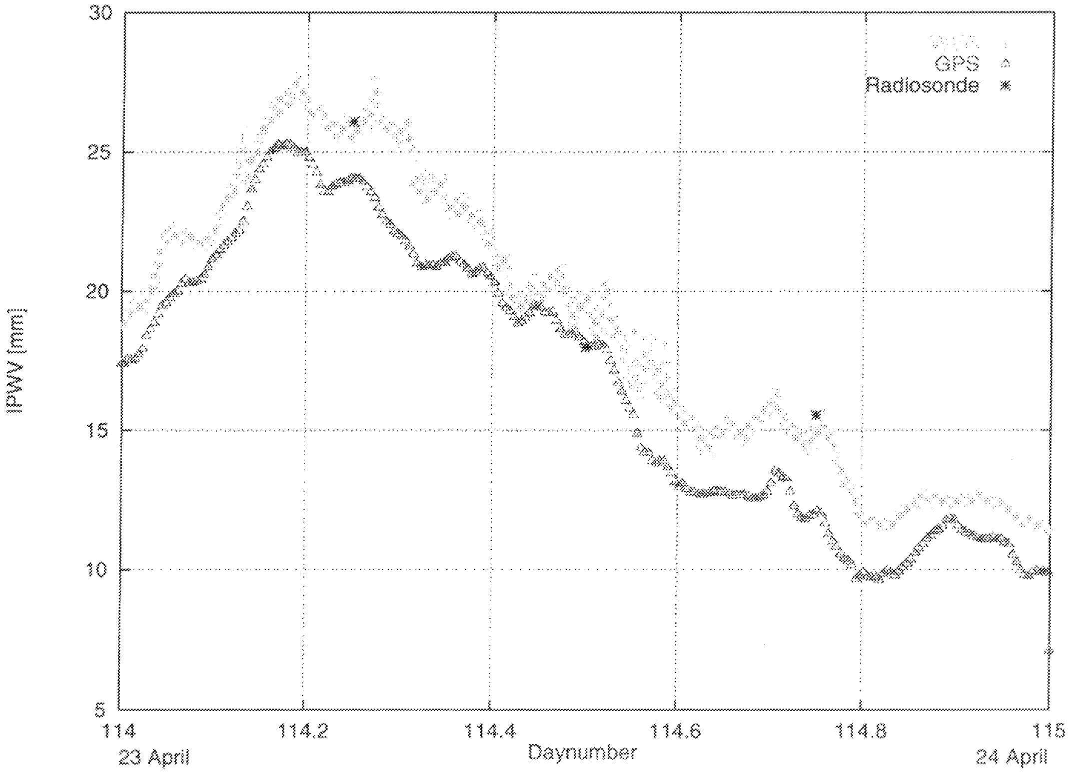
[1] The CLouds And RAdiation-project (CLARA) aims to develop and validate retrieval methods of cloud characteristics from remote sensing data. During 1996 three intensive measurement campaigns in Delft have taken place.

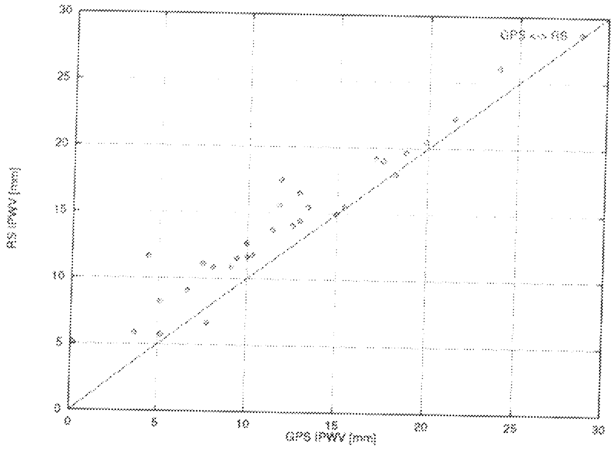


a) All data.

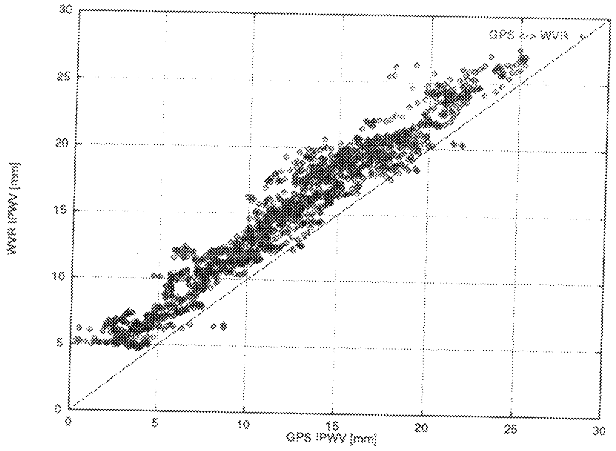


b) Enlargement for daynumber 114, 23 April 1996.

Figure 2.2 A comparison of the estimates produced by three different measurement techniques during the first CLARA campaign: radiosondes, water vapour radiometers and GPS signal delay.



a) GPS versus radiosondes



b) GPS versus WVR

Figure 2.3 The correlation of GPS IPWV estimates with two other measurement techniques, for the first period of the CLARA campaign.

The GPS-IPWV estimates were computed at DUT using the GIPSY software[2]. This software employs a Kalman filter/smoother which allows it to estimate the tropospheric delay as a stochastic parameter, concurrently with many other time-invariant parameters. Fig. 2.2 is an example of a plot in which the GPS water vapour estimates are compared to radiosonde measurements and water vapour radiometer derived estimations. The water vapour estimates were determined by *Jongen* [1996] from the 21.3 and 31.7 GHz brightness temperatures by using the matched atmosphere algorithm as described by *Janssen* [1995].

As can be seen, the trend is captured very well by the GPS-IPWV estimates, although a small constant off-set can be observed. Despite this small bias, the correlation between both radiosonde and WVR measurements is confirmed by the correlation plots in Fig. 2.3. Unfortunately the GPS water vapour estimations for station Delft contain a number of spikes, as can be seen in Fig. 2.2a (*e.g.*daynumber 115). The cause of these errors has not been found jet.

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[2] GIPSY is the GPS Inferred Positioning System software developed by the NASA Jet Propulsion Laboratory (JPL) in the USA.

Chapter 3

Research Overview

Since the beginning of this decade, established institutes have investigated the feasibility of estimating the amount of atmospheric water vapour using the delay in the GPS radio signals. In this chapter some of the larger projects are summarized, together with a description of the research currently conducted. In general the results show that IPWV can be estimated at an accuracy level of 1-2 mm using GPS data. The use of broadcast satellite orbit information is only justified within small networks in combination with reference data from other systems, like WVRs. GPS water vapour estimation proofed to be an all weather system which is able to detect *e.g.* the passages of cold fronts. Furthermore the use of different software packages to process the GPS data showed to have no substantial influence on the results.

3.1 Previous Investigations

3.1.1 GPS-STORM Experiment

From 7 May to 2 June 1993 the University Navstar Consortium (UNAVCO), the University Corporation for Atmospheric Research (UCAR) and the University of Hawaii carried out the GPS-STORM Experiment. Using dual frequency GPS data from six continuously operating GPS receivers, zenith wet delay and precipitable water vapour were estimated relative to Platville, Colorado, every 30 minutes. At three of these sites *Rocken et al.* [1995] compared the GPS estimates of IPWV to water vapour radiometer measurements. The zenith hydrostatic delay was modelled and corrected for using pressure data. Precise ephemerides (see Section 6.1) generated by the Centre for Orbit Determination in Europe (CODE) were used in the analysis. Using this set-up for a network with site-spacing of 500 to 900 kilometers, IPWV was estimated at an accuracy level of 1-2 mm. In this investigation, the quality of the broadcast orbits, revealed not to be sufficient to obtain accurate IPWV estimates in 'large' networks. The investigators however bear out the feasibility of "future meteorological GPS networks providing near real-time high resolution IPWV for weather forecasting".

3.1.2 NOAA/GL Automated Water Vapour Monitoring Project

The Automated Water Vapour Monitoring project by NOAA's Geoscience Laboratory (NOAA/GL) started Mid July 1994. IPWV values were derived from GPS tracking stations co-located with radiosonde launch sites. The GPS measurements are being examined for accuracy under a variety of weather conditions, diurnal signals, and seasonal differences using the co-located radiosonde measurements as a standard. The data is being processed in blocks of 28 hours, with an overlap of 4 hours (2 hours on both sides). With the double differencing technique the ionospheric delay is eliminated and the zenith hydrostatic delay is modelled using surface pressure measurements. The zenith wet delay is computed every 15 minutes, after which it is transformed to IPWV data. GL performed several tests using different reference stations which showed that the estimation of the IPWV is not sensitive to the choice of reference site within reason [*Dodson and Shardlow*, 1996]. Furthermore they produced IPWV estimates once per hour, which showed less detail, but correlated well with the radiosonde estimates.

3.1.3 IRENET 95

IRENET 95 is a regional analysis of GPS derived IPWV over Ireland. This study was performed by the Institute of Engineering Surveying and Space Geodesy (IESSG), in Nottingham. It included a network of 25 European stations, of which 11 were located in Ireland. GPS dual frequency observations, taken at 60 seconds intervals, over a period of 5 days were used to study the feasibility of obtaining IPWV from the GPS observations. Station Onsala, located in South-Sweden, was used as a reference site as water vapour radiometer data is available for this site. The stations were held fixed to coordinates given by the International Terrestrial Reference Frame '93 (ITRF93) and precise ephemerides by CODE were used during the data processing. The GPS Analysis Software (GAS), developed at IESSG, was used to process the data. The zenith hydrostatic delay was modelled using surface pressure data. Results from this campaign were encouraging. At Onsala, the GPS water vapour estimations agreed at a 2 mm level with the WVR estimates [*Dodson and Shardlow*, 1996], with a bias of 1 mm. In addition, the GPS water vapour estimation technique was able to detect the passage of a cold front. As was to be expected, the GPS IPWV estimates showed to be unaffected by rain fall, in contrary to the WVR data.

3.1.4 The Japanese GPS MET Project

Using the GPS network established by the Geographical Survey Institute of Japan (GSI), consisting of more than 600 dual frequency receivers, precipitable water vapour is estimated for several stations. To assess the accuracy obtained by different GPS data processing software, both the GAMIT, developed at Massachusetts Institute of Technology (MIT), and GIPSY, by the Jet Propulsion Laboratory (JPL), packages were used to estimate the IPWV. ZHD was corrected for using observed surface pressure data. Except for an offset of several millimeters compared to the radiosonde data, the GPS-IPWV captures the main trends in the variation of the amount of atmospheric water vapour. The consistent offset, in this case can be explained by the distance between the GPS-site and the radiosonde launch site [*Dodson and Shardlow*, 1996].

The comparison of the data produced by the two different software packages, shows that they are comparable to within several millimeters. Differences that do occur can be appointed to the differing time intervals at which the estimates are being computed. Further comparison of various software packages is to be carried out as part of the WAVEFRONT Project (see Section 3.2.3). It is expected that any software dependent bias will gradually disappear as modeling of unknowns improves in time. If vertical water vapour profiles can be produced within several hours, the Japanese Meteorological Agency (JMA) and GSI hope to use the GPS estimates within the numerical weather prediction [*Dodson and Shardlow*, 1996].

3.1.5 LINEX 96

Within the framework of LINEX 96/1 GPS water vapour estimations are performed at the Meteorological Observatory Lindenberg, Germany. LINEX 96/1 is a field campaign to demonstrate the different possibilities of water vapour observation in the free atmosphere. Many water vapour detection systems were used within the measurement campaign, which took place from 15 April to 13 May 1996. Preliminary results show good agreement of the GPS water vapour estimates with WVR data. The standard deviation of the difference between GPS estimates and WVR measurements was about 1 mm. The bias in the GPS estimates (3.9 mm) was said to be sensitive to the elevation cutoff angle and the antenna model used in the analysis, particularly when different antenna types are mixed [*Gendt*, 1996].

3.2 Current Investigations

At present, several of the investigations on GPS water vapour estimation mentioned above, are still running. NOAA is working on (near) real time processing, but is presently still using improved orbits, which are available 18 hours after the end of the day. Besides that, the processing itself consumes several hours. They expect to have this problem solved before the end of 1997 [*Gutman*, 1996]. The GPS water vapour estimates are used for assessment studies of the impact on climatological studies and mesoscale forecast accuracy and for reduction of biases present in other satellite water vapour data.

The UNAVCO GPS Research Group has begun to analyze GPS data from the NOAA Forecast Systems Laboratory (NOAA/FSL) GPS network in near real-time. Section 3.2.1 describes the current status of this project. Furthermore, within the Baltic Sea Experiment (BALTEX) GPS IPWV estimates are computed for the sites in the Newbaltic network, containing 20 Swedish and 5 Finnish GPS sites. In Section 3.2.2 the Newbaltic project is briefly discussed. The results for the 25 sites are compared to WVR and radiosonde data. These comparisons are used within the WAVEFRONT project as well. As stated before, GSI will continue the comparison of different software packages in the framework of the WAVEFRONT project, which is briefly presented in section 3.2.3.

3.2.1 Real Time IPWV Processing at UNAVCO

At UNAVCO investigations have started to reach for near real-time GPS water vapour estimation. The set-up used to obtain near real-time water vapour estimates is described below [*Rocken*, 1996].

The GPS data is processed in 1-hour segments, using the Bernese software developed at the University of Berne Astronomical Institute. For the estimation of IPWV, the station coordinates are constrained tightly to positions obtained from processing daily solutions for the NOAA/FSL network. The normal equation (NEQ) from the 1-hour analysis is stored and the NEQs of the last 24 1-hour

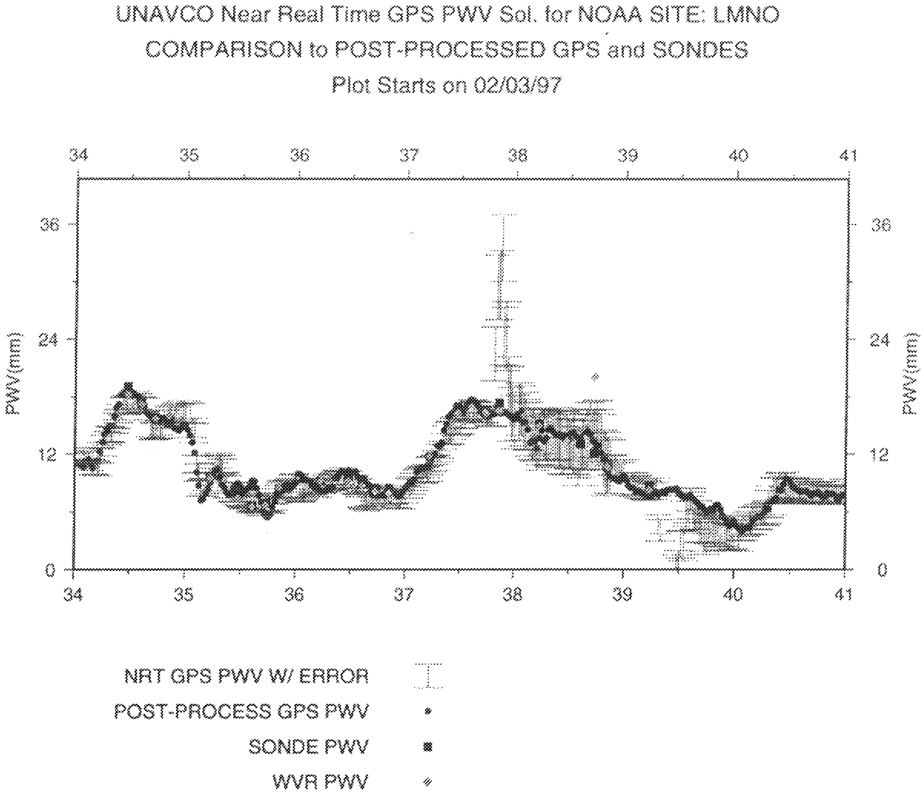

Figure 3.1 Example of the data produced at UNAVCO. The near real-time GPS water vapour estimations are here compared to estimates based on post processed GPS data, radiosonde data and WVR data. (Source: [*Rocken*, 96])

solutions are stacked to obtain the equivalent of a 24 hour GPS solution. By using this stacking technique, it is not necessary to re-process many hours of data thus resulting in significant savings in CPU time. Processing is done with 1-day and 2-day predicted GPS orbits computed at CODE. The NOAA/FSL network consists of 11 GPS receivers located in Colorado, Kansas, Oklahoma, New Mexico and Mississippi. The GPS instruments are co-located with wind profilers and log data every 30 seconds. Every 30 minutes the GPS data, together with the meteo data is transferred to the NOAA hub in Boulder, Colorado, via a telephone line. Fig. 3.1 is an example of a series of GPS water vapour estimates produced by UNAVCO. Here the near real-time estimates are compared to estimates based on post processed GPS orbits, WVR and radiosonde data. One can see that the near real-time estimates are in reasonable agreement with the other three measurements.

3.2.2 The Newbaltic Project

The Newbaltic project has started one year ago. The first year of the project has been used to produce time series of the atmospheric water vapour content at 25 GPS sites in Sweden en Finland, during the period of August, September and October 1995 (see Fig. 3.2). The GPS data has been of good quality and comparisons with data from WVR and radiosondes indicate root-mean square differences of 1-2 mm IPWV. The data is made available to the research community

Figure 3.2 Here the geographical location of the GPS stations included in the Newbaltic project are displayed.(Source: [*Carlsson, 1996a*])

via the Internet by using anonymous-ftp. Fig. 3.3 is an example of the comparisons made at Onsala Space Observatory (OSO), in Sweden [*Carlsson*, 1996*b*]. At OSO, the zenith wet delay is estimated using Very Long Baseline Interferometry (VLBI) measurements as well. As can be seen, both estimates produced by GPS and VLBI agree very well with the WVR measurements. The GPS data has been processed with the GIPSY software package. Surface pressure data is supplied by the Swedish Meteorological and Hydrological Institute (SMHI) and is interpolated to the location of the GPS sites. The water vapour radiometer is co-located with the GPS receiver at Onsala, the radiosondes were launched reasonably close to 4 of the GPS sites used. Currently, at Onsala investigations on the extra uncertainty added to the total error of the IPWV by the use of models for atmospheric pressure, temperature and humidity are running [*Carlsson*, 1996*a*].

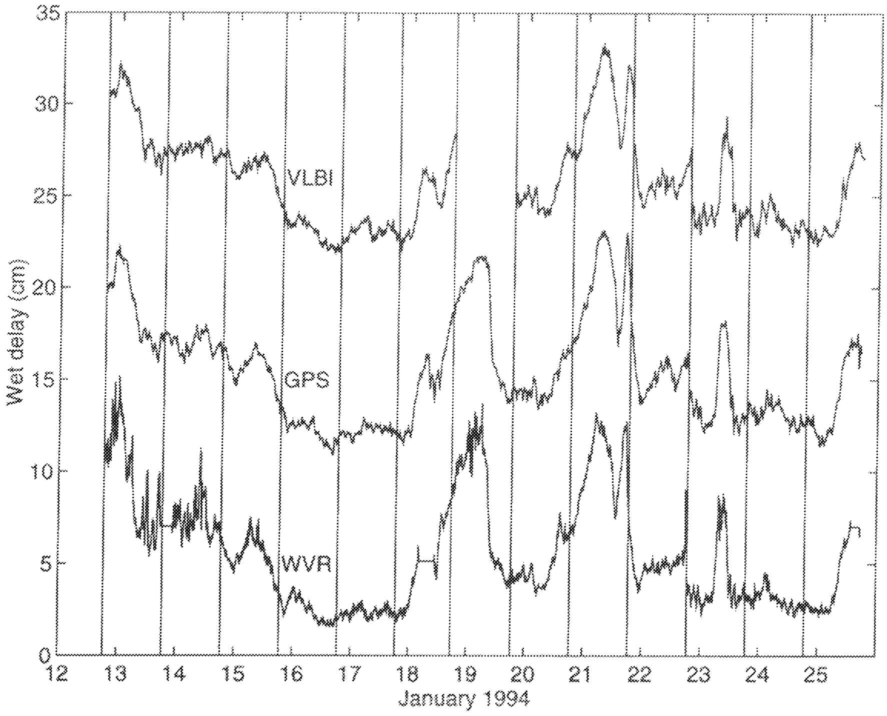

Figure 3.3 Example of the comparisons made within the Newbaltic project. The example shows the wet delay estimated using GPS, VLBI and WVR for station Onsala in Sweden. The values for GPS and VLBI are displayed with an off-set of 10 and 20 centimeters respectively. (Source: *Carlsson, 1996b*)

3.2.3 The WAVEFRONT Project

By accepting the WAVEFRONT Project proposal, the European Union recognised the importance of further work in the area of GPS water vapour estimation. WAVEFRONT, the acronym stands for Water Vapour Experiment for Regional Operational Network Trials, is a cooperation between the University of Nottingham (IESSG), Chalmers Tekniska Hogskola in Sweden, Eidgenossische Technische Hochschule in Switzerland and the Consejo Superior de Investigaciones Cientificas (CSIC) in Spain.

WAVEFRONT aims to demonstrate that GPS can be used to estimate the IPWV at a ± 1 *mm* level by comparison with WVR estimates and will research the feasibility and accuracy of producing estimates on a near real-time basis (less than 3hr latency). Basically the project consists of seven work-packages, which are listed below [*Baker*, 1996]:

1. Ground-based Radiometer/GPS Estimation, comparison and validation
2. Analysis of GPS error sources and processing strategies
3. Analysis of errors induced in conversion from GPS wet delays to GPS IPWV
4. Collection, processing and archiving of a European IGS network of GPS IPWV estimates
5. Statistical analysis of the spatial and temporal characteristics of water vapour
6. Regional water vapour tomography
7. Real-time estimation problems

The WAVEFRONT project started 1 September 1996. The tomographic campaign was planned to take place December 1996 and a comparison of different WVRs (portable versus permanent) was planned to take place in that period as well.

Chapter 4

Analysis of Existing GPS Infrastructure in The Netherlands

4.1 Requirements for GPS Water Vapour Estimation

The NAVSTAR Global Positioning System is a satellite based radio navigation system of the US Department of Defense. For civilian use, the GPS system provides a world wide positioning service with an accuracy of 100 m. This accuracy is typical for a single receiver configuration, that collects C/A-code[1] pseudo-ranges. Since most error sources in the GPS system are locally or regionally correlated, they largely cancel out if data of a single receiver is combined with data of a second receiver. If this second receiver is placed at a known position, the positioning accuracy can be improved to a level of typically 1 to 2 m. Centimeter accuracy can be obtained by including carrier beat phase observables. Since the best positioning results can only be obtained in a relative mode, there is a need for GPS services additional to GPS itself, that provide data of a reference receiver to GPS users to improve their positioning results.

In the Netherlands, several systems of permanent GPS infrastructure exist. These systems aim at providing GPS related data to other GPS users as a special service for positioning and surveying and consist of:

- one or more GPS receivers, that are permanently tracking GPS satellites,
- computers with software for quality control and data-storage, and
- a data-communication link for transmitting data to users.

Some of these systems only provide corrections to the C/A-code pseudo-range observables, computed at a reference station, to users that are satisfied with a maximum accuracy of typically 1 m, either static or dynamic. Other systems aim at satisfying users that need higher accuracy, both static or dynamic, by providing carrier beat phase observations of a reference receiver. The AGRS-NL is such a system. For the use of GPS water vapour estimation, only the second category is important, since the tropospheric delay can be estimated only using carrier beat phase observations in a network of GPS receivers.

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[1] C/A-code pseudo-ranges can be described as ranges measured from observer to satellite, that are biased by the clock errors of satellite and station clock and atmospheric influences. The Coarse Acquisition code is a repeating 1 MHz Pseudo Random Noise (PRN) code which modulates the L1 carrier signal, "spreading" the spectrum over a 1 MHz bandwidth.

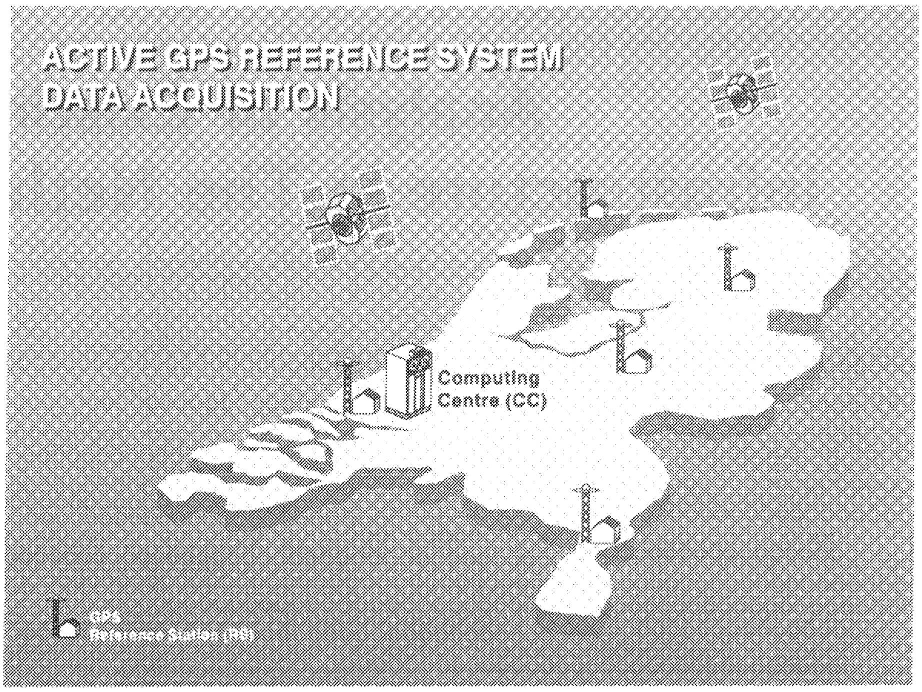

Figure 4.1 Geographic location of the five AGRS GPS stations. As can be seen here, the Computing Centre is located in Delft at this moment.

Other requirements to such a system are:

- the network should have national coverage
- the data should be collected and be available 24 hours a day
- the data should be of high quality, *i.e.* free from possible error sources
- availability of satellite orbit information and reference station outside the network

4.2 AGRS-NL

In 1994, four parties decided to cooperate in building an active GPS reference system for the Netherlands, AGRS-NL. These are :

- Triangulation Department of the Cadastre (KAD)
- Survey Department of Rijkswaterstaat (RWS-MD)
- Delft University of Technology (DUT), Faculty of Geodetic Engineering
- Netherlands Geodetic Commission (NCG)

In 1997, the AGRS-NL will be ready and data will be available. It will primarily provide high quality GPS carrier phase observations, collected at the reference stations. Furthermore there are options to provide other GPS related data for public use, such as differential corrections to the C/A code observations, locally improved satellite orbits, satellite clock parameters, ionosphere and troposphere models etc. There are also options to provide other services, such as dedicated processing for specific purposes or processing of data of clients at the AGRS-NL. KAD and RWS-MD will operate the AGRS-NL and use AGRS-NL data for

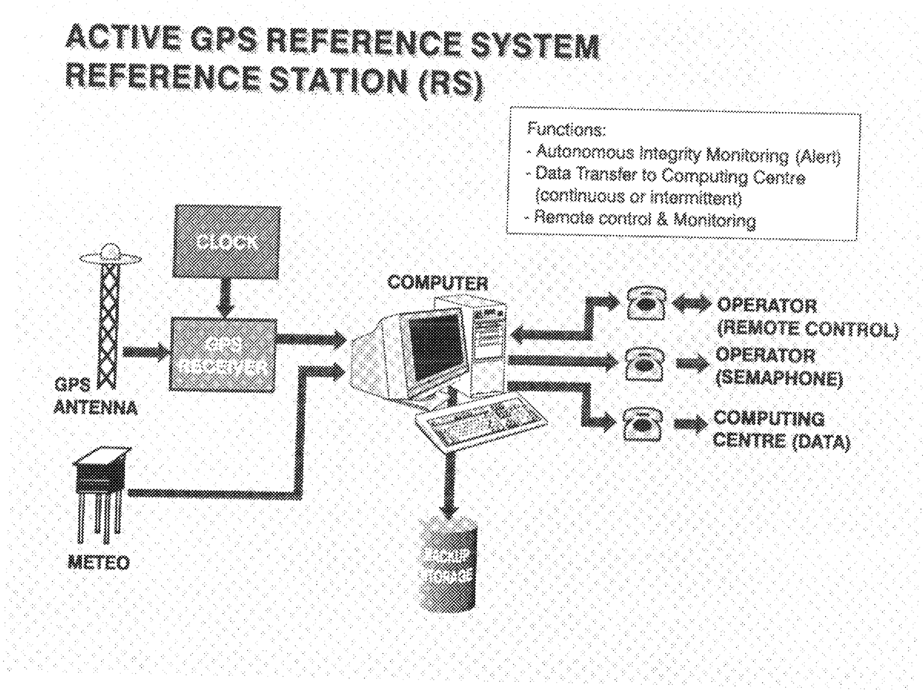

Figure 4.2 The layout of an active GPS reference system reference station.

their own benefit. Data will also be made available to the public for scientific and commercial use. AGRS-NL data will mainly be distributed via the Internet or FTP. The AGRS-NL is the most suitable GPS infrastructure for GPS water vapour estimation in the Netherlands since it meets best the specific requirements given in Section 4.1.

4.3 AGRS-NL Reference Stations

AGRS-NL consists of 5 Reference Stations. The reference stations are in Delft, Kootwijk, Westerbork, Terschelling and Eijsden (see Fig. 4.1). At the reference stations, we find the following sensors:

- a Turbo Rogue SNR12-RM GPS receiver
- Dorne Margolin T GPS antenna
- Vaisala HMP233 Temperature and Humidity Transmitter and Vaisala PTB200A Pressure Transmitter

The Vaisala equipment is not present at Kootwijk and Westerbork, where different meteorological sensors will be used. At each reference station, meteorological data and GPS code and phase data is collected 24 hours a day. The GPS data contains C/A code pseudo-range observations and L1 and L2 phase observations. Parameters such as minimum satellite elevation and data sampling interval can be adjusted. The standard data interval is 30 seconds. At the reference station, a data-validation procedure is performed on each channel, which means that outliers and slips in the phase observations on both channels are flagged or repaired. GPS and meteo data collected at the reference station is stored in an internal data format, the so-called Compressed Binary (CBI) format. After some period, typi-

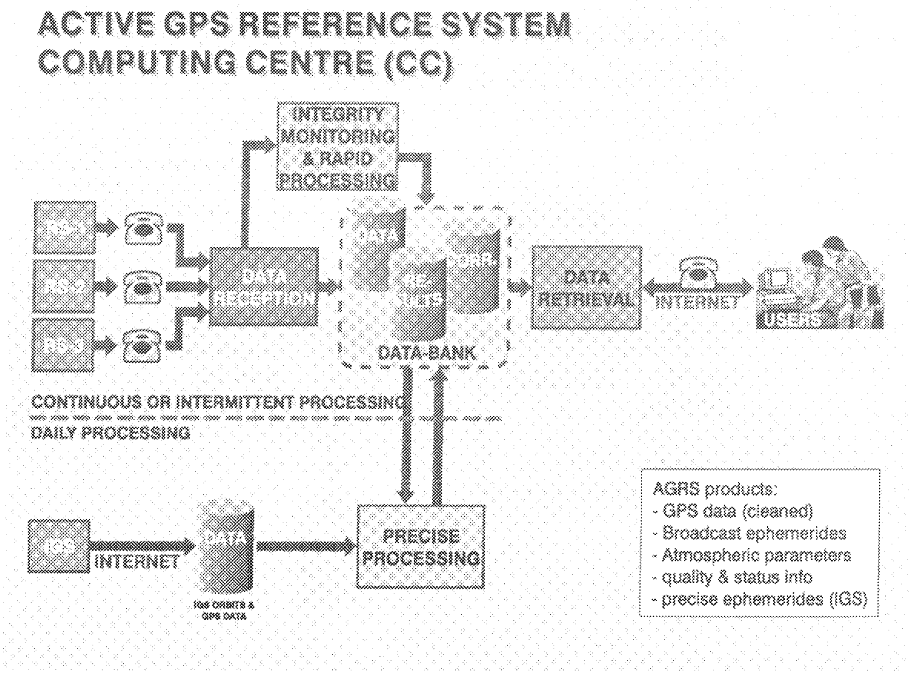

Figure 4.3 The layout of an active GPS reference system computing centre

cally one hour, all data collected in this period is send to the Computing Centre (Fig. 4.2).

The CBI format will be used to transfer data from a reference station (RS) to the Computing Centre and to store this data at the RS.
The CBI format contains:

- Station information
- Meteo data
- Navigation messages
- GPS observables with a quality information included
- Events
- Time and receiver related products of the data processing

After reception of data from all reference stations at the Computing Centre, the Rapid Processing Cycle is started. This processing cycle aims at checking once again the data collected at the reference stations, but now in a network mode. Newly detected slips and outliers are also flagged or repaired. Furthermore, additional parameters can be derived, such as series of reference station coordinates, satellite and receiver clock parameters, ionosphere and troposphere parameters and integer phase ambiguities. This high quality data, typically in one hour bins, will be made available to the public by the Internet or by FTP, in both the CBI and the Receiver Independent Exchange (RINEX) format. For conversion of the CBI format into RINEX, an auxiliary program is available. In Fig. 4.3 the layout of the Computing Centre (CC) is displayed.

A supplementary data processing step is the Daily Processing Cycle. In this step, all data collected on one day at all five reference stations is processed, including the data of some reference stations outside the Netherlands, the IGS-stations.

This processing step is performed with the Bernese GPS processing software and with some days delay. The Bernese processing software has options to enter observed meteo data and to choose a troposphere model. If no meteo data is available, a troposphere model can be chosen, including standard values for temperature, pressure and humidity, which will be extrapolated to the other stations in the network. The zenith tropospheric delay is estimated with respect to this troposphere model and with a selected mapping function.

The Daily Processing Cycle excellently suits the determination of daily series of tropospheric delays at the AGRS-NL reference stations. It might be used as a standard processing procedure, yielding series of parameters, including tropospheric delay parameters, that can be made available for civil use. Another option is to redefine it as a dedicated processing procedure, which is optimized for estimation of tropospheric delay parameters and is run by or by direction of an AGRS-NL client. For the time being, the Daily Processing Cycle is not foreseen as an integral part of the daily AGRS-NL routine. However, once the AGRS-NL is operational, there will be software available to start such a processing cycle.

Chapter 5

User Requirements

5.1 Introduction

Water vapour plays a critical role in atmospheric processes that cover a wide range of temporal and spatial scales, from micro-physics to global climate. Especially for short-range numerical weather forecast water vapour is a very important variable because moisture distribution is closely related to the formation of clouds and precipitation. GPS and also some other satellite techniques provide fairly accurate measurement of integrated precipitable water vapour. Furthermore, the use of ground based GPS stations makes it possible to measure IPWV[1] with an unprecedented temporal resolution of order of minutes. However, the vertical distribution of water vapour is not measured by GPS ground stations, while in general it is the vertical distribution of the water vapour that is needed. The question arises whether it is possible to use precipitable water vapour as a constraint to retrieve the vertical structure of water vapour through some retrieval process. And if so, are the retrieved distributions useful for numerical weather forecast and climate research. These questions are not new and some researchers have already begun with investigation of the (simulated) impact of GPS water vapour measurements on model forecast [*Kuo et al.*, 1993, 1996]. Research effort on this subject is expanding rapidly as an operational status of a (worldwide) GPS water vapour monitoring network is to be expected within a few years. In this chapter we briefly describe the most relevant aspects of numerical atmospheric models for weather prediction and climate research. It is far beyond the scope of this report and project to deal with all the aspects and the interested readers are advised to read the relevant textbooks and articles on this subject [*Arakawa*, 1995; *Baede*, 1988; *Tremberth*, 1992]. Furthermore, we concentrate on the requirements for the models run at the KNMI but this is not a severe restriction as most models have basic features in common. We start with an introduction on numerical weather predictions models and the processing of data obtained from the observations (Section 5.2). In Section 5.3 we briefly summarize the constraints which are imposed by the models on data accuracy, representativeness and timeliness of the data.

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[1] Recent investigations have demonstrated the feasibility of sensing integrated slant-path water vapour along ray paths with GPS [*Ware et al.*, 1997].

5.2 Numerical Atmospheric Models

Accurate weather forecast and climate predictions require numerical models of the atmosphere that deal with a number of processes operating over a broad spectrum. At one end we have molecular viscosity and heat conduction, which are effective at scales of the order of centimeters. On the other end of the spectrum we deal with planetary scale of the order of 10,000 kilometers. It is impossible for any atmospheric model to resolve all the scales. This implies that the combined effect of unresolved scales have to be parametrised in the variables of the resolved scales. This is general formulated as the problem of the parameterisation in atmospheric modeling. Another important aspect of modeling is the required discretisation of the governing (partial differential) equations. The basic governing equations are the equation of state, the continuity equation, the momentum equation, the thermodynamic equation and some kind of mixing-ratio equation. In particular, any realistic model of the atmosphere must predict water-vapour mixing-ratio to calculate the heat of condensation and the effects of water vapour (and clouds) on radiation. Model equations are prognostic if these include the time-derivative of a variable, otherwise the equation is called diagnostic. The main important (prognostic) variables are pressure, wind speed components, temperature and moisture.

In general a whole suite of models is operated at numerical weather prediction centres (NWP) and climate research centres. At the global scale we have the General Circulation Models (GCM) like the ECMWF medium range forecast model with at present a horizontal grid size of approximately 60×60 km and 31 levels in the vertical. Every 12 hours a forecast for the next 10 days is calculated. Limited Area Models (LAM) like the HIRLAM model operated by the KNMI have in general a comparable or higher horizontal resolution. At their lateral boundaries LAM-models use data from global models as boundary input. LAM-models can be nested at different scales. Fig. 5.1 shows the grid used by the Regional Area Climate Model (RACMO). RACMO is a climate research model developed and run by the atmospheric research section of the KNMI. The horizontal resolution is approximately 55×55 km. Models with a very high resolution in space and time are used in research, these so-called Large Eddy Simulation (LES) models resolve scales down to several tenths of meters in space. LES-models are used to study small scale physical processes and are also used to test parametrisation of larger scale models.

For both operational and research models observed data of the model variables are essential. Operational models need a representative present state of the atmosphere as input for each forecast run. As model output for operational use is needed at short time scale this implies an enormous effort in timely data collection and distribution. For testing and validation of models and parameterisations specific data sets are needed, which may need to be global or local depending on the scale of the model and the processes which need to be validated. For long-term climate monitoring the demands on the data accuracy can even be more demanding, as small trends need to be detected in a background signal.

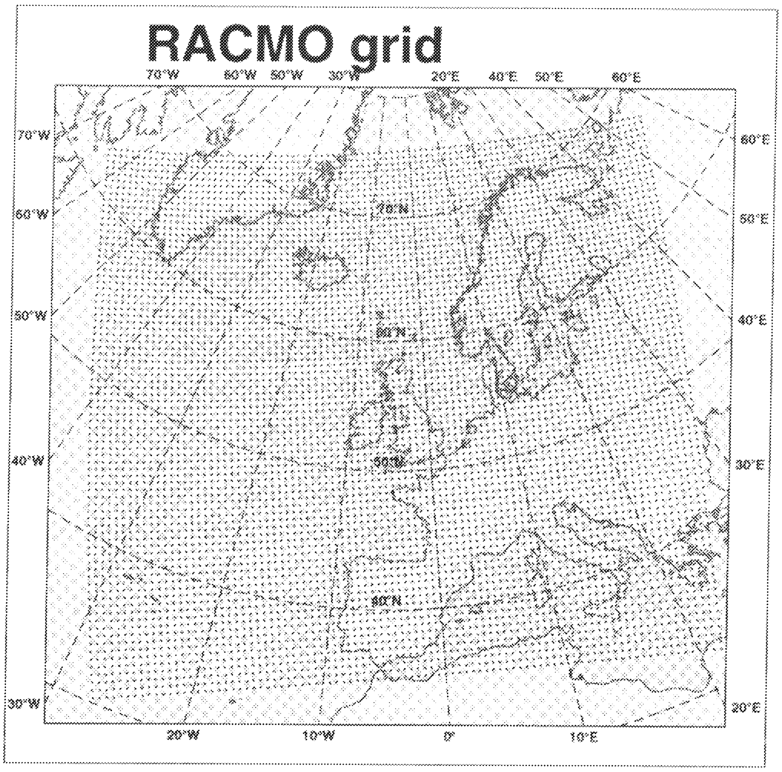

Figure 5.1 Example of the horizontal grid used by a numerical atmospheric model.

5.3 Data Preprocessing in the HIRLAM Model

For operational weather forecast the HIRLAM model is run four times daily at the KNMI. A prediction for 48 hour is calculated for its model domain. Like most present operational models a typical cycle consists of data-assimilation, initialisation and prediction. Data retrieved either from the Global Telecommunications System (GTS) or other networks are collected during a time-window around the time of initialisation. For the HIRLAM this window extends from 3 hours before till 2 hours after the initialisation time. All data collected within this time window will be treated as if these were measured at the initialisation time. Measured data and the first guess results of the previous run (*i.e.*the 6 hour forecast) are combined in the analysis, from which the initial conditions are calculated. Presently most models still rely on the optimal interpolation (OI) technique in the analysis step. OI requires that data are presented as model variables, i.e. other data sources as for example satellite measurements of radiances at the top of the atmosphere must first be transformed to profiles of temperature and humidity. The retrieval procedure for such parameters requires assumptions on the state of the atmosphere [*Tatarskii et al.*, 1996].

A different way to treat observed data is to make use of the variational assimilation schemes (3DVAR and 4DVAR). Variational schemes allow different data sources to be used directly without intermediate conversion to model variables, for example data like satellite measured radiances, refractive index and precipitable water can be directly assimilated in the model. The drawback is that the computational requirements for the 4DVAR (and to a lesser extend for the 3DVAR) are manifold of the OI technique. For the near future research effort concentrates on (operational) application of the 3DVAR. But it is foreseen that in the future 4DVAR schemes will be used operational as well. The HIRLAM model accepts data in BUFR format. Operational production of GPS-PWV data to be used at KNMI should therefore conform to this format

Also the HIRLAM community is developing a 3DVAR scheme. Therefore, no effort will be put in the development of retrieval schemes for temperature and humidity profiles based on GPS precipitable water vapour as this may already be outdated when GPS-data become operationally available. On the other hand research on the operator for the 3DVAR scheme should have high priority in the application of real-time GPS-PWV data. The time-window requirements for the data will remain the same for the 3DVAR and OI version of the HIRLAM model. Most research effort within the HIRLAM community is now directed towards the implementation of the 3DVAR scheme. Some participants like the Danish group already have a 'poor-men's' version of the 3DVAR ready for research on model improvements, impact studies etc. Results of such experiments are shared and distributed amongst the HIRLAM members. It is expected that on the time scale of this GPS-project HIRLAM models may become available which can assimilate GPS-data in a 3DVAR research version and perhaps even already in an operational version of the HIRLAM model.

The use of the GPS data is not restricted to input for operational weather predictions models. Comparison of the observed data with analysis results can be useful to get insight in data accuracy. Also the accuracy of the analysis as far as horizontal distribution of integrated water vapour is concerned can be studied. Integrated PWV data can easily be calculated from model output. HIRLAM model PWV data will be calculated for the model grid points using temperature, pressure and moisture data at locations which coincide with GPS-receiving stations. Primary focus will be on Dutch GPS reference stations within the AGRS-NL network, but other reference stations within the HIRLAM domain may be used as well. Global GPS data from approximately 80 stations are collected by the International GPS Service for geodynamics (IGS) and these data are also available at DUT. Currently, about 20 to 25 of these stations are located in Europe and this network is expected to expand still considerably in the near future. For most of the current stations the required surface pressure and temperature are not yet measured. It will be investigated whether it is possible to use the analysed surface pressure and temperature for these stations instead.

In order to be representative for the scales resolved by the model, the time and spatial scale of the GPS PWV data must match the model scales. For the present OI assimilation method error statistics are used to calculate the relative weight which is attributed to data and to first guess results respectively. For example in data rich areas more weight is assigned to the data than to the first guess. Furthermore each data station is monitored and statistics about the departure from the first guess field is considered to be a measure for the reliability of a station. Statistics for new data sources need to be build up. For this purpose, GPS-PWV data which is already recorded can be compared to model analysis output.

RACMO uses improved representation (parameterisations) of the sub-grid processes compared to the HIRLAM model but the dynamics are almost identical. At present it is run in a semi-operational mode once every 24 hours to calculate a 72 hours forecast. The output of the RACMO model will also be available for comparison with GPS-PWV observed data. Furthermore a one dimensional version of this model is also available. This 1-D model is especially suited to study the impact of different parameterisations as its required computational time is very short. Perhaps model results could be used to investigate the effect on the accuracy of the calculated hydrostatic delay and the conversion from delay to water vapour using surface measurements of pressure, temperature and humidity to approximate the integrated values.

Chapter 6

Definition of the Infrastructure

The main objective of the project is to define and to implement an infrastructure to acquire GPS observations from a regional network of stations and to derive ZWD data from these observations for potential use in meteorology. Since this is a demonstration project, it is not necessary to strive for (semi) real-time operations, but the requirements to implement this at a later stage will be discussed. For the duration of the project, the timeliness of the ZWDs is not critical and a delay in the availability of several days is therefore acceptable. To demonstrate near real-time operations, several experiments will be conducted in which the operational procedures will be simulated.

The procedure to distill ZWD data from GPS observations consists of several steps. In Section 6.1 a general overview of the required infrastructure is presented, and in Section 6.2 a description is given of the particular implementation as used in this study. An important element is the GPS data processing algorithm, which is addressed in Section 6.3. Finally, in Section 6.4 several problems are discussed which arise when such a system will be operated in near real-time.

6.1 Basic Elements of the Infrastructure

The complete process of estimating the amount of water vapour using GPS signal delays, consists of the following steps:

- GPS data collection.
- Acquisition of precise GPS orbit information.
- Meteo data collection.
- Processing of GPS data and computation of tropospheric zenith delay (TZD) estimates.
- Isolation of ZWD from TZD and computation of the water vapour content.

IGS is responsible for collection and supply of global GPS data, AGRS-NL performs a similar task for the national GPS network. To analyse the GPS satellite observations, precise GPS orbit information is required. The satellite orbit information, the ephemerides, is available at different accuracy levels:

- *broadcast* ephemerides, predicted orbits broadcast by the GPS satellites
- *precise* ephemerides, generally computed after the event and as such are more accurate.

As the broadcast ephemerides are sent along with the GPS signal, it is possible to start the processing as soon as the observation data is available. However, the broadcast ephemerides are rather coarse predictions of the satellite orbit and therefore imply less accurate results. The GPS data from small-scale networks (~ 50 km) however, can be analyzed with sufficient accuracy using the broadcast GPS orbits since in this case orbit errors affect all stations quite similarly and therefore largely cancel. It should be noticed that in this case, only relative water vapour estimations are produced with respect to a known value (*e.g.*WVR) within the network [*Rocken et al.*, 1995]. The combined IGS precise ephemerides are currently the most accurate ephemerides available. These are produced by combining the precise orbits produced by the seven IGS Analysis Centres (ACs). They have an accuracy of 10-20 cm, whereas the broadcast ephemerides may be in error up to 25 m.

As mentioned in Chapter 2, the amount of water vapour present in the vertical column can be determined from the zenith wet delay of the GPS signals. This can be done as part of the routine processing of the GPS data, or in separate, dedicated runs. Both RWS-MD and the Faculty of Geodetic Engineering have the disposal of the Bernese processing software, but are not (yet) involved in continuous processing. The Faculty of Aerospace Engineering on the other hand is currently processing GPS data on a routine basis. For several practical reasons, at present the GPS data is processed in batches of 24 hours, solving for station coordinates and several other parameters besides the tropospheric delay. Obviously this results in discontinuities, which can partly be recovered afterwards, using the height difference of the station coordinate solution. Processing of GPS data can be executed by AGRS-NL on a continuous basis as soon as the AGRS-NL network is operational.

Surface pressure and temperature measurements are necessary to isolate ZWD from the TZD estimates and to convert the ZWDs to IPWV values. Unfortunately, only at some of the global GPS stations (accurate) meteo observations are collected. This problem can be solved by using data of meteo stations located near the GPS sites, the usage of data produced by weather forecast models as HIRLAM should be considered as well. The first option implies the use of interpolation routines (both temporal and spatial), to obtain realistic values.

6.2 Infrastructure Used in the Project

For the duration of the project the following infrastructure has been defined. The GPS data collection is conducted by the AGRS-NL for the national GPS network and by IGS for the global GPS stations. The GPS data processing will be executed by the Faculty of Aerospace Engineering of DUT. The precise IGS orbits are used for this analysis. They are retrieved from the Crustal Dynamics Data Information System (CDDIS). The analysis produces TZD results in the form of time-series of estimates at 6 minute intervals in 24 hour batches for each station. ZWD can be obtained by subtracting an accurate estimate of ZHD from the TZDs produced by the program. The GPS data analysis procedure is further described in the next section. Since it was originally intended for network deformation studies, it is not optimized to estimate TZDs. It seems possible, however, to adjust the current settings to fit the GPS water vapour estimation process better, or to perform

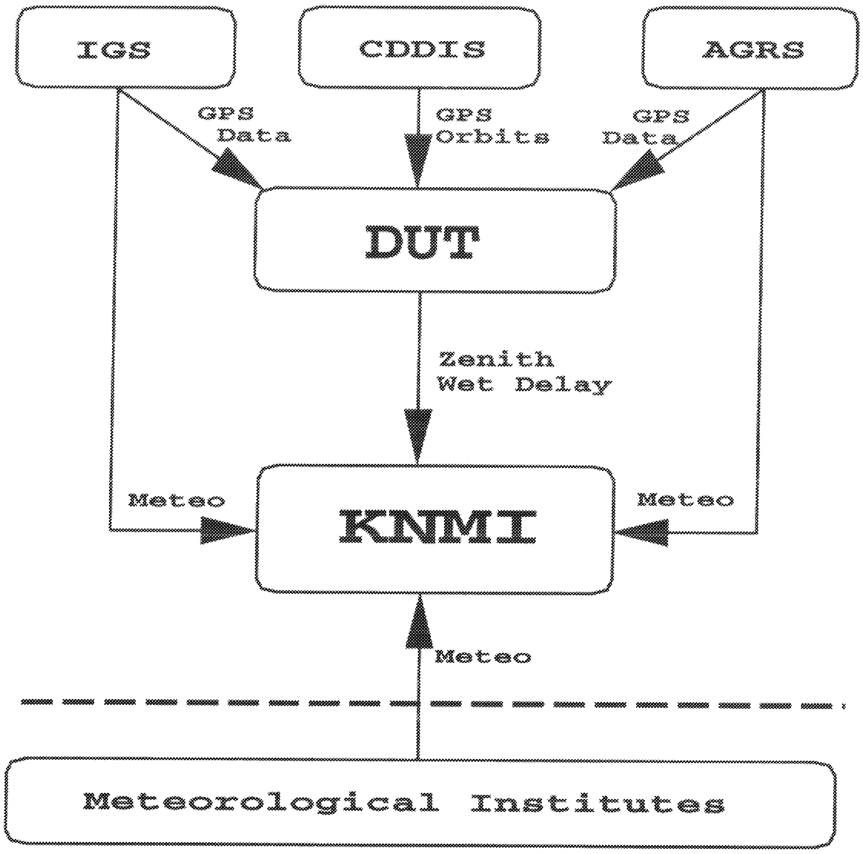

Figure 6.1 The infrastructure selected for the GPS Water Vapour Meteorology project.

(several) post processing steps to increase the accuracy.

Isolation of ZWD from the TZD estimates and conversion of ZWD to IPWV will be handled by the KNMI. Meteo data will be provided by either AGRS-NL and IGS, or will be retrieved from other meteorological data sources. Fig. 6.1 schematically shows the data flow within the selected infrastructure.

It should be noticed that this infrastructure is designed for the duration of the project. It is quite likely that future requirements of the GPS water vapour estimates can not be met with the current available infrastructure. To accomplish near real-time GPS water vapour estimations for example, several problems will have to be solved. These are discussed in Section 6.4.

6.3 GPS Data Processing

The estimation of the TZDs is already an integral part of the standard processing of the GPS data at DUT. Using the GIPSY software package, the data is processed in blocks of 24 hours. Main purpose of the processing routine is to generate a series of independent network solutions over a long period of time. This network consists of about 30 stations which are depicted in Fig. 6.2. The term *independent network solution* implies that no information from previous day is passed on to the next. Because of this, the position of a site for which the TZD is determined is not exactly the same each day. This also affects the height component. Because of

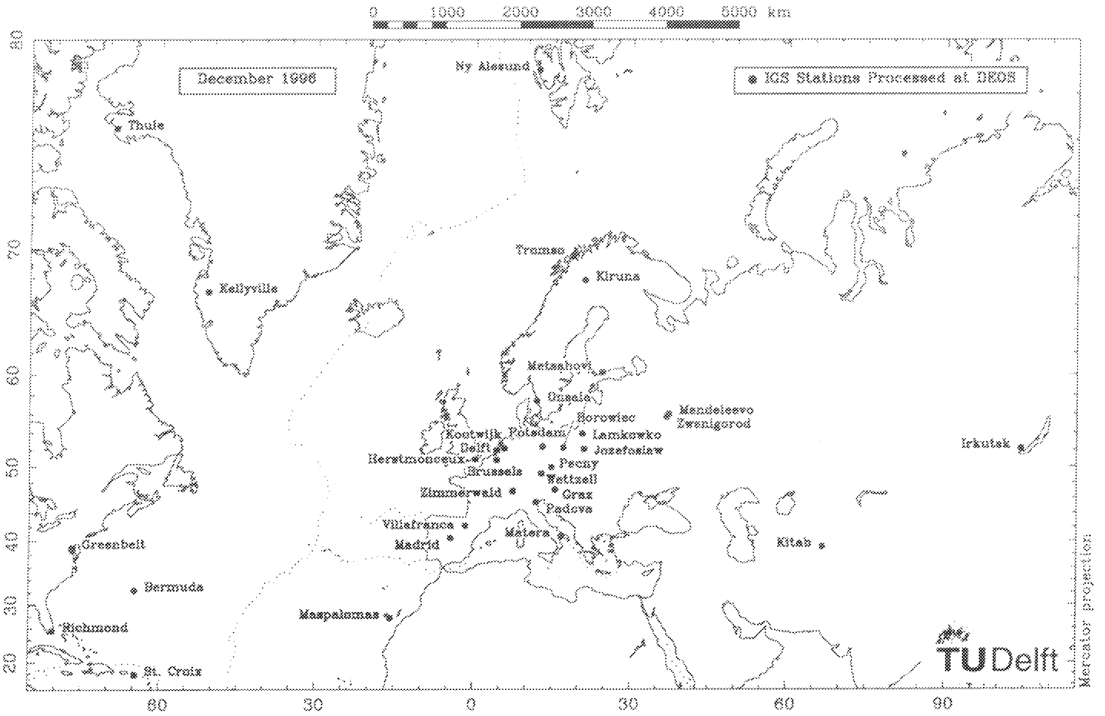

Figure 6.2 Network of selected GPS stations currently processed at DUT. The majority are IGS station.

the high correlation between the height of a station and the estimated TZD, it is necessary to correct for station height differences afterwards. The GPS data is transferred from the IGS data centers at IFAG and IGN via internet, except for the AGRS-NL stations, of which the data is down-loaded from the Computing Centre. As stated above, the precise IGS orbits are retrieved from CDDIS and are available three weeks after the event.

The parameter estimation process of the GIPSY software package is based on a Kalman filter and smoother. Therefore it is possible to obtain an estimate of the TZD every epoch. To save CPU time, the data set has been artificially reduced by sampling, resulting in a TZD estimate every 6 minutes. The output given by the program consists of a series of corrections to an a priori TZD. This a priori delay is composed of a station height dependent term for the ZHD, approximately 230 cm, and a constant, site-independent term for ZWD, at a fixed value of 10 cm. Adding the total a priori TZD to the corrections produced by the program, results in the *true* estimate of TZD. To obtain an accurate estimate of the ZWD, a more realistic model for the ZHD has to be used, *e.g.* by using surface meteorological data (equation 2.12). By use of relations 2.20 and 2.22 the ZWD can be converted into IPWV.

The processing technique used is non-dedicated, hence not the optimal environment for GPS water vapour estimation. However, several experiments will be performed to increase the accuracy of the computed tropospheric delay. Fixing the station coordinates for example, is an option that should certainly be tested. Furthermore, an analysis of the systematic errors (biases, influence of mapping functions etc.) should be carried out as well. As soon as the AGRS-NL processing software is operational, small experiments will be executed to compare ZWD estimates computed by two different software packages.

6.4 Near Real-Time Infrastructure

Computing near real-time GPS water vapour estimations is a rather different undertaking than the off-line process used for the demonstrations. The first problem encountered is the real-time GPS data acquisition. For the tests carried out in this project, mostly IGS data is used, and it is conceivable that in future operational applications the IGS network will also play a major role. However, the IGS data collection strategy is currently based on a 24 hours cycle, in which daily data files are stored in a global data base with a delay of 30 minutes at minimum and up to several days. Technically it is possible to reduce these delays by adopting a shorter cycle time (*e.g.* 1 hour) and speeding up the transfer process. At some IGS stations in the US this procedure has already been adopted. It will require a major effort, however, to implement this at all IGS stations, but it is certainly something which may be discussed with IGS. In addition new dedicated stations may be installed which are controlled directly by a GPS water vapour computing center. Particular attention must be given to operational aspects such as uninterruptable power supplies for continuous operations and reliable communication links. As networks become larger and the observation rates increase too, data storage can become a problem as well. In that case, it should be decided what data is archived and what is kept on-line. At present, DUT gathers GPS observations of about 80 IGS stations and stores this on tape. Each IGS station produces approximately 0.5 Mb of compacted data per day. One day thus requires 40 Mb of space, over one year about 15 Gb of data is stored on tape.

The second problem is the availability of accurate GPS satellite orbit information used. To be able to compute near real-time ZWD data, it is essential that this information is also available in a timely fashion, *i.e.* within one hour from real-time. For relatively small networks, the satellite broadcast ephemerides can be used for this purpose. However, in that case only the ZWD *differences* between stations can be computed with sufficient accuracy, which means that at least one independent measurement of the absolute value at one of the stations must be obtained by other means. In principle, it is possible to use a WVR for this purpose, but as mentioned in Chapter 1, these are rather expensive systems, with operational limitations.

A better solution is to use precise ephemeris data. IGS produces several types of such products, but the highest quality results are only available after several days to weeks. Very recently, several Analysis Centres have begun making *predicted precise orbits*, which are freely available. These orbits are produced daily and predict the orbit over periods of 24 or 48 hours [*Dodson and Shardlow*, 1996]. It seems they are sufficiently accurate to be used for ZWD computations, but this needs to be investigated in more detail. The main problem is that these predictions do not foresee satellite manoeuvres, and can thus be in error occasionally. However, these manoeuvres do not occur very frequently. Furthermore, AGRS-NL is able to detect satellite manoeuvres in real-time, hence it is possible to omit the particular satellite data from that moment on.

The third problem concerns the processing of the GPS data, which still consumes rather large amounts of computer time. This, of course, depends on the number of stations present in the selected network, the number of variables that is solved for, and the interval at which the variables are being estimated. However, if it is assumed that the data are analyzed in 1-hourly batches, the computational burden may turn out to be less of a problem. Besides it may be possible to reduce the number of estimated parameters, for example by fixing the station coordinates since these are already accurately known from earlier network studies. On the other hand, this may introduce additional errors in the remaining unknowns (*e.g.* the ZWDs) since they may absorb some of the errors in the predicted GPS orbits and other model errors [*Dodson and Shardlow*, 1996]. This also needs to be investigated further. The total number of estimated parameters can also be kept relatively small since it is not necessary to estimate a ZWD at every measurement epoch (currently every 30 s), but a sampling interval of 5-10 minutes will probably be sufficient.

Chapter 7

Conclusions

From the first phase of the project, as described in this report, it can be concluded that IPWV can be estimated with an accuracy at the level of 1-2 mm, using GPS signal delays. Preliminary comparisons of water vapour estimations produced in the Netherlands, confirm this statement.

The AGRS-NL network, consisting of 5 reference stations equally distributed across the Netherlands, fits the infrastructure necessary for regional Dutch GPS water vapour estimation perfectly. At least for the duration of the project, the AGRS-NL data together with global GPS data provided by the IGS will be processed at DUT. In addition, small experiments will be conducted to try to improve the accuracy level of the GPS water vapour estimation and to investigate the possibility of real-time GPS water vapour estimation. Correction and conversion of the ZWD data to compute the IPWV will be executed at the KNMI. The meteo data, necessary to perform these transformations, will be provided by AGRS-NL, IGS or shall be obtained from external sources. Data obtained from radiosonde launches, water vapour radiometry and numerical prediction models, will be used to evaluate and validate the results.

Remaining problem areas in real-time GPS water vapour estimation include the delays in GPS data acquisition, availability of accurate GPS satellite orbit information and GPS data processing. Also, the assimilation of GPS water vapour estimates in meteorological models, is a problem which needs to be further investigated.

Regarding the current increase of international interest in GPS Meteorology, and the large number of investigations going on in this field, international cooperation with other project teams will be established either bilateral or within larger framework of *e.g.* COST (WAVEFRONT, NEWBALTIC).

Bibliography

Arakawa, A. (1995), Atmospheric Models, *The Geophys. Mag., Series 2, Vol. 1*, II–i–1 – II–i–28, Special Issue.

Baede, A. P. M. (1988), Numerieke Atmosfeermodellen, *Tech. Rept. TR-107*, Koninklijk Nederlands Meteorologisch Instituut, De Bilt, The Netherlands.

Baker, H. (1996), Private Communication, Institute of Engineering Surveying and Space Geodesy, Nottingham, England, November 1996.

Bevis, M., S. Businger, and T. A. Herring et al (1992), GPS Meteorology: Remote Sensing of Atmospheric Water Vapour Using the Global Positioning System, *J. Geophys. Res., 97 (D14)*, 15,787–15,801.

Boudouris, G. (1963), On the Index of Refraction of Air, the Absorption and Dispersion of Centimeter Waves by Gasses, *J. Res. Natl. Bur. Stand., 67D*, 631–684.

Carlsson, T. R. (1996*a*), Private Communication, Onsala Space Observatory, Onsala, Sweden, November 1996.

Carlsson, T. R. (1996*b*), Site Dependent Error Sources in Geodetic Very Long Baseline Interferometry, *Tech. Rept. 224L*, School of Electrical and Computer Engineering, Chalmers University of Technology, Gothenburg, Sweden.

Davis, J. L., T. A. Herring, I. I. Shapiro, A. E. Rogers, and G. Elgered (1985), Geodesy by Radio Interferometry: Effects of Atmospheric Modeling Errors on Estimates of Baseline Length, *Radio Science, 20*, 1593–1607.

Dodson, A., and P. Shardlow (1996), The Global Positioning System as a Passive Integrated Atmospheric Water Vapour Sensing Device, in *Atmospheric Sensing and Modeling II, SPIE Proc.*, vol. 2582, edited by R. P. Santer, pp. 166–177.

Elgered, G. (1993), Tropospheric Radio-Path Delay from Ground Based Microwave Radiometry, in *Atmospheric Remote Sensing by Microwave Radiometry*, edited by M. A. Jansen, pp. 215–258, John Wiley and Sons.

Gendt, G. (1996), Estimation of Tropospheric Water Vapour Content by Ground-Based GPS Receivers, in *Arbeidsergebnisse Nr. 39 Field Campaign LINEX 96/1*, edited by H. Steinhagen, pp. 40–41, Deutscher Wetterdienst Forschung und Entwicklung, August 1996.

Gutman, S. I. (1996), Private Communication, NOAA Forecast Systems Laboratory, Boulder, Colorado, USA, November 1996.

Hopfield, H. S. (1971), Tropospheric Effect of Electromagnetically Measured Range Prediction from Surface Weather Data, *Radio Science, 6*, 357–367.

Janssen, J. M. M. M. (1995), Desing of Radiometer System for Remote Sensing Applications, *SAI Rept.*, Radiocommunications Group of Eindhoven University of Technology, Eindhoven, The Netherlands.

Jongen, S. C. H. M. (1996), Private Communication, Radiocommunications Group of Eindhoven University of Technology, Eindhoven, The Netherlands, November 1996.

Kuo, Y-H., Y-R. Guo, and E. R. Westwater (1993), Assimilation of Precipitable Water Measurements into a Mesoscale Numerical Model, *Mon. Wea. Rev.*, *121*, 1215–1238.

Kuo, Y-H., X. Zuo, and Y-R. Guo (1996), Variational Assimilation of Precipitable Water using a Nonhydrostatic Mesoscale Adjoint Model Part 1: Moisture Retrieval and Sensitivity Experiments, *Mon. Wea. Rev.*, *124*, 122–147.

Lanyi, G. (1984), Tropospheric Calibration in Radio Interferometry, in *Proceedings of the International Symposium on Space Techniques for Geodynamics*, vol. 2, pp. 184–195, Sopron, Hungary.

Rocken, C. (1996), Real Time PWV Processing, Extracted from World Wide Web node http://www.unavco.ucar.edu/~rocken/realtime.html#Introduction.

Rocken, C., T. Van Hove, and J. Johnsons et al (1995), GPS/STORM - GPS Sensing of Atmospheric Water Vapour for Meteorology, *J. Atm. & Oc. Tech.*, *12*, 468–478.

Rothacher, M., and L. Mervart (1996), *Bernese GPS Processing Software Version 4.0*, September 1996.

Saastamoinen, J. (1972), Atmospheric Correction for the Troposphere and Stratosphere in Radio Ranging of Satellites, in *The Use of Artificial Satellites for Geodesy, Geophys. Monogr. Ser.*, vol. 15, edited by S. W. Hendriksen et al., pp. 247–251, AGU, Washington D. C. USA.

Seeber, G. (1993), *Satellite Geodesy*, De Gruyter, Berlin.

Smith, E. K., and S. Weintraub (1953), The Constants in the Equation for Atmospheric Refractive Index at Radio Frequencies, *J. Res. Natl. Bur. Stand.*, *50*, 39–41.

Tatarskii, V. V., M. S. Tatarskaia, and E. R. Westwater (1996), Statistical Retrieval of Humidity Profiles from Precipitable Water Vapour and Surface Measurements of Humidity and Temperature, *J. Atm. & Oc. Tech.*, *13*, 165–174.

Tremberth, K. E. (ed.) (1992), *Climate System Modeling*, Cambridge Univ. Press.

Ware, R., C. Alber, C. Rocken, and F. Solheim (1997), Sensing Integrated Water Vapor along GPS Ray Paths, *Geophys. Res. Lett.*, *24 (No. 4)*, 417–420.

Westrhenen, R. M. van (1993), Het APL+ programma, *Tech. Rept. TR-153*, Koninklijk Nederlands Meteorologisch Instituut, De Bilt, The Netherlands.