Integrated atmospheric water vapour estimates from a regional GPS network

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Abstract. Integrated atmospheric water vapour (IWV) estimates from a 15-station wide GPS network have been collected continuously since November 1997. The core of this network consists of 5 stations of the active GPS reference system (AGRS.NL) in the Netherlands. A network with sufficient long baselines was chosen to secure the absolute accuracy of the GPS-IWV data. Rapid orbits are used and IWV-data are available with a typical delay of 1 day. Comparison of the GPS-IWV data with data retrieved from a water vapour radiometer and radiosondes show a good agreement. Different network configurations and processing strategies have been investigated to optimise the network and processing for future near real-time use. Of the methods tested the GPS-IWV data retrieved with orbit relaxation compared the best with collocated radiometer data and radiosonde data. An experiment with orbit relaxation applied to predicted orbits for a period of one month showed even a slightly better agreement with collocated radiometer data as compared to GPS-IWV data retrieved with final orbits. Results of the experiments and the analysis of operational acquired data are presented.

1. Introduction.

Water vapour plays an important role in atmospheric processes on a wide range of spatial and temporal scales. In recent years GPS retrieved integrated water vapour (IWV) has become a new source of IWV data for atmospheric and climate research. The delay of the radio signals transmitted by GPS satellites, is closely related to the water vapour content along the atmospheric signal path. The contribution of the water vapour to the atmospheric delay of the GPS signals is difficult to model with sufficient accuracy and is therefore solved as an unknown parameter in the processing. The feasibility of accurate retrieval of IWV from a network of ground based GPS stations has been shown in several experiments [e.g. Baker and Dodson 1998, Bevis et al. 1992, Rocken et al. 1995, Tregoning et al. 1998].

The use of GPS IWV data in operational meteorology as input for short range weather forecast models is hampered by the fact that accurate orbit information from rapid or final orbits is not available in near real-time. For near real-time applications only the information from the less accurate predicted orbits is available. However, the accuracy of the predicted orbits is generally too low for retrieval of IWV with sufficient accuracy. Recently Ge et al [2000] and Kruse et al [1999] showed promising results for reducing the effects of orbit error in the predicted orbits by estimating one or more orbital parameters during the processing itself. Their methods are very similar to the method discussed by Van der Hoeven et al [1998] who applied orbit relaxation to predicted orbits for a one week period in March 1998. Van der Hoeven et al found comparable accuracy for the IWV data retrieved from predicted orbit with orbit relaxation applied as those retrieved with the much more accurate final IGS orbits. In section 6 we present data for an extended period of four weeks in 1998 for which we applied orbit relaxation to predicted orbits and compare these with final orbits and collocated radiometer and radiosonde data.

In the Netherlands a continuously operating GPS reference station network (AGRS.NL) became in full operation in spring of 1997 mainly to support surveying applications using GPS. Preliminary results using the AGRS.NL network for retrieving IWV-data during three intensive measurement campaigns in 1996 were encouraging. A follow-up project on GPS-meteorology for operational application for input in numerical weather forecast models and for climate research was initiated [Klein Baltink et al, 1999]. One of the objectives of this project was to investigate the feasibility of near-real time GPS IWV processing. Several experiments were conducted to select a GPS-network consisting of a low number of stations to reduce the computational load, but still large enough to secure absolute IWV estimates. In section 2 we describe the selected GPS network of ground based GPS receivers and the processing of the GPS-data. The processing of the meteorological data is presented in section 3. We also determined the local relationship between the weighted mean atmospheric temperature T_m and the surface temperature T_s based on the analysis of seven years of radiosonde data. These results are presented in section 4. In section 5 we present the results of the analysis of the operational GPS-IWV data acquired since November 1997.

Because of the ultimate goal of near real-time processing we focussed our experiments on assessing the influence of the accuracy of the different orbits and processing on the quality of the IWV estimates. This included experiments to improve the accuracy of the orbits during the processing by applying orbit relaxation. During orbit relaxation the accuracy of the orbits is improved by estimating the satellite orbital parameters together with the tropospheric estimates. In section 6 we discuss briefly the initial experiments and present the results of the experiment with GPS-IWV data retrieved with predicted orbits with orbit relaxation applied respectively. Conclusions are given in section 7.

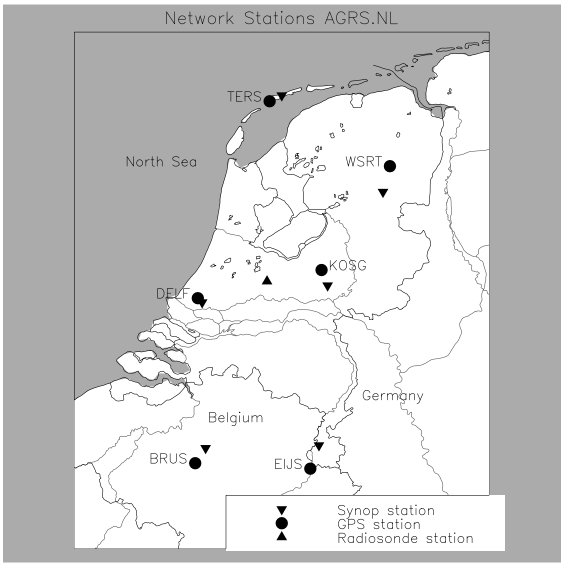

Figure 1 The AGRS.NL network in The Netherlands, the distance between DELF and KOSG is approximately 100 km

2. The GPS network and processing.

In 1995 a permanent network of 5 GPS reference receivers was build in the Netherlands. This network, called Active GPS Reference System for the Netherlands (AGRS.NL), is in full operation since spring 1997 and consists of 5 stations distributed over the Netherlands (figure 1).

The data are transmitted to a central computing centre on an hourly basis. The AGRS.NL is connected to the IGS global network through the stations Kootwijk (KOSG) and Westerbork (WSRT). For the tests described in this paper and as well for the operational processing the AGRS.NL network is embedded in an extended regional network in total consisting of 15 stations distributed over the Northern Hemisphere. Long baselines secure absolute GPS-IWV estimates, stations Onsala (Sweden) and Graz (Austria) are included because of the accurate clocks available at these sites. The location and height of the 15 stations are summarised in table 1.

The GPS data are processed at the Delft University of Technology with the GIPSY/OASIS II software package developed at JPL. During the processing station coordinates, satellite and receiver clocks and zenith delays are estimated. Other typical processing parameters applied are: a cut-off elevation angle of 15°, a mapping function by Lanyi, an a priori troposphere delay estimate by the Saastomoinen model and a modified Kalman filter with a tropospheric drift parameter of 1.10^{-7} km/√s. In the newer version of GIPSY/OASIS, in use since February 1999, a cut-off angle of 10° and the Neill mapping function is applied instead. Tropospheric parameters are estimated at 6 minutes intervals and data are processed in batches of 24 hours without any overlap at the day boundaries.

The GPS-processing delivers only the zenith total delay (ZTD) of the radio signals. The wet part of the zenith delay (ZWD) is computed by subtracting the zenith hydrostatic delay (ZHD) from the observed total zenith delay. The hydrostatic part of the delay is calculated from surface pressure P_s only, using:

$$\begin{aligned} ZHD &= 10^{-6}\frac{k_1 R_d P_s}{g_m} \\ &= (2.2768 \pm 0.0024)\frac{P_s}{f(\theta,H)} \end{aligned} \quad (1)$$

where

$$f(\theta,H) = 1 - 0.00266\cos(2\theta) - 0.00028\,H \quad (2)$$

and k_1 is an empirical constant, R_d is the gas constant of dry air, g_m is the mean gravity, θ is the site latitude in degrees, and H is the station height in km above the ellipsoid.

The ZWD is given by:

$$ZWD = 10^{-6}\int \frac{P_v}{T}\left[\frac{k_3}{T} + k_2 - \frac{R_d}{R_v}k_1\right]dz$$

(3)

where k_2 and k_3 are empirical constants, R_v is the specific gas constant for water vapour, P_v is the partial water vapour pressure and T the air temperature. Commonly integrated precipitable water vapor (PW) is used instead of IWV, where PW in mm is equivalent to IWV in kg/m². The conversion of ZWD to IWV is given in section 4.

One of the main problems for accurate near real-time GPS-IWV estimation is the accuracy of the satellite orbits [Rocken et al, 1997]. For application in short range weather forecast models data have to be available typically within 2 hours after acquisition. This constraint on timeliness of the data prohibits the use of the accurate rapid orbit data which is available only 12-24 hours after acquisition. For real-time application predicted orbits have to be used. These predicted orbits have a typical accuracy of 100 cm compared to the final IGS orbits. But regularly some of the predicted orbits have much larger errors.

From the initial experiments with the AGRS.NL network we found that the use of predicted orbits resulted in unacceptable large errors in the IWV estimates. Therefore we conducted several experiments with the processing set-up and orbits to assess accuracy of the retrieved IWV data. The experiments were conducted for the period 20-27 March of 1998 (see section 6). In this period the rms-differences between the predicted orbits and IGS final orbits varied strongly for the different satellites. The rms-difference was below 100 cm for most of the satellites. However, the rms difference ranged from 800 to 1600 cm for satellites 14, 16 and 24. Furthermore, the mean difference between the predicted and the final orbits as function of time of day show a steadily increase whereas the rapid orbits only lost accuracy near the end of the day [Van der Hoeven et al, 1998].

3. Meteorological surface data.

Surface pressure, temperature and humidity are measured at some of the GPS stations and at nearby stations of the mesoscale synoptical network of the KNMI (figure 1). At the KNMI stations data are averaged over 10 min interval, but in the database only the last 10 minute period before the hour is available. The pressure sensors have an accuracy of 0.1 hPa. However, pressure data stored are reduced to mean-sea-level. The pressure at GPS antenna height is calculated from the mean sea level pressure data. The accuracy of the reduction to mean-sea-level and the conversion to GPS sensor height afterwards is not known, but given the small corrections involved we estimate the total pressure error to be less than 0.3 hPa, which corresponds to an error in IWV of approximately 0.1 kg/m^2. The surface meteorological data are checked for outliers, and are spline interpolated to the GPS observation time. Valid meteorological observations must be available within 30 min of the GPS observation time otherwise GPS-IWV data is annotated as suspect and is not used in the intercomparison with radiometer and radiosonde data. The surface meteorological data are also used to estimate the water vapour content between ground level and GPS-antenna, which is in general a small amount but with some sensors 20 to 30 m above ground level it should not be ignored.

Because of the different locations of the GPS and meteo-stations errors will be introduced in the ZHD estimates derived from the pressure data, due to horizontal pressure gradients. We did not interpolate the pressure data to the GPS stations, but simply selected the pressure of the nearest station. From analysis of one year of pressure data we estimated that the resulting rms-error is less than 0.3 hPa for the largest separation (at WSRT),

Table 1. Location and height of the stations of the operational network. Height is above the WGS84-ellipsoid. During orbit relaxation co-ordinates of stations annotated with * are fixed to their ITRF96 values.

ID	Country	Lon (E)	Lat. (N)	Height. (m)
DELF	Netherlands	4.38	51.98	74
KOSG	Netherlands	5.81	52.18	97
WSRT	Netherlands	6.60	52.91	76
EIJS	Netherlands	5.68	50.75	104
TERS	Netherlands	5.21	53.36	56
BAHR*	Bahrein	50.60	26.21	-16
BRUS	Belgium	4.35	50.79	151
CRO1*	USA (Virgin Islands)	-64.58	17.75	-31
GODE*	USA	-76.82	39.02	16
GRAZ	Austria	15.49	47.06	539
KIRU*	Sweden	20.96	67.85	392
KIT3*	Uzbekistan	66.88	39.13	624
MAS1	Spain (Canary Islands)	-15.63	27.76	198
ONSA	Sweden	-11.92	57.39	47
REYK*	Iceland	-21.95	64.13	94

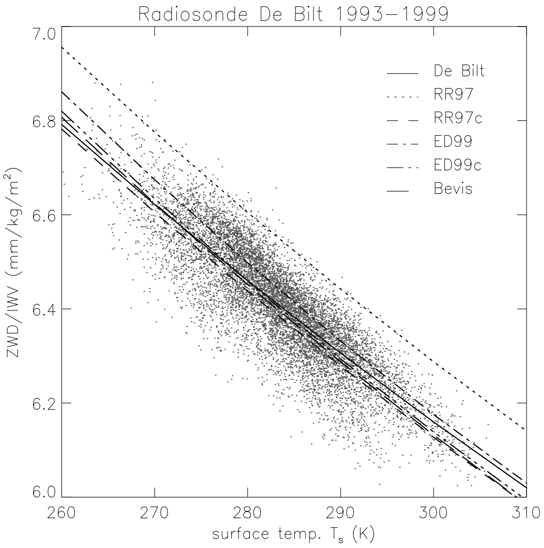

Figure 2 The conversion factor Q=ZWD/IWV as function of the surface temperature T_s. The suffix c denotes the corrected results. See text section 4 for explanation.

corresponding to a rms-error of 0.1 kg/m^2 in IWV.

4. Radiosonde data analysis: determination of Tm.

Radiosondes (Vaisala RS80, A-humicap) are launched four times daily at De Bilt at approximately 00, 06, 12 and 18 hours UTC. Data are stored at 10 s intervals which, on the average, approximates in the lower troposphere a vertical resolution of 50 to 60 m. The radiosonde sensor measures temperature, pressure and relative humidity. The accuracy of these sensors is according to the manufacturer, 0.2 °C, 0.5 hPa and 2 % respectively. However it is well known that especially the humidity measurements can have larger errors [Leiterer et al, 1997]. Also, it was found that the accuracy of the humidity sensor degraded over time due to contamination by outgassing of the packing material. Correction functions are being developed but have not been applied here. The magnitude of the contamination correction is a function of age and relative humidity (RH). For an "A"-humidity sensor the correction is zero at zero age and zero RH, it is also zero at zero RH at any age. The magnitude of the correction is approximately 2% for a 1 year old sonde at 70% RH [Paukkunen, personal communication]. But as most of the radiosondes are released within half a year after manufacturing, we can ignore the contamination effect in this dataset.

Radiosonde data were analysed for the period 1993-1999. The radiosonde profile data are integrated to retrieve ZWD, IWV, and the weighted mean temperature T_m defined as:

$$T_m = \int \frac{P_v}{T} dz \Big/ \int \frac{P_v}{T^2} dz \qquad (4)$$

The water vapor pressure P_v is calculated using the equation for saturated water vapour pressure presented by Sonntag [1994]. The ratio $Q(T_m)$=ZWD/IWV is given by:

$$Q(T_m) = 10^{-3} R_v \left[\frac{k_3}{T_m} + k_2 - \frac{R_d}{R_v} k_1 \right] \qquad (5)$$

The 1993-1999 radiosonde dataset is used to analyse the local relationship between T_m and the surface temperature T_s. Commonly the linear relationship $T_m = 0.72T_s + 70.2$ [Bevis et al, 1992] is applied, although it is location and seasonal independent. Moreover, the data analysed were retrieved only over a period of 2 years for 13 radiosonde locations in the US. More recently Ross and Rosenfeld [1997, hereafter RR97] analysed a large number of radiosonde data over a 23-year period and at 53 locations worldwide. RR97 applied in their analysis a cut-off pressure of 500 hPa for the radiosonde data, which resulted on the average in a 1.5 K warm bias in T_m. This finding was confirmed in our analysis of the data from station De Bilt. Emardson and Derks [1999, hereafter ED99] analysed radiosonde data for 38 sites in Europe over a period of 9 years. From both studies it is clear that a location and seasonal dependent relationship based on T_s provides the most accurate result for the conversion of ZWD to IWV. ED99 analysed the quotient

Table 2 Analysis of the operational acquired data, GPS (DELF+KOSG) versus radiosonde (BILT). Processing applied: A) 2-day a priori fit, B) 1-day a priori fit, C) 1-day a priori fit + orbit relaxation. CODE rapid orbits were used in all three periods.

	Period	Pairs	Bias (kg/m²)	RMSE (kg/m²)	Linear Regression results: Intercept	Coefficient	Std. Dev. Residuals
A	29/10/97-15/02/99	1240	0.58	1.79	1.82	0.92	1.59
B	16/02/99-30/06/99	355	0.08	1.43	1.17	0.93	1.37
C	01/07/99-31/07/00	1138	0.01	1.36	0.63	0.96	1.32

Q=ZWD/IWV, directly as a function of T_s, T_m was not determined in this study. Furthermore they retrieved ZWD from radiosonde data using the commonly applied values for k [Thayer, 1974]: $k_1=77.604\pm0.014$, $k_2=64.79\pm0.08$ and $k_3=(3.776\pm0.004)*10^5$ respectively (all values in K/hPa). We applied the values presented by Bevis et al [1994], which are 77.60±0.05, 70.4±2.2 and $(3.739\pm0.012)*10^5$ respectively. The k-values applied by ED99 will result in approximately a 0.6% increase of Q as compared to our calculation. In figure 2 our results are compared with ED99 and RR97.

Since radiosonde station De Bilt was not included in the RD97 analysis, we used as approximated values for De Bilt the values for Bordeaux (France) instead. From figure 2 it is concluded that ED99 obtained a similar result as in our analysis, and after correction for the k-values the result is almost identical. However, the results from RR97 show a distinct bias, but after correction for an error in their code [Ross and Rosenthal, 1999] and the bias due to the 500 hPa cut-off the agreement is also very good. Furthermore the regression proposed by Bevis et al [1992] corresponds also well with our result.

The effect of the diurnal cycle in the surface temperature on the relation between T_m and T_s is shown in figure 3a-d. The data is plotted separately for each of the four daily launch times. Especially for the higher values of T_s at 0 and 6 UTC the deviation from the linear regression line is obvious and a larger spread around the regression line is also noticed. Surface temperature inversions in the stable (nocturnal) boundary layer are a likely cause. However, scatter of the data around the four regression lines is much larger than the differences between the four linear regression results. Therefore we did not attempt to apply a time of the day dependent correction to the overall linear regression relation between T_m and T_s. The least squares linear regression result for station De Bilt based on 9129 radiosonde ascents reads $T_m=0.673T_s+83.0$, and is applied in the retrieval of the

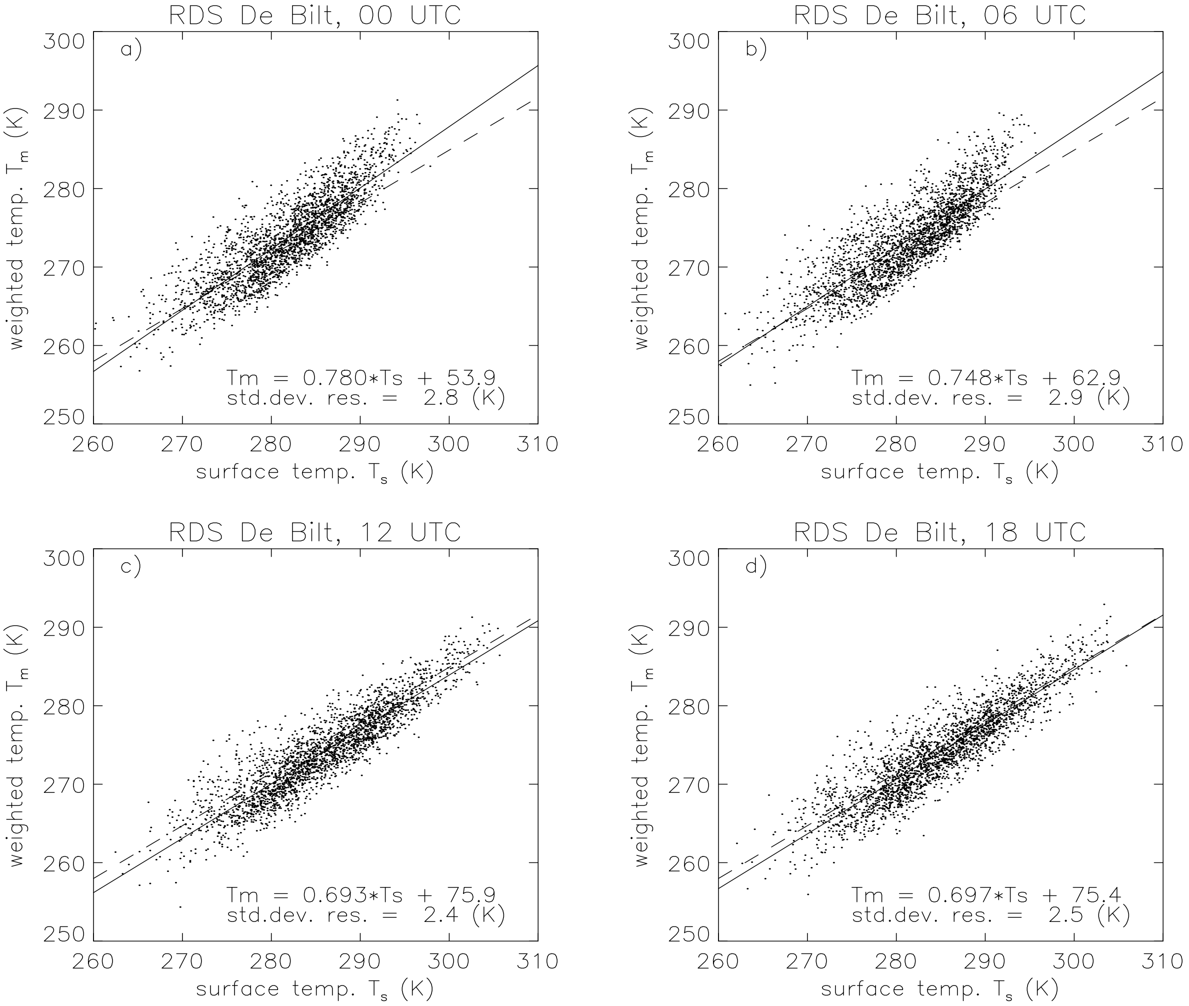

Figure 3. Weighted temperature T_m as function of surface temperature T_s for four different radiosonde release times. Solid line is the regression line for the subset, the dashed line is the regression line for the whole dataset.

IWV data from the ZWD estimates from GPS-network and the analysis of the radiosonde data. The standard deviation of T_m about the regression line is 2.7 K which results in an error less than 1 % in Q(Ts). Note that the uncertainty in the k-values as determined by Bevis et al [1992], corresponds to an uncertainty in $Q(T_s)$ of almost 1.5 %.

5. Intercomparison operational GPS results and radiosonde.

From November 1997 onwards the GPS tropospheric delay estimates from the 15 stations operational network were stored. The CODE rapid orbits are used for the daily operational processing. We present results for three different periods, each with a slightly different set-up of the processing. Based on the results of some initial experiments we started with a 2-day a priori orbit fit (see section 6). Since February 1999 a new version of the GIPSY/OASIS package is used for the processing and the 2-day a priori orbit fit is reduced to 1 day. Also the elevation cut-off is reduced from 15° to 10°, and the Neill mapping function is applied instead of the Lanyi function. In the experiments we conducted, orbit relaxation proved to provide the most accurate IWV data. Therefore we decided in July 1999 to change to orbit relaxation during the operational processing as well, although still applied to rapid CODE orbits. Orbit relaxation also implied that the coordinates of six of the peripheral stations are fixed during the processing (see table 1).

For intercomparison with radiosonde data the GPS data are time averaged over the interval from start of the radiosonde ascent till the time when the H95 height was reached. The height H95 is the height below which 95% of the total integrated water vapour is present. About 90% of the H95 heights for station De Bilt were located between 3.5 and 6.5 km above ground level. In general

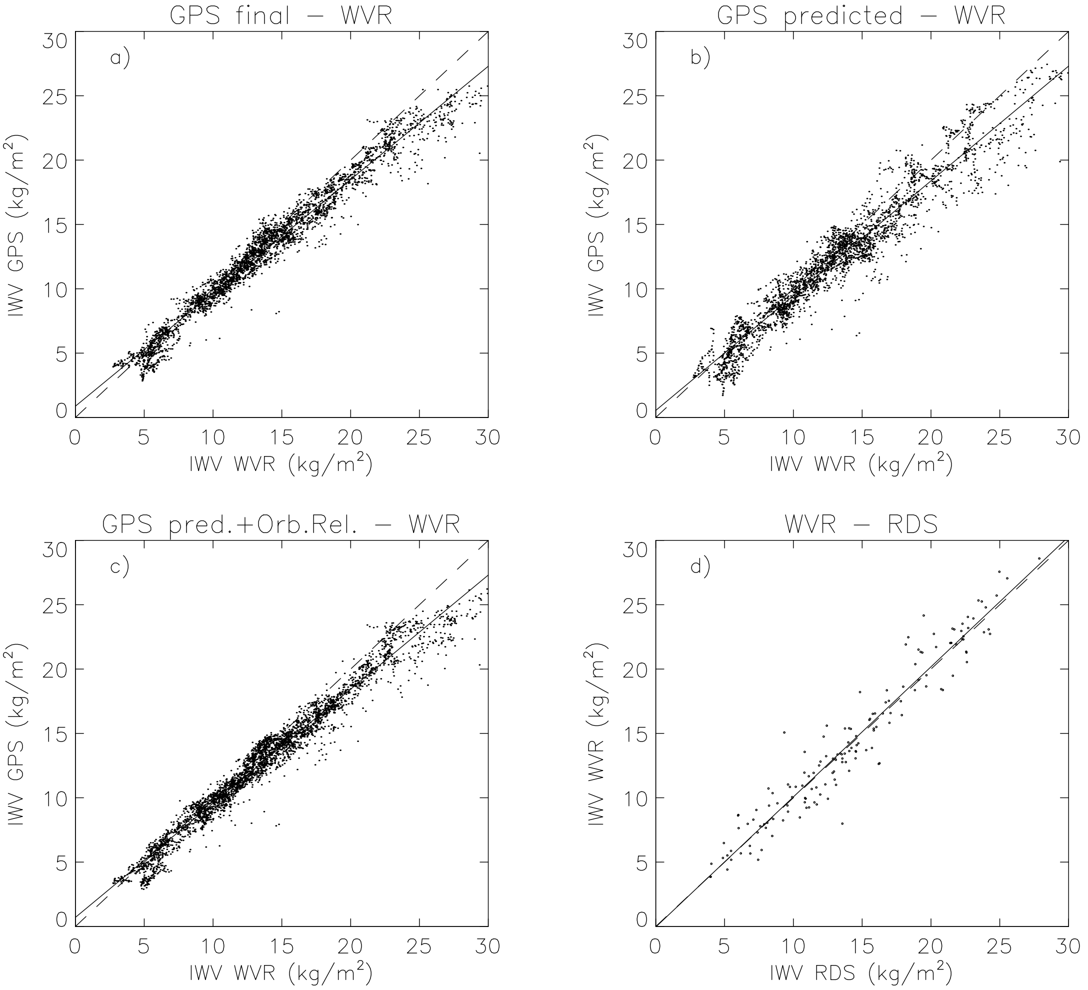

Figure 4 GPS-IWV versus radiometer data for a) final orbits, b) predicted orbits and c) predicted orbits with orbit relaxation applied. In d) the comparison of radiometer versus radiosonde data for the same period. Solid line is the linear regression line

the time to reach H95 is of the order of 15 minutes.

The spatial separation between De Bilt and GPS-stations Delft and Kootwijk respectively increases the deviation due to spatial gradients in the IWV-field. Therefore, the radiosonde data from De Bilt were compared to a weighted average of the GPS-IWV data from stations Delft (56 km) and Kootwijk (43 km). The coefficients used are .425 and .575 respectively. These values correspond to a Gaussian weight function with a full width half maximum of 84 km. The coefficients are determined by finding a minimum in the standard deviation of the residuals around the regression line for subset C in table 2. The standard deviation of the residuals for the weighted results are reduced by 10% to 30% as compared to the comparison of radiosonde to each of the two stations separately. The height difference between De Bilt and Kootwijk (40 m) has been ignored in the intercomparison.

The overall results for the four different periods are summarised in table 2. For period A there were mainly problems near the end of the day, which have to be attributed to a poor performance of the older GIPSY/OASIS version used for that period. For the other periods a good agreement is found, comparable to results found in other experiments. Note that orbit relaxation applied to rapid orbits still does improve the accuracy.

6. Comparison with radiometer data.

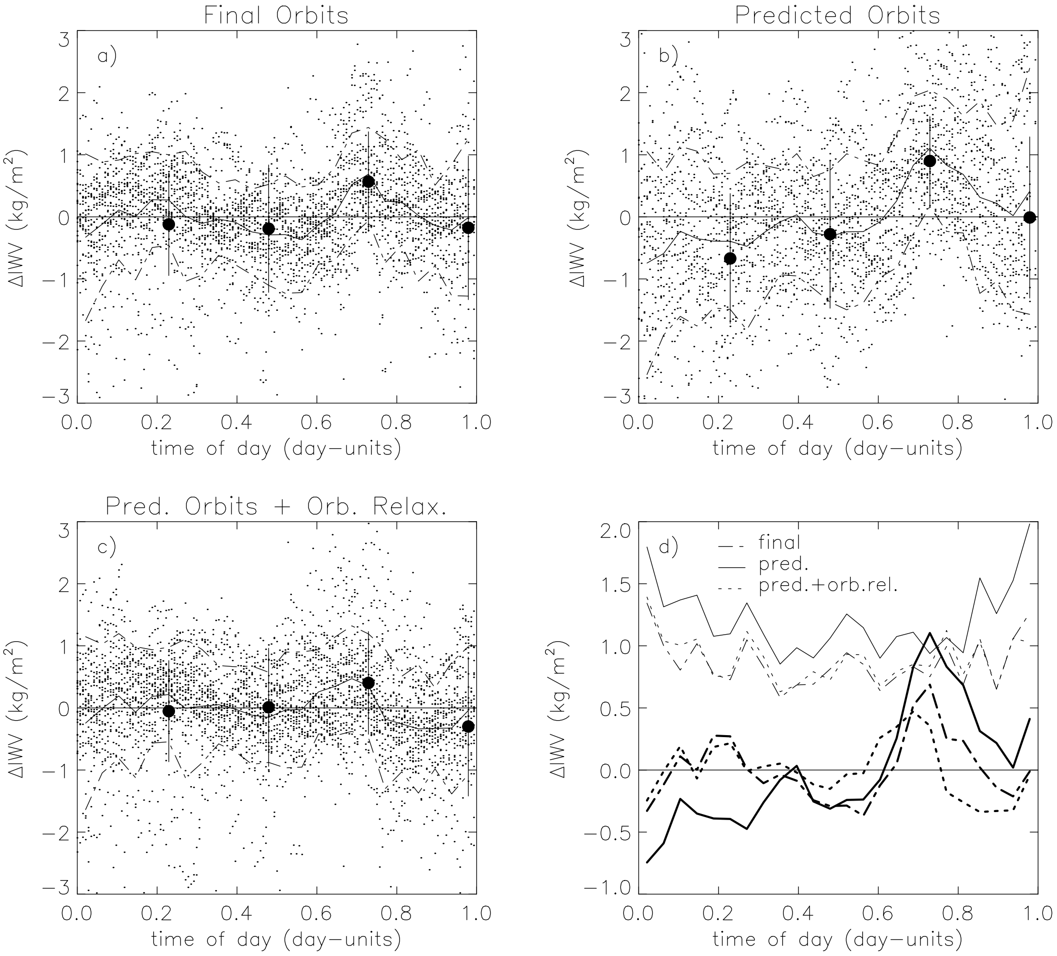

Figure 5. The deviation from daily mean for GPS-WVR (DELF), solid line hourly mean, dashed lines hourly mean ± standard deviation. Solid dots, the difference from daily mean for GPS (DELF) – RDS (BILT). In d) the mean (thick lines) and standard deviation (thin lines) for the three data sets plotted in a), b) and c) are plotted together.

Table 3 Analysis results for period 23/feb/98 – 24/mar/98,
A,B,C: GPS (DELF) versus WVR (DELF), D,E,F: GPS (DELF+KOSG) versus RDS (BILT),G: WVR (DELF) versus RDS (BILT).

	Orbit	Pairs	Bias (kg/m²)	Std. Dev. (kg/m²)	Linear Regression results: Intercept	Coefficient	Std. Dev. Residuals
A	Final	3266	-0.77	0.17	0.88	0.88	0.95
B	Predicted	2799	-0.87	1.51	0.55	0.89	1.39
C	Pred.+Orbit Relaxation	3653	-0.85	1.12	0.71	0.89	0.93
D	Final	95	-0.65	1.39	0.47	0.92	1.30
E	Predicted	79	-0.81	1.39	-0.04	0.94	1.34
F	Pred.+Orbit Relaxation	104	-0.77	1.34	0.33	0.92	1.26
G		152	0.11	1.61	-0.05	1.01	1.61

During a two-and-half month period in 1998 a Rescom Ka-1 21.3/31.7 GHz water vapour radiometer (WVR) was located in Delft. The WVR was installed on the roof of a 90 m tall building at 1.5 km from the GPS-antenna location. Atmospheric signals are sampled at 1 s intervals, but in the preprocessing 60 s averaged data were calculated. Tipping-curve calibrations were performed regularly during the 1998 measuring period. Furthermore in our analysis a threshold of 1.5 mm for the liquid water content signal was applied for removing WVR data possibly contaminated by rain.

WVR IWV data were retrieved using two different methods: 1) a linear regression method with constants applicable for the Northern Hemisphere supplied by the manufacturer and b) a non-linear matched atmosphere algorithm which uses only surface meteorological data and, if available, information on cloud base and height [Jongen et al, 1998]. From the analysis of both methods compared to radiosonde and GPS data the non-linear method provided the best result. Therefore all results presented here are based on the WVR data processed by the non-linear matched atmosphere algorithm. Although the radiometer was located 90 m above the surface we have not applied a correction to the WVR-IWV data to account for the difference in height between the radiometer and GPS sensor.

Initially for a one week period GPS IWV data were calculated using different orbits, different number of (fixed) stations and processing methods [Van der Hoeven et al, 1998, Klein Baltink et al, 1999]. E.g experiments were conducted in which one orbit was fitted through the orbit of the day to be processed and the orbit of the day before, trying to decrease the influence of offsets between the orbits of two consecutive days. In this paper we call the fitted orbit the 2-day a-priori orbit fit. At a later stage the BERNESE package was also used for this week. The BERNESE results did not show the offset at the day-boundaries. Also the newer version of GIPSY/OASIS produced no offset at the day boundaries.

With the new GIPSY/OASIS program we reprocessed the GPS data for the period 23rd of February till 24th of March 1998. We used final and predicted CODE orbits, and reprocessed the predicted orbits also with orbit relaxation applied. The WVR and GPS data are averaged over 10 minutes interval before analysis. The length of the interval is not very critical. Longer intervals reduce the standard deviation only slightly e.g. for predicted orbits + orbit relaxation the standard deviation for an averaging period of one hour is 1.06 kg/m^2 as compared to 1.12 kg/m² at 10 minute average interval. The weighted average of GPS stations DELF and KOSG is compared to the radiosonde of station De Bilt (see section 5). The result of the analysis is summarised in table 3 and scatter plots are shown in figure 4. The regression results are calculated assuming the WVR and RDS as the independent variable. However, the errors for GPS, WVR and RDS are of the same magnitude, when the linear regression line is calculated assuming equal errors in both variables the coefficient is only 1 % to 2 % higher.

From the results presented in table 3 it is concluded that the GPS-IWV data retrieved with predicted orbits and orbit relaxation compared the closest to both WVR and radiosonde data. Moreover, we retrieve almost 10 % more data as compared to the processing with final orbits. The GPS-IWV data do show a systematic lower value of about 10 % compared to WVR data. The WVR and radiosonde data show an almost one-to-one fit. However as we did not correct for the height of the radiometer we would expect the WVR data to be 3 to 4 % lower than the radiosonde (and GPS) data. From the results of the operational processing we found a very good agreement between GPS and radiosonde for the same GPS processing and network. We have no explanation for the lower values of the GPS data in this period.

We assume that the standard deviation of the difference between the WVR and radiosonde has a contribution of about 20 % due the spatial separation of the measurements. From the values of the standard deviations in table 3 from C, F and G we now can calculate (assuming no dependence of the errors in the three different systems) an estimate of the precision of the IWV data. We find that GPS and WVR are comparable with a precision of 0.8 kg/m^2 and the radiosonde data has a precision of about 1 kg/m^2.

We also calculated the difference from the daily mean of GPS-WVR and GPS-RDS respectively. The results are presented in figure 5. A typical consistent pattern does show. As the pattern is present in both the comparison with WVR and RDS we conclude that most likely the pattern has to be contributed to the GPS-data. Note also that the pattern is the smallest for predicted orbits with orbit relaxation. Comparison of 4 days of data retrieved with BERNESE program and final orbits showed a similar pattern, except for the first 3 hours. Further analysis is needed to find the source of this pattern, although this seems to indicate that at least a part of the pattern is caused by the GPS-data itself.

7. Conclusion.

Operational acquired GPS-IWV data from a 15 stations wide regional GPS network show in general a very good agreement with collocated radiometer data and with radiosonde. The operational GPS-IWV data have been obtained using the CODE rapid orbits. However, an experiment with orbit relaxation applied during the processing showed that even with the less accurate predicted orbits a reliable estimate of the IWV-data can be calculated. The accuracy of these data is the same as GPS-IWV data retrieved with final orbits. This is in line with experiments by Kruse et al [1999] and Ge et al [2000]. A four week experiment to test the combination of predicted orbits and orbit relaxation showed that GPS-IWV estimates obtained from final orbits and from predicted orbits with orbit relaxation applied compare very similar to radiometer and radiosonde measurements. Furthermore the processing with orbit relaxation increased the number of available data by 10 %. We conclude that GPS processing with orbit relaxation is a very promising technique for accurate near real-time GPS water vapour retrieval.

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