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Integrated atmospheric water vapor estimates from a regional GPS network

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[1] Integrated atmospheric water vapor (IWV) estimates from a 15-station-wide network of Global Positioning System (GPS) receivers have been collected continuously since November 1997. The core of this network consists of five stations of the active GPS reference system in the Netherlands. A network with sufficient long baselines was chosen to secure the absolute accuracy of the GPS IWV data. Rapid satellite orbits available 12 to 24 hours after data acquisition are used in the processing of the GPS data, and IWV estimates are available with a typical delay of 1 day. Comparison of the GPS IWV data with data retrieved from a water vapor radiometer and radiosondes shows a good agreement. Different network configurations and processing strategies have been investigated to optimize the network and processing for future near-real-time use. In near-real-time applications, only predicted orbits are available; however, the accuracy of the predicted orbits is, in general, not sufficient for accurate IWV retrieval. We tested whether orbit relaxation, i.e., the simultaneous adjustment of orbit parameters during the processing of the GPS data, could increase the accuracy of the IWV estimates. During an experiment with orbit relaxation applied to predicted orbits a significant improvement of the accuracy of the GPS IWV data was found. The accuracy was comparable to GPS IWV data retrieved with final orbits, the most accurate orbit data available. Results of the experiments and the analysis of operational acquired data are presented. *INDEX TERMS:* 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 1299 Geodesy and Gravity: General or miscellaneous; *KEYWORDS:* GPS meteorology, water vapor, orbit relaxation

1. Introduction

[2] Water vapor plays an important role in atmospheric processes on a wide range of spatial and temporal scales. In recent years, GPS-retrieved integrated water vapor (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 vapor content along the atmospheric signal path. The contribution of the water vapor 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 receivers has been shown in several experiments [e.g., *Bevis et al.*, 1992; *Emardson et al.*, 1998; *Tregoning et al.*, 1998]. Networks of GPS receivers are already installed worldwide mainly for geodetic purposes but, in some cases, also dedicated to GPS IWV retrieval [*Ware et al.*, 2000; *Wolfe and Gutman*, 2000]. Data from these networks can provide valuable IWV data for meteorological purpose at low (additional) costs and with a high temporal resolution [e.g., *Iwabuchi et al.*, 2000]. Near-real-time retrieval of GPS IWV data, especially important for short-range numerical weather forecast models, is a subject of ongoing research.

[3] In the Netherlands a continuously operating GPS reference station network (AGRS-NL) began full operation in the 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 2we describe the selected GPS network of ground-based GPS receivers and the processing of the GPS data. 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 7 years of radiosonde data. These results are presented in section 3. In section 4we present the results of the analysis of the operational GPS IWV data acquired since November 1997.

[4] Because of the ultimate goal of near-real-time processing we focused 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 satellite orbital parameters together with the tropospheric estimates. In section 5 we describe the experiment to improve the accuracy of the predicted orbits. The results of the experiment, with GPS IWV

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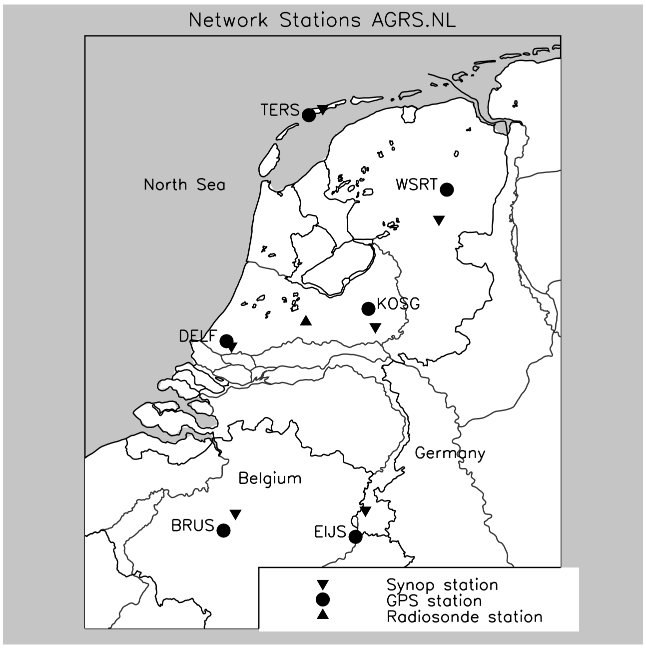

Figure 1. AGRS-NL network in the Netherlands; the distance between GPS stations DELF and KOSG is ~100 km.

data retrieved with predicted orbits with orbit relaxation applied, and the comparison to collocated radiometer data are discussed in section 6. Conclusions are given in section 7.

2. GPS Network and Processing

[5] In 1995 a permanent network of GPS reference receivers was built in the Netherlands. This network, called the active GPS reference system in the Netherlands (AGRS-NL), has been in full operation since the spring of 1997 and consists of five stations distributed over the Netherlands (Figure 1). The data are transmitted to a central computing center on an hourly basis. The AGRS-NL is connected to the International GPS Service (IGS) global network through the stations Kootwijk (KOSG) and Westerbork (WSRT). For the tests described in this paper, as well as for the operational processing, the AGRS-NL network is embedded in an extended regional network consisting of 15 stations, in total, distributed over the Northern Hemisphere. Long baselines secure absolute GPS IWV estimates and are also necessary for simultaneous orbit improvement; 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 summarized in Table 1.

[6] The GPS data are processed at the Delft University of Technology with the GIPSY/OASIS II software package developed at the Jet Propulsion Laboratory (JPL) [*Webb and Zumberge*, 1993]. During the processing, station coordinates, satellite and receiver clocks, and zenith delays are estimated. Other typical processing parameters applied are (a) a cutoff satellite elevation angle of 15°, (b) mapping function by Lanyi, (c) a priori tropospheric delay estimate by the Saastamoinen model, and (d) a modified Kalman filter with a tropospheric drift parameter of 1.10^{-7} km/$\sqrt{}$s. In the newer version of the GIPSY/OASIS, in use since February 1999, a cutoff angle of 10° and Niell mapping function are applied instead. Tropospheric parameters are estimated at 6-min intervals, and data are processed in batches of 24 hours without any overlap at the day boundaries. Rapid satellite orbit data computed by the Centre for Orbit Determination in Europe (CODE) are used.

[7] 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 zenith total delay. The hydrostatic part of the delay can be calculated accurately from surface pressure P_s only, using

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

where

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

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 kilometres above the ellipsoid. The function $f(\theta, H)$ is derived from an approximation of the gravity formula [*Saastamoinen*, 1971]. The conversion of GPS ZWD data to IWV data is given in section 3. Also, commonly integrated precipitable water (PW) vapor is used instead of IWV, where PW in millimeters is equivalent to IWV in kg/m^2.

[8] Surface pressure, temperature, and humidity are measured at nearby stations of a mesoscale synoptical network (Figure 1). The mean of the last 10-min period before the hour is available. The surface meteorological data are interpolated to the GPS observation time. The pressure sensors have an accuracy of 0.1 hPa. However, the 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 afterward is not exactly 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 ~0.1 kg/m^2. Because of the distance between the locations of the GPS and the meteorological stations, errors will be introduced in the ZHD estimates derived from the pressure data, due to horizontal pressure gradients. We did not spatially interpolate the pressure data to the GPS stations but simply selected the pressure of the nearest station. From analysis of 1 year of pressure data we estimated that the resulting root-mean-square (RMS) error is less than 0.3 hPa for the largest separation (at WSRT), corresponding to a rms error of 0.1 kg/m^2 in IWV. The surface meteorological data are also used to estimate the water vapor content between ground level and GPS antenna, which is in general a very small amount, but with some GPS antennas up to 30 m above ground level, it should not be ignored.

3. Weighted Mean Atmospheric Temperature *Tm*

[9] Radiosonde profiles are integrated to obtain the IWV data for comparison with GPS IWV data. The radiosonde data are

Table 1. Location and Height of Stations of Operational Network[a]

ID	Country	Long. (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*	Virgin Islands, USA	−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	Canary Islands, Spain	−15.63	27.76	198
ONSA	Sweden	−11.92	57.39	47
REYK*	Iceland	−21.95	64.13	94

[a] Height is above the WGS84 ellipsoid. During orbit relaxation, coordinates of stations annotated with an asterisk are fixed to ITRF97.

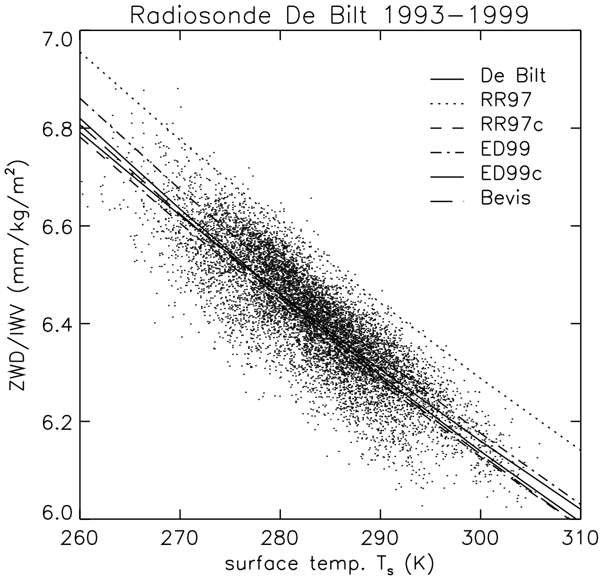

Figure 2. Conversion factor Q = ZWD/IWV as a function of the surface temperature T_s. The suffix c denotes the corrected results. See text, section 4, for explanation.

also used to determine the local relationship between the surface temperature T_s and the weighted temperature T_m. The latter is used in the conversion of GPS ZWD to IWV. Radiosondes (Vaisala RS80, A-humicap) used in this study are launched 4 times daily at De Bilt (see Figure 1) at ~0000, 0600, 1200, and 1800 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 and possibly a small dry bias [*Leiterer et al.*, 1997]. Also, the accuracy of the RS80 humidity sensor degraded over time because of contamination by outgassing of the packing material. The magnitude of the contamination error is a function of age and relative humidity. However, as most of the radiosondes used for comparison in this study are released within half a year after manufacturing, we can ignore the contamination effect in this data set.

[10] Radiosonde data were analyzed for the period 1993–1999 to determine T_m as function of T_s. The radiosonde profile data are integrated to retrieve ZWD, IWV, and the weighted mean temperature T_m. The ZWD is given by

$$ZWD = 10^{-6}\int \frac{P_v}{T}\left[\frac{k_3}{T}+k_2-\frac{R_d}{R_v}k_1\right]dz \qquad (3)$$

where k_2 and k_3 are empirical constants, R_v is the specific gas constant for water vapor, P_v is the partial water vapor pressure, and T is the air temperature. The water vapor pressure P_v is calculated using the equation for saturated water vapor pressure presented by *Sonntag* [1994]. The ratio $Q(T_m)$ = ZWD/IWV is given by

$$Q(T_m) = 10^{-3}R_v\left[\frac{k_3}{T_m}+k_2-\frac{R_d}{R_v}k_1\right] \qquad (4)$$

where the weighted mean temperature is T_m defined as

$$T_m = \int\frac{P_v}{T}dz/\int\frac{P_v}{T^2}dz. \qquad (5)$$

Commonly, the linear relation $T_m = 0.72T_s + 70.2$ [*Bevis et al.*, 1992] is applied, although it is known that the relation between T_m and T_s is location and seasonally dependent [*Ross and Rosenfeld*, 1997 (hereinafter referred to as RR97]. RR97 analyzed a large number of radiosonde data over a 23-year period and at 53 locations worldwide. RR97 applied in their analysis a cutoff 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* [2000], [hereinafter referred to as ED2000] analyzed radiosonde data for 38 sites in Europe over a period of 9 years. From both studies it is concluded that a location and seasonally dependent relationship based on T_s provide the most accurate result for the conversion of ZWD to IWV. ED2000 analyzed the quotient Q directly as a function of T_s; T_m was not determined in this study. Furthermore, they retrieved ZWD from radiosonde data using the

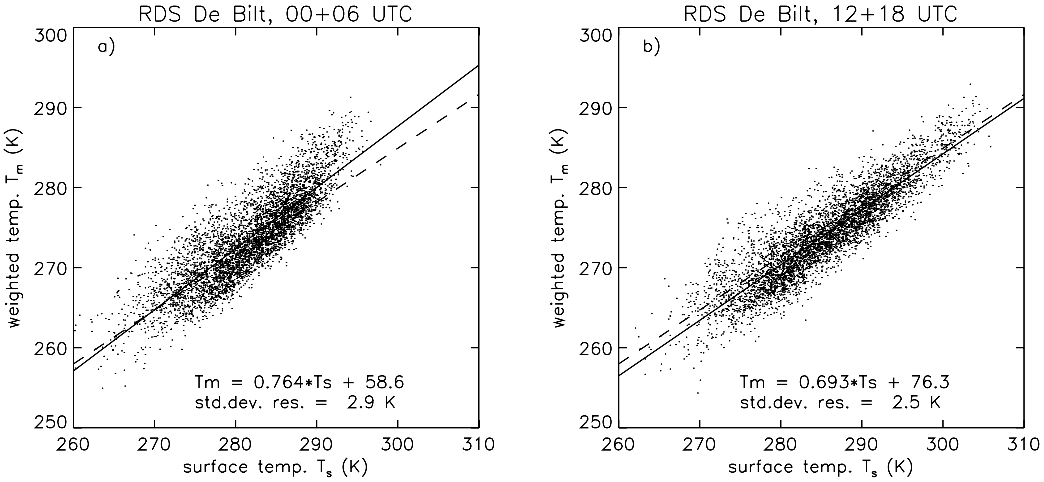

Figure 3. Weighted temperature T_m as function of surface temperature T_s for nightime (0000 and 0600 UTC) and for daytime (1200 and 1800 UTC) radiosonde ascents. Solid line is the regression line for the subset; the dashed line is the regression line for the whole data set.

Table 2. Analysis of Operationally Acquired IWV Data, GPS (Weighted Average DELF and KOSG) Versus Radiosonde[a]

Period	Pairs	Bias, kg/m^2	SD, kg/m^2	RMSE, kg/m^2	Linear Regression Results		
					Intercept	Coefficient	SD Residuals
A 29/10/97–15/02/99	1240	0.58	1.69	1.79	1.45	0.94	1.60
B 16/02/99–30/06/99	355	0.08	1.43	1.43	0.73	0.96	1.38
C 01/07/99–31/07/00	893	0.01	1.35	1.35	0.36	0.98	1.33

[a] Processing applied: A, 2-day a priori fit; B, 1-day a priori fit; C, 1-day a priori fit plus orbit relaxation. CODE rapid orbits were used in all three periods. SD is the standard deviation around the mean; RMSE is root-mean-square error. Read 29/10/97 as 29 October 1997.

values for k_i presented by *Thayer* [1974]: k_1 = 77.604 ± 0.014, k_2 = 64.79 ± 0.08, and k_3 = (3.776 ± 0.004) × 10^5 , respectively (all values in K/hPa). We used the values presented by *Bevis et al.* [1994], which are 77.60 ± 0.05, 70.4 ± 2.2, and (3.739 ± 0.012) × 10^5, respectively. The k values applied by ED2000 will result in approximately a 0.6% increase of Q as compared to our calculation. In Figure 2 our results are compared with RR97 and ED2000 (in Figure 2 referred to as ED99). Since radiosonde station De Bilt was not included in the RR97 analysis, we used as proxy values for De Bilt their values for Bordeaux (France) instead. From the results presented in Figure 2 it is concluded that ED2000 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 Rosenfeld*, 1999] and the bias due to the 500 hPa cutoff, the agreement is also very good. Furthermore, the regression proposed by *Bevis et al.* [1992] gives a similar result for our (midlatitude) location.

[11] The effect of the diurnal cycle in the surface temperature on the relation between T_m and T_s is shown in Figure 3. The data are plotted separately for day and nighttime radiosonde launch times. Especially for the higher values of T_s at 0000 and 0600 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) atmospheric boundary layer are a likely cause. However, scatter of the data around the two regression lines is large compared to the difference between the two linear regression results. Therefore we applied one 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

$$T_m = 0.673T_s + 83.0 \tag{6}$$

Relation (6) is used in the retrieval of the IWV data from the ZWD estimates from the GPS network. The standard deviation of T_m about the regression line is 2.7 K, which results in an error less than 1% in $Q(T_s)$. 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%.

4. Intercomparison of Operational GPS Results and Radiosonde

[12] From November 1997 onward 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 setup of the processing. Based on the results of some initial experiments, we started with a 2-day a priori orbit fit (see section 5). Since February 1999, a new version of the GIPSY/OASIS package is being used for the processing, and the 2-day a priori orbit fit is reduced to 1 day. Also, the elevation cutoff is reduced from 15° to 10°, and the Niell 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 (see Table 1) have been constrained to the International Terrestial Reference Frame (ITRF97), using a standard deviation of 0.1 mm for the ITRF coordinates during the processing.

[13] Before the intercomparison with radiosonde data the GPS data are time averaged over the interval from the start of the radiosonde ascent to the time when the *H*95 height was reached. The height *H*95 is the height below which 95% of the total integrated water vapor is present. About 90% of the *H*95 heights for station De Bilt were located between 3.5 and 6.5 km above ground level. In general, the time to reach H95 is of the order of 15 min.

[14] The spatial separation between De Bilt and GPS stations Delft and Kootwijk, respectively, increases the difference in IWV 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 0.425 and 0.575, respectively. 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 result is reduced by 10–30% as compared to the comparison with radiosonde for each of the two stations separately.

[15] The overall results for the three different periods are summarized in Table 2; the results for the period with rapid orbit relaxation are also presented in Figure 4. For period A (2-day a priori fit) there were mainly problems near the end of the day,

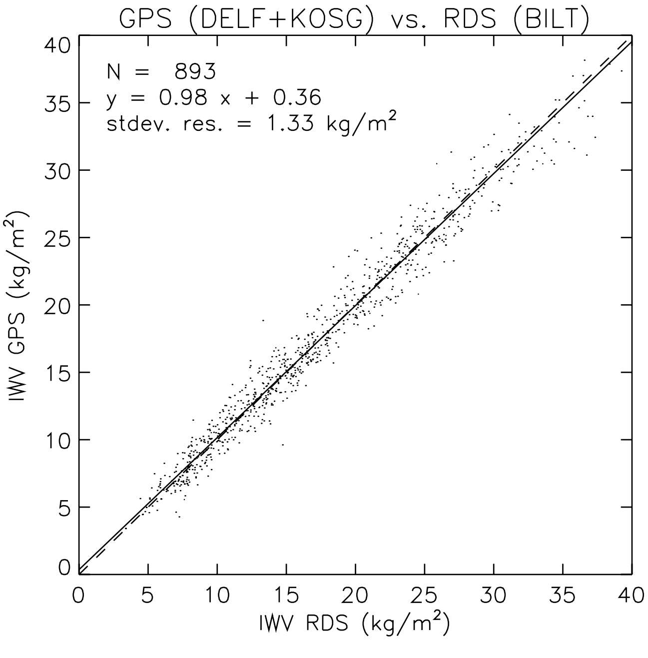

Figure 4. GPS IWV versus radiosonde. GPS IWV is weighted average of stations DELF and KOSG and retrieved with rapid orbits and orbit relaxation applied. Solid line is linear regression line.

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 several other experiments [*Emardson et al.*, 1998; *Rocken et al.*, 1995; *Tregoning et al.*, 1998; *Wolfe and Gutman*, 2000]. The bias in these experiments is usually less than 1 kg/m^2, while the standard deviation typically ranges from 1 to 2.5 kg/m^2.

5. Improving the Accuracy of Predicted Orbits

[16] One of the main problems for accurate near-real-time GPS IWV estimation is the accuracy of the satellite orbits [*Rocken et al.*, 1997; *Kruse et al.*, 1999]. 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, which have an accuracy of 5 cm. However, 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 setup and orbits to assess accuracy of the retrieved IWV data. The experiments were conducted for the period 20–27 March 1998. 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 shows a steadily increase, whereas the accuracy of the rapid orbits decreased only near the end of the day [*van der Hoeven et al.*, 1998]. For this 1-week period, GPS IWV data were calculated using a different type of orbits, a different number of (fixed) stations and processing methods [*van der Hoeven et al.*, 1998; *Klein Baltink et al.*, 1999]. For example, 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.

[17] Accurate satellite orbit information, the so-called "rapid" orbits, is available from GPS data analysis centers 12–24 hours after data acquisition. The most accurate orbit information (final orbits), for example, from the IGS, is available only after a delay of several days to weeks. However, it is possible to reduce the effects of orbit errors in the predicted orbits by estimating one or more satellite orbital parameters during the processing itself and/or by applying a weight to "bad" satellites based on the quality index of the predicted orbits [*Ge et al.*, 2000; *Kruse et al.*, 1999; *van der Hoeven et al.*, 1998]. The quality index of the predicted orbits is an integral part of the orbit files and is based on the RMS deviation of the last seven rapid orbit solutions from their average.

[18] *Kruse et al.* [1999] investigated the use of the CODE orbit quality index to improve the accuracy of the predicted orbits. They investigated the use of the quality index either (1) as a threshold to remove bad satellites, (2) as a weighting factor, or (3) as a weighting factor in combination with estimating one orbital parameter (argument of latitude of the satellite position) during the processing. Comparison with radiometer data for a short period of 8.75 days is presented. Kruse et al. found that their method 3 provided the most accurate IWV results. The standard deviation of the comparison with radiometer data was ≈ 2.0 kg/m^2 for method 3, while for the precise final IGS orbits, it was ≈ 1.4 kg/m^2. Although the use of the quality index does improve the estimates, the index is calculated on the basis of the orbit information from previous days and is not always representative [*Ge et al.*, 2000]. Therefore *Ge et al.* extended the estimation of the orbital parameters to three Keplerian parameters that represent the main error sources in predicted orbits: (1) the semimajor axis, (2) inclination, and (3) argument of perigee. They applied an iterative method to reweigh the orbital parameters. They compared their results to the IWV data with the final IGS orbits and found an improvement of 20% in RMS error compared to their methods of using the quality index to remove bad satellites and to weigh the remaining orbits without iteration. They used GPS data from a 15-station-wide network in western Europe.

[19] More recently, ultrarapid orbits became available from IGS, which now replace the predicted orbits. The ultrarapid orbits are produced twice daily, reducing the interval over which the orbit parameters have to be predicted, resulting in an improved orbit accuracy and reliability. The ultrarapid orbits have not been used in our studies, but we are convinced that also with ultrarapid orbits, orbit relaxation is still necessary.

[20] Initially, we applied orbit relaxation to predicted orbits for a 1-week period in March 1998 and found comparable accuracy for the IWV data retrieved from predicted orbit with orbit relaxation applied as those retrieved with the accurate final IGS orbits. We estimated the six elements of the initial state vector (i.e., satellite position and velocity at the beginning of an orbit arc) for each satellite orbit and removed satellites orbits with quality index 13 or larger from the processing; that is, satellites with RMS error larger than 2^{13} = 819.2 cm are removed. All station coordinates are estimated, but the coordinates of the "fixed" stations are constrained to the ITRF using a standard deviation of 0.1 mm. In section 6we present data for an extended period of 4 weeks in 1998 for which we applied this same method and compare these results with final orbits and collocated radiometer and radiosonde data.

6. Comparison With Radiometer Data

[21] During a two-and-half month period in 1998 a Rescom Ka-1 21.3/31.7 GHz water vapor 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.

[22] The WVR IWV data were retrieved using a nonlinear matched atmosphere algorithm, which uses only surface meteorological data and, if available, information on cloud base and height [*Jongen et al.*, 1998]. Although the radiometer was located 90 m above the surface and approximately 60 m above the GPS antenna, we have not applied a correction to the WVR IWV data to account for the difference in height between the radiometer and the GPS sensor.

[23] With the new GIPSY/OASIS program we reprocessed the GPS data for the period 23 February to 24 March 1998. We used final IGS and predicted CODE orbits and reprocessed the predicted orbits also with the orbit relaxation applied. The WVR and GPS data are averaged over a 10-min interval before analysis. The length of the interval is not very critical. Longer

Table 3. Analysis Results of Experiment for Period 23 February 1998 to 24 March 1998 for Station DELF[a]

	Pairs	Bias, kg/m^2	SD, kg/m^2	RMSE, kg/m^2	Linear Regression Results		
					Intercept	Coefficient	SD Residuals
Final versus WVR	3266	−0.77	1.17	1.40	0.69	0.89	0.95
Predicted versus WVR	2799	−0.87	1.51	1.75	0.14	0.92	1.40
Predicted plus orbit versus WVR	3653	−0.85	1.12	1.41	0.51	0.90	0.93
Predicted versus final	2430	−0.13	1.02	1.03	−0.59	1.04	1.02
Predicted plus orbit versus final	3262	−0.11	0.48	0.50	−0.21	1.01	0.48
WVR versus RDS	152	0.11	1.61	1.61	−0.63	1.05	1.63

[a] GPS versus radiometer (WVR), GPS-predicted orbit, and predicted plus orbit relaxation versus final orbits and radiometer versus radiosonde (RDS, station BILT).

intervals reduce the standard deviation only slightly; for example, for predicted orbits with orbit relaxation, the standard deviation for an averaging period of 1 hour is 1.06 kg/m^2 as compared to 1.12 kg/m^2 at a 10-min average interval. The weighted average of GPS stations DELF and KOSG is compared to the radiosonde of station De Bilt. The result of the analysis with the radiometer is summarized in Table 3 and scatterplots are shown in Figure 5. The result of the comparison with radiosonde is presented in Table 4. All regression results are calculated assuming equal uncertainties in both variables.

[24] From the results presented in Tables 3 and 4 it is concluded that the GPS IWV data retrieved with predicted orbits and orbit relaxation compare very well to the final orbit IWV data, and both are close to the WVR data. For the comparison with radiosonde data we find a slightly better agreement for the final orbits, but the difference in standard deviation is not statistically significant. However, we retrieve almost 10% more data with orbit relaxation as compared to the processing with final orbits. The GPS IWV data do show a systematic lower value of about 8–10% compared to WVR and radiosonde data. The values of the standard deviation and bias of the GPS-radiometer comparison are comparable to results from other studies. The WVR and radiosonde data compare also reasonably well. However, as we did not correct for the height of the radiometer, we would expect the WVR data to be 3–4% lower than the radiosonde (and GPS) data. From the results of the

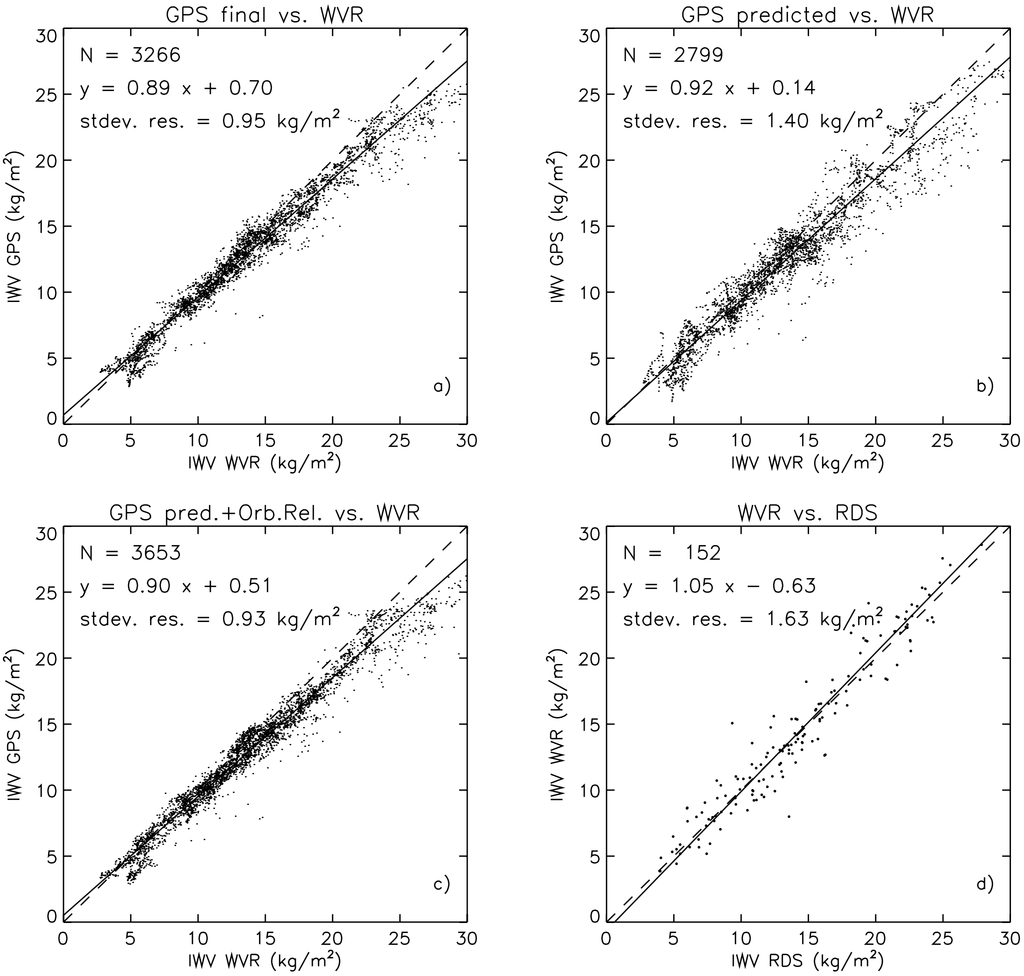

Figure 5. GPS IWV versus radiometer data for (a) final orbits, (b) predicted orbits, and (c) predicted orbits with orbit relaxation applied. (d) Comparison of radiometer versus radiosonde data for the same period. Solid line is the linear regression line.

Table 4. Analysis Results of Experiment for Period 23 February 1998 to 24 March 1998[a]

	Pairs	Bias, kg/m^2	SD, kg/m^2	RMSE, kg/m^2	Linear Regression Results		
					Intercept	Coefficient	SD Residuals
Final versus RDS	95	−0.64	0.92	1.11	0.38	0.92	0.78
Predicted versus RDS	79	−0.84	1.14	1.41	−0.23	0.95	1.08
Predicted plus orbit versus RDS	104	−0.80	0.96	1.24	0.10	0.93	0.85

[a] GPS IWV weighted average of station Delft (DELF) and Kootwijk (KOSG) versus radiosonde (RDS, station BILT).

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 particular period.

[25] Because the predicted orbits lose accuracy as a function of the time of day, we also calculated the deviation from the daily mean of GPS-WVR and GPS-radiosonde differences, respectively. The results for the comparison with radiometer data are presented in Figure 6. A typical consistent pattern does show a maximum in the bias near 1800 UTC. This pattern is also present in the comparison with radiosonde data. 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 in the bias is the smallest for predicted orbits with orbit relaxation. Comparison of 4 days of data retrieved with the Bernese software 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.

[26] The results from this experiment compare favorably to those of *Kruse et al.* [1999]. They found that compared to radiometer data the estimation of IWV with weighing predicted orbits and relaxation of one orbital parameter improved the estimate (RMS with radiometer ≈ 2.0 kg/m^2) but was still not so accurate as the final orbit estimate (RMS ≈ 1.4 kg/m^2). We found comparable RMS values (≈ 1.4 kg/m^2) compared to the radiometer for both methods. The results of *Ge et al.*[2000] for their iterative method are similar to our results; they found a mean RMS difference between predicted orbits with relaxation and final orbits of 0.6 kg/m^2, while we found a RMS of 0.5 kg/m^2 for both stations Delft and Kootwijk.

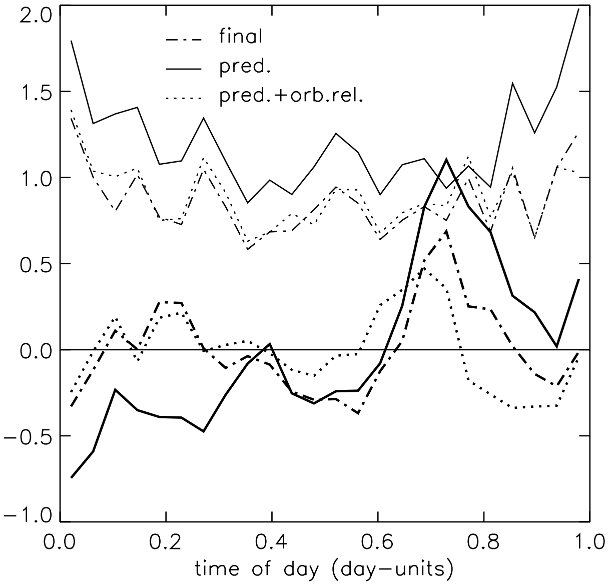

Figure 6. Deviation from daily mean for difference GPS-WVR (DELF). Thick lines are hourly mean values; thin lines are standard deviations. Results for final orbits (dashed-dotted lines), predicted orbits (solid line), and predicted orbits with orbit relaxation applied (dotted line).

7. Conclusion

[27] Operationally acquired GPS IWV data from a 15-station-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 could be calculated. The accuracy of these data is the same as GPS IWV data retrieved with final orbits. This is in line with experiments with orbit relaxation applied to predicted orbits by *Kruse et al.* [1999] and *Ge et al.* [2000]. A 4-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 similarly 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 applied to predicted orbits is an accurate technique for near-real-time GPS water vapor retrieval.

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References

Bevis, M., S. Businger, T. A. Herring, C. Rocken, R. A. Anthes, and R. H. Ware, GPS meteorology: remote sensing of atmospheric water vapor using the global positioning system, *J. Geophys. Res.*, *97*, 15,787–15,801, 1992.

Bevis, M., S. Businger, S. Chiswell, T. A. Herring, R. A. Anthes, C. Rocken, and R. H. Ware, GPS meteorology: Mapping zenith wet delays onto precipitable water, *J. Appl. Meteorol.*, *33*, 379–386, 1994.

Emardson, T. R., and H. J. P. Derks, On the relation between the wet delay and the integrated precipitable water vapour in the European atmosphere, *Meteorol. Appl.*, *7*, 61–68, 2000.

Emardson, T. R., G. Elgered, and J. M. Johansson, Three months of continuous monitoring of atmospheric water vapor with a network of Global Positioning System receivers, *J. Geophys. Res.*, *103*, 1807–1820, 1998.

Ge, M., E. Calais, and J. Haase, Reducing satellite orbit error effects in near real-time GPS zenith tropospheric delay estimation for meteorology, *Geophys. Res. Lett.*, *27*, 1915–1918, 2000.

van der Hoeven, A. G. A., B. A. C. Ambrosius, H. van der Marel, H. J. P. Derks, H. Klein Baltink, A. C. A. P. van Lammeren, and A. J. M. Kösters, Analysis and comparison of integrated water vapor estimation from GPS, in *Proceedings of the ION-GPS 98 Conference*, Inst. of Navig., Nashville, Tenn., 1998.

Iwabuchi, T., I. Naito, and N. Mannoji, A comparison of Global Positioning System retrieved precipitable water vapor with the numerical weather prediction analysis data over the Japanese Islands, *J. Geophys. Res.*, *105*, 4573–4585, 2000.

Jongen, S., M. Herben, H. Russchenberg, and A. C. A. P van Lammeren, On the accuracy of water vapor and liquid water retrieval with the Matched Atmosphere Algorithm, paper presented at the 1998 USNC/URSI National Science Meeting, Union Radio Sci. Int., Boulder, Colo., Jan. 5–9, 1998.

Klein Baltink, H., H. J. P. Derks, A. C. A. P van Lammeren, B. A. C. Ambrosius, A. G. A. van der Hoeven, H. van der Marel, F. Kleijer, and A. J. M.M Kösters, GPS water vapour meteorology, final report, *Rep. USP-2 98-27*, Neth. Remote Sens. Board, Delft, Neth., 1999.

Kruse, L. P., B. Sierk, T. Springer, and M. Cocard, GPS-meteorology: Impact of predicted orbits on precipitable water estimates, *Geophys. Res. Lett.*, *26*, 2045–2048, 1999.

Leiterer, U., H. Dier, and T. Naebert, Improvements in radiosonde humidity profiles using RS80/RS90 radiosondes of Vaisala, *Beitr. Phys. Atmos.*, *70*, 319–336, 1997.

Rocken, C., T. van Hove, J. Johnson, F. Solheim, and R. Ware, GPS/STORM-GPS sensing of atmospheric water vapor for meteorology, *J. Atmos. Ocean. Technol.*, *12*, 468–478, 1995.

Rocken, C., T. van Hove, and R. Ware, Near real-time GPS sensing of atmospheric water vapor, *Geophys. Res. Lett.*, *24*, 3221–3224, 1997.

Ross, R. J., and S. Rosenfeld, Estimating mean weighted temperature of the atmosphere for Global Positioning System applications, *J. Geophys. Res.*, *102*, 21,719–21,730, 1997.

Ross, R. J., and S. Rosenfeld, Correction to "Estimating mean weighted temperature of the atmosphere for Global Positioning System applications", *J. Geophys. Res.*, *104*, 27,625, 1999.

Saastamoinen, J., 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. Henriksen, A. Mancini, and B. H. Chovitz, pp. 247–251, AGU, Washington, D. C., 1971.

Sonntag, D., Advancements in the field of hygrometry, *Meteorol. Z.*, *3*(2), 51–66, 1994.

Thayer, D., An improved equation for the radio refractive index of air, *Radio Sci.*, *9*, 803–807, 1974.

Tregoning, P., R. Boers, D. O'Brien, and M. Hendy, Accuracy of absolute precipitable water vapor estimates from GPS observations, *J. Geophys. Res.*, *103*, 28,701–28,710, 1998.

Ware, R. H., D. W. Fulker, S. A. Stein, D. N. Anderson, S. K. Avery, R. D. Clark, K. K. Droegemeier, J. P. Kuettner, J. B. Minster, and S. Sorooshian, Suominet: A real-time national GPS network for atmospheric research and education, *Bull. Am. Meteorol. Soc.*, *81*, 677–694, 2000.

Webb, F. H., and J. F. Zumberge, An introduction to the GIPSY-OASIS-II, *JPL Publ. D-11088*, 300 pp., Jet Propul. Lab., Pasadena, Calif., 1993.

Wolfe, D., and S. I. Gutman, Developing an operational, surface-based, GPS, water vapor observing system for NOAA: Network design and results, *J. Atmos. Oceanic Technol.*, *17*, 426–440, 2000.

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