# Analysis and Comparison of Integrated Water Vapor Estimation from GPS

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## ABSTRACT

In the Netherlands a network of five permanent GPS receivers is operated (AGRS.NL). The Delft University of Technology (DUT), in collaboration with the Royal Netherlands Meteorological Institute (KNMI) and Survey Department of Rijkswaterstaat, processes this data on a daily basis, together with selected stations from the IGS network. Vertically integrated water vapor (IWV) estimates are computed every six minutes, with a delay of 1-2 days. Since 1 July 1997 the IWV timeseries is stored at the KNMI, in addition to radiosonde data and IWV forecasts from the Regional Atmospheric Climate Model (RACMO). In addition, during three experimental campaigns (CLARA) the GPS receiver in Delft was collocated with a microwave radiometer (WVR) and radiosonde launches. During one other period the GPS receiver was collocated only with a microwave radiometer.

Using the database of GPS IWV data, IWV derived from radiosonde launches, radiometer measurements and RACMO IWV predictions, the accuracy and reliability of the GPS IWV estimates is assessed. In this paper the GPS IWV estimates are compared to radiosonde, radiometer and RACMO IWV predictions. The comparisons have also been used to optimize the GPS processing and the computation of GPS IWV. The target of this optimization was to develop a processing method which is able to perform IWV estimations in near real-time. This target is met by incorporating an orbit relaxation in the process, generating a result which is independent of the accuracy of a priori orbit data generated by IGS or any other institute.

The results of several tests are reported. Finally, it is shown that GPS proves to be a reliable, all weather system, which is capable of estimating IWV with an accuracy of 0,5-1 kg/m$^2$.

## INTRODUCTION

The atmosphere of the earth causes a delay in the travel time of GPS satellite signals. By using two-frequencies the delay caused by the charged particles in the ionosphere can be eliminated. The delay caused by the neutral part of the atmosphere can not be eliminated so easily, because of its independence of transmitting frequency and its unpredictability. This delay reaches a value of about 2.0-2.5 meters in the zenith direction and increases approximately with the 1/sine of the elevation angle up to about 20-28 meters at a 5° angle [*Brunner & Welsch*, 1993]. The delay in the slant direction can be written as the product of a mapping function and the total delay in the zenith direction. The zenith delay (ZD) can then be solved for in the GPS data processing, resulting in a timeseries of zenith delay values for every station [*Leick*, 1995, *Kleusberg & Teunissen*, 1996].

The zenith delay can be divided in two parts, one caused by the total amount of dry gases (hydrostatic delay) and one caused by total water vapor constituent (wet delay). The hydrostatic delay can be calculated using the surface pressure within an accuracy of about 1-2 mm [*Saastamoinen*,1972]. When the hydrostatic delay is subtracted from the total delay the zenith wet delay (ZWD) is left. The estimated ZWD can be converted to estimates of the Integrated Water Vapor (IWV) [kg/m$^2$] using:

$$IWV = \frac{1}{k} \cdot ZWD \tag{1}$$

In which $k$ is approximately equal to 6.5 and dependent of a weighted mean temperature of the atmosphere [*Derks*, 1997]. Another frequently used quantity is the Integrated Precipitable Water Vapor (IPWV) which has the same value as IWV, except it is expressed in [mm] of liquid water when the water vapor would be condensed.

This technique to estimate the integrated atmospheric vapor from GPS has been tested successfully by several groups of scientists [*Bevis et al.*, 1992, *Baker, Dodson & Moore*, 1998, *Emardson et al.*, 1998, *Ware et al.*, 1997], and recently also the successful estimation of horizontal gradients has been reported [*Bar-Sever & Kroger*, 1998]. In 1996 a project was started in The Netherlands to retrieve the integrated water vapor (IWV) values from GPS measurements collected by the Active GPS Reference System for The Netherlands (AGRS.NL).

## THE AGRS-NETWORK

In 1995 the Triangulation Department of the Cadastre, the Survey Department of Rijkswaterstaat, Delft University of Technology and the Netherlands Geodetic Commission, started to build a permanent GPS network in The Netherlands for national use. The permanent network is called Active GPS Reference System for The Netherlands (AGRS.NL), and is operational since the spring of 1997. The permanent network consists of five stations distributed over the Netherlands (fig. 1). The data is transmitted to a central computing center on a hourly basis [*Van der Marel*, 1998]. The network is connected to the IGS global network through the stations Kootwijk (KOSG) and Westerbork (WSRT).

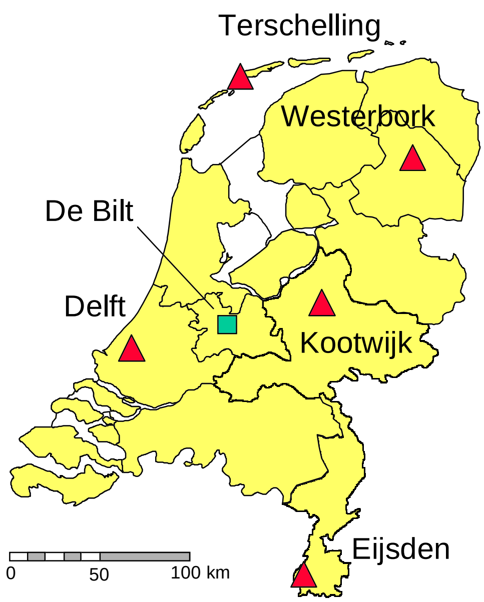


**Figure 1. The AGRS.NL permanent GPS network (triangles) and location of 'De Bilt' where the radiosondes are launched.**

For the tests which are described in this paper the AGRS.NL network was embedded in an extended regional network consisting of 15 IGS stations, distributed over the Northern Hemisphere (fig. 2). The selection criteria for the IGS stations were:

- Station data should be available as soon as possible after generation, but at most with one day of delay
- For the peripheral stations there should be a backup station within 2000 km to insure a complete network, therefore couples of stations were formed (KIRU-REYK, BAHR-KIT3, CRO1-RCM6)

- Stations should be equally distributed in every direction

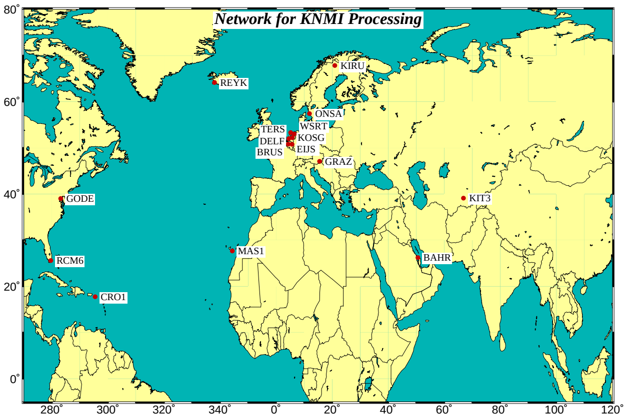


**Figure 2. The extended regional network used for the IWV tests.**

## METHOD OF PROCESSING

The GPS data were processed with the Gipsy software package, developed by the Jet Propulsion Laboratory in the USA. This package makes use of a Square Root Information Filter (SRIF) during the processing to solve for the parameters in the process [*Gregorius,* 1996]. Typical for the processing with Gipsy is that no explicit double differences of the observations are formed. Every parameter in the process can be solved for as a stochastic parameter, which means that orbit maneuvers can be taken into account when the satellite positions are treated as stochastic.

During the processing station coordinates, satellite and receiver clocks and zenith delay are estimated. When the final or rapid IGS orbits are not available predicted orbits or broadcast ephemerides are used as a first guess and orbit relaxation is used to improve the results. During the orbit relaxation tests the IGS stations at the periphery of the network were constrained to known positions. The elevation cut-off is set to 10° for all tests. Satellite clocks and tropospheric delay are estimated as white noise processes.

For the estimation of the tropospheric delay an a priori hydrostatic delay and wet component are subtracted from the observations. The residual wet zenith delay is estimated as a random walk process using the Lanyi [*Lanyi,* 1984] mapping function to transform the path delays to zenith delays. Finally, after the total delay is restored, the real zenith wet delay is calculated using pressure and temperature data from different AGRS sites.

## OPERATIONAL PROCESSING

The main objective of the GPS-Water Vapor Meteorology project was to set up an infrastructure for the acquisition, storage and processing of GPS IWV data. During the first half of 1997 the necessary steps were defined and implemented and since 1 July 1997 the GPS IWV estimation within The Netherlands is performed on a routine basis. A core network was defined, consisting of the five AGRS.NL stations complemented with the IGS station in Brussels. For this network, the GPS IWV time-series are derived on a daily basis. A number of distant IGS stations was added, securing the absolute value of the tropospheric delay. At present eight stations at the periphery of a wide region around The Netherlands are used (fig. 2). Also the data from stations Graz and Onsala was added because of their accurate clocks.

The GPS data is processed by DUT in batches of 24 hours using the procedure of the previous section. At present, CODE rapid orbits are used, which come available with a delay of 12 hours. The orbit information of two days is used to fit an orbit to diminish the gaps at the transition from one day to the next. No orbit relaxation has been used so far in the operational processing. Timeseries of IWV are generated for the stations within the core network on a daily basis and stored in an IWV database. In addition, radiosonde data from De Bilt and IWV forecasts from the Regional Atmospheric Climate Model (RACMO) are also stored. The RACMO model is a research atmospheric climate model. But the model is also run in forecast mode once per day to generate a three day weather forecast, similar to numerical weather prediction models. Once per day the model is started using the meteorological data measured around 12.00 UTC. For every grid point (fig. 3) a prediction of several quantities is generated including surface temperature and IWV. The results of the IWV processing are displayed on the Internet as soon as these come available (fig. 4).

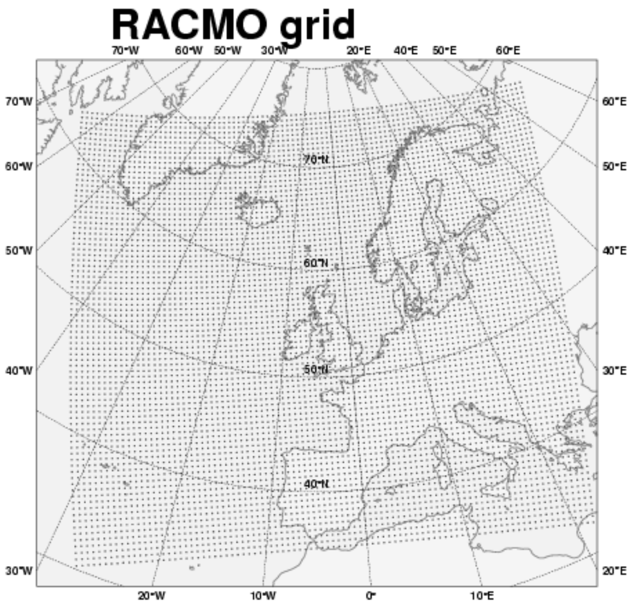


**Figure 3. The KNMI RACMO processing grid.**

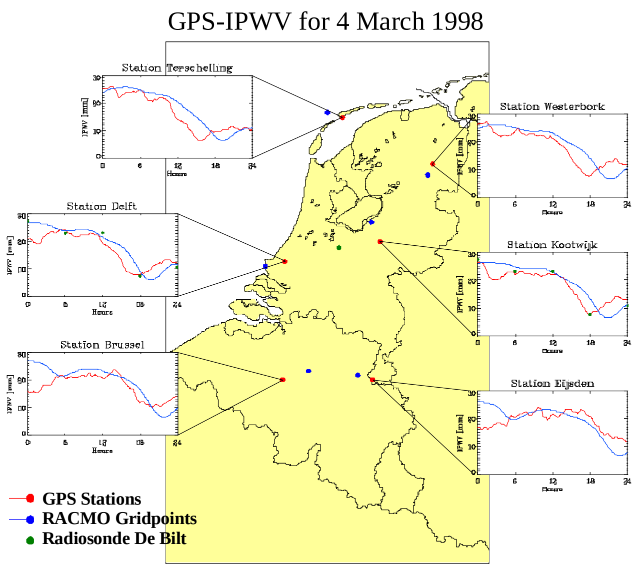


**Figure 4. Results of the IWV processing on the Internet.**

An extensive comparison has been made of IWV data generated by the GPS processing, data from radiosonde measurements in De Bilt and the results of the Regional Atmospheric Climate Model (RACMO) for a period in 1997/1998. Also, during the three experimental campaigns of the Clouds and Radiation (CLARA) project at Delft in 1996, the GPS receiver in Delft was collocated with a microwave radiometer (WVR) and radiosonde launches in Delft. In comparison with the measurements performed in the framework of the CLARA project, the GPS IWV resulting from the IGS processing proved to be an accurate estimation. The GPS IWV estimates agree with radiosondes and water vapor radiometer with a standard deviation of 1-2 kg/m$^2$. WVR data contaminated by rain was filtered out using a threshold of 0.5 kg/m$^2$ for the liquid water content, a quantity that also is measured by the WVR.

Comparing the results of the operational processing of stations Delft and Kootwijk to the radiosonde launches from De Bilt, again standard deviations of 1-2 kg/m$^2$ are obtained. From the results of the CLARA campaigns, however, it was found that the distance between the GPS station and the radiosonde launch site contributes to both the bias and the standard deviation. A statistical comparison of the GPS IWV results and the RACMO IWV forecast was made as well. In general the off-set between both data types is very small. The overall standard deviation ranges from 2 kg/m$^2$ for the +0-12 hours forecast to approximately 4 kg/m$^2$ for the +60-72 forecast.

## REAL TIME PROCESSING TESTS

Besides the operational processing further investigation had to be performed to achieve a real-time GPS IWV estimation. For real-time operations only predicted orbits or broadcast ephemerides are available. Therefore, results will suffer from the lower accuracy of these products. By using orbit relaxation the a priori orbits can be improved during the processing by estimating the real satellite positions at every epoch, resulting in better real-time results.

To assess the influence of orbits and orbit relaxation on the real-time water vapor estimates several experiments were performed. For these experiments a special test period was chosen ranging from day 079-1998 till 086-1998. During this period a radiometer was installed in Delft, close to the GPS receiver. Data was gathered from different sites worldwide (fig. 2) and the tests were performed in daily batches. Orbits used were CODE rapid orbits generated by CODE in Bern and IGS predicted orbits generated by a combination of seven IGS analysis centers. These orbits were integrated using the Gipsy orbit integrator in 1-day intervals. To investigate the influences of the orbits a comparison was made between results generated by the regular processing method with both predicted and rapid orbits, and the processing with orbit relaxation using the same types of orbits.

The radiometer data of the test campaign was taken during a period in which there was some rain. During rainfall the radiometer IWV data is not reliable and need to be taken out of the statistics. We used as criterion the liquid water content measured by the radiometer. Based on several trials, the optimum value for this criterion was found to be 0,5 mm of liquid water. It turned out that only 3-4% of the radiometer data was affected by rainfall.

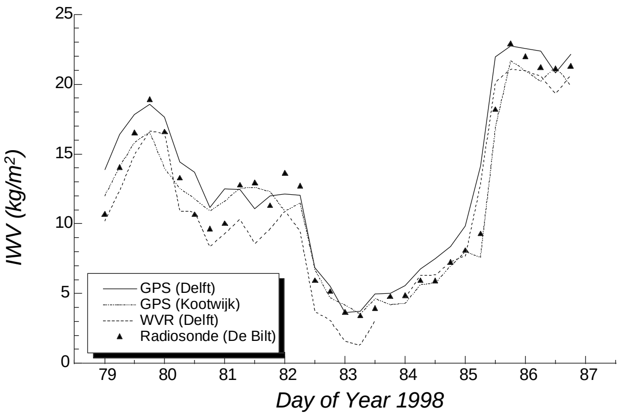


**Figure 5. GPS IWV estimate versus radiometer and radiosonde measurements.**

Firstly, a comparison was made with the radiosonde data retrieved during the test period. An overview of GPS IWV estimates sampled at 6 hour intervals using orbit relaxation together with radiosonde and radiometer data is shown in figure 5. The radiosonde data used during the test week was retrieved from balloon launches four times a day at De Bilt, located in the middle between the GPS stations Delft (DELF) and Kootwijk (KOSG). The statistics of table 1 show that the offset of GPS with the radiosonde is -1,02 kg/m$^2$ for Delft and +0,34 kg/m$^2$ for Kootwijk. This can be expected because the weather in De Bilt is much more alike that in Kootwijk than Delft, which is near to the North Sea coast. Also, the IWV in De Bilt is expected to be in between those of Delft and Kootwijk. The RMS about mean for GPS and radiosonde ranges from 1,15 for Kootwijk to about 1,45 for Delft. Values for the predicted orbit and rapid orbit situation, with and without orbit relaxation, are given in table 1. The results for different orbits are very much alike, although it seems that relaxation gives a small improvement.

**Table 1**

| Type of processing | RMS incl Offset [kg/m$^2$] | RMS about mean [kg/m$^2$] | Offset [kg/m$^2$] |
|---|---|---|---|
| *Kootwijk (KOSG)* | | | |
| Rapid Orbit | 1,28 | 1,16 | 0,53 |
| Predicted Orbit | 1,29 | 1,12 | 0,64 |
| Predicted with orbit relaxation | 1,16 | 1,11 | 0,34 |
| *Delft (DELF)* | | | |
| Rapid Orbit | 1,69 | 1,57 | -0,62 |
| Predicted Orbit | 1,83 | 1,64 | -0,82 |
| Predicted with orbit relaxation | 1,76 | 1,43 | -1,02 |
| WVR | 1,75 | 1,48 | -0,94 |

Secondly, a comparison was made with the radiometer during the test campaign in Delft. The radiometer has a much better time-resolution than the radiosonde data, thus giving a better view of the capabilities of GPS to follow short-term fluctuations.

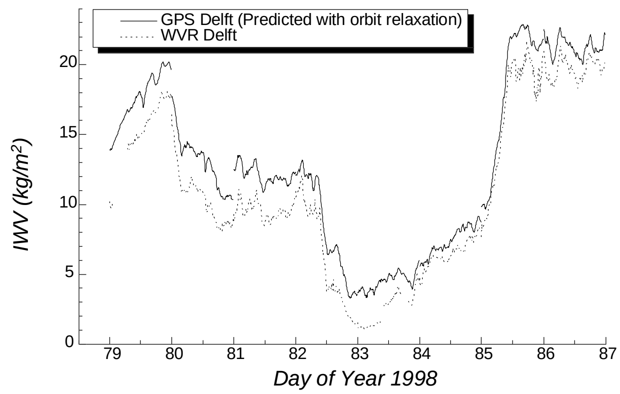


**Figure 6. Comparison of GPS IWV estimates with radiometer data.**

In figure 6 an overview is given of the radiometer data in Delft together with the data generated by the orbit relaxation procedure for station Delft at 6 minute intervals. Firstly, figure 6 shows jumps during the transition of day 79 and 80. Comparison with other stations showed that at this day-break a steep time gradient was present, causing the least-squares-algorithm to be unable to follow this phenomenon over the day-break. Secondly, figure 6 shows that an offset is present between the radiometer and the GPS measurements. This is not a surprise, because the Technical University of Eindhoven, who provided the radiometer data, has not yet finished the calibration of the radiometer. As can be observed from figure 7 the offset is not constant as there is a clear trend to be seen in the offset over the test period. Only day 084 seems to deviate significantly from the observed trend, but clear arguments for this deviation can not be given yet.

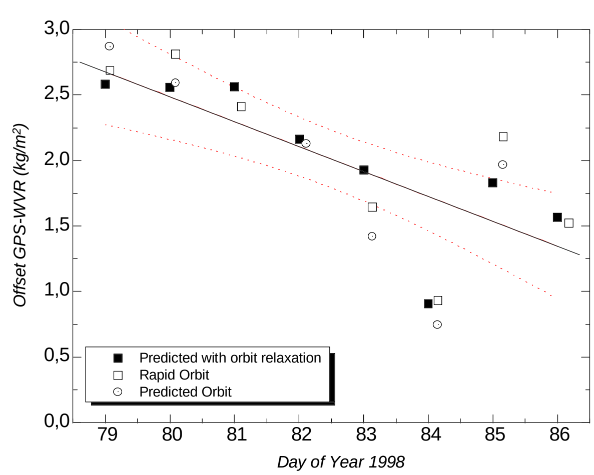

**Figure 7. Daily mean offset between GPS and WVR.**

The analysis then focussed on the overall trend-performance of GPS in comparison with the radiometer with the daily means removed. First, the radiometer data was interpolated to the same interval as the GPS data, which means that its values were changed from about 2-minute intervals to 6-minute intervals using a linear interpolation. Next, the WVR data was corrected for the daily means. Figure 8 shows the RMS about the daily mean of the difference between IWV derived from GPS and the interpolated WVR data.

Comparing the RMS values of the different orbit types shows that the predicted orbits using orbit relaxation give the best results. Also can be seen that the RMS of the rapid orbits results is smaller than the RMS of the predicted orbits when used without orbit relaxation. This result shows that using orbit relaxation real-time results might be generated with high accuracy, independent of the quality of the a priori orbit. To test this conclusion the experiment was repeated using broadcast ephemerides, which have an accuracy of several meters. The same results were obtained as with using predicted orbits during the relaxation.

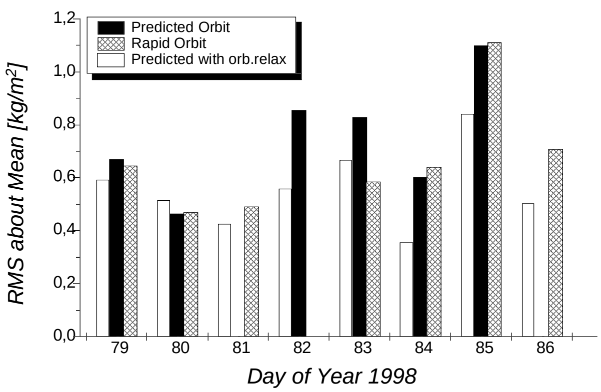


**Figure 8. RMS errors of different processing methods.**

## ORBIT ACCURACY

After comparing the radiometer and GPS data, the next step consisted of analyzing the accuracy of the used orbit files. CODE rapid orbits are claimed to have an accuracy of about 20 cm while IGS predicted orbits should have an accuracy of about 100 cm. Therefore the RMS differences between these orbits and the IGS final orbits were calculated (fig. 9 and 10).

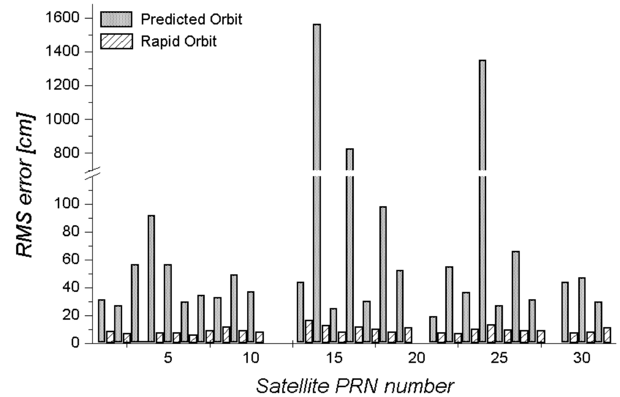


**Figure 9. RMS errors for rapid and predicted orbits.**

From figure 9 badly predicted satellites can be detected because of their large RMS errors. In this case these are the satellites GPS-14, GPS-16 and GPS-24. These satellites were also marked in the orbit files as having a low accuracy. Therefore these satellites were deleted from the processing when using predicted orbits. However, when orbit relaxation is used these satellites may still be used, as the orbit is corrected during the processing. This results in a larger amount of available data, which could lead to higher stability during the processing.

From figure 10 it can be seen that the overall accuracy of the rapid orbits is well within the 20 cm, although at the end of the day the accuracy is about half of the accuracy during the rest of the day. This could explain in part the jumps we have seen at the day-breaks, especially since the values in figure 10 are averages, and the accuracy at the end of the day for the different satellites ranges from 8-60 cm. Figure 10 also shows that the accuracy of the predicted orbits is about 10/20 times lower than the rapid orbits and clearly rises with the time of day. This is to be expected as the prediction comes further from the initial state. Comparing the predicted with rapid orbit accuracy, it will be clear that rapid orbits give better results than predicted orbits without using orbit relaxation.

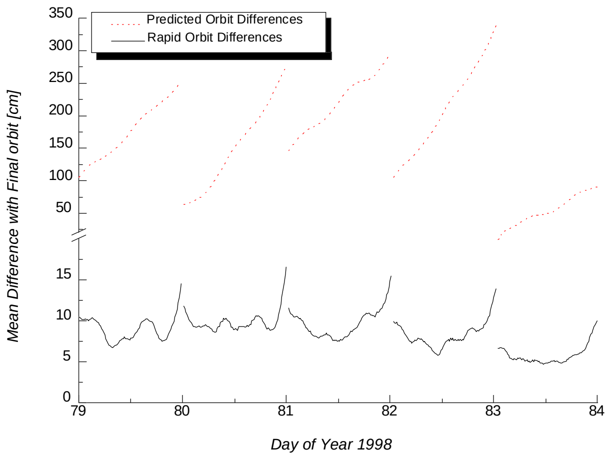


**Figure 10. Overall RMS error for predicted and rapid orbits.**

## CONCLUSIONS AND DISCUSSION

The experiments have shown that it is possible to perform real-time water vapor estimation using GPS without being dependent on the availability of accurate a priori orbits when using orbit relaxation. Comparing the GPS estimated IWV with values derived from the WVR shows an agreement of about 2 kg/m$^2$. The major part of the difference is most likely caused by mis-calibration of the radiometer, therefore it can be assumed that GPS is capable of an accuracy of about 0,5-0,7 kg/m$^2$ of IWV in real-time processing, provided that the GPS data is not biased. To realize this goal in an operational system the availability of the GPS data at the processing centers within a short time period after acquisition will be necessary.

Initial results from this experiment are very encouraging for performing real-time estimation, but an extended data-set is required to further test and confirm the results that have been found.

## ACKNOWLEDGEMENTS

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