TOWARDS SEQUENTIAL WATER VAPOR PREDICTIONS BASED ON TIME SERIES OF GPS AND MERIS OBSERVATIONS.

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ABSTRACT

Water vapor is a main constituent of the Earth's atmosphere. In order to obtain optimal monitoring results, water vapor observations from different sensors can be combined. Complementary Integrated Water Vapor (IWV) observations are available with high temporal resolution from GPS ground stations and with high spatial distribution from the MERIS spectrometer on board of the ENVISAT satellite. The gain in combining data from different sensors can be quantified by determining the average decrease in error variance. As a main preparation for an actual combination of one month of IWV observations, more than twenty consecutive MERIS scenes are compared to times series of hourly GPS IWV observations during one month from forty GPS ground stations, mainly situated in The Netherlands and Belgium. The final goal is to obtain a reliable near real-time water vapor product of high spatio-temporal resolution.

Key words: water vapor; GPS; MERIS; spatio-temporal; data fusion; accuracy.

1. INTRODUCTION

Water vapor is the atmosphere's dominant greenhouse gas, but it is difficult to determine its spatial-temporal distribution with contemporary meteorological instruments. It is however possible to retrieve water vapor content from two complementary types of satellite systems. At ground stations from the world wide Global Positioning System (GPS), the zenith Integrated Water Vapor (IWV) is derived from estimates of GPS signal travel time delay in the troposphere, (Bevis et al., 1992). This derivation results in relative good measurements with high temporal, 1 hour and less, but low spatial resolution, e.g tenths of kilometers over Western Europe. GPS IWV observations are available under all weather conditions. The Medium Resolution Imaging Spectrometer (MERIS) on the Envisat satellite retrieves integrated water vapor by comparing radiances in two spectral bands in the near infrared, with a maximum spatial resolution of 300 m, (Bennartz and Fischer, 2001). It's temporal resolution is restricted to 3 days. Moreover, MERIS only provides useful IWV observations under clear sky conditions.

The topic of this paper is twofold: on one hand a comparison is described between one month of MERIS and GPS based IWV observations, on the other hand we propose a data fusion approach that will allow for estimating a one month long time series of hourly IWV estimates at 10 km spatial resolution. The region of interest covers The Netherlands and a large part of Belgium.

For the data comparison and combination, GPS IWV estimates of 39 ground stations in the region of interest will be used, see Fig. 1. These IWV estimates, available at at least hourly intervals, were processed by the KNMI (Royal Dutch Meteorological Institute). The MERIS data product used here is MER_RRC_2P, the so-called Level 2 Reduced Resolution Cloud and Water vapor product with a spatial resolution of about 1 km^2, (ESA, 2006). There are more than 20 MER_RRC_2P scenes available from April 2006 that have at least a partial overlap with the region of interest. In Figure 1 the IWV and the optical cloud thickness is visualized for one such MERIS scene.

For a first data combination, MERIS and GPS IWV observations of one day only were combined using a collocated spatio-temporal Kriging approach, (Lindenbergh et al., 2007). This approach can be used to obtain an optimal IWV estimation at a given time and location as a linear combination of nearby GPS- and MERIS-based observations. Except for the estimations itself, this method also provides an individual variance value for each observation. These variance values give insight in the quality of each estimation in the final data fusion product but can also be used to quantify the additional value of adding e.g. MERIS observations to the GPS observations.

The outcoming variances values depend on two factors. First, they depend on the incoming variances, that is, the quality description of the GPS and MERIS observations used in the data fusion process. Second, the outcoming variance depend on both the spatial and temporal correlation or covariance between the different observations. Therefore it is essential to obtain insight in the mutual consistency of the GPS and MERIS IWV observations.

Moreover, it should be analyzed what is needed to identify and consecutively remove outlying observations.

This research will be a next step towards a near real-time integrated water vapor product. Once this product is available, it can be used as extra input for e.g. numerical weather prediction models but it will also serve to reduce the uncertainty in geodetic positioning applications using GPS and radar interferometry, Li et al. (2006).

In Section 2 it is outlined how IWV is derived at GPS ground stations and from the MERIS sensor. The method to combine both type of observations while incorporating their uncertainty, and how this uncertainty propagates in a final product accuracy is discussed in Section 2 as well. In Section 3 one month of IWV observations, both MERIS and GPS based, is compared. The paper finishes with conclusions.

2. METHODOLOGY

In this section it is shortly described how integrated water vapor estimates are obtained at GPS ground stations on one hand and by the MERIS spectrometer on the other hand. Then methods for comparing and combining estimates from both systems is described.

2.1. IWV from GPS

In the nineties a technique to measure integrated water vapor (IWV) has been developed, Bevis et al. (1992), based on the estimation of the tropospheric delay time of GPS signals. The delay, regarded as a nuisance parameter by geodesists, can be directly related to the amount of water vapor in the atmosphere, and hence is a product of considerable value for meteorologists. Furthermore, ground based GPS is not affected by rain fall and clouds, and is therefore an 'all-weather' system. It takes minor effort to obtain GPS water vapor estimates from existing GPS infrastructure, as follows. In GPS networks the so-called zenith total delay (ZTD) is estimated along with other parameters. The known relation between slant and vertical delays is used to infer ZTD from observed delays. After the ZHD (hydrostatic delay), which is obtained from the surface pressure, the zenith wet delay (ZWD) is obtained. The integrated water vapor (IWV) can be inverted from the ZWD and the mean temperature of the atmosphere. The typical accuracy of the GPS IWV is 1-2 kg/m^2. For more information see Elgered et al. (2005).

2.2. IWV from MERIS

The Medium Resolution Imaging Spectrometer (MERIS) is a push-broom imaging spectrometer with a maximum spatial resolution of 300 m. MERIS makes part of the payload of the Envisat satellite, that was launched in 2002. Envisat flies in a sun-synchronous polar orbit of about 800-km altitude. For most sensors, including MERIS, it provides a complete coverage of the globe within one to three days. MERIS measures the solar radiation reflected by the Earth in 15 spectral bands. Integrated Water Vapor values are obtained by a differential absorption method from the radiances measured in the two bands centered around 885 and 900 nm resp. Because stronger absorption over water occurs, different methods are required over land and water, Bennartz and Fischer (2001). MERIS also retrieves cloud type and cloud top height. The theoretical accuracy of the estimated water vapor column is 1.7 kg/m2 over land and 2.6 kg/m2 over water at full resolution. The IWV accuracy at the reduced resolution of 1.04 km $\times$ 1.16 km is specified to be at most 20 % of the IWV estimation.

2.3. Method of comparison

To assess the consistency of the GPS and MERIS IWV estimates, the MERIS pixel values in the direct neighborhood of a GPS ground station are compared to the corresponding IWV estimate at that station. That is, for a given MERIS scene and a given GPS ground station, all MERIS pixels in a radius of 1.5 km^2 around that GPS station location are determined. If all MERIS pixels are available, this results in about seven MERIS pixels per ground station. Then the average of the MERIS pixel values is compared to the GPS IWV estimate at the first whole hour after the acquisition time of the MERIS scene. In a previous comparison, (Lindenbergh et al., 2007), applying this value of the radius turned out to give an optimal match between MERIS and GPS IWV estimates. The GPS IWV estimate at the whole hour after MERIS acquisition time is taken, because the GPS observation in fact represents a time averaged estimate of the amount of water vapor above the station.

2.4. Spatio-temporal combination

The MERIS IWV observations have a high spatial resolution, but at a given location less than one observation a day is available. On the other hand, the GPS IWV observations are spatially sparse but are available at every whole hour. We show how to estimate IWV values at the whole hours for pixels of the same size as the MERIS reduced resolution pixel. The estimation is obtained as a linear combination of all available GPS IWV observations at that moment and of the most recent MERIS observation for that pixel. The weights for each observation involved is obtained from the solution of a system of linear equations. The coefficients of the equations are obtained from a spatio-temporal covariance function that characterizes the average variability in water vapor signal as a function of both space and time. The variability at zero distance is the variance and expresses the accuracy of individual observations. The more far an observation

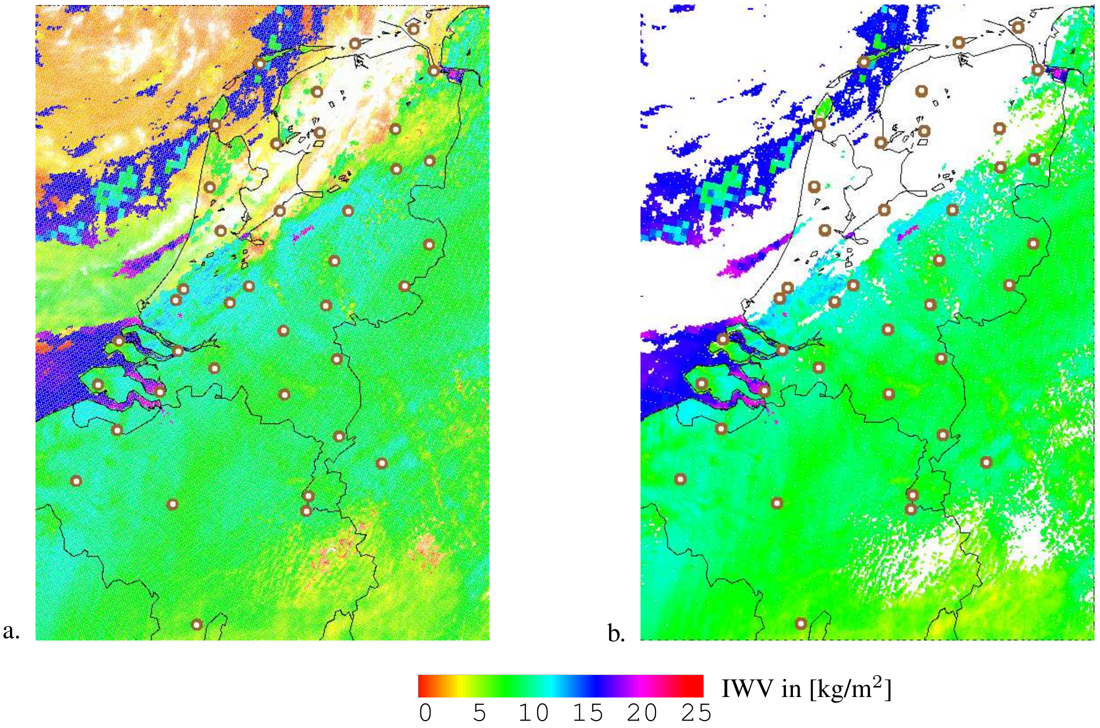

Figure 1. MERIS IWV data from April 28, 2006. a.) Before filtering. Higher optical cloud thickness is indicated by a lower saturation. b.) After filtering. The location of the 39 GPS ground stations is indicated by brown dots.

is away relative to the other available observations, either in time or in space, the less weight such observation will get.

Except for the IWV estimation itself, also a variance of the estimation is obtained, that expresses the propagated uncertainty of the individual observations and the correlation between the observations. Basically, the variance expresses the proximity, both in space and time, of the observations to the estimation point. It is minimal at the GPS IWV observation locations and at MERIS acquisition times and increases with increasing distance, in space and time, between the estimation location and observation locations until no correlation with any of the observations remains, (Goovaerts, 1997; Lindenbergh et al., 2007).

2.5. Quantifying additional value of observations

The variances of the spatio-temporal interpolated IWV estimates can be used to quantify the impact of for example adding the MERIS IWV estimates to the GPS IWV estimates. For this purpose first the GPS IWV estimates only are interpolated to a suitable grid, resulting in a IWV estimate and an error variance for every grid point. Next, the combined estimation based on both the GPS and MERIS IWV observation is determined for the same grid and this gives again a grid point wise error variance. The latter variance is never higher than the former one, as information is added to the system. The average decrease in variance gives a numerical indication of the gain. In case perfect measurements were available at every grid point and every estimation time, the variance would be zero and maximal gain would be achieved.

3. COMPARING GPS AND MERIS IWV

In this section available IWV observations are described. This research focuses on a Region Of Interest, ROI, between 3° and 7.5° longitude and 50° and 53.7° latitude, covering The Netherlands and a large part of Belgium, cf. Fig. 1. This region is chosen because here a dense network of KNMI processed ground stations is positioned. Such a configuration is typical for e.g. the main land of Western Europe, Elgered et al. (2005), but such station densities are rare in the rest of the World. In Section 3.1 first the GPS based observations are introduced, followed by the MERIS observations in Section 3.2. In Section 3.3 IWV estimates from both systems are compared.

3.1. GPS IWV estimates

Time series for April 2006 of integrated water vapor estimates are used from the 39 GPS ground stations as processed by the KNMI in the region of interest. The position of the ground stations is visualized in Fig. 1. Each station is identified by a 4-letter acronym, see Fig. 3.c for the location of each station. In total a number of 25 000 GPS IWV observations is available for the region and period of interest. Except for some missing data, one GPS IWV estimate is given at each whole hour at every station. Two examples of such GPS IWV time series are shown in Fig. 2. In green the estimates at DELF are given, in red the estimates at ZOET. The distance between these two ground stations is only 11 km. In brown the difference in GPS IWV estimation is given. It is striking that the estimation at the DELF station is always higher than at ZOET. The mean difference is +1.55 kg/m^2, the minimum difference equals +0.20 kg/m^2 and the maximum +3.40 kg/m^2. A similar bias is found when comparing the observations of the stations of EIJS and MSTR that are at a distance of 10 km of each other. The mean difference here is +1.47 kg/m^2 with a st.dev. of 0.46 kg/m^2.

These systematic deviations are a well-known phenomenon in GPS based IWV estimation. Reasons can be found in in the antenna calibration or in near field effects, that is, the influence of the direct surroundings of the GPS antenna on the estimates, Elgered et al. (2005). A solution has to be found for coping with these biases when incorporating the GPS IWV observations in the data fusion method. One solution could be to estimate a constant correction value for a bias as shown in Fig. 2 from comparison with the MERIS IWV observations. As the MERIS observations are more sparse in the temporal domain, this approach will only give acceptable results when sufficient MERIS scenes are available.

3.2. MERIS IWV estimates

Twenty-one MERIS scenes were found that have non-empty intersection with the ROI in April 2006. Probably a few additional scenes exist, but these are not available to the authors. The ROI has a size of 127 500 km^2, corresponding to 106 000 MERIS reduced resolution pixels of 1.2 km × 1.2 km. Some MERIS scenes have only partial overlap with the ROI while many MERIS pixels are removed in a pre-processing step because quality flags indicate uncertain total water vapor contents or cloudy conditions. An overview of the scenes is given in Table 1. The numbers in this table show that many potential MERIS estimates are lost, mainly because of cloud cover: in total about half of the data had to be removed. This is also illustrated in Fig. 1. In Fig. 1.a the raw data are shown. Cloudy pixels are given a higher saturation. Note that cloudy pixels mostly have lower values than 'good' estimates, because the integrated water vapor can only be determined to the top side of the cloud cover. In Fig. 1.b the same scene is given after the filtering step. Many discontinuities in the water vapor field are removed, but especially near the coast jumps are still visible. These are either due to physical properties or to the use of different algorithms over land and water, (Bennartz and Fischer, 2001; Lindenbergh et al., 2007). The amount of cloud cover in April 2006 was probably quite normal. The KNMI reports 161 hours of sunshine at its headquarters in the middle of the Netherlands, compared to 158 hours on average for April, KNMI (2006). 161 hours corresponds to 39 % of maximal sunshine duration.

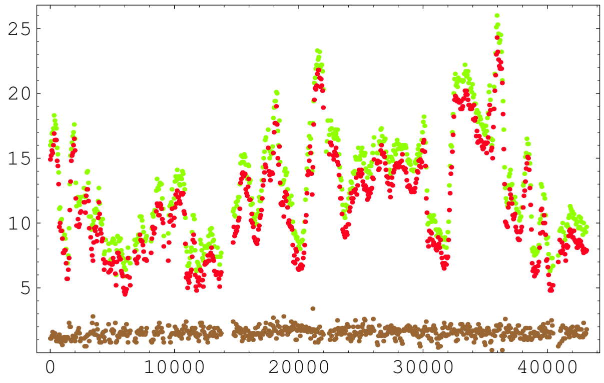

Figure 2. GPS IWV estimates at ground stations DELF, green, and ZOET, red. In brown the difference in estimation is given.

3.3. MERIS-GPS comparison

Spatio-temporal intersection of the GPS IWV time series with the MERIS scenes listed in Table 1 results in 386 pairs of comparable GPS-MERIS IWV estimates. The final comparison of estimation is performed as described in Section 2.3. In Fig. 3.b the histogram of the differences between the MERIS and GPS estimates at the same

April	Time	Filtering		
		before	after	left
1	10:43	72 886	27 825	38 %
2	10:12	103 899	32 906	32 %
3	9:40	57 444	7 719	13 %
4	10:49	39 840	31 545	79 %
5	10:17	103 745	66 984	65 %
9	9:51	104 645	69 602	67 %
10	11:00	125	125	100 %
11	10:28	103 501	37 362	36 %
12	10:05	104 409	34 946	33 %
14	10:42	102 628	55 775	54 %
15	10:11	104 181	23 967	23 %
16	9:39	7 820	0	0 %
17	10:48	87 148	53 323	61 %
18	10:16	103 993	33 293	32 %
21	10:22	103 820	57 517	55 %
23	11:00	23 340	0	0 %
24	10:28	103 678	53 411	52 %
25	9:56	103 101	79 308	77 %
27	10:34	103 565	60 419	58 %
28	10:02	104 526	69 217	66 %
30	10:39	103 454	34 492	33 %
Total		1 741 748	829 736	47.6 %

Table 1. Overview MERIS scenes. Number of pixels in ROI is indicated before and after filtering.

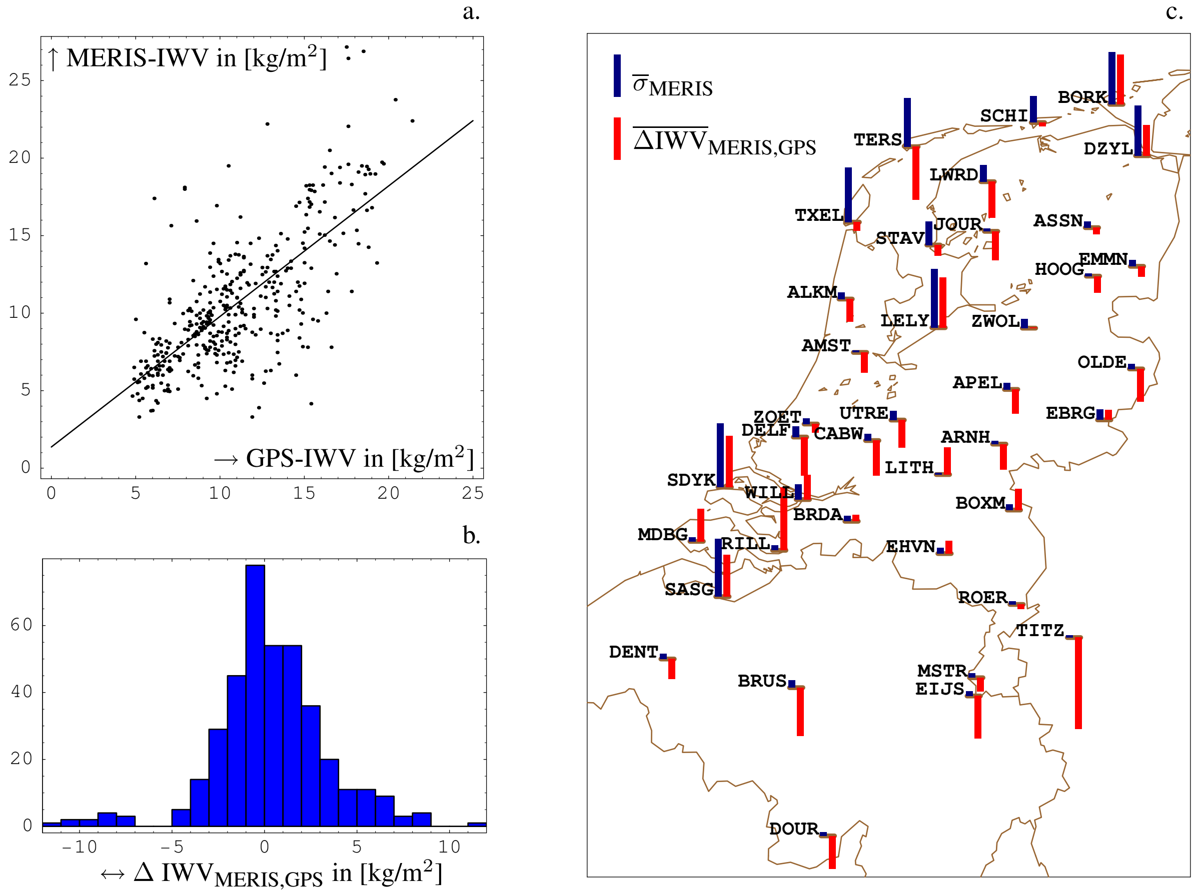

Figure 3. **a.** *Scatterplot of 386 pairs of GPS-MERIS IWV observations.* **b.** *Histogram of the differences in GPS and MERIS IWV observations.* **c.** *Relative variance of MERIS IWV estimates in blue and relative difference with GPS IWV estimates per GPS ground station.*

time and location is shown. The mean difference equals 0.36 kg/m^2. The root mean square difference between the GPS estimates and the mean of the MERIS pixels within 1.75 km radius equals 3.06 kg/m^2. In Fig. 3.a the scatterplot of differences is given, together with best fitted line in the least squares sense. The bias or vertical offset of the best fitted line equals +1.36 kg/m^2. That is, on average the MERIS IWV estimates are higher than the GPS estimates. A reason for this phenomenon is not known.

Maximal differences.

In fourteen cases the difference between MERIS and GPS IWV estimation exceeds 8 kg/m^2. In nine of these cases the MERIS estimation can be considered less reliable: either large jumps occur between 8 and 18 kg/m^2 between the MERIS pixels used for the comparison, or only one or two MERIS pixels were available for comparison at all. The latter case indicates that nearby pixels are removed in the filtering procedure, as described in Section 3.2. In the remaining five cases there are several MERIS pixels available for the comparison with consistent but completely different values when compared to the GPS based estimations. These five cases occur all in different MERIS scenes and at different ground stations and need further investigation.

Differences per station.

On average, ten common MERIS-GPS IWV estimates per ground station are available. For each ground station in the ROI at least seven common estimates were found, with a maximum of fifteen. The results of a comparison per ground station are shown in Fig. 3.c. At each station two bars are drawn. For each GPS-MERIS comparison, all MERIS pixels within 1.5 km of the ground station location are used. The variance σ_{MERIS} of a MERIS estimate at a station at a given time is the variance in IWV value of these pixels. The left or blue bars in Fig. 3.c indicate the relative size of the average $\overline{\sigma}_{\text{MERIS}}$ of these MERIS variances over all MERIS scenes. A high bar indicates a high variability in the MERIS pixel values in the direct neighborhood of a ground station. Most coastal stations, e.g. SDYK, TXEL, TERS, BORK and DZYL display a large average variance, in the order of 7 to 9 (kg/m^2)^2. This is in accordance with the one

MERIS scene in Fig. 1.b where a clear change in IWV at the coast, especially in the South-West is visible. These coastal jumps were discussed in Section 3.2 as well.

The right or red bars in Fig. 3.c indicate the mean difference between the MERIS estimate and the GPS estimate. The largest value occurs at TITZ, in the South-East of the ROI. Here the GPS estimate is on average 3.91 kg/m^2 larger than the MERIS estimate. At ZOET the GPS IWV estimation is on average 0.38 kg/m^2 larger, at the nearby station of DELF the GPS IWV estimation is 1.64 kg/m^2 larger. The difference of +1.22 kg/m^2 is within the st.dev of the mean difference in GPS IWV estimates at both stations of +1.55 kg/m^2, compare Section 3.1. Similarly, the mean difference of +1.47 kg/m^2 in GPS IWV estimates between EIJS and MSTR is comparable to the difference between MERIS and GPS comparisons at EIJS (-1.81 kg/m^2) and at MSTR (-0.60 kg/m^2).

This analysis shows that one explanation for the differences in GPS and MERIS estimates can be found in systematic offsets in GPS IWV estimates. Comparison with longer time series can enhance this type of conclusions. Another explanation is again found in high variability in MERIS pixel values in the vicinity of a GPS ground station. As can be seen in Fig. 3.c large discrepancies sometimes occur at coastal stations. These discrepancies look more random however.

4. CONCLUSIONS AND FURTHER STEPS

In this paper a method is sketched for deriving one month of both high spatial and high temporal resolution IWV estimates by combining IWV observations from GPS ground stations and from MERIS spectrometric satellite images. This method incorporates the uncertainty in the observations and delivers, except for the IWV estimation itself, also an uncertainty value of this estimation.

This uncertainty value cannot only be used to describe the quality of the derived combined product, but can also be used to directly quantify the gain that is achieved by adding observations from an additional sensor.

An important part of this paper consists of an consistency check between MERIS and GPS IWV observations. Consistency exists, but is not completely satisfactory. By comparing observations from close by GPS stations, biases between GPS estimates can be observed. These biases are confirmed by comparisons with the MERIS observations as well. Therefore it seems feasible to correct GPS ground station biases after estimating them from a comparison to MERIS IWV observations. Before such correction is applied the spread of the station wise differences between GPS and MERIS IWV should be considered as well.

There are two types of problems with the MERIS observations that are known and were once confirmed here: jumps in neighboring pixel values in coastal areas and large loss of MERIS observations because of cloud cover. The research presented here is part of an ongoing project on combining MERIS and GPS IWV observations. The next step is to actually compute hourly time series of IWV at high spatial resolution over the region of interest as described here. Because of the large loss of MERIS pixels it is recommended however to add at least an additional month of observations to this combination step, in order to obtain more extensive statistics.

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