InSAR based validation of MERIS IWV cloud gap filling using GPS IWV

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ABSTRACT

High spatial resolution integrated water vapor (IWV) estimates are available from the MERIS spectrometer on board of Envisat. Unfortunately cloud cover results in loss of a large amount of MERIS IWV pixels. Here methods are presented for filling cloud gaps in MERIS IWV scenes, first, by directly interpolating remaining pixels not affected by clouds, and second, by fusion with cloud insensitive IWV observations from ground stations of the GPS network. Results are validated by independent IWV estimates obtained from suited SAR interferograms. The results indicate that the procedure works mathematically in a correct way, but that the physical application of the results is strongly hampered by MERIS pixels affected by not automatically detected clouds.

1. INTRODUCTION

Water vapor is the atmospheres dominant greenhouse gas, and is an important error component for remote sensing applications like global positioning and InSAR based deformation analysis. Still it is a challenge to obtain reliable, all weather estimates at spatial resolutions in the order of a few kilometer from one single type of contemporary meteorological instrument. It is possible however to retrieve and consecutively combine water vapor estimates from complementary satellite systems. The MERIS spectrometer on board of the Envisat satellite obtains Integrated Water Vapor (IWV) estimates in swaths of 1150 km at unprecedented spatial resolutions of up to 300m, [3]. As Envisat also carries the ASAR instrument, [4] and is only separated by 30 minutes from the ERS-2 SAR instrument, MERIS IWV has potential to assess the impact of water vapor on both ERS-2 and ASAR data. Unfortunately, MERIS only gives reliable IWV estimates under clear sky conditions, [1]. For a country as The Netherlands, this implies that more than 50 percent of the MERIS IWV pixels is lost. To correct for this loss it is proposed to fill gaps in MERIS IWV scenes using GPS IWV observations, that are not affected by cloud cover and are available from GPS ground stations, [2].

Cloud gaps will be filled using two types of information: I) by MERIS IWV observations from around the cloud gaps, and II) by co-temporal GPS IWV observations, available from ground stations with inter station distances in the order of tenths of kilometers. First observations from each type will be interpolated to the same grid using a geostatistical method that not only provides an IWV estimate at each grid point, but also a variance value. In the second step these variance values will be exploited to obtain for each pixel a weighted mean between the GPS based and MERIS based IWV estimate at that pixel location.

To validate the quality of the filled pixels, a completely independent data source is used. Coherent SAR images allow the estimation of high quality, high resolution water vapor interferogram data, [7]. The validation procedure will not only be used to assess the new filling approach, but also special attention will be paid to the method of cloud masking, as this is expected to have high impact on the quality of the final repaired MERIS IWV scenes.

The rest of this paper is organised as follows. In Section 2 the method for combining co-temporal GPS and MERIS IWV is explained, in Section 3 it is explained how results can be validated using InSAR IWV, while the results itself are presented in Section 4, before arriving at conclusions.

2. COMBINING MERIS AND GPS IWV

The combination of MERIS and GPS IWV is done at the time of acquisition of a MERIS scene. From the MERIS scene, all pixel locations within the region of interest are stored. GPS IWV observed at stations within the region of interest is interpolated to these pixel locations. From the MERIS IWV, ideally all pixel values are removed that are affected by clouds. A MERIS based estimate of the IWV at the location of the cloudy pixels is obtained by interpolation from the non-cloudy pixels. Finally, a weighted mean of the interpolated MERIS and GPS IWV is taken to obtain a combined IWV map.

2.1. Interpolating GPS IWV

GPS IWV from the available stations within the region of interest is interpolated by Ordinary Kriging, [10]. For this purpose first an experimental covariance function is estimated. The resulting covariance function is applied in the Kriging procedure to divide weights over the available station observations. Except for an interpolated value, also a Kriging variance value is obtained at each pixel location. The value of the variance at a certain pixel location depends on the distances of the pixel to the observations and to the correlation between the observations. The result of such a GPS IWV interpolation is shown in Fig. 2.C.

In this case Ordinary Kriging is computational feasible as the number of observations equals the number of GPS stations and is therefore limited to at most a few dozens. From the station observations, only once a VC-matrix is built that is applied in the interpolation for each pixel. Additionally for each pixel the so-called proximity vector is built containing the covariances between the pixel location and each of the observations.

2.2. Filtering and interpolating MERIS IWV

From the MERIS scene, cloudy pixels are removed based on the information in the MERIS product, although it is known that the built-in MERIS cloud detection procedure is in general not capable to detect all affected pixels, e.g. [5]. Based on the product information, all pixels are removed with either a positive cloud optical thickness, or with a 'True' CLOUD flag, a PCD_14 flag, or TOAVI_CSI flag value, [3].

If performed for a scene from a cloudy day, the cloud removal procedure will result in an image with many gaps, like the one in Fig. 2.A. Still the number of remaining pixels will in general be quite large, in the order of tenths of thousand, depending on size and resolution of the MERIS scene. As a consequence it may not be feasible to use all remaining pixels simultaneously in a Kriging procedure. In order to still be able to produce at each pixel an interpolated MERIS IWV estimate plus variance, we need a fast method for determining for each empty pixel a small set of relevant valid MERIS IWV pixels to be used as input for a local Kriging interpolation.

As a solution we propose to use Natural Neighbor Kriging. For each empty pixel, first the natural neighbors of the Voronoi cell of the pixel location in the Voronoi Diagram of the valid MERIS IWV pixel locations plus the location at hand are determined, [8]. Then Ordinary Kriging is applied on the valid MERIS IWV pixels that are natural neighbor of the empty pixel. This procedure is illustrated in Fig. 1.

The empty pixel location is indicated in red. The image shows the Voronoi diagram of the green points (valid MERIS pixels) and the red point. The natural neighbours of the red points are the pixels

$$23, 27, 36, 37, 18, 10$$

From Fig. 1 it is not clear if pixel 17 is also a natural neighbor. The main idea is that valid pixels that do not
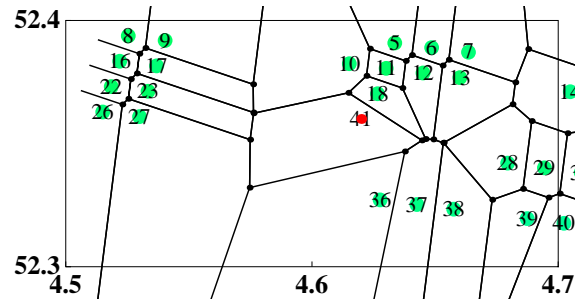

Figure 1. Voronoi diagram of non-cloudy pixels (green) and pixel location (red).

belong to the natural neighbors would hardly contribute anyway to an interpolated value If this holds in Fig. 1 for pixel 9 for example should still be validated. For filling all the empty pixels, only once the Voronoi diagram of the valid pixels needs to be computed. Additionally a covariance function is obtained once from an experimental analysis. The natural neighbor pixels of each empty pixel are used to estimate an IWV value and its variance for the empty pixel location.

2.3. Fusing interpolated MERIS and GPS IWV

The previous steps result for each pixel location into two IWV estimates (1 MERIS, 1 GPS) plus variances. These estimates are simply combined in an adjustment procedure, [9], that takes the mean of the two estimates relative to their variance values.

3. VALIDATION USING INSAR IWV

The observed interferometric phase Φ is typically decomposed as:

$$\Phi = \Phi_T + \Phi_D + \Phi_A + \Phi_E \qquad (1)$$

where Φ_T is the phase term due to surface topography, Φ_D accounts for surface deformation within the interval between satellite acquisitions, Φ_A the phase variation due to atmospheric disturbance and Φ_E a term accounting for unmodeled orbit errors, Earth curvature and different types of observation noise.

In our study, topographic phase Φ_T is modeled and subtracted using the 3-arc SRTM DEM. SAR images used in this study were required within a short period (35 days) and the deformation rate in the area of interest is expected less than 1 cm/year. Φ_D is therefore neglected. After noise suppression the phase spatial resolution is reduced to 1 km. Therefore, the unwrapped phase only represents the spatial and temporal variation of water vapor in the lower part ($\sim < 2$km) of the Earth's troposphere.

Unlike GPS or MERIS IWV measurements, InSAR only 'observes' IWV temporal differences with respect to a chosen reference pixel. The wrapped phase nature of interferograms results in the phases of all pixels in an interferogram being shifted with a constant value after
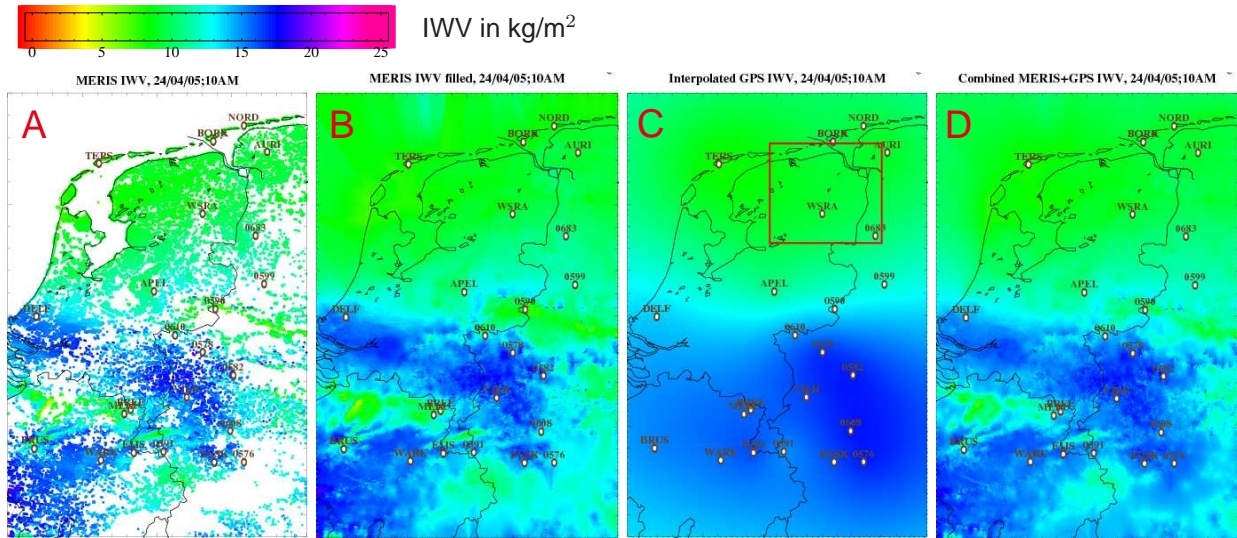
Figure 2. IWV estimates for April 24, 2005, 10.00 AM. A) MERIS IWV after removal of cloudy pixels according to MERIS product. B) Cloud gaps in MERIS IWV have been filled using natural neighbor Kriging. C) GPS IWV from the indicated stations interpolated by Ordinary Kriging. D) Mean of B) and C), weighted according to pixel wise variances.
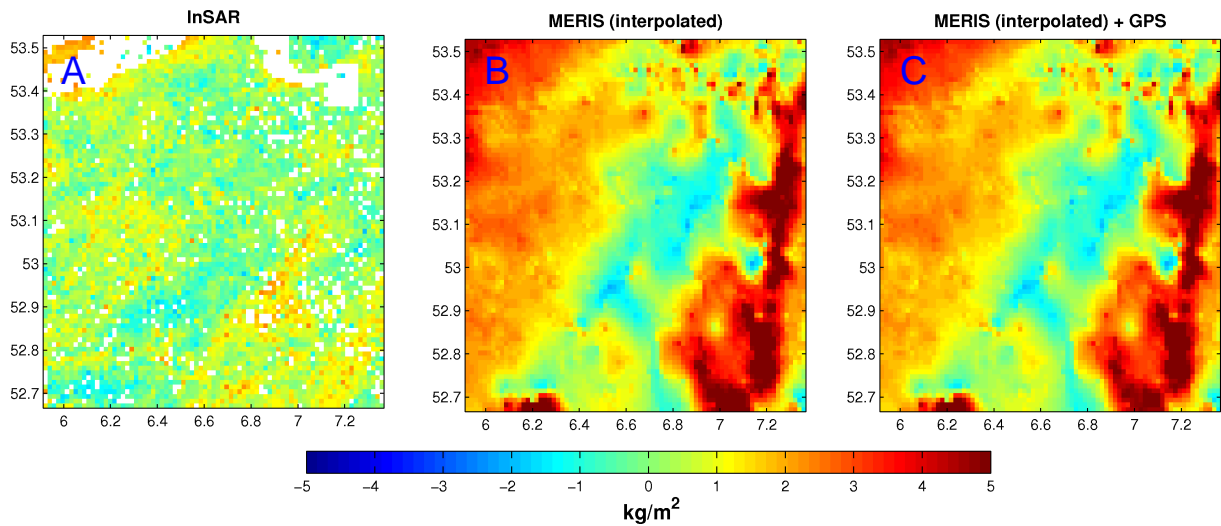

Figure 3. Validation results for the IWV double differences for the area indicated in Fig. 2.C. A) IWV double differences derived from SAR interferogram combining the April 24 and May 29 acquisitions. B) IWV double differences derived from the filled MERIS maps of April 24 and May 29, C) IWV double differences derived from the combined GPS + MERIS maps of April 24 and May 29.

phase unwrapping, [6], and it is not possible to estimate this phase shift from the interferogram itself. Therefore, neither GPS nor MERIS can be compared with InSAR in the pixel-wise sense. However, the spatial phase difference between two pixels is not biased. This phase difference is sometimes called double differential phase. For the filled GPS, MERIS and combined GPS and MERIS IWV maps, we first take the pixel wise difference in IWV value between the two maps in the map pair to be validated. Then we shift the value of the temporal difference at each pixel by a constant equal to the dif-

ference between the unwrapped interferogram and the differenced IWV at a certain pixel (e.g. centre pixel).

4. RESULTS

4.1. Data description

For this research MERIS reduced resolution scenes from 24/4/2005 and 29/05/2005 were used, acquired at 10 AM over The Netherlands. In Fig. 2.A MERIS IWV is plotted after removal of cloudy pixels as indicated in the MERIS product. GPS IWV from the same two moments

is available at 23 GPS ground stations visible in e.g. Fig. 2.C. All GPS IWV has been processed by GFZ, except for the stations of MEEU and BREE, that were processed by ROB. For the purpose of validation, Envisat SAR images of track 380, acquired simultaneously with the MERIS images were processed to an interferogram.

4.2. Visual results

In Fig. 2.A it can be seen that also after cloud filtering, patches with a suspicious low IWV value remain, for example just above the station BRUS. These patches are even more clear in the filled MERIS IWV map, Fig. 2.B. In general, the filled map gives details when many unfiltered pixels where present, e.g. in the blue band in the middle, while the map smooths out, as it should, far away from available pixels, like in the North. In Fig. 2.C the interpolated GPS IWV is shown. In general, the trend is the same as for the filled MERIS IWV map, but the comparison confirms that the remaining MERIS IWV in the south is of bad quality. The influence of the outlying patches in the filled MERIS IWV map is tempered in Fig. 2.D after averaging (relative to the variance) with the GPS IWV map. Notice however, that MERIS pixels affected by undetected clouds still have a low variance (no interpolation) and will therefore not be tempered much by GPS IWV.

4.3. Validation using InSAR △ IWV

The filling and combination results for two epochs were validated against IWV double differences obtained from an InSAR interferogram of the same epochs, see Fig. 3.A. In Fig 3.B the IWV double differences derived from the filled MERIS IWV maps are shown. The big dark red feature on the right is corresponding to a patch of MERIS IWV pixels affected by undetected clouds in the scene of May 29. The remaining of the image shows reasonable agreement with Fig. 3.A. Adding GPS IWV, Fig. 3.C. is not visually changing the results.

These findings are confirmed by the numeric results shown in Table 1. IWV double differences obtained from InSAR and GPS match well, but it should be noted that taking double differences implies that a linear trend in IWV is removed. The IWV double differences from filled MERIS deviate stronger from the InSAR double differences, probably because of the undetected cloudy patch. This would also explain why averaging with GPS gives only limited improvement.

5. CONCLUSIONS AND RECOMMENDATIONS

A procedure has been developed to fill gaps due to cloud cover in MERIS IWV scenes. Although the results of the mathematical procedure itself are satisfying, the physical correctness of the results is strongly degraded by MERIS IWV pixels affected by undetected clouds. As such, current results are considered of insufficient quality to be applied in InSAR processing

The results suggest that in case a MERIS scene is partly affected by clouds, interpolated GPS IWV could

Table 1. Validation w.r.t. double difference InSAR

unit: kg/m^2	InSAR - filled GPS	InSAR - filled MERIS	InSAR - filled GPS + MERIS
median	0.22	-1.24	-1.15
st.dev.	0.71	1.55	1.53

be applied to some extent to test whether individual MERIS IWV pixels are unaffected by clouds in a testing procedure, incorporating the interpolation variance of the GPS IWV. Test results could again be validated by means of independent IWV double differences as derived from InSAR.

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REFERENCES

[1] R. Bennartz and J. Fischer. Retrieval of columnar water vapour over land from back-scattered solar radiation using the Medium Resolution Imaging Spectrometer (MERIS). *Remote Sensing of Environment*, 78:271–280, 2001.

[2] G. Elgered. An overview of COST Action 716: Exploitation of ground-based GPS for climate and numerical weather prediction applications. *Phys. Chem. Earth.*, 26A:399–404, 2001.

[3] ESA. MERIS Product Handbook, Issue 2.1, 2006. http://envisat.esa.int/dataproducts/meris/, last visited: September 19, 2008.

[4] ESA. ASAR Product Handbook, Issue 2.2, 2007. http://envisat.esa.int/handbooks/asar/, last visited: August 20, 2009.

[5] L. Gomez-Chova, G. Camps-Valls, J. Calpe-Maravilla, L. Guanter, and J. Moreno. Cloud-screening algorithm for ENVISAT/MERIS multi-spectral images. *IEEE Trans. on Geoscience and Rem. Sensing*, 45(13):4105 – 4118, 2007.

[6] R. F. Hanssen. *Radar Interferometry*. Kluwer Academic Publishers, Dordrecht, 2001.

[7] R. F. Hanssen, T. M. Weckwerth, H. A. Zebker, and R. Klees. High-Resolution Water Vapor Mapping from Interferometric Radar Measurements. *Science*, 283(5406):1297–1299, 1999.

[8] A. Okabe, B. Boots, K. Sugihara, and S. N. Chiu. *Spatial tessellations: Concepts and applications of Voronoi diagrams*. Wiley, NYC, 2nd edition, 2000.

[9] P. J. G. Teunissen. *Adjustment theory*. Delft University Press, Delft, 2000.

[10] H. Wackernagel. *Multivariate Geostatistics*. Springer, Berlin, third edition, 2003.