CROSS-VALIDATION OF MERIS AND ASAR-InSAR WATER VAPOR OBSERVATIONS

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ABSTRACT

During the ERS-1 and ERS-2 missions, the application of synthetic aperture radar interferometry (InSAR) become known as a very important method for topographic mapping and high accuracy surface displacement measurements. Further investigations, however, showed that the expected accuracy could not be achieved in practice. It appeared that radiowave propagation heterogeneities through the atmosphere cause significant distortion to the observed signal and consequently to the derived topography and/or deformation signal. Inversely, it was shown that if topography is known and deformation is absent, the InSAR observations can be used to derive very accurate information on the state of atmosphere at the time of measurements. Due to the co-existence of MERIS (Medium Resolution Imaging Spectrometer) and ASAR (advanced synthetic aperture radar) on board of ENVISAT and the fact that their acquisitions can be collocated both in time and space, there are unique opportunities for complementary analysis. In this work we compare MERIS water vapor products and the integrated precipitable water vapor as observed with ASAR. Three complementary applications of the sensors are discussed. First, this is the correction of the atmospheric phase screen in InSAR products using the MERIS-derived water vapor signal. Second, we discuss the possibility for validating the MERIS water vapor product using InSAR data. Finally, we comment on the joint estimation of water vapor above and below the top of the cloud layers.

1 INTRODUCTION

During the last years InSAR has been consolidated as a high accuracy technique for deformation monitoring and topographic mapping. Nevertheless, heterogeneities in the atmospheric refractivity, mainly water vapor, constitute a distortive element in the propagation of the electromagnetic wave in its path through the atmosphere. This introduces an additional delay signal, which we refer to as the atmospheric phase screen (APS). In order to obtain reliable and precise deformation maps or topographic models, it is essential to have a quantitative estimation of the effect produced on the interferometric phase.

It would be desirable to compensate interferograms for the atmospheric phase screen. This requires observations of the total integrated water vapor column, at a spatial resolution of 100-200 m, within a few minutes relative to the times of the SAR acquisitions, and with a high precision (~2 mm, or 0.03 g/cm²). Ground-based instruments, such as GPS or microwave radiometers have been used to account for the atmospheric effect, see e.g. [1], but these are only scarcely available and lack spatial resolution. Satellite-based imagery data does not fulfill the temporal coincidence requirement, does not observe full atmospheric column data, and is often too coarse spatially for a direct comparison. Moreover, passive meteorological sensors only operate during daytime. As a result, there is not yet any technique that fulfills all conditions to compensate for the unwanted atmospheric delay. The European satellite ENVISAT is in principle able to operate simultaneously a SAR instrument, ASAR (advanced synthetic aperture radar), and a medium resolution imaging spectrometer (MERIS). MERIS can obtain the precipitable water vapor integrated over an atmospheric column of 300 by 300 m. base resolution. However this is fulfilled only in the absence of clouds at the time of the acquisition. If clouds are present, MERIS will provide columnar water vapor products over the cloud tops [2]. As a result, a first complementary operation of ASAR and MERIS is to use the MERIS-derived water vapor distribution to correct for the APS in SAR interferometric products.

When topography is known and under the assumption that any deformation process within the time span of the two acquisitions is negligible the residual interferometric phase can directly be interpreted as high resolution.
(20 m) atmospheric signal. Using relatively short temporal baselines and simultaneous acquisitions from both instruments, independent maps of MERIS water vapor distribution could be directly used in comparison with SAR interferograms. This yields a second potential for the complementary use of the two instruments—the validation of the MERIS water vapor products using the SAR interferograms.

Although the direct comparison of both signals, as in the first two objectives, is only possible in cloud-free circumstances, it is also possible to interpret the differences to separate effects within and below the clouds and effects above the clouds. Such an application forms the third potential of complementary applications of both sensors. In this paper the three potential applications of using MERIS and ASAR data are discussed.

2 InSAR Atmospheric Signal

The interferometric combination of two radar images gives information on the state of the atmosphere at the time of the acquisitions. Although it is often an unwanted component of the total interferometric phase, it is essentially a very accurate representation. In this sense there have been several investigations to find a good description of the stochastic behaviour of the atmospheric delay [3, 4]. Others, based in ground instruments, have tried to improve the interpretation of InSAR observations [1].

The observed interferometric phase is a superposition of a number of contributions [3]:

\[ \Delta \Phi_{\text{obs}} = \Delta \Phi_{\text{geo}} + \Delta \Phi_{\text{scat}} + \Delta \Phi_{\text{prop}} \] (1)

where \( \Delta \Phi_{\text{geo}} \) accounts for the geometrical effects and \( \Delta \Phi_{\text{scat}} \) comprises all the scattering properties of the earth surface. The phase difference caused by the propagation effects, can in turn be decomposed as the superposition of an ionospheric and a tropospheric contribution to the phase delay. The contribution of the ionospheric part has only limited influence to the C-band interferometric phase variability and will be neglected here. On the other hand, three terms contribute to the tropospheric term:

\[ \Delta \Phi_{\text{tropo}} = \Delta \Phi_{\text{hydro}} + \Delta \Phi_{\text{wet}} + \Delta \Phi_{\text{liquid}} \] (2)

The hydrostatic component results in a long wave delay variation [5] and can be reduced by spatial detrending of the interferometric delay. The wet delay can be modeled as:

\[ \Delta \Phi_{\text{wet}} = \frac{10^{-6}}{\cos \theta} \int (k_2 \frac{e}{T} + k_3 \frac{e}{T^2}) \, dh \] (3)

where \( k_2 = 71.6 \text{K hPa}^{-1} \) and \( k_3 = 3.75 \times 10^5 \text{ K}^2 \text{ hPa}^{-1} \) [6], \( T \) the temperature in Kelvin degrees and \( e \) the partial pressure of water vapor in hPa. Even though for strong rain intensities the delay due to the scattering on liquid particles \( \Delta \Phi_{\text{liquid}} \) can be important, it is usually much smaller than the wet delay. The conclusion is that the variation in the concentration of the water vapor will be the main cause of the delay produced by the propagation contribution to the interferometric phase. MERIS supplies of this independent information.

3 MERIS

The Medium Resolution imaging spectrometer (MERIS) on board of ENVISAT measures the solar radiation reflected by the Earth at a ground spatial resolution of 300 m. The radiance ratio between the MERIS channels 15 (900 nm) and 14 (885 nm) can be used to retrieve the columnar water vapor under cloud-free conditions over land [7, 2, 8, 9]. On a global scale, the water vapor products can be generated with a spatial resolution of \( \sim 1 \text{ km} \), but it is possible to zoom into areas with full resolution (300 m).
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Table 1: Available MERIS and SAR acquisitions and their characteristics. An interferogram was computed for 10/09/03-15/10/03.

In cloudy atmospheres, MERIS cannot derive the full vertical atmospheric water vapor column. In these cases, the water vapor content between the cloud tops and the top of the atmosphere are retrieved. The total swath width is 1150 km, centered at the nadir track.

Columnar water vapor, in g/cm², derived by MERIS, can be converted to signal delay, in mm, using

\[ \delta^v = \Pi_T I \]  

where \( \delta^v \) is the zenith delay in [mm], \( I \) is the (columnar) water vapor (or integrated precipitable water) in [g/cm²], and \( \Pi_T \) is the conversion factor approximated using the surface temperature \( T_s \) in [K]. See [10] for an approximation of \( \Pi_T, T_s, t_D \) as function of the mean annual surface temperature for the location, \( T_0 \), and the day of the year, \( t_D \). As an approximation, we use \( \Pi = 65 \) for \( \delta^v \) in mm and \( I \) in g/cm². The accuracy of the retrieved water vapor content is 1.6 kg/m² or 1.04 cm delay accuracy, using eq. (4).

4 RESULTS

4.1 Conditions for complementary use

Although both MERIS and ASAR can in principle be simultaneously operated, there are a number of practical restrictions that limit the formation of comparable products. First, it should be possible to form a coherent interferogram. This implies that (i) the two data acquisitions should not be too far separated in time, say not more than 35 days, (ii) the baseline should be less than, say, 500 m, and (iii) a digital elevation model should be available for topographic correction. Second, the MERIS images should be available (iv) at the same times as the SAR acquisitions, (v) including the water vapor product, (vi) at full resolution, and (vii) preferably under cloud-free circumstances. Currently, only combined ASAR and MERIS acquisitions in the visibility mask of the Kiruna/Matera downlink stations are possible. This restricts the data possibilities to European sites. Since the required resampling necessary to obtain full-resolution images is performed on-board, reduced resolution data cannot be upgraded to full-resolution data at a later stage. Table 1 lists the data available for this study.

4.2 Data quality analysis

MERIS water vapor maps are shown in fig. 1. In all these images a cloud and water mask is applied. The structure function of the MERIS atmospheric signal provides the variance of the difference in atmospheric delay between two points separated by a certain distance \( \rho \). In fig. 2 the structure functions of all available MERIS images are shown.

These results show a clear correlation between the state of the atmosphere at the time of the acquisition and the spatial variation of the signal. It can be observed that the image of 15.10.2003 shows a completely clear sky. For this day the structure function shows the lowest level of variance for all the distances considered. As the atmosphere becomes increasingly more turbulent the spatial variance in atmospheric delay gets larger. Overlapped on the fig. 2 are the dotted lines representing the Kolmogorov scaling powerlaws (5/3 for distances greater than 2 km or 2/3 for shorter distances [3].
Figure 1: MERIS water vapor maps. A cloud and water mask is applied

Figure 2: Structure functions of the cloud-free MERIS water vapor channel observations

The first and last acquisition (corresponding to cloud-free days) have structure functions which are in relatively good agreement with the reference dotted lines. In these cases the reliability of the MERIS water vapor products seems good and it is expected that it is able to correct the interferogram APS. On the other hand the structure function gets flatter as the cloud cover increases. The absolute value of the variance increases and the difference between the scaling regimes vanishes. For these acquisitions the quality of the water vapor products is limited. 10.09.2003 was almost completely overcast, but still water vapor estimates from 'holes' can been used. In this case the variation over small distances gets even greater and the structure function becomes very noisy.

4.3 Correcting interferograms

In the set of available images (see table 1) there was no ‘perfect combination,’ meaning two consecutive acquisitions where ASAR and MERIS data is available and free cloud conditions are fulfilled. Nevertheless, we can make a preliminary analysis of the variation that the atmospheric signal shows. Furthermore the amount of columnar water vapor over the cloud layer can be used as a complementary measurement for an estimation of the columnar water vapor from the earth surface until the top of the cloud.

Here, as an example, we use the following pair of acquisitions: 10.09.2003, completely overcast and 15.10.2003, cloud-free (see figs. 1 and 3). In fig. 4 the wrapped water vapor maps of the area under study are shown. The
Figure 3: MERIS data of 10/09/2002, completely overcast. Left: MERIS cloud top pressure. Dark corresponds with low pressures, that is high altitudes. Right: MERIS channel 3 observation showing visually interpretable cloud cover. The square corresponds with the dimension of the radar image.

interferogram has been filtered and multilooked in range and azimuth and resampled to the MERIS image in order to make them comparable. A phase screen in azimuth and range direction has been applied to remove the orbital trends. Topographic signal has not yet been removed from the interferogram, but is limited to some

Figure 4: MERIS water vapor signal, converted to the wrapped interferogram. Left: 10/09/03, Right 15/10/03, Bottom: interferogram.

dune areas and an area in the northeastern section of the image. Fig. 4a shows a slow variation of the wrapped data from North to South that cannot interpret the atmospheric signal depicted in the interferogram. On the
other hand the complementary image only gives information about the water vapor over the cloud layer and more information is needed. However it still can be interpreted looking at the maps of cloud top pressure and reflectivity (see fig. 3). Black areas in fig. 3 correspond with low pressures and therefore high top cloud altitudes and therefore the explanation of the low value of the water vapor over the clouds in fig. 4. The same correlation can be found for white areas correspondent to higher pressures.

5 CONCLUSIONS

The correction of the atmospheric signal in interferograms using MERIS water vapor retrieval seems to be possible for cloud-free acquisitions. In this case the water vapor signal displays the characteristic behavior of atmospheric signal as the structure function (fig. 2) shows. However in the presence of clouds the quality of the water vapor products is limited. Subtracting it from the atmospheric signal in an interferogram would only give information over the cloud layer but would not compensate for it. Two images are necessary to create an interferogram. It seems very opportunistic to find two consecutive days with no clouds for the area under study. In our case we did not find such a combination. Nevertheless one could subtract only a day (no clouds) and give a first assessment about the variability experimented by the signal. In our case a single subtraction could be done in 33% of the cases. Nevertheless, it seems insufficient to explain the atmospheric signal in an interferogram. The applicability is therefore limited. As the archive of MERIS data grows and different locations can be examined, it might be possible to create a virtually atmosphere-free interferogram.

References


