Validation of the Tropospheric Corrected Interferograms and Analysis of the expected Performance in Deformation Rate Estimation

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Abstract

Previous studies have shown that a consistent reduction of tropospheric-related phase biases can be introduced mitigating the interferometric phase using numerical weather models. The work investigates the achieved accuracy of the tropospheric corrections and their effects on deformation rates estimation using GNSS data. The GNSS derived Zenith Path Delay is used to assess if the corrected interferogram reaches the expected numerical weather models accuracy. Then the GNSS derived deformation rates are compared with DInSAR results to validate their expected accuracy.

1 Introduction

The Sentinel-1 mission provides systematically SAR data suitable for interferometric applications with a swath width of 250 km. Future SAR satellites will further extend this to even larger swaths. The measurement of tectonics movements particularly benefit from the large scale deformation measurements that SAR interferometry provides. Nevertheless, since the magnitude of relative errors increases with distance [4], the performance of relative deformation measurements between very distant points may not achieve the required accuracy for tectonic applications. Therefore a compensation of low-pass spatial components is necessary.
In [1] an investigation of the gain in terms of performance achieved after the correction of systematic effects has been carried out. The measured gain has been proved to be mainly related to the correction of the tropospheric components (in C-Band) and quantified up to factor 10 at large distances. This work investigates firstly if the achieved gain reaches effectively the performance provided by the weather data used for the corrections. In a second stage the procedure proposed in [1] to forecast the final performance of the InSAR derived deformation rates is also validated.

2 Error variograms and impact on the accuracy of the estimated deformation rates

In [1] the variogram of the interferograms phase have been computed in order to estimate the gain provided by the geodetic corrections. The differential phases have been empirically evaluated using the unwrapped phase of PS points. Exotic effects such as soil moisture are thus avoided. Moreover the phase has been averaged over a $2500 \times 2500\ m^2$ window, reducing the impact of signal clutter and high pass residual topographic components. The mean variogram behavior provide an evaluation of the error covariance present in average on the stack's phases. Short time interferograms have been generated combining every acquisition with the previous and the next. This approach should prevent bias due to a common master as well as the impact of deformation.
In particular the effect of motion deserve some specific discussion. The fast revisit time of Sentinel mission allows to compute short time interferograms having δt of $6, 12$ or 24 days in worst cases. Since the residual error like tropospheric turbulence are assessed to be in centimeter order of magnitude deformation rates of several tens of cm/y are necessary in order to be comparable with the effect to be observed (troposphere). Such rates can be reached in landslides or mining areas that are typically restricted in coverage therefore since the variograms are computed averaging many different measurements on the whole scene the effect of such areas should not strongly impact on the estimation. However the projection of the tectonic plate motion onto the different line of sights is a a large scale effect that could seriously bias the estimation of the variograms. Such movements are mainly horizontal and can reach 6-7 cm/y. Projecting this number onto the different LoS (far range and near range) it is possible to observe that at the previously mentioned revisit times its impact should be negligible. The eventual presence of seismic events in the time series shall also be assessed and the eventual coseismic interferometric pair not used to generate the variograms.
Considering the tropospheric error uncorrelated between the different acquisitions[1] it is possible to state that the interferometric phase variogram between the acquisitions n and m $\Gamma_{n,m}$ is the sum of the two variograms of the errors in the acquisition n and m γ_n and γ_m.

[1]Hypothesis that should hold be at least for the tropospheric corrected phases since all the seasonal effects are included in the weather model and hence compensated

$$\Gamma_{n,m}(d) = \mathbb{E}\left[\left((\phi(A)_n - \phi(B)_n) - (\phi(A)_m - \phi(B)_m)\right)^2\right] = \gamma_n + \gamma_m \tag{1}$$

where ϕ is the phase computed a the generic points A and B and d is the distance between A, B.Then the average variogram $\bar{\Gamma} = \mathbb{E}[\Gamma]$ represents the average behavior of the residual error of the interferograms. For a given stack it is hence possible to derive the accuracy variogram of the deformation rates estimation properly scaling $\bar{\Gamma}$ with the linear regression formula.

$$\Gamma_{defo}(d) = \frac{1}{2}\frac{\lambda^2}{16\pi^2}\frac{M\bar{\Gamma}}{M\sum_i t_i^2 - (\sum_i t_i)^2} \tag{2}$$

Equation 2 shows the estimation of the deformation rates error variogram derived from the average error variogram of the interferograms $\bar{\Gamma}$. The factor $1/2$ takes in account that in the linear regression all the phases are computed w.r.t. a common reference SLC: M is the number of acquisitions and t_i are the time differences w.r.t. the reference image of the phase measurements.

3 Validation work

Following the discussion of [1] and the previous section this work addresses two related open issues:

- validate that the achieved accuracy of the tropospheric corrections (in this case ECMWF-ERA5) saturates to the accuracy of the numerical weather models for large distances
- validate the error description of the deformation rates products derived as in Equation 2

GNSS data have been used as reference data using the estimated ZPD to validate the tropospheric corrections and the deformation rates estimates to validate the predicted error for DInSAR derived deformation rates.

3.1 Validation of the tropospheric corrections using error variograms and interferometric performance forecasting

The assessment and validation of the performance of phase screen mitigation, has been performed using long Sentinel interferometric stripes over Germany. The unwrapped phases from multiple slices have been mosaicked allowing the evaluation of variograms up to 250 km distance.
Analogously to what have been done in [2] the zenith path delay predicted by ERA-5 has been computed and compared with the estimates coming from GNSS data. Since the numerical weather models accuracies varies with the geographic location a subset of 9 GNSS station in Germany has been used. The deviation between the GNSS ZPD and the ZPD derived by ERA-5 data σ^2_{NWP} should represent the absolute error of the numerical weather models correction for a single delay computed in vertical. This comparison has been performed at the time of Ascending 18:00 and Descending 6:00. In order to compute the error between GNSS and ERA-5 the deviations over one year data and the 9 stations has been averaged for Ascending and Descending times.
Considering a SAR interferogram corrected using ERA-5 data and taking two points at large distance the error should approach the saturation value $\sigma^2_Z = 4\sigma^2_{NWP}$. Hence as a validation test it has been proved if the variograms saturate in average at the value $4\sigma^2_{NWP}$. The results in Figure 1 show as the value $4\sigma^2_{NWP}$ well justify the variogram saturation values fo Ascending and Descending data. It is interesting to notice how the performance in two cases are comparable in terms of error at 250 km. One would have expected better performance in the Descending pass, due to the morning acquisition. This is anyway partially true if we look at the mid-scale 50-80 km where the stronger turbulence makes the Ascending a bit worse in average and deviation. However it seems reasonable to observe that once the distance reaches the scale of the numerical weather models the error follow the error of the numerical weather models independently from the daytime.
It is then important to conclude that a global analysis of the ERA-5/GNSS deviation as done in [2] could provide a reasonable estimation of the achievable accuracy in measuring large scale deformation using DInSAR.

3.2 Validation of the deformation rates error variograms

As final validation task is necessary to check whether the derived error variograms in Equation 2 really represents the error of the estimated deformation rates. The interferometric processing covers the whole area of Germany both in Ascending and Descending geometry for a total of 41 processed stacks having more than 100 acquisitions each. The GNSS data used have been processed by Nevada Geodetic Laboratories [6] and covers pretty well the area of interest. However the coverage is not uniform and can vary 4-5 stations per stack up to more than 50.
Assuming the GNSS rates to be much more accurate, the difference between InSAR derived and GNSS derived deformation rates [5] has been computed in order to generate a vector of Offsets $\underline{\Delta}$ [3] where every offset is defined as follows:

$$\Delta_i = v_{insar} - \underline{v}^T_{gnss}\,\underline{s} = \delta_i + v_{ref} + n_i \tag{3}$$

where $\underline{s}$ is the radar line of sight, v_{ref} is the velocity of the reference point used in InSAR processing, δ_i is a space variant error screen in interferometric data measured in correspondence of the i^{th} location and n_i is the random error.Now since a statistical description of the errors is available it is possible to standardize each difference with its own variance as follows:

$$\Xi^{std}_{i,j} = \frac{\Delta_i - \Delta_j}{\sqrt{\sigma^2_{GNSS,i} + \sigma^2_{GNSS,j} + \Gamma(d_{i,j})}} \tag{4}$$

where the σ^2_{GNSS} is the accuracy of the GNSS measurements (supposed to be incorrelated in space) in LoS and

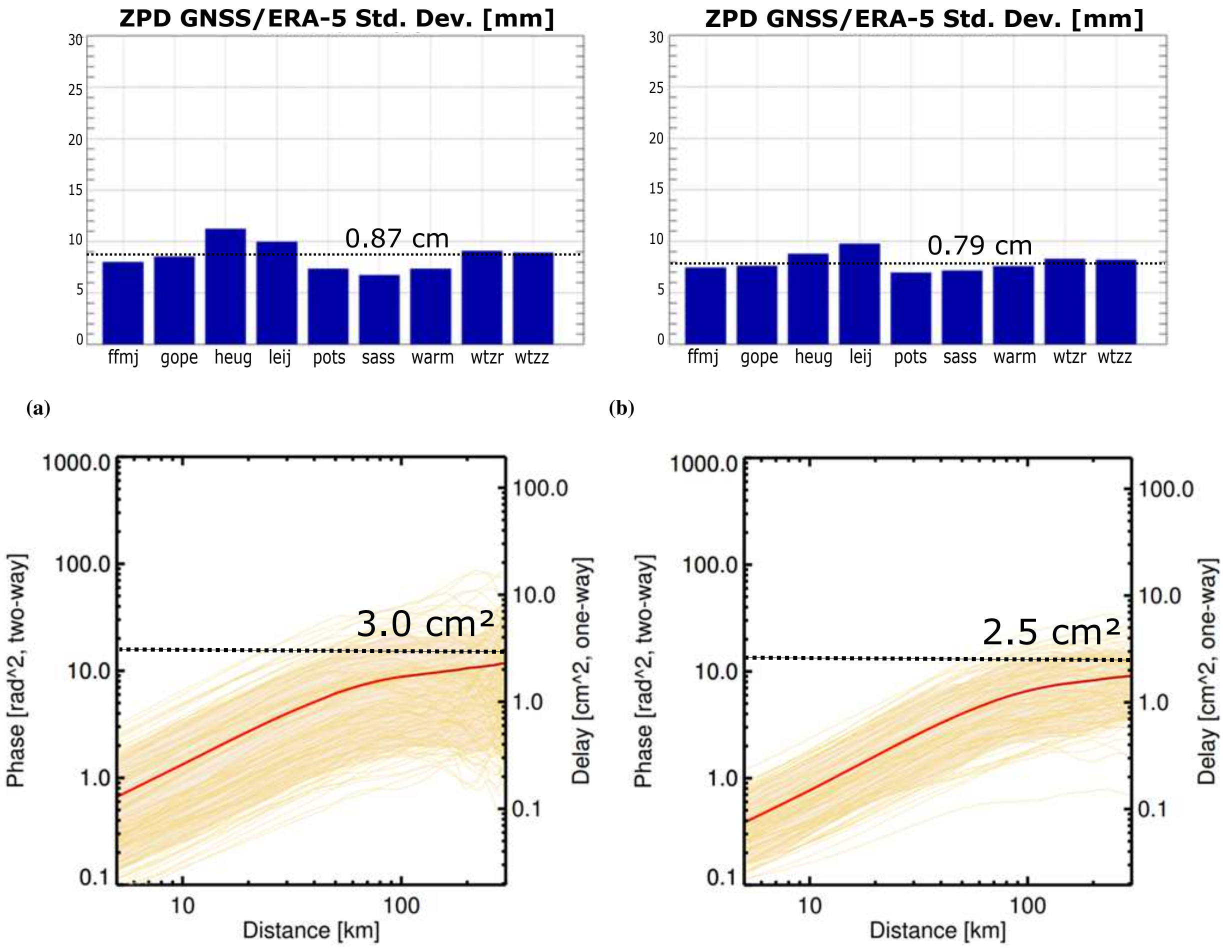

Figure 1 In (a) and (b) the standard deviation of the ZPD computed from ECMWF ERA5 and GNSS in correspondence of the GNSS stations used. In (a) the Ascending Pass (18:00) and in (b) theDescnding (6:00). In (c) and (d) the estimated variograms that show a saturation in correspondence of the numerical weather models error. In (c) the Ascending Pass in (d) the Descending

$\Gamma(d_{i,j})$ is the estimated error variogram evaluated at the distance between the two GNSS stations. If the error has been properly described the distribution of Ξ^{std} should approach a standard normal distribution, $N(0,1)$. The histograms of Ξ^{std}computed where possible shows a good agreement with the $N(0,1)$ distribution as shown in Figure 3. Moreover the quadratic differences $(\Delta_i - \Delta_j)^2$ have been also compared to the estimated variogram taking also in account the further spatially uncorrelated noise introduced by the GNSS measurements. In Figure all the generated quadratic differences are plotted according to their distance and compared to the variogram. Since this measurements can be rather noisy some the measured quadratic differences have been averaged in distance bins of ten kilometers (green dots in Figure)

This operation ha been carried out on all the processed stacks. Therefore in order to have a plot that could encompass and resume all the results an histogram of all the standardized differences of all the processed stacks has been computed and compared with the $N(0,1)$.

Figure shows the result, the agreement with the $N(0,1)$ is pretty good the statistics are shown in Table

Table 1 Validation Statistics

Moments of Ξ^{std}	
Mean	-0.06
Std. Deviation	0.98
Skewness	-0.01
Kurtosis	0.01

4 Conclusions

The study has been carried out on a consistent amount of real data focusing on the validation the tropospheric correction in InSAR products showing basically that the error variogram saturates at large distance (>100 km) to the error of the ECMWF products calculated w.r.t. the GNSS tropospheric delays and the validation of the error variograms estimated using short temporal baseline interferograms using GNSS measurements.

5 Literature

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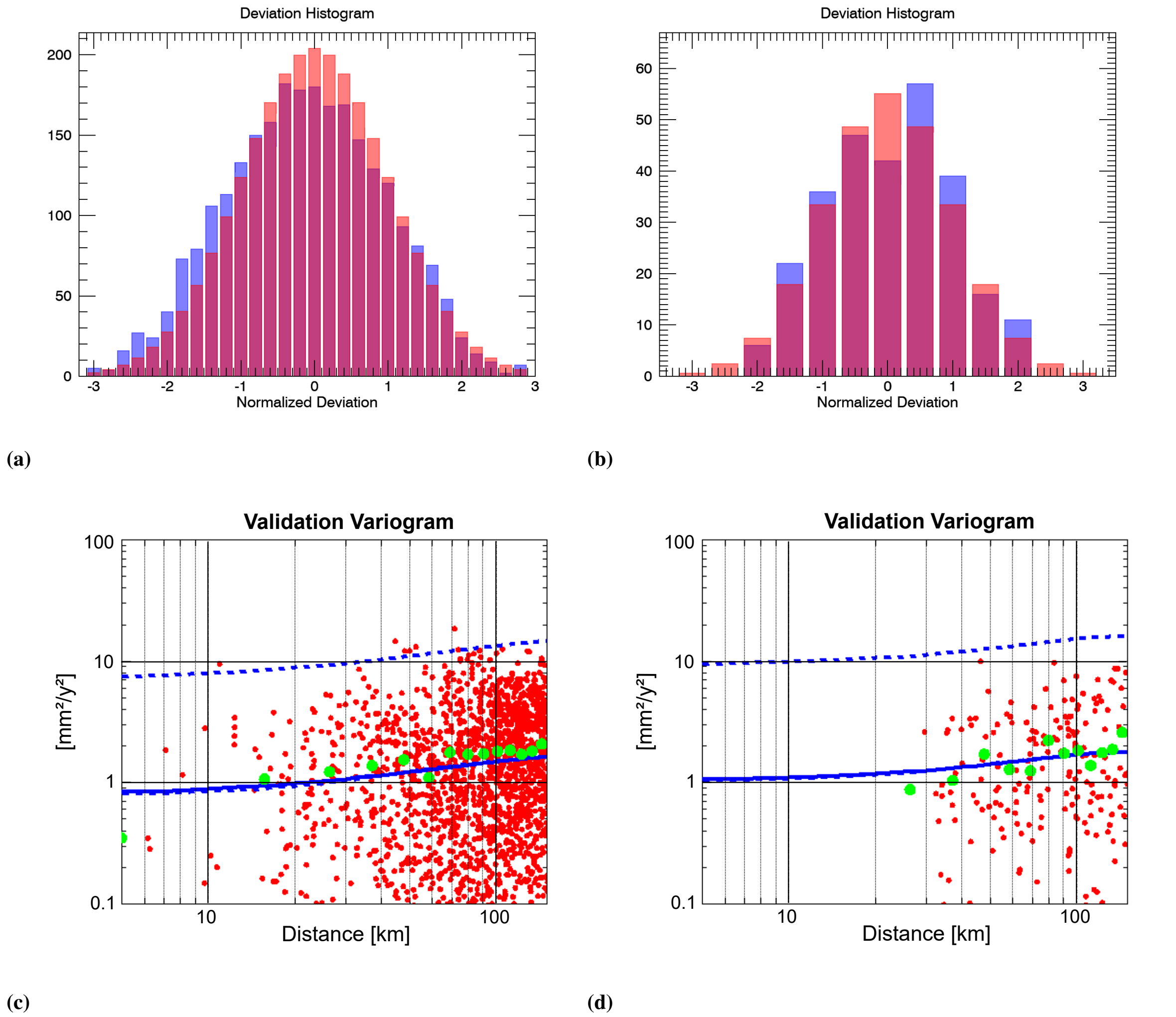

Figure 2 Standardized Offsets Ξ histogram compared with the $N(0,1)$ distribution (blue line). In (a) an Ascending stack in (b) a Descending

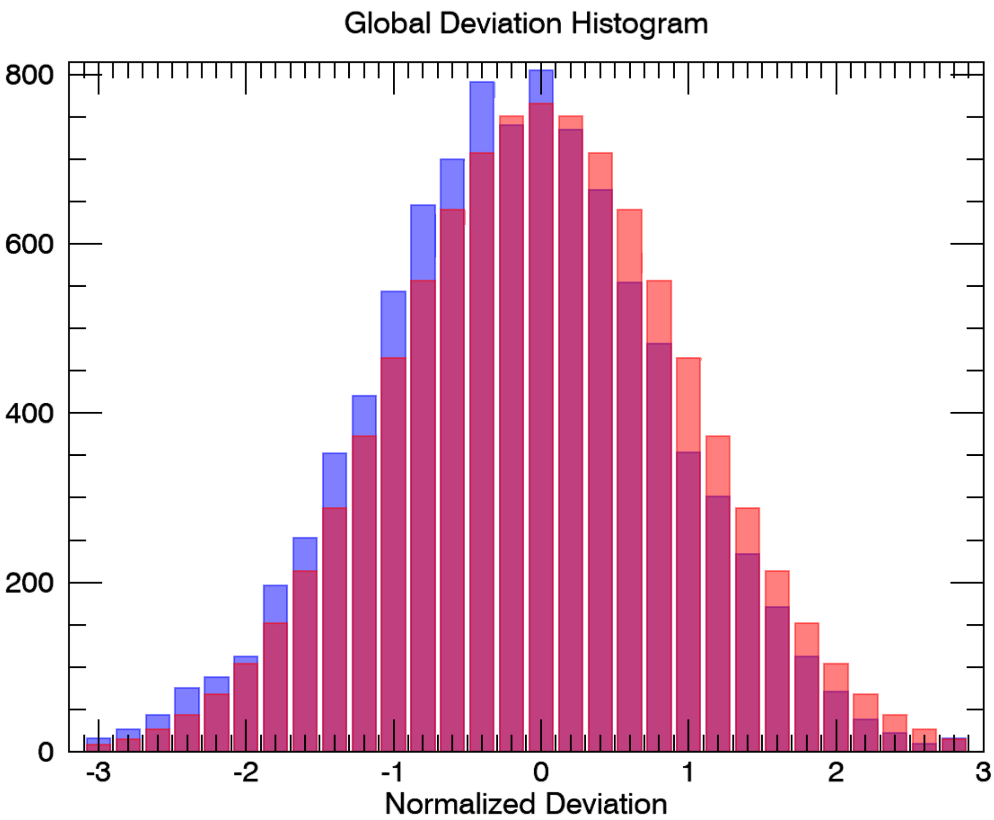

Figure 3 Standardized Offsets Ξ histogram compared with the $N(0,1)$ distribution (blue line). In (a) an Ascending stack in (b) a Descending