Effect of DEM inaccuracy on precision of satellite InSAR results

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Abstract

This short paper summarizes effects of DEM errors influencing precision of deformation monitoring results using satellite SAR interferometry and presents basic mathematical approaches to quantify DEM accuracy needed for proper estimation of SAR interferometry parameters. While in case of appropriately large SAR dataset for multitemporal interferometry processing the height difference is usually well estimated, still DEM accuracy should be carefully considered in case of using low number of images – and especially in case of processing differential InSAR with only one image pair. Depending on interferogram pair combination characteristics, especially parameter known as perpendicular baseline Bperp describing distance between satellite positions during their image acquisitions, the interferogram is more or less prone to DEM accuracy errors. In case of higher Bperp, a relatively high quality DEM is necessary to remove stereoscopic effect apparent in interferogram in order to distinguish interferogram phase element caused by temporal terrain deformation.

Keywords: InSAR, DEM, accuracy, deformation monitoring

INTRODUCTION

Satellite Synthetic Aperture Radar Interferometry (InSAR) is a valuable modern technology currently being used mainly for generation of high quality DEM models – projects including global models as SRTM (2000) or WorldDEM (2014, continuously updated), and for monitoring of terrain deformations such as subsidence, landslides, structure deformations, effects of eartquakes or volcano activity etc. Satellite missions as TanDEM-X can deliver data allowing to extract DEM models in resolution of few meters and height estimation accuracy generally of first meters. In terms of deformation monitoring, satellite InSAR is able to deliver information of near-vertical movements of observed objects in millimetric precision. To achieve such precision, however, majority of non-deformation effects influencing phase of the radar wave must be filtered out – including phase induced by topography changes. Generally, the phase change Δφ between two SAR images can be ascribed as due to displacement in time, height difference, atmosphere-caused delay and various noise - as described by Eq. 1.

$$\Delta\varphi = \Delta\varphi_{displacement} + \Delta\varphi_{height} + \Delta\varphi_{atmosphere} + \Delta\varphi_{noise} \quad (1)$$

HEIGHT EFFECTS IN DIFFERENTIAL SAR INTERFEROMETRY

A rate of influence of topography in satellite SAR interferogram can be described using parameter called Height ambiguity (H_{amb}) that is a height difference corresponding to a 2π phase difference (a fringe). This parameter is directly corresponding to image pair parameters, like perpendicular baseline (B_{perp}) between satellite positions at the time of image acquisition – a larger B_{perp} yields more sensitivity of interferogram to height – see Eq. 2.

$$H_{amb} = \frac{\lambda}{2} \cdot \frac{R \sin \theta_{inc}}{B_{perp}} \tag{2}$$

where λ... satellite SAR carrier wavelength, θ_{inc}... incidence angle of SAR line of sight, R... distance of satellite from observed terrain.

So, the effect of topography is dependent on the B_{perp} of computed interferogram. With a very small perpendicular baseline up to several meters, meaning the satellite is scanning both images from almost the same spot in some time delay, there will be a very small or negligible stereoscopic effect. This is an optimal configuration for deformation monitoring. Higher effect of topography is visible in higher rates of B_{perp} – example is demonstrated in interferograms at Fig. 1. The phase contributions of topography should be removed by using a proper DEM, converted to SAR coordinates as a simulated phase with the same H_{amb} as in the interferogram.

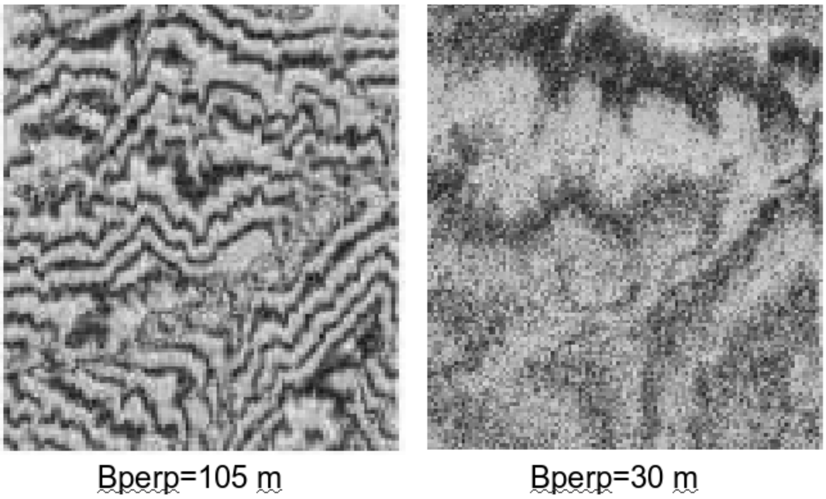

Fig. 1. Topography effects in Envisat interferograms of B_{perp} = 105 m (left) and B_{perp} = 30 m (right). Images contain same hilly area (Kampes et al., 2006)

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Any errors of DEM inaccuracy will cause a residual topographic signal $\Delta\varphi_{res,topo}$ that can be described as modified from (Hlaváčová, 2008):

$$\triangle\varphi_{topo}^{res} \backsimeq \frac{4\pi}{\lambda} \left(\frac{B_{perp} + \triangle B_{perp}}{R \sin \theta_{inc}} \triangle H_P \right) \tag{3}$$

where ΔB_{perp}... error in local B_{perp} estimation due to height error ΔH_P. Value of ΔB_{perp} is for practical purposes often neglectable, however it can yield significant impact in case of detecting displacements at steep slopes.

Such value of $\Delta\varphi_{res,topo}$ can be misinterpreted as signal caused by displacement $\Delta\varphi_{displacement}$ [rad]. This equals a value of detected deformation in SAR line of sight (D_{LOS}) by relation $D_{LOS}=\lambda \cdot \Delta\varphi_{displacement} / 4\pi$ [m] (Hanssen, 2001). In case of Envisat at B_{perp} = 100 m, the error of H_P = 5 m will yield $\Delta\varphi_{res,topo}$ = 0.3 rad (i.e. error in deformation estimation is neglectable: D_{LOS} = 1.5 mm) but in case of higher B_{perp} = 600 m, the same DEM error H_P would yield $\Delta\varphi_{res,topo}$ = 2 rad (i.e. D_{LOS} = 9 mm). This indicates that it is not necessary to use a very precise DEM for topography removal in shorter B_{perp} configurations, especially in areas with not very high terrain gradients. Currently active SAR missions tend to minimize B_{perp} by establishing precise satellite orbital tracks. Different situation can occur in case of huge displacements where millimetric-decimetric sensitivity of InSAR phase can be strongly affected by outdated DEM.

Different satellite SAR systems have different sensitivity to height errors – relation between B_{perp} and H_{amb} is demonstrated for three most popular SAR systems in Fig. 2: Envisat (C-band SAR), Alos (L-band SAR) and TerraSAR-X (X-band SAR).

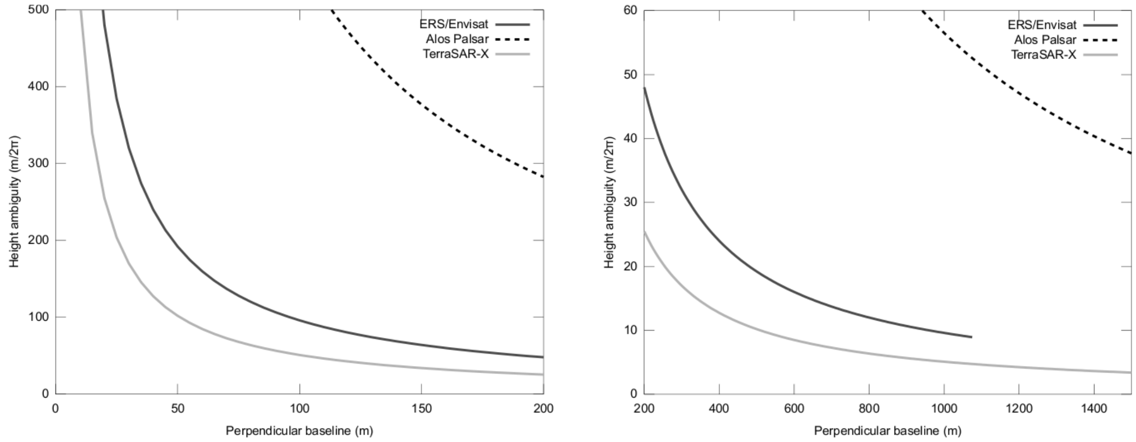

Fig. 2. Relation between height ambiguity and a perpendicular baseline of selected popular SAR missions.

ISSUES WITHIN APPLICATION OF POPULAR DEMS IN INSAR

During previous decades and even today, the most popular DEM model for topography removal in InSAR used to be the global SRTM from year 2000 with a resolution of ~90 m (in Europe) and vertical accuracy that should be better than 15 m (with some 90% coverage within a tolerance of 5 m). Such model was considered sufficient for most of the InSAR uses and more reliable than other global projects as Aster GDEM (with significantly lower vertical accuracy). Since September 2014, the SRTM (2000) of 1 arcsecond resolution (~30 m in Europe) is available (Simon, 2015). Obviously, two properties should be considered in selection of DEM for InSAR topography phase removal: DEM precision in terms of accuracy and resolution (see Fig. 3) and whether DEM is up-to-date with regards to InSAR images timeline (see Fig. 4).

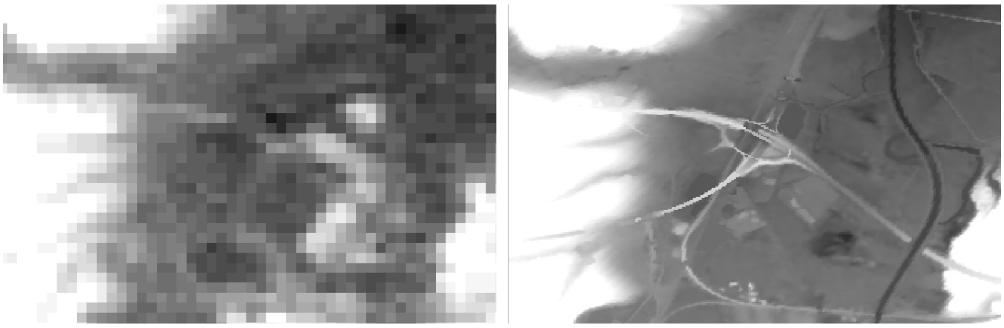

Fig. 3. Resolution difference between SRTM (left) and custom DEM based on Czech national geodetic base ZABAGED (right), used for InSAR monitoring of highway bridge deformations (Lazecký et al., 2014).

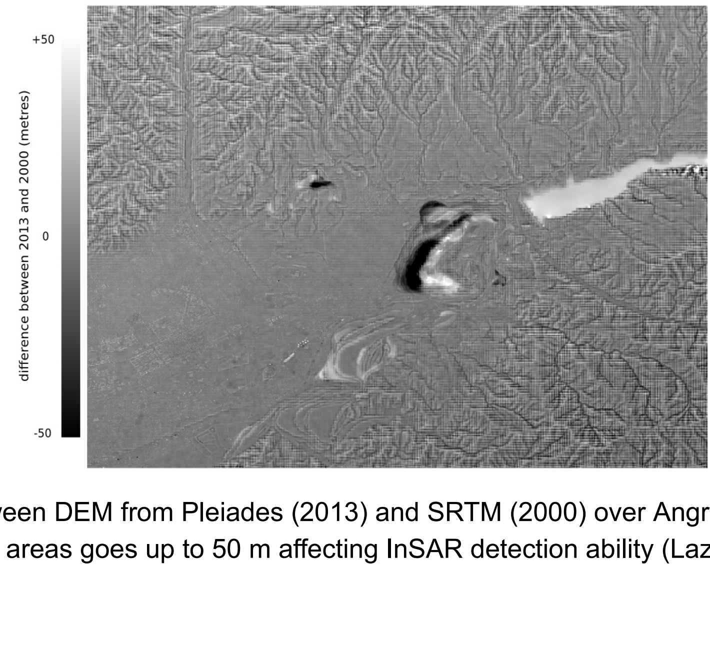

Fig. 4. Difference between DEM from Pleiades (2013) and SRTM (2000) over Angren, Uzbekistan – difference in landslide areas goes up to 50 m affecting InSAR detection ability (Lazecký et al., 2013)

DEM INACCURACIES IN MULTITEMPORAL INSAR

Since availability of TerraSAR-X (2006) and other high resolution SAR systems, the focus field of InSAR started to be directed into monitoring of structure health, using multitemporal InSAR (MTI) methods. Thanks to usage of multiple images, it is possible to estimate both deformation trends in time but also height, relatively precisely, using information about correlation of SAR phase changes and B_{perp}. Depending on quality of dataset (especially in terms of number of input images and their B_{perp} configuration), as well as on quantitative values of major phase elements $\Delta\varphi$, it is possible to accurately estimate height from MTI, supposing the height difference of processed points is in reasonable range (a coarse DEM is helpful to allow such proper range).

Let's consider that the most reliable estimation of any major $\Delta\varphi$ element is in case where this element doesn't exceed critical value corresponding to $\lambda/4$ (i.e. $\Delta\varphi=\pi$) between neighboring measurements in the MTI dataset, based on (Hanssen, 2001). If we consider two major elements: due to linear deformation in time $\Delta\varphi_{defo}$ and due to height $\Delta\varphi_{height}$, we can coarsely suppose that maximally reliable estimation will happen if both of them don't exceed value of $\pi/2$ in most of interferograms. A maximal $H_{amb,max}$ is at the same time representing maximal DEM error possible to correct in such dataset – this $H_{amb,max}$ then is simply computable using Eq. 4 (where $B_{perp,max}$ can be selected as the highest B_{perp} from the majority of image pairs, e.g. from 25-75% quantiles of the dataset).

$$H_{amb,max} = H_{amb}(B_{perp,max})/4 \qquad (4)$$

For example using TerraSAR-X dataset of 11 images with majority of B_{perp} spreading between quantiles -164 and 107 m, the $H_{amb,max}$ = 6 m – means that DEM errors of up to 6 m will be reliably corrected. Note that this estimation is simplified and condition of critical value of $\Delta\varphi=\pi$ was chosen as rather strict, however can help in analysis of basic quality of SAR dataset and need of input DEM quality for MTI processing.

Once a DEM error is already estimated in MTI, it is possible to evaluate its accuracy using standard deviation of phase residuals $\delta_{\Delta\varphi}$. One should take into account number of input images *M* and compute standard deviation error due to estimated height $\delta_{\Delta h}$ using Eq. 5, based on (Perissin, 2006). Such reliability analysis describes goodness of fitting of height estimation model for the input data.

$$\delta_{\Delta h}=\sqrt{\left(\frac{\lambda R\sin\theta}{4\pi}\right)^2 \frac{\delta^2_{\Delta\varphi}}{M\,\delta^2_{B_{perp}}}} \qquad (5)$$

In the same example of TerraSAR-X dataset, described further in (Lazecký et al., 2015), a DEM error was estimated for selected point ID 2274 to be Δh = 7.5 m. Phase residuals after removal of modelled parameters varied with a standard deviation of $\delta_{\Delta\varphi}$ = 0.4 rad. Therefore standard deviation of estimated height was calculated to be $\delta_{\Delta h}$ = 0.58 m -> the height was estimated as Δh = 7.5 m ± 0.58 m.

CONCLUSIONS

This paper summarizes issues and gives directions in analysis of height accuracy needed for proper InSAR processing for deformation monitoring. The own idea of estimation of needed DEM accuracy is basically delivered as term $H_{amb,max}$ in Eq. 4. It can be said from experience that in case of having dataset spreading 20 or more images, the theoretical limit of $\lambda/4$ for reliable estimation is neglected – depending on site-to-site experience, it can be summarized that dataset with higher number of images (especially with more spread perpendicular baselines) is usually not prone to most of DEM errors. Results of Hong-Kong processing using 73 TerraSAR-X images (Perissin, 2013) shows potential to perform estimation of heights even of very high skyscraper buildings using MTI processing. Still, DEM accuracy should be carefully considered in case of using low number of images – and especially in case of processing differential InSAR with only one image pair – the sensitivity for DEM errors is estimable using Eq. 3.

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