

# ALPINE DIGITAL ELEVATION MODELS FROM RADAR INTERFEROMETRY - A GENERIC APPROACH TO EXPLOIT MULTIPLE IMAGING GEOMETRIES

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## ABSTRACT:

The generation of Digital Elevation Models (DEMs) from Synthetic Aperture Radar Interferometry (InSAR) has developed rapidly in the last 10 years. This new method proved to be operational with the global success of the Shuttle Radar Topography Mission in the year 2000 and with several companies offering regional topographic mapping campaigns based on airborne InSAR today. However, the current radar systems and the current processing methods will deliver robust results only over moderate terrain. When confronted with steep mountains or canyons, the measurement principle poses a number of problems that are quite hard to solve. The reason being the radar viewing geometry that limits the range of observable terrain slopes in one acquisition and the problem to unwrap the ambiguous phase, a measure for the radar look angle. The paper shows examples from the Shuttle Radar Topography Mission in mountainous terrain and demonstrates some specific deficiencies. Then, some processing techniques are sketched that can help to achieve improved results with available data. Finally, techniques for future high resolution InSAR DEM missions are proposed to minimize the artefacts in mountainous terrain and to actively use multi-angle, multi-frequency observations for more robust and more complete DEM reconstruction.

## 1. INTRODUCTION

Radar interferometry exploits the highly accurate distance measurement contained in the phase of each pixel of a complex synthetic aperture radar (SAR) image to triangulate the topographic height of a scattering facet on ground. The achievable horizontal resolution is determined by the capabilities of the SAR system, in the order of 5 to 30 meters for space based SAR systems and in the order of 0.1 to 1 meter for airborne systems. The vertical accuracy depends on the wavelength which is between 3 and 20 centimeters for microwave SARs, on the thermal noise of the SAR system and, most important, on the baseline, i.e. the effective distance between the two antennas. Limited by the named technical parameters, vertical DEM accuracies between 0.1 meters for airborne systems to 20 meters for space borne systems are achievable. An important InSAR DEM mission was the Shuttle Radar Topography Mission (SRTM), which mapped the Earth with a resolution of 30 meters and an accuracy in the order of 6 meters (90 %) between 57° southern and 60° northern latitude.

Compared to optical stereo systems the interferometric SAR technique is robust in many ways: The system carries its own microwave illumination and can penetrate clouds with negligible attenuation. There is no scene contrast needed as for because the distance information is inherent in the phase of each single pixel.

On the other hand some properties specific to the InSAR technique limits its applicability to flat and moderately rough terrain: Earth observation SARs are imaging with an incidence angle between 20° and 60° from nadir. This leads to shadowing effects at mountain backsides and to multiple reflections (layover) from slopes that are tilted towards the radar steeper than the incidence angle. Shadow and layover effects do not only distort certain parts of the imaged surface, they interfere with another property of InSAR: the ambiguous measurement of the range by exploiting the phase. The phase of a SAR pixel changes several hundred cycles between adjacent pixels and offers the high accuracy that allows to work with relatively small baselines and

work independent of scene contrast as a shift in pixel geometry is not required between the “stereo” observations. On the other hand, only the fractional part can be exploited since the absolute cycle number is unknown. This limits SAR interferometry to applications where the differential phase change between two neighbouring pixels in two images is less than half a cycle. Larger height changes, e.g. caused by steep topography, are estimated integrating smaller changes, a computation step called *phase unwrapping*. The phase unwrapping process is so far only solved reliably for moderate topography. Errors in phase unwrapping propagate as large errors (multiple phase cycles) into large areas of the scene. Radar layover and shadow complicate phase unwrapping extremely and cause InSAR DEMs in alpine topography generally not to be very reliable.

The problem of phase unwrapping errors is generally detected by processing DEMs from independent passes and comparing the results. Phase unwrapping errors lead to strong vertical and horizontal shifts which are easy to detect. If no errors are present, the DEMs can be averaged reducing the relative vertical error caused by thermal sensor noise or signal decorrelation due to temporal changes.

If however, phase unwrapping errors are detected, robust methods to improve the results are scarce. The majority of approaches published so far help only to combine SAR acquisitions of almost identical viewing geometry. Only then are the geometric distortions in the acquisitions in the magnitude of a pixel and the phase values can be compared. If different incidence angles from different orbital tracks are mixed or even different aspect angles as viewed from ascending and descending orbits, then the 3D geometric distortions are so different that the images can not be overlaid for further joint processing. To overlay would require first the 3D geometry that should finally be derived – a circular problem.

A solution for this has been derived, tested and published in [4]. It will be shortly summarized in this paper.

## 2. SRTM X-SAR DATA IN MOUNTAINOUS TERRAIN

Fig. 1 shows the intensity image of the STRM X-SAR over Nanga Parbat mountain (8125 m) in the Himalayas. Clearly visible are the large shadow areas where no radar echo is received and hence, no height can be reconstructed from the interferometric phase. For convenience the image has been geocoded to UTM projection. The interferometric phase of the Nanga Parbat area is shown in Fig. 2, again geocoded for convenience. It can be clearly seen that many fringes are missing and hence the phase unwrapping and DEM reconstruction is not very reliable. Even if there is no signal present in the shadow areas, the 3D shadow line can be reconstructed by exploitation of the special geometry of shadow and its relationship to the interferometric phase [ 5].



Fig. 1. Geocoded SRTM X-SAR intensity image of Nanga Parbat (NP) area with large regions in radar shadow. The image covers an area of 23 kilometers by 15 kilometers.

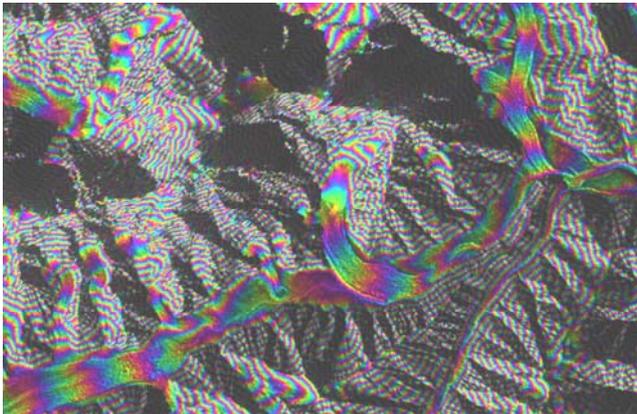


Fig. 2. Geocoded SRTM X-SAR interferometric phase image of Nanga Parbat (NP). The phase is shown in cyclic false colors, the luminance taken from the SAR intensity. One fringe corresponds to app. 175 meters elevation difference.

However, even if this method succeeded in several experiments it was not used for operational SRTM DEM production because of the limited experience that was available with this method. Furthermore, the method would help with phase unwrapping but would not provide true heights in the shadow area neither could it not help to cure the problem of layover. Therefore, as shown in Fig. 3, larger areas of the SRTM-X band DEMs have been

masked because of the risk of wrong heights due to phase unwrapping errors. The C-Band DEMs of SRTM have been produced at NASA/JPL with different phase unwrapping algorithms and with double (ascending and descending) coverage. Fig. 4 shows an the corresponding area and it can be seen that also there areas are left “white” because of shadow and phase unwrapping problems.



Fig. 3. SRTM X-SAR DEM of larger area round Nanga Parbat (ca. 70 km x 50 km). Not covered areas and problematic areas have been masked by DLR.



Fig. 4. SRTM C-band DEM of larger area round Nanga Parbat (ca. 70 km x 50 km). Problematic areas have been masked by NASA.

Having two radar systems (X and C band) and two passes (ascending and descending) one might argue that it should be possible to process the data jointly and make phase unwrapping more stable. However, SAR systems were so far mostly limited to one frequency and hence algorithms to unwrap multi frequency interferograms are little developed. An increasing number of publications can be noticed in the recent years. So far, the existing algorithms are restricted to the case that both radar systems were at almost the same position and the viewing geometry almost identical. A general approach to fuse interferograms of completely different observation geometries was missing because the geometric distortions of the different geometries need to be corrected prior to fusion. But to correct

the distortions would require the DEM that should be the output of the process. A reflexive problem?

### 3. A MULTI GEOMETRY FUSION APPROACH

Efficient algorithms and the power of today's computers allowed a first demonstration that the problem is solvable [ 4]. The key ideas of this method are as follows:

- since a projection of one radar imaging geometry into another one is not possible without having a DEM, the whole reconstruction is best performed in the DEM geometry and not in the radar slant range geometry as usual
- given the three dimensional position of a point on an assumed DEM surface, the slant range coordinates and the expected interferometric phase of this point can be determined easily and efficiently [ 6]
- no phase unwrapping is performed on the single interferograms
- instead phase unwrapping is performed by maximization of the probability that all interferometric observations match this estimate
- the maximization process is slow due to an iteration for each DEM pixel. It can easily be accelerated and stabilized if a priori knowledge, e.g. in the form of available DEMs is included

As shown in [ 4] renouncement of phase unwrapping requires a minimum number of observations before the algorithm stabilizes on the correct height.

Since this generic approach models the geometric radar imaging process, it is very well suited for future expansions. E.g. neighbourhood relationships that are completely ignored in the current version could be incorporated. Fig. 5 shows a DEMs reconstructed from an increasing number of interferograms.

### 4. OPTIMIZATION FOR FUTURE MISSIONS

In the recent years several InSAR missions for DEMs with improved accuracy have been proposed, such as the interferometric cartwheel [ 8] by CNES, an L band satellite constellation by ESA [ 10] and recently TanDEM-X a constellation of two X-band satellites in formation flight [ 3].

Due to their flexible baseline geometry and the multiple incidence angles, such missions are well suited to be optimized to map alpine areas without gaps and with correct phase unwrapping.

As shown in [ 7], shadow and layover effects can not be completely avoided but minimized at an incidence angle of  $45^\circ$  or, reduced to a larger extent by combining observations with different viewing geometries.

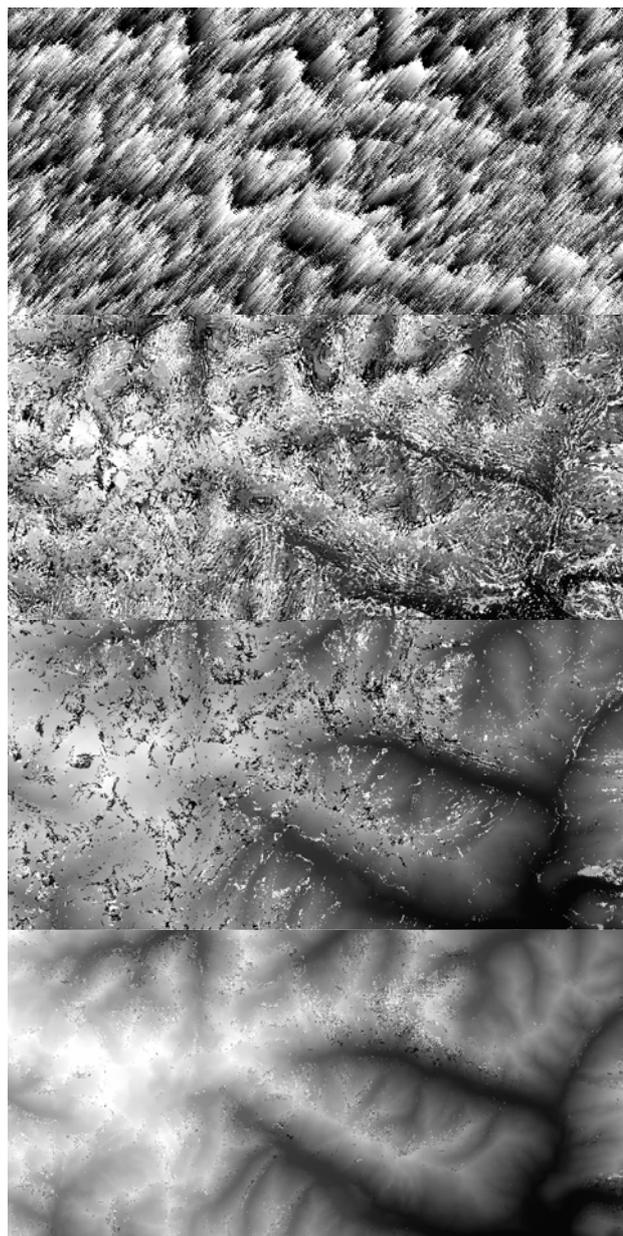


Fig. 5. Digital Elevation Model of Sterzing, Italy, reconstructed from multi-geometry SRTM data using a maximum likelihood approach. Size: 30 km by 15 km. Top to Bottom: increasing accuracy with increasing number of observations: 1, 2, 4, 4 observations plus external refernece

Fig. 6 shows such a combination for extremely rugged mountainous terrain. Shadow and layover have been simulated with the help of a 10 meter resolution DEM for the viewing geometry of TerraSAR-X [ 2], a German X-band satellite to be launched in summer 2006. There is a total number of 13 possible observations in the 11 day repeat orbit. From those, two observations in the nominal right looking mode have been selected that minimize the area of layover and shadow to 3%, when they are combined.

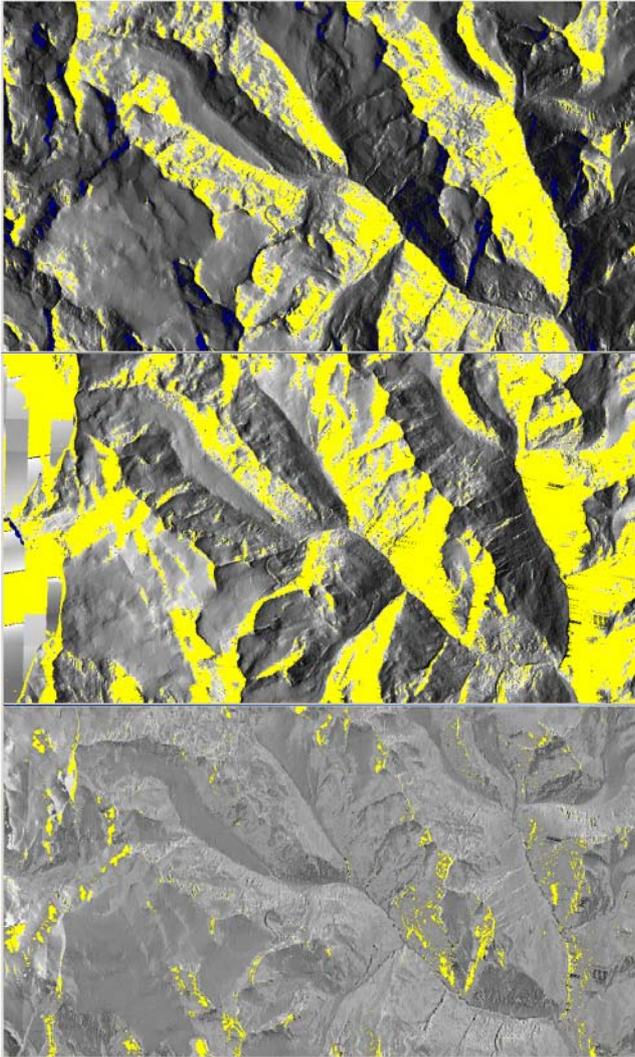


Fig. 6. Simulated shadow and layover areas (yellow) in the steep Ötztal mountains (Austria) for 41° incidence angle descending (top), 30° incidence angle ascending (mid) and a combination of both (middle).

Further optimizations with respect to height reconstruction can be performed by varying the baseline. Large baselines are desirable to achieve a small height error of the DEM. On the other hand, the danger of phase unwrapping errors grows with the length of the baseline. It is the strong belief of the author, that for rugged terrain phase unwrapping can only be solved reliably if multi-geometry, multi-baseline or multi-wavelength observations are performed and are jointly processed.

For example, small baseline interferograms that are easier to unwrap can be used to derive the phase constant of larger baseline interferograms. Small baselines can be achieved by reducing the difference between the orbits of the two satellites. They can also be synthesized by taking the phase difference from two interferograms with larger but similar baselines. An effectively smaller baseline can also be reached by changing the incidence angle significantly but then the image geometries will no more be compatible and methods as described in chapter 3 must be used. Another approach is to use the wavelength dispersion within the range bandwidth for phase unwrapping [ 1], [ 9].

## 5. SUMMARY

While InSAR DEMs are operational over moderate and hilly topography they are not yet reliable in rugged terrain. New reconstruction methods, based on multiple observations must be used in the future. New options will be available with future sensors like, e.g. TerraSAR-X which allows precise orbit control, multi mode SAR imaging and large bandwidths.

## 6. REFERENCES

- [ 1] Bamler R. ; Eineder M.: Accuracy of Differential Shift Estimation by Correlation and Split-Bandwidth Interferometry for Wideband and Delta-k SAR Systems, IEEE Geoscience and Remote Sensing Letters, Volume PP, Issue 99, 2005 Page(s):1 – 5, 2005.
- [ 2] Buckreuss, S.; Balzer, W.; Mühlbauer, P.; Werninghaus, R.; Pitz, W.; The TerraSAR-X Satellite Project, IGARSS 2003, Toulouse, 21.-25.07.2003, IEEE, IGARSS 2003, (2003).
- [ 3] Ebner, H.; Riegger, S.; Hajnsek, I.; Hounam, D.; Krieger, G.; Moreira, A.; and Werner, M.; “Single-Pass SAR Interferometry with a Tandem TerraSAR-X Configuration”, presented at *EUSAR* conference, Ulm, 2004.
- [ 4] Eineder, M., Adam, N.: A maximum likelihood estimator to simultaneously unwrap, geocode and fuse SAR interferograms from different viewing geometries into one digital elevation model. IEEE Transactions on Geoscience and Remote Sensing, CD-ROM, -, , pp. 24-36, 2005.
- [ 5] Eineder, M., Suchandt, S.: Recovering Radar Shadow to Improve Interferometric Phase Unwrapping and DEM Reconstruction. IEEE Transactions on Geoscience and Remote Sensing, 41, 12, pp. 2959-2962, 2003.
- [ 6] Eineder, M.: Efficient Simulation of SAR Interferograms of Large Areas and of Rugged Terrain. IEEE Transactions on Geoscience and Remote Sensing, 41, 6, S. 1415-1427, 2003.
- [ 7] Eineder, M.; Problems and Solutions for InSAR Digital Elevation Model Generation of Mountainous Terrain, ESA FRINGE workshop, ESA, Frascati 2003.
- [ 8] Massonnet, D.; Thouvenot, E.; Ramongassie, S.; Phalippou, L.; A wheel of passive radar microsats for upgrading existing SAR projects, , IGARSS 2000.
- [ 9] N. Veneziani, V.M. Giacobozzo, F. Bovenga, Height Retrieval by Using a Pseudo-Differential Approach in SAR Interferometry - Preliminary Results with Actual SAR Data, IGARSS 2004, Anchorage.
- [ 10] Zink, M.; The TERRASAR-L Interferometric Mission Objectives, ESA FRINGE workshop, ESA, Frascati 2003.