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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 proofed 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.

Zusammenfassung: *Erzeugung digitaler Höhenmodelle von gebirgigen Gebieten aus interferometrischen Radardaten – ein allgemeiner Ansatz zur Verschmelzung unterschiedlicher Aufnahmegeometrien.* Die Erzeugung digitaler Höhenmodelle aus interferometrischen Radardaten hat sich in den letzten zehn Jahren zu einem anerkannten Verfahren entwickelt. Im Jahr 2000 wurden große Teile der Erde durch die Shuttle-Radar-Topografie-Mission SRTM aus dem Weltraum kartiert. Im regionalen Bereich bieten heute mehrere Firmen hoch auflösende Höhenmodelle aus interferometrischen Flugzeugradardaten an. Allerdings sind die Ergebnisse dieser Technik bisher nur in moderatem Relief zuverlässig. In steilem Gebirge oder bei tiefen Canyons leidet das Verfahren unter systeminhärenten Nachteilen. Die Gründe liegen zum einen in der Schrägsichtgeometrie des Radars, welche die abbildbare Geländeneigung begrenzt, und zum anderen im Abrollen der mehrdeutigen interferometrischen Phase, einem Maß für den Blickwinkel des Radars. Der Artikel zeigt Beispiele der Shuttle-Radar-Topografie-Mission in gebirgigem Gelände und erläutert die Abbildungsprobleme dort. Weiterhin werden neuere Verarbeitungstechniken vorgestellt, welche zu besseren Rekonstruktionsergebnissen führen können. Außerdem wird erläutert, wie zukünftige interferometrische DEM-Missionen verschiedene Aufnahmewinkel und verschiedene Radarwellenlängen nutzen können, um auch unter schwierigen Bedingungen qualitativ hochwertige und lückenlose Höhenmodelle zu erzeugen.

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1 Introduction

Radar interferometry exploits the highly accurate distance measurement contained in the phase of each pixel of two complex synthetic aperture radar (SAR) images 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 25 centimeters for common 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 5–20 meters for space borne systems are currently achieved. 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 non-coherent optical systems because the distance information is inherent in the phase of each single pixel.

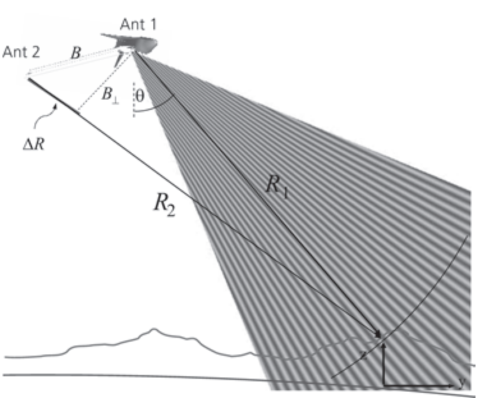

Fig. 1: Imaging geometry and phase field in the zero Doppler plane of a single pass interferometer like SRTM.

Fig. 1 shows the imaging geometry of a side looking single-pass SAR interferometer. A microwave pulse with wavelength λ is transmitted from antenna 1 to the earth surface. The echoes from different distances are recorded by antenna 1 and antenna 2. Both are separated by the baseline B with an effective component $B_\perp$ orthogonal to the line of sight. The radar echoes are sampled with a frequency between 10 MHz and 150 MHz resulting in a spatial resolution between 15 meter and 1 meter. Due to coherent demodulation of the received echo each sample carries also a phase information which is a sensitive measure for the delay time and hence, the distances R_1 and R_2:

$$\phi_1 = -2\pi \frac{2 R_1}{\lambda} \quad \text{and}$$

$$\phi_2 = -2\pi \frac{R_1 + R_2}{\lambda} \tag{1}$$

The interferometric phase difference

$$\phi = \phi_1 - \phi_2 = \frac{2\pi}{\lambda} \Delta R \tag{2}$$

is a measure for the range difference with sub-wavelength accuracy and hence, also for the elevation angle θ

$$\frac{\partial \theta}{\partial \phi} = \frac{\lambda}{B_\perp 2\pi} \tag{3}$$

But because ϕ_1 and ϕ_2 can only be determined in the interval $[-\pi, \pi]$, also the difference ϕ is only an ambiguous measure for θ. In other words, one interferometric phase value ϕ may be caused by different elevation angles θ separated by approximately

$$\Delta\theta = \frac{\lambda}{B_\perp}$$

At one echo sample with a distance R_1 this corresponds to ambiguous height values separated by

$$\Delta z = \frac{\lambda R \sin\theta}{B_\perp} \tag{4}$$

For SRTM X-SAR conditions ($\lambda = 3.1\,\text{cm}$, $R = 400\,\text{km}$, $B_\perp = 60\,\text{m}$, $\theta = 54^\circ$) Δz is about 167 meters.

While the InSAR technique is robust and simple, some specific properties currently limit 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 by 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.

Phase unwrapping errors are generally detected by processing DEMs from independent passes and then comparing the results. Phase unwrapping errors lead to large 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 by using multiple observations 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 less than one pixel and the phase values can be compared in the image geometry. If different incidence angles from different orbital tracks are mixed or even different aspect angles as viewed from ascending and descending orbits, then the three dimensional geometric distortions are so different that the images can not be co-registered for further joint processing. To co-register them requires the three dimensional geometry that should finally be derived – a circular problem.

A solution for this problem has been derived, tested and published in (Eineder & Adam 2005). It will be shortly summarized in this paper.

2 SRTM X-SAR Data in Mountainous Terrain

Fig. 2 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 ease of interpretation the image has been geocoded to UTM projection. The interferometric phase of the Nanga Parbat area is shown in Fig. 3, as well geocoded to UTM. It can be clearly seen that many fringes are missing and hence the phase unwrapping and DEM reconstruction are not very reliable. Even if there is no signal present in the shadow areas, the three dimensional shadow line can be reconstructed by exploitation of the well known geometry of SAR shadow and its relationship to the interferometric phase (Eineder & Suchandt 2003).

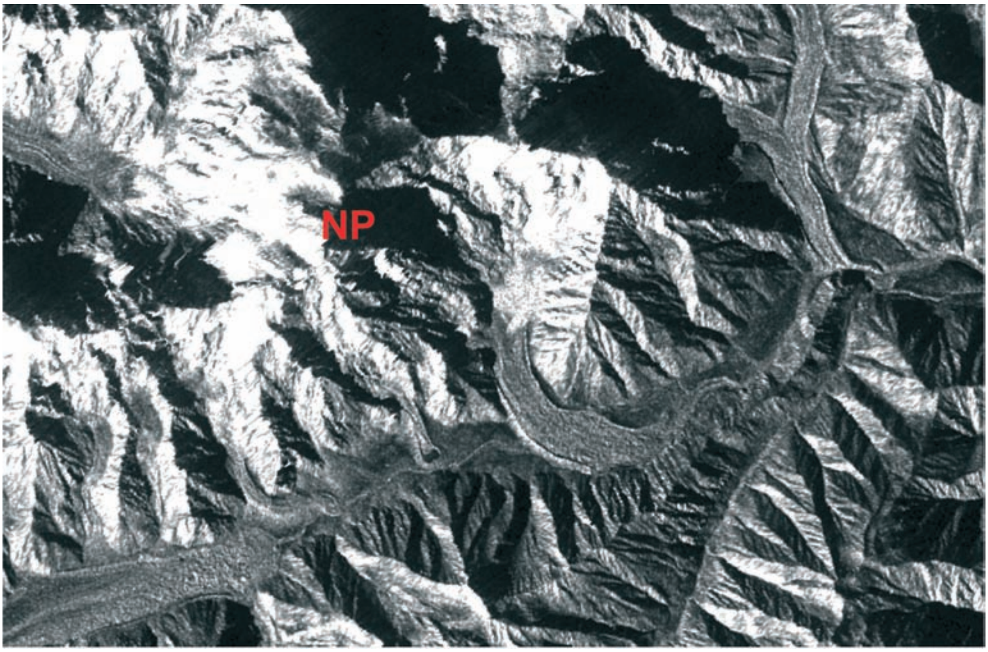

Fig. 2: Geocoded SRTM X-SAR intensity image of Nanga Parbat (NP) area with large regions in radar shadow. The image covers an area of 23 km × 15 km.

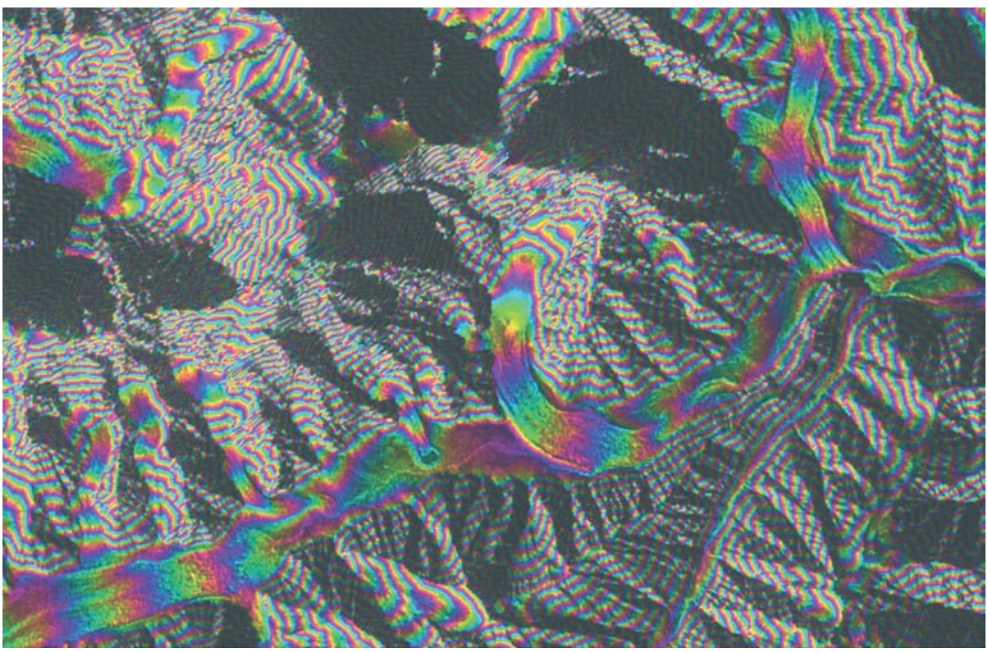

Fig. 3: Geocoded SRTM X-SAR interferometric phase image of Nanga Parbat (NP). The phase is shown in cyclic false colors, the luminance taken from the SAR intensity. One fringe corresponds to app. 175 meters elevation difference.

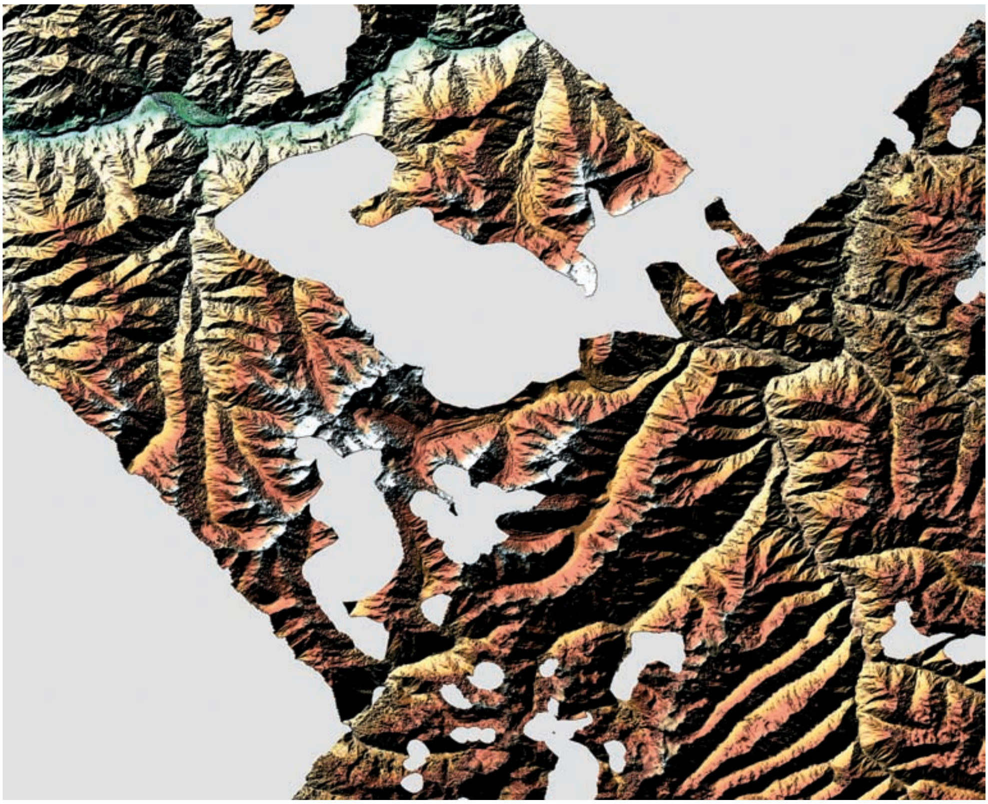

Fig. 4: SRTM X-SAR DEM of larger area round Nanga Parbat (ca. 70 km × 50 km). Not covered areas and problematic areas have been masked by DLR.

However, even if this method succeeded in several experiments it was not used for operational SRTM DEM production at DLR because of the limited experience that was available with it. Furthermore, the method would help with phase unwrapping but would not provide true heights in the shadow area neither could it help to cure the problem of layover. Therefore, as shown in Fig. 4, 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. 5 shows the corresponding area and it can be seen that also there areas are left "white" because of shadow and phase unwrapping problems.

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 on this subject 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

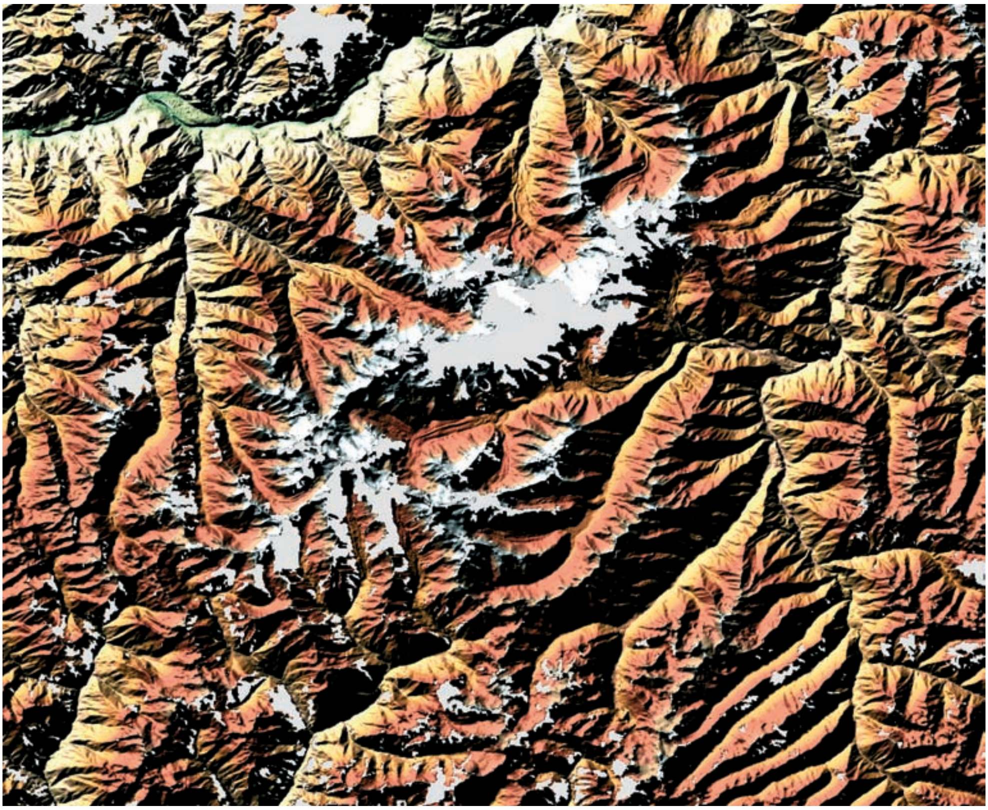

Fig. 5: SRTM C-band DEM of larger area round Nanga Parbat (ca. 70 km × 50 km). Problematic areas have been masked by NASA.

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 (EINEDER & ADAM 2005). 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 commonly done,
- given the three dimensional position of an estimated point on an assumed DEM surface, the slant range coordinates and the expected interferometric phase of this estimate can be determined easily and efficiently (EINEDER 2003a),
- 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 in the vertical direction 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 (Eineder & Adam 2005) and in Fig. 6 the renouncement of phase unwrapping requires a minimum number of observations before the algorithm stabilizes on the correct height.

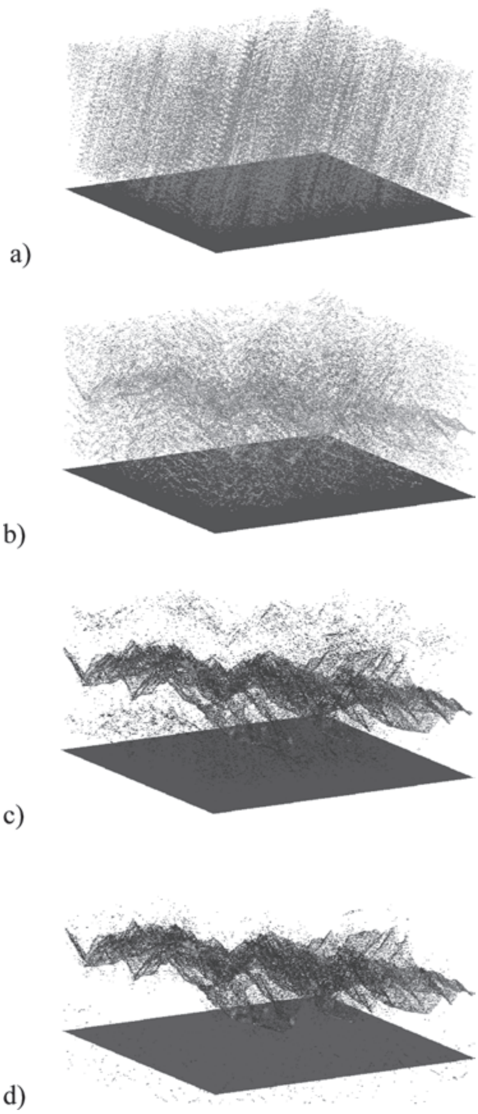

Fig. 6: Digital Elevation Model of Sterzing, Italy, reconstructed from multi-geometry SRTM data using a maximum likelihood approach. Size: 30 km × 15 km. Top to Bottom: improving convergence with increasing number of observations: a) descending X-band; b) descending X-band and ascending C-band; c) X-band and C-band, both in ascending and descending; d) X-band and C-band, both in ascending and descending plus 1 km GLOBE DEM as reference.

Since this generic approach models the radar imaging process and its error sources, it is very well suited for future expansions. For example, neighbourhood relationships that are completely ignored in the current version could be incorporated. Fig. 6 shows how a DEM solution reconstructed from different numbers of interferograms stabilizes with increasing number of observations.

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 (Massonnet et al. 2000) by CNES, an L band satellite constellation by ESA (Zink 2003) and recently TanDEM-X, a constellation of two X-band satellites in formation flight (Moreira et al. 2004).

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 (Eineder 2003b), shadow and layover effects can not be completely avoided but minimized at an incidence angle of 45° or, reduced to a larger extent by combining observations with different viewing geometries.

Fig. 7 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 (Buckreuss et al. 2003), 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 %, if they are combined.

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

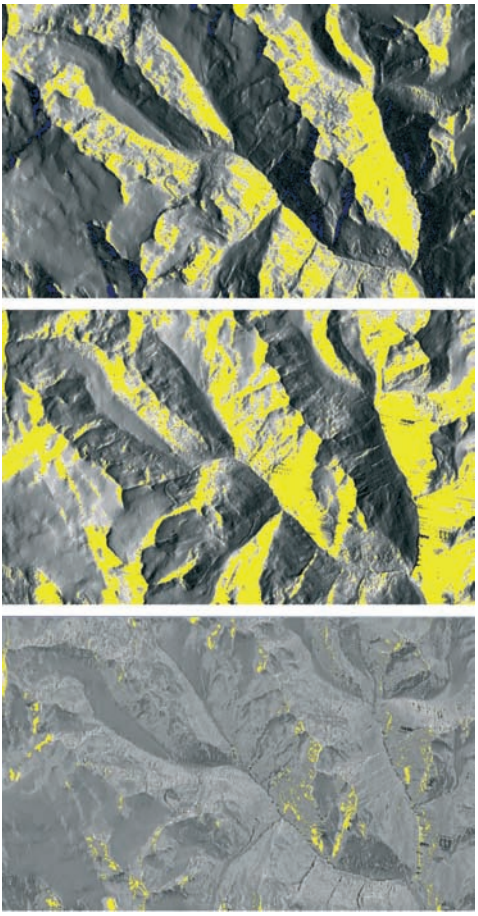

Fig. 7: Simulated shadow and layover areas (yellow) in the steep Ötztal mountains (Austria) for 41° incidence angle descending (top), 30° incidence angle ascending (mid) and a combination of both (middle).

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. Given a fixed baseline, a different effective 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 to achieve multiple wavelengths is to use the wavelength dispersion within the range bandwidth for phase unwrapping (Bamler & Eineder 2005, Veneziani et al. 2004).

5 Summary

While InSAR DEMs are operational over moderate and hilly topography they are not yet reliable in rugged terrain. In order to minimize shadow and layover effects, the viewing geometry must be optimized for single observation to approximately 45°. Multiple observations are required to achieve complete coverage, but then incidence angle combinations different from 45° with either different incidence angles or different aspect angles must be selected. Beneath optimization of the viewing geometry new reconstruction methods based on multiple observations will have to be used in the future. All those options may soon be available with future missions like, e. g. TerraSAR-X in a tandem (Moreira et al. 2004). A configuration which allows precise orbit control, multi mode SAR imaging, large bandwidth and high resolution.

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