Radar remote sensing for surveying and monitoring of earthquakes and mass movements in Southern Kyrgyzstan

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1. Introduction

Kyrgyzstan is landlocked mountainous nation of around five million people, which borders China, Kazakhstan, Tajikistan and Uzbekistan. The total area of high mountainous terrain, alpine meadows and pastures exceeds 70% of the Republic's territory, whereas the greater part of the Kyrgyz Republic is occupied by the Tien-Shan mountains. Kyrgyzstan is a highly active seismic region and has been shaken by numerous significant earthquakes as a consequence of the ongoing collision between the Indian and Eurasian tectonic plates. In the result, the mountainous country is faced with a large variety of natural hazards (mainly earthquakes, large landslides and floods) which frequently lead to the occurrence of natural disaster (e.g., 1994: about 1,000 landslides failed and 115 human fatalities; 2008: Nura earthquake M=6.6, 74 human fatalities and 150 injured, 90 glacial lakes endangered for regularly occurring outburst floods). Under these conditions, there is high demand for efficient and spatially differentiated hazard assessment requiring an improved understanding of natural processes with high hazardous potential. Since large areas with often limited accessibility are affected, satellite remote sensing plays an important role in contributing to improved process knowledge in this region (Roessner et al., 2005). In the presented work the potential of advanced remote sensing techniques based on Synthetic Aperture Radar (SAR) satellite data is investigated for characterizing spatio-temporal surface changes related to mass movement and earthquakes. Methodological focus has been put on using Differential SAR Interferometry (InSAR) based on data from different satellites for detecting surface displacements as a consequence of slope instabilities and earthquakes in Southern Kyrgyzstan. In the presented work we focus on one study site of high landslide activity in the Osh province and on another study site which has been affected by the recent destructive Nura earthquake in 2008 (Fig.1).

Case study 1 – landslides: Osh province is one of the most landslide-prone areas in Central Asia. In this region outlined in Figure 1 topography ranges between 800 m and 3500 m with regular winter snow coverage in the higher areas.

Case study 2 – earthquakes: On 5thOctober of 2008, the 6.6 magnitude Nura earthquake struck Alai region, killing about 74 people, injuring many and destroying dozens of buildings in the southern province of Osh. The area most affected was the village of Nura situated in a mountainous region close to the border with China. Seismic shaking of this earthquake affected large parts of Southern Kyrgyzstan as well as the border region with Uzbekistan, Tajikistan and China.

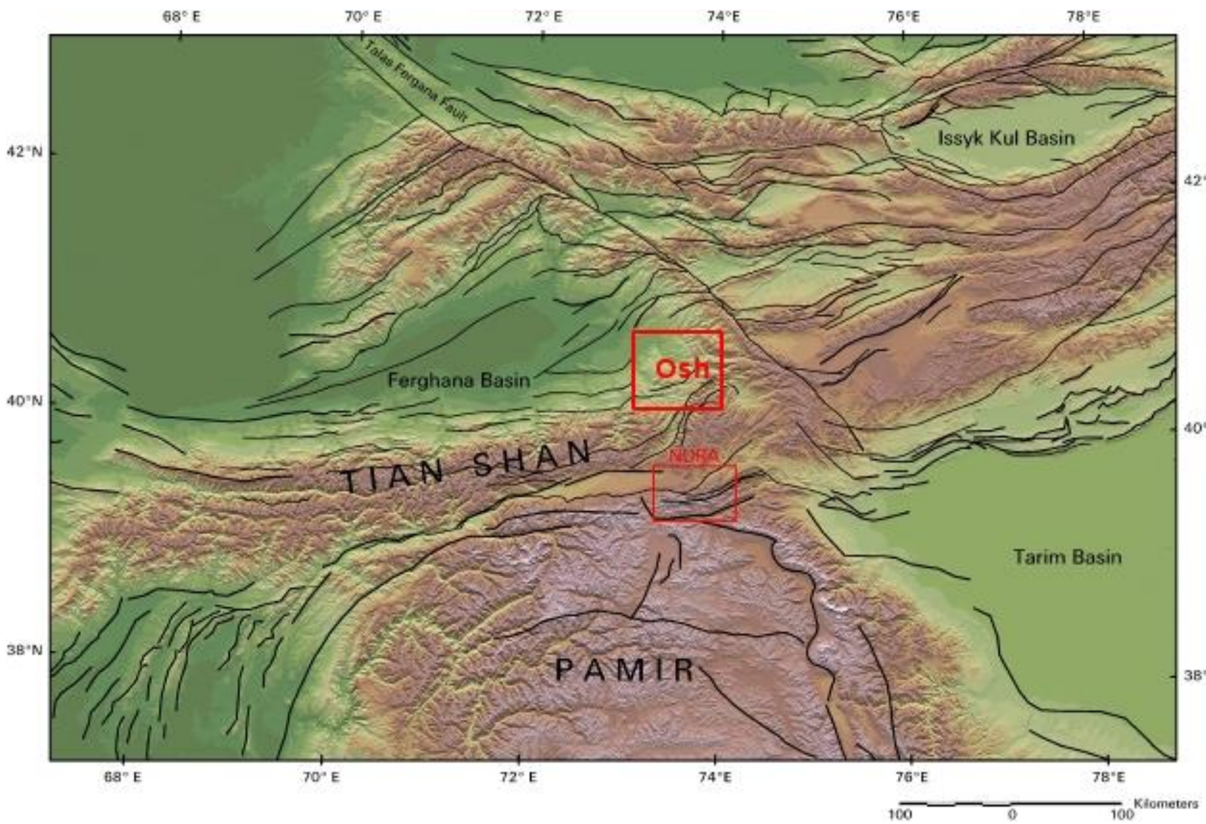

Figure 1. Tectonic map of the Pamir - Tien-Shan region showing the active faults overlaid on the colour-shaded topographic relief based on SRTM data (after Taylor & Yin (2009) and Kalmetieva et. al. (2009). The red boxes indicate the case study areas: Osh province and Nura earthquake.

2. Methodology and remote sensing data

Differential SAR Interferometry (InSAR) allows detecting ground deformation of the Earth’s surface occurring among others in connection with earthquakes and slope instabilities. InSAR extracts such information about the Earth's surface using the phase difference between two SAR images of the same area. These two complex SAR images are taken from slightly different positions by the same antenna at two different acquisition times. Their combination and differentiation according to phase forms the radar interferogram. Differential InSAR comprises of the idea of subtracting the topography-related phase from the interferogram in order to retrieve line-of-sight (LOS) surface displacement. Only in the ideal case of an image pair with a very small baseline, this effect of topographic phase contribution becomes negligible.

In this study InSAR processing has been performed using ALOS-PALSAR and ENVISAT radar data. PALSAR is an L-band sensor onboard the Japanese ALOS Satellite with a wavelength of 23.6 cm and the C-band sensor of the European ENVISAT satellite has a wavelength of 5.6 cm. Thus, PALSAR uses a longer microwave wavelength which is known for achieving good coherence even in densely vegetated areas (Rosen et al. 1996). The ALOS data used in this study were provided by the JAXA ALOS Research Program (Proposal P610). For case 1 – landslides - a total of 26 ascending ALOS/PALSAR raw SAR data sets were received from JAXA covering the study area during the time period between 2007 and 2010. For case 2 – Nura earthquake - we used 22 ascending PALSAR and 10 descending ENVISAT images. InSAR processing has been performed using the SarScape software.

The raw PALSAR scenes were processed to single-look complex (SLC) images. All SLC images were processed in the zero-Doppler coordinate system, simplifying the interferometric processing. The best combinations for InSAR pairs with small baseline were chosen to derive the interferograms. The SRTM DEM (90 m resolution) was used to remove the topographic phase. In order to exclude decorrelated areas from the study, we performed Goldstein filtering. During InSAR analysis, the data were processed in the radar coordinate system obtained by the SAR satellite. In a second step the results were converted to the ground-based UTM coordinate system by using elevation data. In this process, pixels holding information are rearranged according to their longitude and latitude within the UTM coordinate system. For the SAR-based earthquake analysis

InSAR was complemented by the pixel offset method using the SAR amplitude images in order to derive displacements.

3. Results and discussion

3.1 Case 1 – landslides

For this study we selected InSAR datasets with less than 300 m perpendicular baseline and a temporal baseline of less than 14 month. In total, 38 InSAR ALOS/PALSAR pairs from the ascending mode with an off-nadir angle of 34.3 degrees were processed and interferograms were calculated. In the ascending orbits, these side-looking observations are made from the west. Applying the InSAR method, only one-dimensional displacements in the satellite's line of sight can be observed. Therefore, the SAR interferograms only show such displacements where the surface moves towards or away from the satellite along this line of sight. Analysis of the processed interferograms shows very good coherence also for pronounced mountainous terrain and vegetated slopes (Fig. 2). This figure also contains the results which were obtained for this area by analyzing TerraSAR-X data using the same InSAR technique (Motagh et al., 2010). The analyzed time periods comprise of a more than one year period between July 2008 and August 2009 for ALOS and an 11 days period in August 2009 for the TerraSAR-X data which is embedded within the ALOS time period (Fig. 2).

The results show that ALOS/PALSAR maintains very good coherence even during a long period of time of more than one year in this mountainous and vegetated area. Thus, the data area suitable for mapping mobilization of slopes related to landslides. So far, for the study area 18 of such areas could be identified for the analyzed three years time period of ALOS-PALSAR data availability. They still need to be verified using results obtained from interpretation of optical satellite remote sensing data and field investigations carried out in September of 2011 and 2012. Comparison with results obtained by TerraSAR-X data analysis show that mobilization was detected in the same area. Due to the short analyzed time period of 11 days, only one smaller area was identified. Thus, it can be concluded that the results obtained by the two systems are consistent and can be used complementary in order to assess short- and long-term landslide activity in this area. In this context it would be desirable to analyze ascending and descending interferograms for the same area and time period in order to increase the extent of slopes for which InSAR can be applied successfully to monitor mass movement (Motagh, et al., 2010).

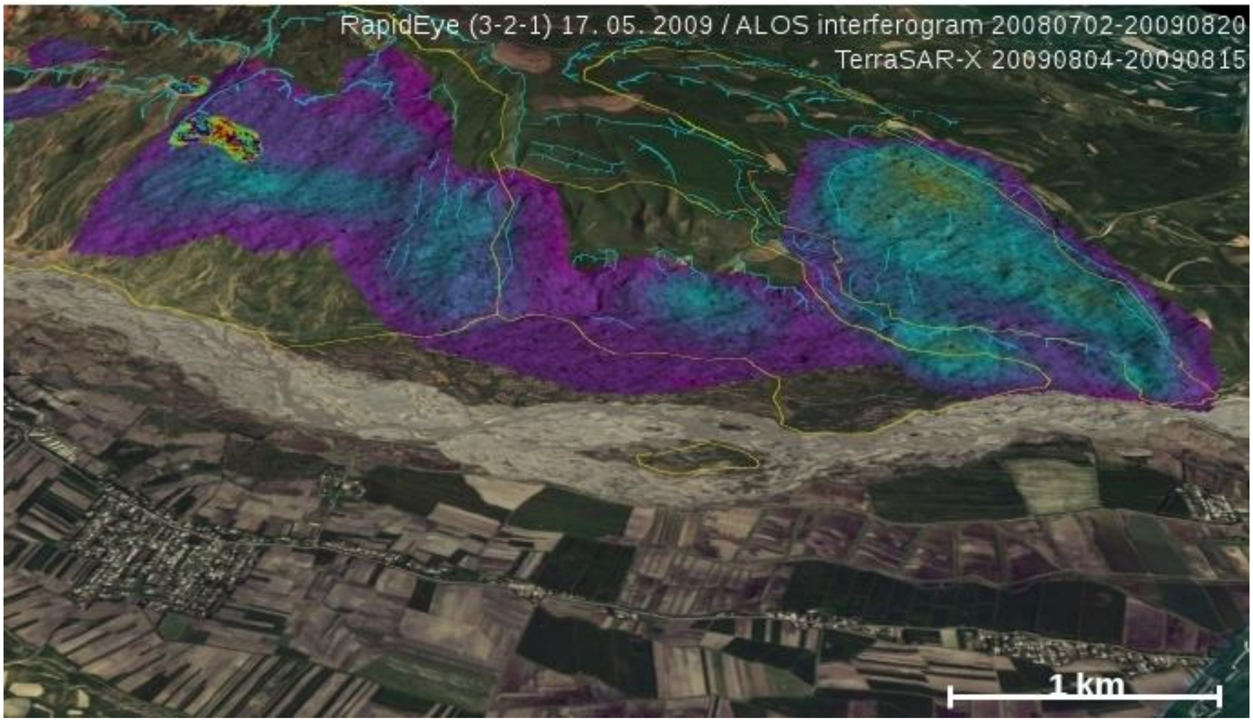

Figure 2. View of landslide prone slope near Uzgen, Osh province. Results from ALOS/PALSAR showing mobilization of entire slope (blue to violet color) and compared with TerraSAR-X results which show a local slope failure (upper left corner color changes from green to red).

3.2 Case 2 – Nura earthquake

For this study we selected suitable InSAR ALOS PALSAR datasets with less than 250 m perpendicular baseline and a temporal baseline with less than 30 month. In total, seven InSAR pairs were processed and interferograms were calculated. Additionally, suitable ENVISAT datasets were selected applying the same baseline constraints. In the result 10 descending ENVISAT images were processed.

The Nura earthquake has been situated in the area of the water divide between the Tarim and the Tadjik west basin. Applying the InSAR technique to the earthquake area has resulted in reliable deformation measurements mostly on the footwall of the Frontal Pamir Thrust in the eastern part of Alai valley (Fig.3). In particular, the ENVISAT data are strongly suffering from layover originating from the surrounding area of high topographic relief and steep slopes. Additionally, in the area close to the epicentre of the Nura earthquake the interferometric phase is highly decorrelated in all interferograms, most likely due to snow coverage. In the ascending ALOS interferograms we measure a large and sudden change of negative and positive line-of-sight displacements that amount to about -36 cm and 48 cm, respectively in the area north-east of the ep-icenter at the footwall of the Irkeshtam thrust fault. In contrast, in the corresponding descending ENVISAT interferogram in total there are only two fringes visible which compare to ~6 cm line-of-sight displacement. Such large differences in the measured line-of-sight displacements between ascending and descending images are to be expected only for a considerable amount of horizontal deformation. Some far-field deformation can be observed in both interferograms (Teshebaeva et al., 2012).

Due to the described limitations of the InSAR methods for the Nura area, pixel offset measurements using the SAR amplitude images has been carried out in addition to the displacement measurements of InSAR. However, they are often strongly affected by noise. Our offset measurements in azimuth direction (the satellite flight direction) using the ALOS data show a clear left-lateral component of movement at the Irkeshtam thrust fault (Fig. 3). This observation is supported by the azimuth offset measurements using the descending ENVISAT data. Even though their quality is poorer compared to the results obtained from the ALOS data, they also show a clear change in the azimuthal offsets across the Irkeshtam thrust fault. These changes have the opposite leading sign compared to the ALOS azimuth offsets, which is to be expected due to the nearly opposite flight direction (Fig.3). The settlement Nura destroyed by the earthquake is located close to the outcropping of the Irkeshtam thrust fault. At this location we measured the highest structural displacement situated at the footwall of the so far defined Frontal Pamir Thrust using both of the described SAR based remote sensing methods.

The results from surface displacement, pixel offset measurements and the distribution of seismic aftershocks (Krumbiegel et al., 2011) allow the determination of an active thrusted part limited by a very prominent topography gradient defined as co-seismic active inverse faults partly with slip components. These findings are in accordance with the results from previous geodynamic investigations in this region. Recent studies of Strecker et al. (2003), Burtman (2000), Arrowsmith and Strecker (1999), Burtman and Molnar (1993), Nikonov et el. (1983), Davidzon et al.(1982) reveal the active closure of the Alai Valley for late Pleistocene up to recent times which is concurrent with GPS data analysis carried out by Zubovich et al. (2010), Mohadjer et al. (2010), Reigber et al. (2001). Thus, these investigations underline the definition of the most active segment of the Pamir-Alay collisional structure. The obtained results suggest the existence of an active fault pattern of constructional upthrusting strain which may be interpreted as recently formed active wedge and possibly as northward propagation at the eastern termination of the Alai Valley into its footwall.

Ongoing work is focussing on detailed analysis of the deformation patterns and on source model estimation of the Nura earthquake. The expected results will support studies of stress change caused by the earthquake and analyses of active tectonics in the area. Thus, they will contribute to an improved understanding of surface manifestation of seismic activity in this high mountainous area in support of improved seismic hazard assessment.

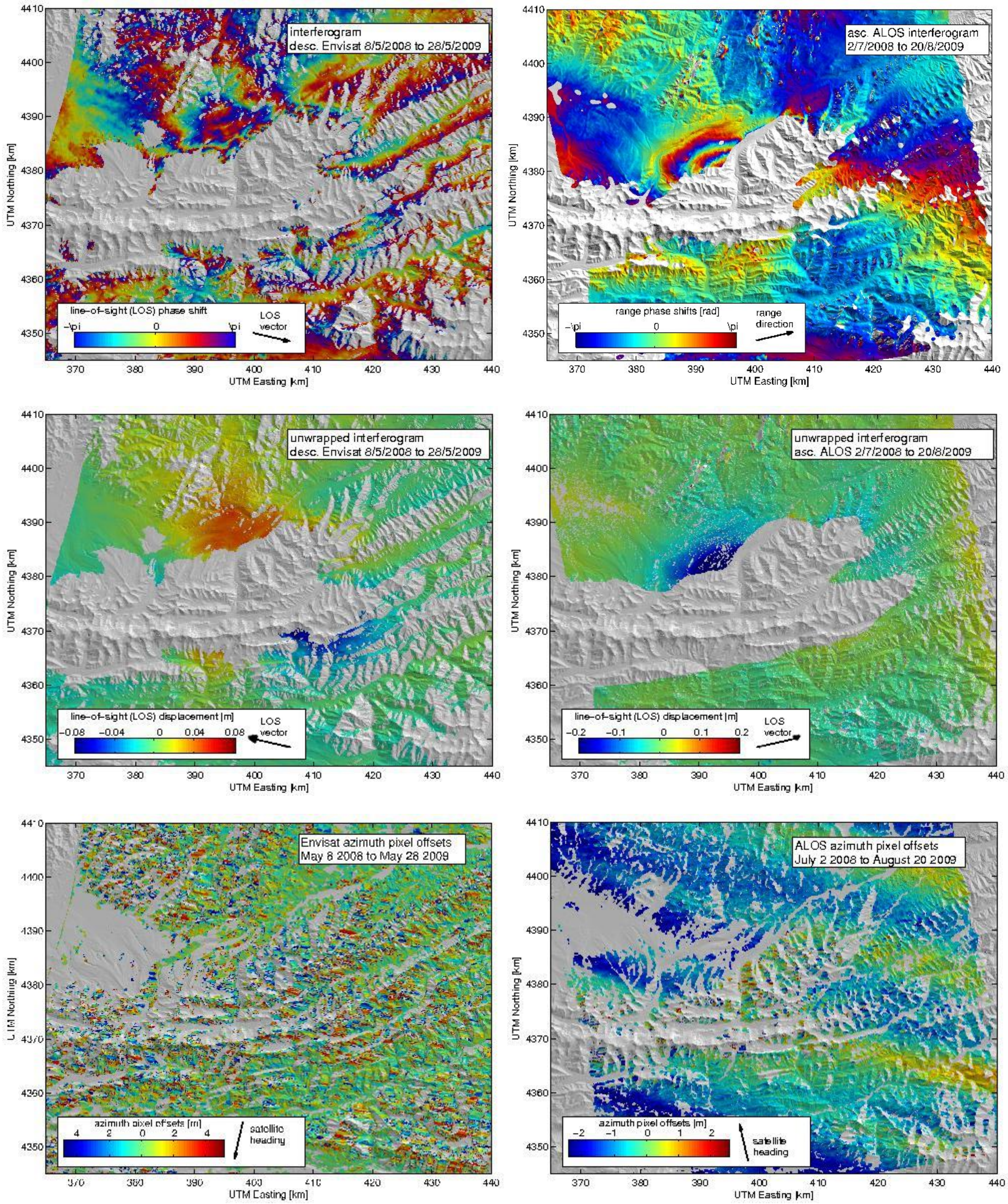

Figure 3. Surface displacement measurements from SAR products of (right panels) ALOS satellite (L-band sensor, wavelength 23.6 cm) and (left panels) ENVISAT satellite (C-band sensor, wavelength 5.6 cm). Interferograms (top panels) are filtered and areas of incoherent interferometric phase are masked. Middle panels show unwrapped interferograms and right panels azimuth pixel offset measurements, corresponding to horizontal movement on the surface in the satellite's flight direction.

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