ABSTRACT

We investigated two landslides in the Northern Caucasus above railroad tunnels near the Kepsha and Mamayka villages using the StaMPS software. We discuss approaches to careful selection of processing strategy that is especially important in mountainous highly vegetated areas. For the rural Kepsha area we incorporated ALOS, Envisat (both ascending and descending), and TerraSAR images. For the mostly urban Mamayka area we used Envisat and TSX images. For the Kepsha landslide we found that average displacement rate in the line of site (LOS) direction (mean LOS velocity - $V_{LOS}$) do not exceed 10 mm/year, i.e. the Kepsha landslide has been stable since at least 2004. Mamayka landslide appeared to be much more active. Mean LOS velocities in the active area reach 60 mm/year. Corner reflector installed in the rural area above the tunnel permitted us to estimate $V_{LOS}$ equal to 49 mm/year.

1. INTRODUCTION

Landslides are numerous in the Great Caucasus and problems of landslide risk assessment are of vital importance. Repeat-pass satellite SAR interferometry (InSAR) is now widely used to monitor small ground deformations. In order to investigate ground displacements, a pair of satellite SAR images of a study area from the same track is processed to form an interferogram which shows phase shift of the reflected signal between acquisitions. Temporal changes of scattering properties of the Earth’s surface and look angle direction reduce the efficiency of SAR interferometry. Besides, the signal due to displacement of the ground reflectors is often overprinted by atmospheric noise and artefacts caused by inaccuracy of satellite orbit and digital elevation model (DEM).

Advanced techniques based on simultaneous processing of series of SAR acquisitions make it possible to mitigate problems of conventional InSAR. One category of algorithms for processing multiple acquisitions is so-called Persistent Scatterers (PS) methods. The main principle of these methods is in simultaneous analysis of a number of pair interferograms, considering only those pixels that retain some “stable behaviour”. The main difference to existing PS-InSAR methods is in mathematical definition of the quoted term. There exist a number of persistent scatterers processing methods (e.g. [1]-[6]). In all the above mentioned techniques identification of an initial set of PS pixels is based on analysis of their amplitude in a series of interferograms. This approach is especially efficient in urban areas where man-made structures increase the likelihood of finding of non-fluctuating scatterers. Although density of PS pixels identified by this technique in natural terrains is much lower there exist a number of examples of successful implementation of this technique for monitoring of ground displacements of natural objects, in particular, landslides (e.g. [7]-[12] and others).

For PS-InSAR processing we used the StaMPS software (Stanford Method for Persistent Scatterers) which was developed particularly for non urban areas dominating in the Great Caucasus. We incorporated ALOS, Envisat (ascending and descending tracks) and TerraSAR-X acquisitions covering different time periods.

First we discuss the study areas – the Kepsha and Mamayka landslides and existing SAR data. Then we briefly describe the method, general strategy and some specific approaches to data processing in the areas under study. Finally we present results of calculations and their interpretation.

2. METHOD AND ITS APPLICATION

The StaMPS [13] has proven to be effective in low coherence areas. For applications in non-urban environments it is advantageous that StaMPS finds PS using spatial correlation of interferometric phase. Initial PS candidates are selected based on the analysis of their amplitude using the amplitude dispersion [2]. The phase stability of each of these candidates is then a subject of
phase analysis using temporal coherence measure of the variation of the phase residual to characterize PS quality. Finally, pixels are selected based on the probability of being PS calculated from the amplitude dispersion and temporal coherence. StaMPS also includes advanced algorithms for damping of artefacts caused by atmosphere and DEM errors, as well as 3D unwrapping [14].

In practice when using StaMPS one has to crop study area and assign parameters to filter orbital, atmosphere and DEM errors, to drop images with high noise level and set a «reference area» relative to which displacements are calculated. When coherence is relatively low and small quantity of images is available the results are sensitive to processing strategy. Discussion on setting parameters can be found in the StaMPS Manual [15]. Below we consider approaches which we used for some parameters selection for the particular cases.

Image crop. Results of calculations in mountainous areas sometimes depend upon cropping of a study area. Varying crop size one incorporates areas with different topography drops, includes or excludes high mountain peaks or valleys where strong atmosphere perturbations occur. Optimal crop should be small enough to minimize topography variations within it and also reduce processing time but it should be large enough to avoid boundary effects. Thus, for the Kepsha landslide we cut off a rectangular area of 3500 lines (azimuth) and 700 pixels (range) from Envisat, 4700 lines and 800 pixels from ALOS, 3000 and 3000 pixels from TSX images. For Mamayka landslide the sizes of crops were as follows: Envisat - 2500 lines and 500 pixels, TSX - 2000 lines and 2000 pixels. These crops are much larger than the study areas, hence preventing edge effects. The results for Mamayka do not depend upon cropping as topography of the study area is rather smooth and not high.

Master image selection. In PS technique all images in each set are to be coregistered with a single so-called “master” image. In order to select the master image we first selected several images with low baseline values (perpendicular and temporal) and the mean Doppler centroid frequency difference using a functional suggested in [14]). Then we calculated interferograms and corresponding coherence maps for each of these candidate masters with all the other images in the set. Finally we selected as the master the image whose interferograms had shown the best mean coherence in the study area for all the interferograms. This approach allows considering not only the geometry of acquisitions but also impact of atmosphere, vegetation and snow cover.

It is worthwhile to note that “master image” selection has been done for every particular crop because coherence in different parts of the images varies. This is due to the fact that some parts of the images cover urban territories showing poor dependence of coherence upon periods of vegetation while coherence in the areas covered by forests strongly depend upon seasons. Snow covers high mountains in winter, while in low topography areas snow retains only for few days. This leads to better coherence of winter images in the coastal parts and low topography areas compared to summer images. Thus, “master images” selected for different crops may not be the same.

DEM. In order to subtract the topographic phase from the interferograms we tried three different DEMs: SRTM3, ACE-2 and Aster. For the Kepsha landslide we compared values of all three DEMs in a number of points with heights from ground topographic maps considered to be “ground truth”. Height differences between DEMs and ground map data exceed 30 m in the gill along the eastern boundary of the landslide. The resolution of ACE-2 and SRTM3 is the same (90m), but SRTM3 has gaps near the western part of the Kepsha landslide in the Mzymta canyon. The DEM gaps cause errors that can propagate to the study area. Resolution of the Aster DEM is much better (30m) but in the central part of the Kepsha landslide it differs from both ground geodesy, SRTM and ACE-2 DEM for about 8-10 m. The Aster DEM is based on optical sensor data, hence, in densely vegetated areas this DEM follows tops of the plants. The Kepsha study area is almost fully covered with different types of vegetation so, finally, we proceeded for Kepsha with the ACE-2 DEM and for much less vegetated Mamayka - with Aster DEM.

Reference area. By default, StaMPS relates PS displacements to the mean phase shift of the crop which is assumed to be close to zero. If mean phase shift of a crop is different from zero then calculated displacements will be underestimated or overestimated. That is why we looked for a reference area that was (1) stable during the acquisitions period and (2) close enough to the landslide so that artefacts (e.g. atmospheric) in both areas are to be almost the same. As the Kepsha area is one of extensive construction sites of the Sochi Olympics facilities we failed to get a priori information about stable targets and determined the reference area based on calculations of coherence.

First using all images we localized pixels with high average coherence assuming that highly coherent pixels most likely coincide with comparatively stable objects. In general, not every highly coherent pixel will be identified as PS by StaMPS due to specific procedures applied, and, thus, can be treated as a reference area. We chose candidate areas that incorporate no more than 3 PS. Then considering every candidate area in turn, we calculated time series for the PS in that area with respect to every other candidate area. If time series for PS from a candidate area always show noticeable trends or high velocity dispersion then it cannot be considered as
stable. If the PS time series with respect to some areas display negligible relative displacements and small dispersion of velocities, we conclude that these areas can be regarded as stable and treated as reference areas. In general the best reference area need not be the same for acquisitions from different satellites and tracks. Therefore, we applied this procedure for Kepsha for Envisat and ALOS sets of images presented in Fig. 4. TSX images are more detailed and span short time period, thus, it appeared possible to fix targets which can be considered stable during the time of observations and used as a reference area for this case.

As mentioned above, when there are few coherent man-made structures and short series of images, the results obtained may depend upon the processing strategy and chosen parameters. To mitigate this effect we performed multiple calculation varying parameters until maximum number of PS were selected in the study area while the dispersion of their mean velocities was kept to a minimum. The best results (in sense of this criterion) are presented below.

3. DATA

We investigated two landslides at the foothills of the Northern Caucasus: (1) in the Mamayka village near the Black Sea beach above the tunnel of the Tuapse-Sochi railroad and (2) near the Kepsha village in the vicinity of the new railroad and highway from the Sochi airport up to the Sochi 2014 Olympic Games site in Krasnaya Polyana (Fig. 1). In both regions landslide bodies are formed of seasonally saturated clays or loams covering stable marl and limestone rocks.

The conditions for application of SAR interferometry for these two landslides are very different. The Mamayka landslide is located in a highly populated area with lots of facilities being good reflectors while the Kepsha landslide is in rural area and few reflectors can be revealed. There are no any ground measurements of the present landslides’ deformations. Thus, for both landslides we had to incorporate indirect evidences to control results of SAR processing.

3.1. Kepsha landslide

Size of the landslide slope is approximately 500x800m; its topography is rather complex being steeper in the upper part of the slope and broken by many gills. The landslide is fully covered by vegetation (Fig. 2); old, tall and wide trees alternate here with bushes and subtropical plants. Topography in the vicinity of the Kepsha landslide is very much dissected, heights range within 200 to 1200m. There are very few man-made structures on the landslide, thus conditions for SAR interferometry are not favourable.

The landslide is not homogeneous, being composed of several bodies. According to geological data some of them has been moving mostly N-NE, however, there are some parts moving to N-NW, especially at the foot of the slope. As SAR interferometry is not sensitive to displacements parallel to the satellite orbit, data from ascending tracks are more favourable to monitor N-NE displacements while data from descending tracks are more sensitive to N-NW displacements. Hence we used data from both tracks in this study.

Figure 2. Kepsha landslide from the North

Figure 3. Geometry of SAR acquisitions for the Kepsha landslide
To investigate landslide displacements we employed C-band Envisat (5.6 cm), L-band ALOS (23.4 cm) and starting with 2012 - X-band TerraSAR-X (3.1 cm) images. Fig.3 shows the geometry of acquisitions and frames of the satellite images. For acquisition times and baselines see Fig.4.

Envisat track 85A images span the period 08. 2004 - 02.2009, which partly overlaps the time period of 18 ALOS images from track 588A (01.2007 – 09.2010). Because of ENVISAT orbit transfer manoeuvre in October 2010 images from track 35D were divided into two sets: 11.2007-07.2010 and 11.2010-03.2012 containing 12 and 13 images respectively. As ALOS and Envisat missions were terminated in 2011 and 2012 respectively we also incorporated data from the TerraSAR -X track 107D which span the time period 07.2012-05.2013.

Results of calculations. Figures 5-9 demonstrate results of StaMPS processing for all sets of images shown in Fig.4, specifically distribution of the PS over the landslide slope and mean LOS values \( (V_{LOS}) \) for them. The reference area was selected according to the procedure described above and is marked by asterisk in the plots. In general, estimates of dispersion do not exceed 3 mm/year and only for ALOS reach 5 mm/year.

Envisat track 85A, 11 images 28.05.2006-01.02.2009. (Fig.5). 4569 PS were identified in our crop area, 27 of them being at the landslide slope.

ALOS track 588A, 18 images 22. 01.2007-17.09.2010 (Fig. 6). Total number of identified PS in the crop is 14630, 27 of which were in the study area.

Envisat track 35D, images 01.11.2007- 08.07.2010 (Fig.7). Within the crop 5131 PS were revealed with 29 PS being in the study area.

Envisat track 35D, images 29.11 2010 - 23.03.2012 (Fig.8). Reference area for these images is the same as for the images before October 2010. Totally 2340 PS were identified in the crop, 41 of them being in the study area.

TerraSAR-X track 107D images 13.07.2012-17.05.2013.(Fig.9). Quantity of PS for the whole crop is 4630 with 92 PS on the study slope.

Figure 4. SAR data used for the Kepsha landslide. Vertical dashed lines mark acquisition time of master images.

Figure 5. PS above the Kepsha landslide slope identified using  Envisat 85A images (05.2006-02.2009). Landslide slope is marked by yellow dashed line. Green circles - PS which \( V_{LOS} \) do not exceed dispersion estimates. Red circles - PS moving away from the satellite (negative \( V_{LOS} \) values). Reference area is marked by asterisk. Small values of \( V_{LOS} \) demonstrate stability of the slope.

Figure 6. The same as in Fig.5 for ALOS track 588A images 01.07- 09.2010. Blue circles - PS moving towards the satellite (positive \( V_{LOS} \) values).
2.2. Mamayka landslide

The size of the Mamayka landslide is approximately the same as the Kepsha one: about 600x800m, but topography is rather smooth, heights vary from 0 to 300 m. Landslide is located in highly populated area with lots of facilities being good reflectors. So the conditions for SAR interferometry are much better than for the Kepsha landslide. The target of monitoring was the railway tunnel in the landslide body. (Fig.10)

Envisat images from tracks 85A and 35D shown in Fig.4 cover the Mamayka landslide as well so we processed the same data sets. Although a lot of PS were identified on the landslide slope (comparing to Kepsha) but no PS were found in the areas where active deformations had been fixed at the surface. We located only small zones of displacements with $V_{\text{LOS}}$ up to 10mm/year. So we do not present here these results.

Starting with 2011 we incorporated TerraSAR images from track 54A spanning the period 24.12.2011-24.05.2013 (Fig.11).

The set of TerraSAR images includes images from both
TerraSAR-X and TanDEM-X missions, the later is characterised by large spatial baselines. Our attempts to obtain reliable results using StaMPS PS processing for the whole set of 38 images was not successful. Incorporation of StaMPS Small Baselines (SB) processing appeared to be fruitful. We used 152 pairs and identified 117306 PS in our crop.

The lower part of the landslide above the railway tunnel is rural. No reflectors have been found there. On November 22, 2012 we installed there a corner reflector (CR) (Fig.12). The CR with a 1m edge was made from black metal and painted.

4. DISCUSSION

As it was expected quantity of PS identified for Mamayka far exceeds those for Kepsha, although for Kepsha we also managed to identify sufficient quantity of persistent scatterers to evaluate displacements. Location of PS on the Kepsha landslide is not the same for all the satellites because we used data from sensors with various wavelengths, both ascending and descending tracks spanning different periods of time. During 2009 forest was cut in the lower part the landslide slope to install electric power line equipment and also construction camp was build in the northern part of the study area (compare Fig. 6,7 and 8,9). As a result many new PS were identified there when
processing Envisat images from track 35D (29.11 2010 - 23.03.2012) and TerraSAR track 107D images 13.07.2012-16.01.2013. (Fig.8,9). That made it possible to use also images from TerraSAR -X to monitor displacements of the Kepsha landslide.

For the Kepsha landslide \( V_{\text{LOS}} \) for all data sets does not exceed 10 mm/year (Fig.5-9) (except ALOS data set having 3 PS with a just little higher values in the lower part of the slope in the area of wood cutting. Dispersion of velocity values for all data does not exceed 3-5mm/year. That means that the Kepsha landslide has been more or less stable since at least 2004. Cutting woods in the lower part of the landslide and exploitation of the railroad tunnel constructed in the landslide body may increase landslide activity, thus, continuous surface and satellite monitoring is very important. To compare results obtained from different tracks with different LOS direction we suggested and used approach based on assumptions about direction of landslide movement. In particular, if PS in the central part of the Kepsha landslide moves down the slope parallel to topography gradient, its LOS displacement is negative for ascending track and positive for descending one (see Fig.7 for example). Description of this approach is a subject of special publication which is now under preparation.

Mamayka landslide appeared to be much more active. Incorporation of TerraSAR images permitted us to locate active area above the railway tunnel with \( V_{\text{LOS}} \) up to 60 mm/year (Fig.14). The size of this area is about 300x300m. Surface deformations there are shown in Fig. 15.

![Figure 15. Surface deformations in the vicinity of the check point 3 on the Mamayka landslide.](image)

PS-INSAR monitoring of surface displacements in mountainous and densely vegetated areas demands a careful justification of processing strategy and parameters choice. Selection of crop and reference area is of particular importance. All results for Kepsha were obtained when setting reference area in accordance with the procedure described in section 2. The suggested procedure of reference area selection may be useful in rural mountainous areas with no information about stable units. For the Mamayka landslide with comparatively low topography and plenty of PS reference area selection appeared not to be so important. For the mostly urban area of the Mamayka landslide the best results were obtained using TSX data, while for the rural Kepsha landslide joint analysis of data from different satellites with different wavelengths is preferable.

5. CONCLUSION

Although environmental conditions of the North Caucasus are not favourable for application of SAR interferometry, obtained results demonstrate that satellite monitoring is an efficient tool for landslide monitoring. As landslides are numerous in the North Caucasus satellite monitoring could contribute to landslide risk assessment and mitigation.

Images from L-band, C-band and X-band satellites can be used to monitor displacements of the landslides in the mountainous areas of the Northern Caucasus. To get reliable results comparative analysis of results obtained from satellites with different wavelengths is preferable.

In mountainous highly vegetated areas careful selection of processing parameters is necessary. This promotes damping of nuisance signals. Suggested approaches permitted us to obtain LOS velocity values using datasets from different satellites and both ascending and descending tracks being in good agreement.

Experiments showed that corner reflectors in rural areas may be very helpful and ground control is necessary everywhere for verification and interpretation of results.

Acknowledgments. Authors acknowledge the European Space Agency ESA (project C1-7991), the Japanese Space Agency JAXA and Deutsches Zentrum für Luft- und Raumfahrt DLR (project LAN1247) who kindly supplied us with SAR data for this study. This study was partly supported by RFBR research project 12-05-31127.

6. REFERENCES


