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IPL Project (IPL - 221) Annual Report

1 January 2022 to 31 December 2022

1. **IPL-221 (2017) Title**: PS continuous streaming for landslide monitoring and mapping
2. **Main Project Fields**:
   (X) Technology Development
   X. Monitoring and Early Warning,
3. **Name of Project leader**
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   Matteo del Soldato, Research Assistant, DST-UNIFI

5. Objectives

The main objective of this project is to perform the transition from historical analysis of radar satellite image archives to monitoring of ground deformation at wide scale using radar satellite scenes. To accomplish this objective the global coverage, the short revisiting time and regularity of acquisitions of Sentinel-1 constellation of SAR (Synthetic Aperture Radar) satellite sensors were exploited.

6. Study Area

The area of Lake Sarez (Figure 1) is a particularly relevant site, being affected by different hazards (seismic, landslide, flood) with the potential for cascading effects: indeed, Tajikistan is located in one of the most seismically active regions of the world (Droz and Spasic-Gril 2002) within the Euro-Asian and Indian tectonic plates collision zone (Ischuk 2011). Located in the Rushan and Murgab districts of Gorno-Badakhshan Autonomous Oblast (Pamirs, Tajikistan) along the Murghab River, the Usoi dam (Figure 1), is one of the most hazardous situations in the Country. The impounded Lake Sarez, with its 500 m of depth, is the world deepest landslide-dammed lake (Costa and Schuster 1991). The area is characterized by a highland plateau at 3500 – 5000 m a.s.l. with a few warm periods and long severe winters with the presence of snow for most of the year.

Lake Sarez (Figure 2), 60 km long and with a stored volume of about 17 billion m^3, originated on February 18, 1911, when a MW 7.7 earthquake generated a giant wedge-failure of about 2.2 billion m^3 of rock and debris that blocked the Murgab River and a tributary valley, forming the 560 m high Usoi dam, impounding Lake Sarez and creating the smaller Lake Shadau. The blockage, named after the small village with 54 inhabitants that was buried, is 5 km long and 4 km wide and blocks the Murghab River at an elevation of higher than 3000 m.

After the earthquake in 1911, the area drew immediate attention and, despite the inaccessibility and remoteness, some researchers started preliminary studies estimating the volume, around 2.2 km^3 and the mass, 6x109 tons. Based on these data, Preobrazhenskiy (1920) and Galitzin (1915) calculated the potential energy released by the landslide and concluded that it would be sufficient to produce the seismic amplitudes recorded on the Pulkova seismic station ~3800 km away (Kulikova et al. 2016).

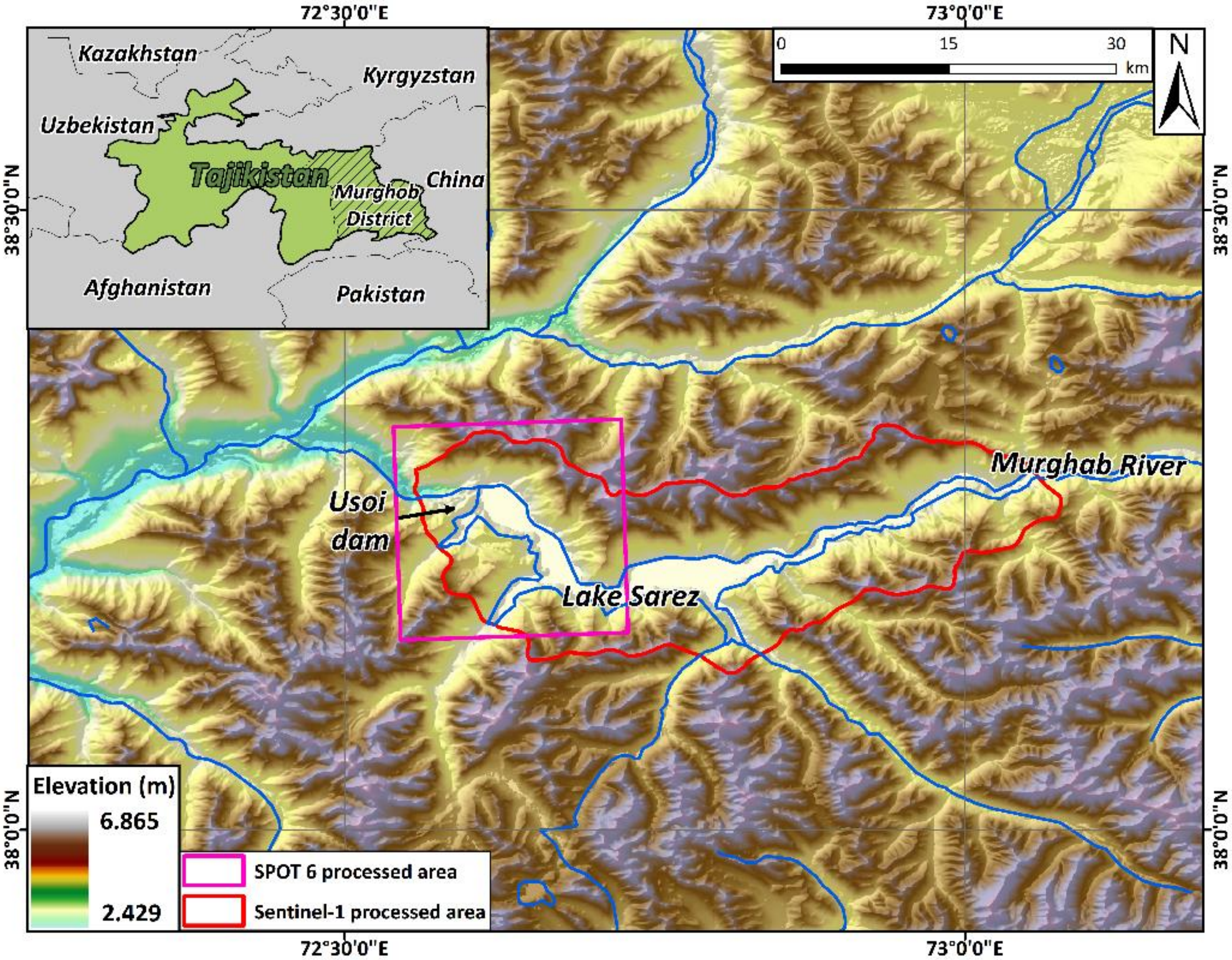

Figure 1 – Localization of the Usoi dam and Lake Sarez within the Murghab River valley in eastern Tajikistan. The extension of the areas processed with Sentinel-1 and SPOT images is also indicated.

From a geological point of view, the main part of the landslide body consists of terrigenous carbonate deposits with quartzite, sandstone and schist of the Carboniferous Sarez Formation and the northern part is composed of marble and shale with subordinate gypsum, anhydrite, and dolomite of the Perm-Triassic age (Ischuk 2006). There is no information about the internal composition of the dam. Due to the landslide, the river has been completely blocked without the capability to cut the landslide deposits to create a natural outlet. However, around 1914 the water found its way through the landslide deposit in the uppermost and most permeable part of the dam generating a spring about 140 m below the water level (Strom 2010). Since 1925, significant filtration from the dam was observed and has created a canyon in the landslide dam. The lake level is currently rising at an average of 0.2 meters per year (Schuster and Alford, 2004), and approximately 50 to 60 m^3/s of water leaks through the dam body (Risley et al. 2006), rising to 85 m^3/s during flood periods, when the water level increases (UN International Strategy for Disaster Reduction, 2010).

Both the left and right sides of the bank have the same rock composition and belong to the Carboniferous Sarez Formation, with the left one being less complex from a tectonical point of view. Both sides are affected by slope movements (Figure 2).

In the worst-case scenario that assumes the collapse of the dam (extremely unlikely), a catastrophic outburst flood from Lake Sarez would destroy the villages and infrastructure in the Amu Darya basin between the lake and the Aral Sea, endangering tens or possibly hundreds of thousands of people in the Murgab, Bartang, Panj, and Amu Darya valleys downstream across a distance of over 2000 km. The most endangered people would be those in the villages and towns along the lower Bartang River in Tajikistan (Barchidiv, Supomji, Shojan, Rushan) and along the Panj River, which forms the Tajik–Afghan border, because these mountain valleys are narrow and there would be short warning times. An assessment of the flood scenario is presented by Schuster and Alford (2004). The general evaluation of the dam and the slope stabilities with detailed geotechnical studies and using modern methods and equipment were found necessary.

Currently, the Lake Sarez Risk Mitigation Project, funded by the World Bank, has been created and has the aim to try to reduce the landslide risk, setting up an early warning system with the idea of making people aware of the risk and the impact that an event could cause, to ensure that inhabitants know how to behave during a possible emergency (Droz and Spasic-Gril 2006), and for this reason the dam and the lake banks are closely monitored with in situ instruments. The monitoring network and the early warning system are expected to protect the villages located along the Murgab and the Bartang rivers and reduce the vulnerability of the population to natural disasters, including the potential outburst of Lake Sarez. Due to the enormous consequence that a possible event could entail, it is important to take into account the relevant data that occurred in the area until the present day, and the landslide has obtained significant attention from the scientific community (Papyrin 2001; Kazakov 2004; Ischuk 2006).

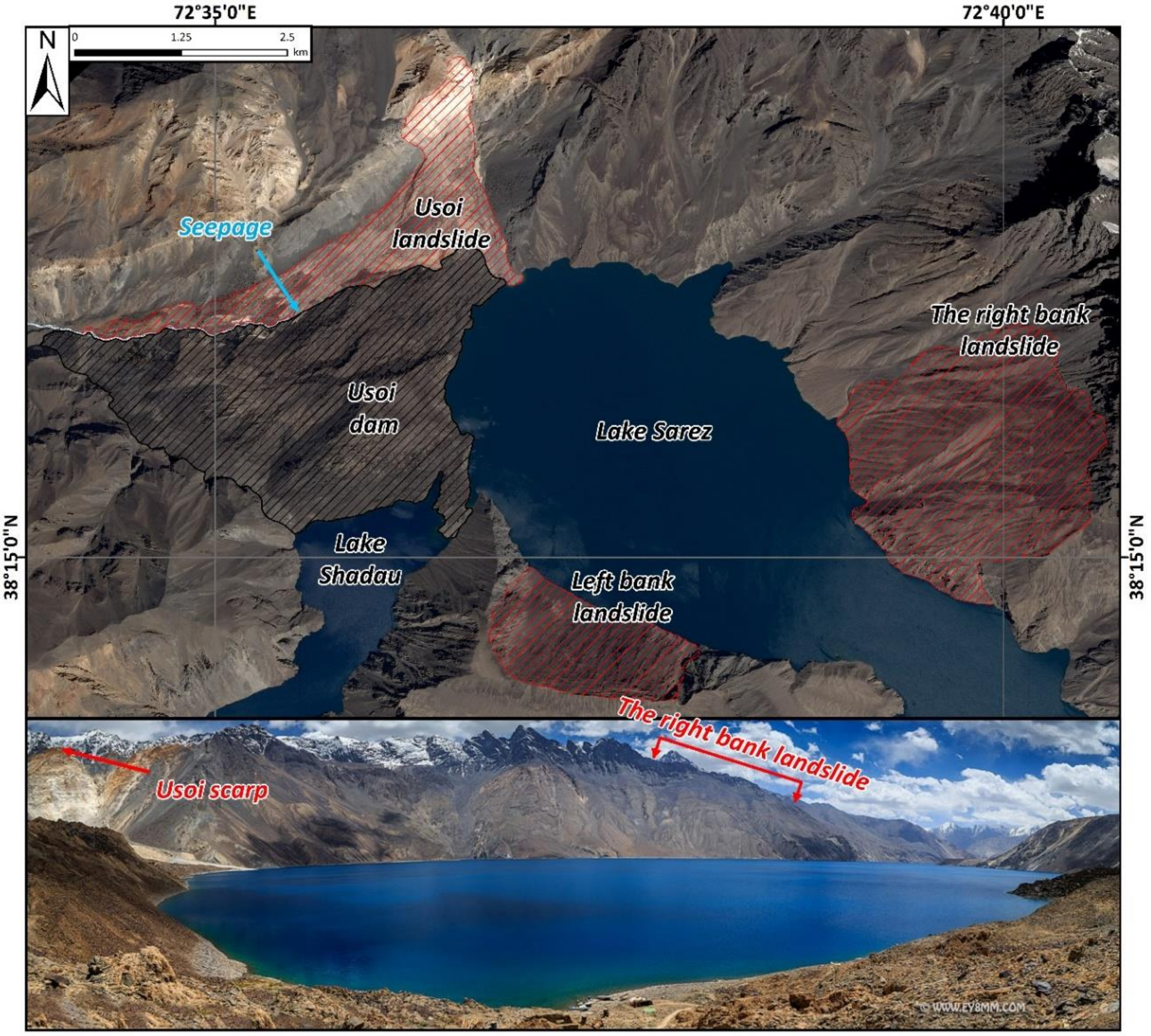

Figure 2 – Above: SPOT 6 view of Lake Sarez and Usoi Landslide Dam in Tajikistan: on the left view of the Usoi dam with seepage phenomenon in its body. Below: frontal view of the lake, with the named "Right-bank landslide" (from Strom, 2010), whose failure may cause a surge wave in the lake (photo from www.ey8mm.com).

While the danger of a general Usoi dam failure caused either by the water pressure, internal erosion or by seepage was found to be low (Ischuk 2006), the hazard of an overtopping wave from new landslide masses falling into Lake Sarez is considered more relevant (Strom, 2014 and reference therein).

In particular, a major concern is represented by the right-bank landslide, located about 4 km upstream of the dam (Figure 2). This bank belongs to the anticlinal complex of the Muskhol Range with an approximate E-W direction. From a geological point of view, the upper and lower parts of the bank present mainly sandstones, and the central part is characterized also by detrital shales. The main bedding is predominantly NE-dip, and a slope of 10-30° leading to break lines in the bedrock.

The landslide has a width along the lake shore of approximately 1 km. The estimated volume ranges from 300 million to 2 billion m^3 (Schuster and Alford 2004; State Committee on Emergencies 1997, 1999). The huge range in the estimate of volume exists both because the thickness of the landslide is very uncertain and because potential movement (single, large, monolithic landslide or smaller individual landslides) is still unclear.

The whole area is characterized by high seismic activity (Ambraseys and Bilham et al. 2012), potentially leading the landslide slumping into the lake, creating a huge wave that could top over and possibly breach the Usoi dam, creating a destructive flood downstream. On 7 December 2015, an earthquake with a magnitude of 7.2 occurred in Rushon district of Gorno-Badakhshan Autonomous Oblast in Tajikistan, at 12:50 Tajikistan Local Time approximately 10-20 km from Sarez Lake and Usoi Dam in Tajikistan. This earthquake is comparable and similar to the 1911 event (Kulikova et al. 2016). After this earthquake, four aftershocks have been recorded near the lake that created a lot of difficulties and damages, especially for the people who lived there (it killed two people and more than thousand people became homeless) but the landslide was not significantly affected by the event (Metzger et al. 2017). Along the valley of Murghab River (a headwater tributary to the Amu Darya River basin, also known as Bartang from the junction with Ghunda River just below the Sarez Lake) there are several villages along both sides of the valley.

7. Project Duration

The duration of the project is five years: the project has been proposed in 2017 and it started in 2018.

8. Report

1) Progress in the project: Generation of ground deformation maps

In order to depict completely the deformation scenario of the Lake Sarez, an integrated satellite analysis has been applied, aimed at extracting as much information as possible about the slope instability phenomena affecting the area of interest. The necessity of a synergistic approach derives from the complexity of the displacement pattern that is expected by the landslides in this area (Raetzo et al. 2006). The purpose of the analysis of satellite radar data was twofold:

1. detect, record and map any slow deformation phenomena (from mm up to several cm per year), potentially affecting the surroundings of Lake Sarez, using advanced InSAR techniques.
2. detect and measure any surface changes produced faster displacement (from meters to hundreds of meters per year), exploiting the correlation of pairs of optical images.

Ground deformation maps in ascending and descending geometries produced with the SqueeSAR processing of the Sentinel-1A acquisitions are shown in Figure 3. PS and DS were detected and classified according to their mean annual LOS velocities. Given the lack of vegetation, Lake Sarez is a suitable scenario for InSAR processing, with only snow cover limiting its effectiveness. With almost 300,000 points for each geometry of acquisition, these maps include a wealth of information that can be exploited to scan wide areas, spot instabilities, and reconstruct their deformation histories back to 2016.

While the Usoi dam (UD in Figure 3) shows moderate to low deformation rates (about 8,000 point in each geometry with velocity ranging between -15mm/yr to 15 mm/yr), PS data show clear patterns of active displacement along the sides of Lake Sarez, both in ascending and descending geometry, confirming literature information.

For the right-bank landslide (Figure 3) ca. 4,500 PSs are available for the ascending geometry (with a PS density of about 1,000 PS/km2), and 6,100 PSs for the descending one (with a PS density of about 900 PS/km2).

For the left-bank landslide (Figure 3) ca. 1,600 PSs are available for the ascending geometry (with a PS density of about 1,000 PS/km2), and 1,550 PSs for the descending one (with a PS density of about 950 PS/km2).

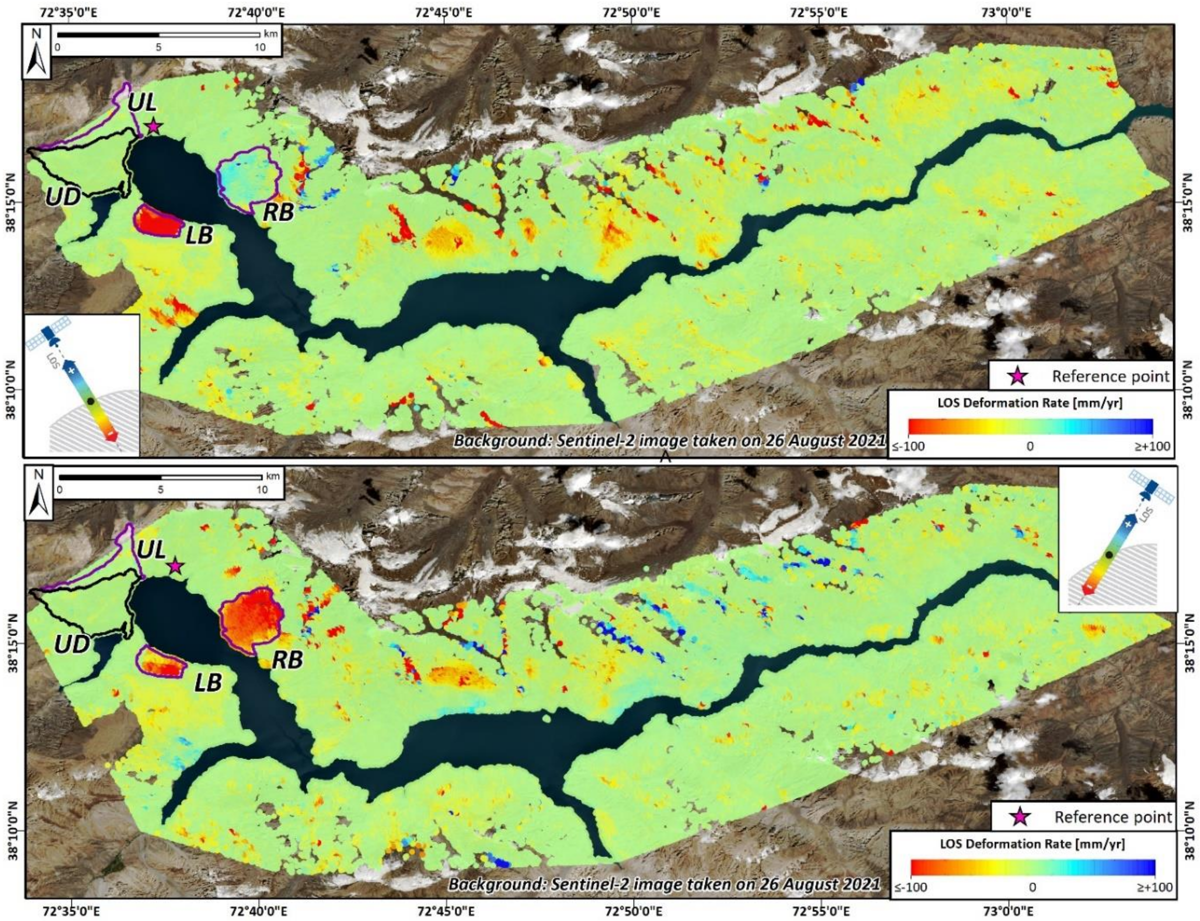

Figure 3: Ground deformation maps for the Lake Sarez along ascending (above) and descending (below) geometries. PS and DS were detected and classified according to their mean annual LOS velocities. RB: the right-bank landslide; LB: the left-bank landslide; UL: the Usoi landslide; UD: the Usoi dam.

The four SPOT -6 and -7 images from 2015 to 2021 chosen for the analysis on the Lake Sarez area formed three image pairs using two temporally adjacent images, (2015-2017; 2017-2019; 2019-2021); moreover, an image pair encompassing the 2015-2021 interval, covering the entire period was used to study and to derive the ground deformation.

Figure 4 shows the analysis of the SPOT images using a 128-128-pixel combination that identified a movement which is exclusively concentrated in the left-bank landslide. The values of the movements are around 8-10 m in 6 years (around 1.5 m/year) for the E-W components and the movement is especially between 2015-2017. From 2017 to 2021 the landslide shows a small movement especially focused on the right sector of the landslide with maximum values around 0.5 m/year. In the N-S component the movement is high, around 12-18 m in 6 years (2-3 m/year) and also in this case most of the movement is between 2015 and 2017. From 2019 there is no movement in the landslide. From the N-S component, both in 2015-2017 and 2015-2021, it is possible to see that most of the movement is located in the right sector of the landslide, characterized by a more intense colour.

Moreover, looking in detail the results provided by the COSI-Corr software (Leprince et al. 2007), a small movement within the landslide mapped on the right side of the lake is visible, especially in the increased initial-final window size 128-128 using the cumulated 2015-2021 pair, even if it is visible also in 2015-2017, with velocity values around 6-8 m in 6 years along the east-west component. In the north-south component this movement is very small. This area coincides precisely with a sector within the landslide body where InSAR data are missing.

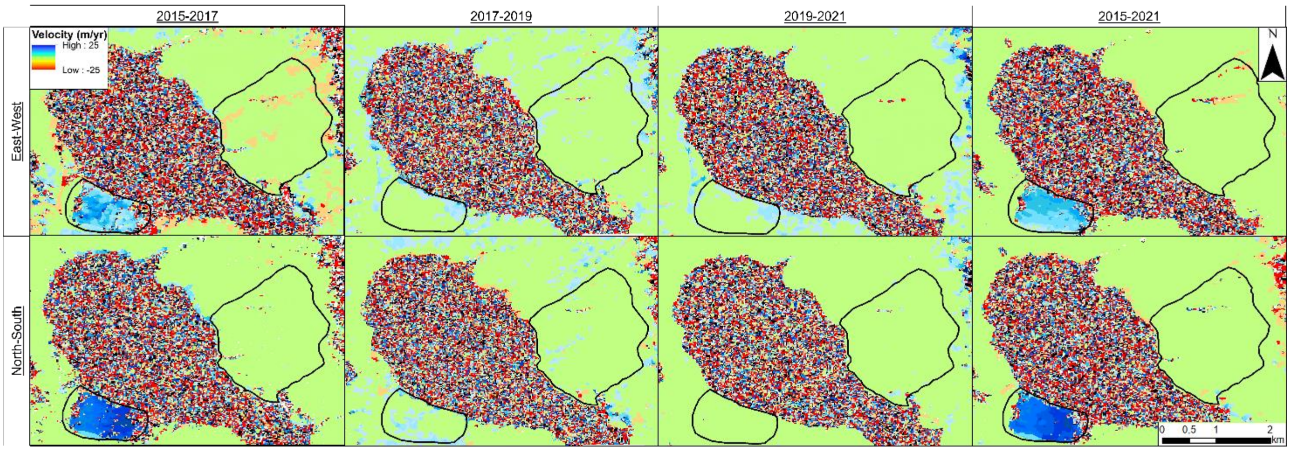

Figure 4: Representation of COSI-Corr analysis of left-bank landslide surrounded in black for the four pair images analysed: 2015-2017; 2017-2019; 2019-2021; 2015-2021 both in east-west and north-south components.

2) Planned future activities or Statement of completion of the Project

Tajikistan is a mountainous and largely inaccessible area with a complex topography, but it hosts several sites which drawn the attention of geoscientists interested in landslide analysis. One such case is represented by the slope sectors surrounding the famous Lake Sarez, formed by a landslide dam event, that has been analysed in this IPL report. In particular, two large landslides, one on the right-bank, and the other on the left-bank of the lake have been the target of this study, as they could generate disastrous consequences in case of failure within the lake. The collapse of the landslides could indeed generate an anomalous wave overtopping it, endangering the people living along the lake and the river downstream. Despite this serious threat, the knowledge about the kinematics and size of these landslides is still scarce, due to logistic constrains that make surveying difficult.

Next steps of the work will be

1. the analysis of information provided by the displacement time series, which represent the most advanced product of any multi-temporal InSAR processing providing the deformation history of the measured point acquisition by acquisition, with millimetric precision. Displacement time series are necessary for the study of the kinematics of a phenomenon because they show possible seasonal trends, non-linear movements, ground acceleration and any change that may have occurred during the monitoring period;

2. the reconstruction of displacement cross sections of the mapped landslides to analyse how the kinematics change with space;

3. the exploitation of InSAR data to postulate the geometry and depth of the sliding surface of both the right-bank and left-bank landslides using a method originally developed by Carter and Bentley (1985), improved by Cruden (1986), and validated with the use of satellite interferometric data by Intrieri et al. (2020), who also dubbed it the Vector Inclination Method (VIM). This method assumes that the direction of the superficial ground reflects the geometry of the sliding surface, which is generally true in the case of landslides with no strong internal deformations along the vertical axis.

3) Beneficiaries of Project for Science, Education and/or Society

Overall, this project provides regional authorities continuous information on where, when and how fast the ground is moving. However, prioritization and mitigation of these hazards can be done, starting with issues deemed to be most urgent. Further beneficiaries include Civil Protection Authorities, Regional Authorities, local authorities and any other entities in charge of management of risk posed by landslide. The successful application of InSAR analysis, coupled with the global coverage, and regular acquisition planning ensured by the Sentinel-1 constellation, allowed to deliver very precise and spatially dense information on ground motion. These qualities make it possible to scan wide areas, and to identify unstable zones, especially where remoteness, vastness, and climatic conditions make it difficult to perform field activities. We demonstrate the effectiveness of InSAR in the Lake Sarez in Tajikistan. Here, we identify all possible ground deformation with potential to directly impact on the community and we localize areas within the landslide where ground deformation is more intense for prioritized further investigations.

4) Results

In this section a list of papers, sharing content and topic with the IPL project 221 on PS continuous streaming for landslide monitoring and mapping is presented:

The paper "*Continuous, semi-automatic monitoring of ground deformation using Sentinel-1 satellites*" by Federico Raspini et *alii* has been published on Scientific Reports in 2018. https://www.nature.com/articles/s41598-018-25369-w/;

The paper "*From Picture to Movie: Twenty Years of Ground Deformation Recording Over Tuscany Region (Italy) With Satellite InSAR*" by Silvia Bianchini *et alii* has been published on Frontiers in Earth Science in 2018. https://www.frontiersin.org/articles/10.3389/feart.2018.00177/full;

The paper "*Permanent Scatterers continuous streaming for landslide monitoring and mapping: the case of Tuscany Region (Italy)*" by Federico Raspini *et alii* has been published on Landslides in 2019. https://link.springer.com/article/10.1007/s10346-019-01249-w;

The paper "*Monitoring Ground Instabilities Using SAR Satellite Data: A Practical Approach*" by Matteo Del Soldato *et alii* has been published on ISPRS International Journal of Geo-Information in 2019. https://www.mdpi.com/2220-9964/8/7/307;

The paper "*A Sentinel-1-based clustering analysis for geo-hazards mitigation at regional scale: a case study in Central Italy*" by Roberto Montalti *et alii* has been published on Geomatics, Natural Hazards and Risk in 2019. https://www.tandfonline.com/doi/full/10.1080/19475705.2019.1690058;

The paper "*Landslide-Induced Damage Probability Estimation Coupling InSAR and Field Survey Data by Fragility Curves*" by Matteo Del Soldato *et alii* has been published on Remote Sensing in 2019. https://www.mdpi.com/2072-4292/11/12/1486;

A chapter entitled "*InSAR data for the continuous monitoring of ground deformation at regional scale*" by Nicola Casagli *et alii*, has been accepted for publication in the Book "*Advances in Remote Sensing for Infrastructure Monitoring*" edited by Springer.

The paper "*The Maoxian landslide as seen from space: detecting precursors of failure with Sentinel-1 data*" by Emanuele Intrieri et *alii* has been published on Landslides in 2018. https://link.springer.com/article/10.1007/s10346-017-0915-7;

The paper "*Perspectives on the prediction of catastrophic slope failures from satellite InSAR*" by Tommaso Carlà et *alii* has been published on Scientific Reports in 2019. https://www.nature.com/articles/s41598-019-50792-y;

The paper "*Combination of GNSS, satellite InSAR, and GBInSAR remote sensing monitoring to improve the understanding of a large landslide in high alpine environment*" by Tommaso Carlà et *alii* has been published on Geomorphology in 2019. https://www.sciencedirect.com/science/article/pii/S0169555X19301084;

The paper "*Review of satellite interferometry for landslide detection in Italy*" by Lorenzo Solari et *alii* has been published on Remote Sensing in 2020. https://www.mdpi.com/2072-4292/12/8/1351;

The paper "*Time-series analysis of the evolution of large-scale loess landslides using InSAR and UAV photogrammetry techniques: A case study in Hongheyan, Gansu Province, Northwest China*" by Qingkai Meng et *alii* has been published on Landslides in 2021. https://link.springer.com/article/10.1007/s10346-020-01490-8;

The paper "*Satellite-based interferometric monitoring of deformation characteristics and their relationship with internal hydrothermal structures of an earthflow in Zhimei, Yushu, Qinghai-Tibet Plateau*" by Qingkai Meng et *alii* has been published on Remote Sensing of Environment in 2022 https://www.sciencedirect.com/science/article/pii/S0034425722001018;

The paper "*Nation-wide mapping and classification of ground deformation phenomena through the spatial clustering of P-SBAS InSAR measurements: Italy case study*" by Davide Festa et *alii* has been published on ISPRS Journal of Photogrammetry and Remote Sensing in 2022 https://www.sciencedirect.com/science/article/pii/S0924271622001253;

The paper "*Unsupervised detection of InSAR time series patterns based on PCA and K-means clustering*" by Davide Festa et alii has been published on International Journal of Applied Earth Observation and Geoinformation in 2023. https://www.sciencedirect.com/science/article/pii/S1569843223000985;

The paper "*Landslide detection, monitoring and prediction with remote-sensing techniques*" by Casagli et alii has been published on Nature Reviews Earth & Environment in 2023 https://www.nature.com/articles/s43017-022-00373-x;

The paper "*Spatial and temporal characterization of landslide deformation pattern with Sentinel-1*" by Poggi et alii has been selected for publication in the book titled Progress in Landslide Research and Technology (P-LRT) Volume 2 Issue 1 that will be released in 2023.