Date of Submission	06/06/2025

IPL Project (IPL-Number) Annual Report Form

Period of activity under report from 1 January 2024 to 31 December 2024

1. **Project Number and Title:** IPL Project 221 (2017): PS continuous streaming for landslide monitoring and mapping

2. **Main Project Fields**
   Select the suitable topics. If no suitable one, you may add new field.
   (1) Technology Development
   B. Hazard Mapping, Vulnerability and Risk Assessment
   (2) Targeted Landslides: Mechanisms and Impacts
   A. Catastrophic Landslides
   (3) Capacity Building
   B. Collating and Disseminating Information/ Knowledge
   (4) Mitigation, Preparedness and Recovery
   A. Preparedness

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   Core members of the Project:
   Nicola Casagli, Full Professor, DST-UNIFI
   Veronica Tofani, Researcher, DST-UNIFI
   Matteo del Soldato, Research Assistant, DST-UNIFI

4. **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.

5. Study Area

The Baipaza landslide is situated within the Tajik depression, in the western region of Tajikistan (Figure 1). From a geological perspective, the Tajik depression is characterized by a diverse range of rock formations, including Jurassic evaporites; Lower Cretaceous cross-bedded red sandstone; Upper Cretaceous and Paleogene interbedded limestone, shale, and gypsum; and Neoproterozoic quartzose molasse (Leith et al., 1986). This landslide presents a significant case study due to its potential to threaten the Baipaza Hydropower Station and the adjacent dam, located 5 km to the north. Covering an area of over five km2, it lies along the right bank of the Vakhsh River, which originates in Southern Kyrgyzstan and flows westward through Northern Tajikistan before turning south toward the West-ern Pamir region (Immerzeel et al., 2012; Sidle et al., 2023).

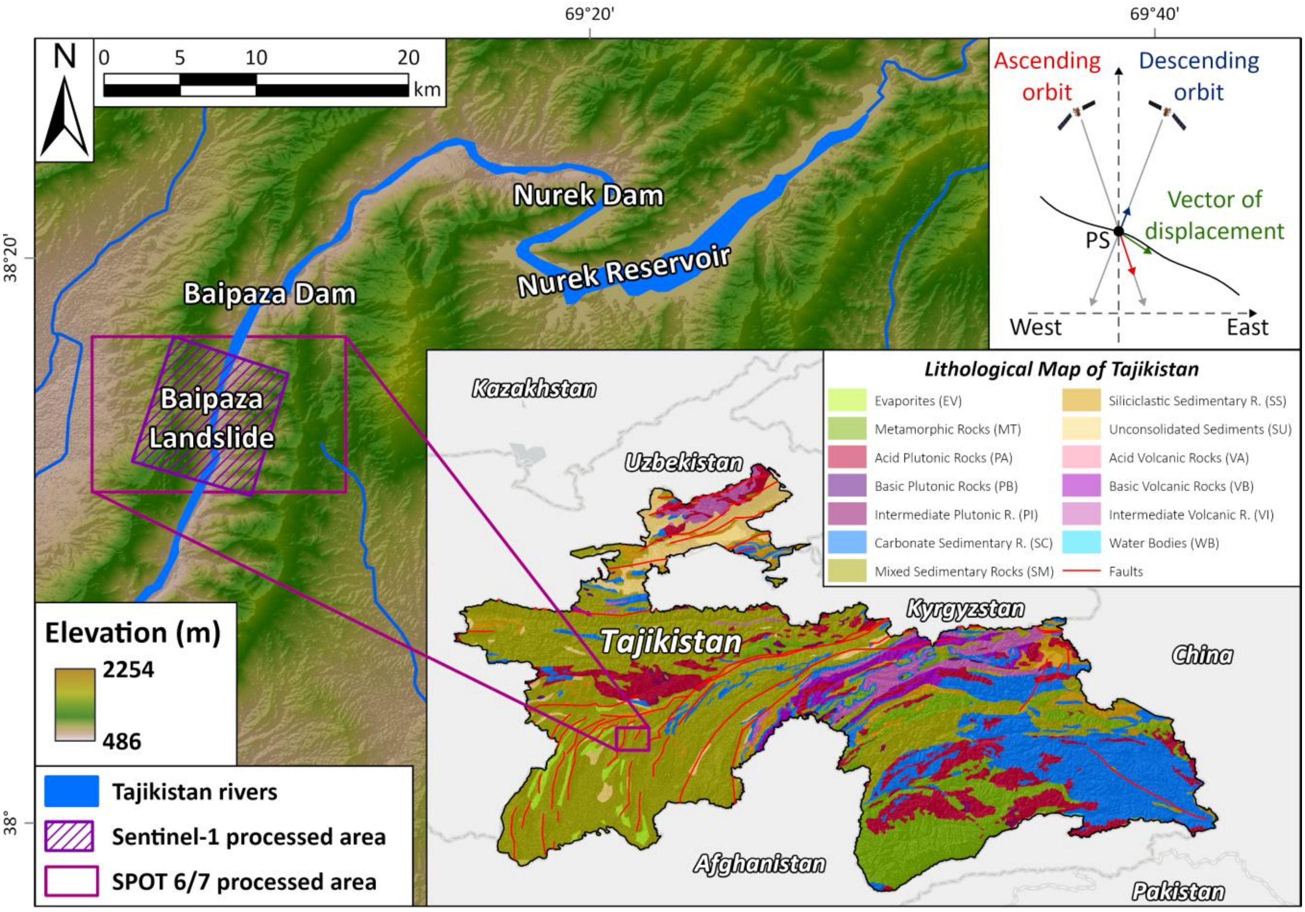

Figure 1: Baipaza Landslide location near the Baipaza dam in the Vakhsh River. This figure highlights the elevation model taken from the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 3 (ASTGTM), and the lithological map of Tajikistan is taken from the GLiM database (Hartmann et al., 2012). The angular relationship between the geometry of the landslide and the satellite acquisition LOS is illustrated in the upper right-hand quadrant of the figure.

The landslide has a long and complex history, marked by multiple movements and reactivations. The first documented reactivation occurred in 1968, partially obstructing the Vakhsh River. The volume of material involved in that event was estimated to be between 20 and 25 million m^3 (Havenith et al., 2015). A second significant displacement event took place in May 1992, triggered by intense rainfall again damming the Vakhsh River. Following a 7.4-magnitude earthquake in the Hindu Kush region on 3 March 2002, the landslide began its third phase of movement, once more partially blocking the Vakhsh River (Havenith et al., 2015). The estimated volume of this event was 5–10 million m^3 (Evans et al., 2011). This event led to the formation of a lake, posing a threat to the hydropower station, with the water level rising by 7 m. Subsequently, the debris accumulated in the riverbed was removed using explosives, effectively mitigating the risk of flooding (Mamatkanov et al., 2009).

In light of the history of sudden reactivations and the high potential for abrupt future movements due to the region's seismicity and other characteristics, Tajik authorities have implemented a mitigation program. The objective of this program is to prevent and reduce the risk of complete blockage of the Vakhsh River. Such a blockage would pose a significant challenge, as it could disrupt the power generation of the dam. The mitigation strategy involves stabilizing the landslide by removing material from the landslide's head and creating a series of benches in the head scarp area. Additionally, open-trench drains are being installed in the upper part of the landslide to improve stability. The plan also includes removing landslide debris from the river channel to restore its capacity and ensure normal flow. To further facilitate disaster mitigation, a proposal has been made to con-struct a bypass tunnel through the steep left bank of the Vakhsh River (Evans et al., 2011).

In particular, the purpose of the activities performed during the refence period (January – December 2024) is to enhance the comprehension of Baipaza landslide behavior between 2014 and 2020, adopting a remote-sensing analysis, utilizing two distinct image sets acquired by Sentinel-1 SAR and Sentinel-2 optical satellites.

6. Project Duration

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

7. Report

1) Progress in the project

The Sentinel-1 SAR images will be processed using advanced radar interferometry (InSAR) techniques in conjunction with Principal Component Analysis (PCA). The results obtained from the remote-sensing techniques will be subsequently used for the image interpretation of the landslide employing a high-resolution elevation model taken from the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 3 (ASTGTM). A flowchart detailing the proposed techniques is shown in Figure 2.

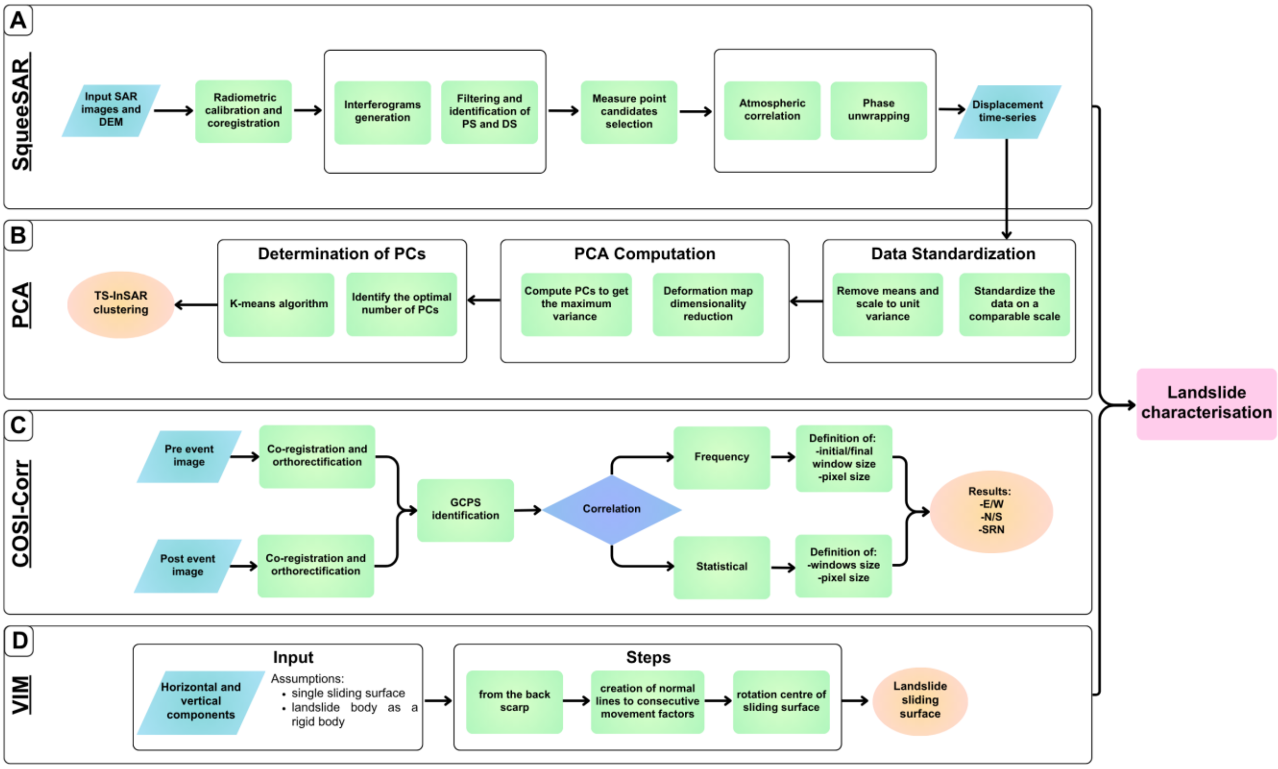

Figure 2: Simplified flowchart of the three techniques that will be applied in the work: SqueeSAR (A), Principal Component Analysis (B), COSI-Corr (C), and Vector Inclination Method (D). The outcomes of these analyses are used for the landslide characterization.

Table 1 presents the information and parameters of the SAR dataset exploited in this study for the implementation of the SqueeSAR approach (Ferretti et al., 2011). The InSAR measurements acquired from ascending and descending satellite geometries have been found to yield the LOS displacement velocities, which represent the component of ground displacement along the radar sensor's look direction.

Table 1: The Sentinel-1 dataset is employed in the SqueeSAR process.

SqueeSAR		
SAR imagery	Sentinel-1A	
Band	C	
Acquisition geometry	Ascending	Descending
Satellite track	71	78
Sensor mode	IW	IW
Number of scenes	147	142
Time range	10 October 2014–2 October 2020	23 October 2014–3 October 2020
Line-of-sight angle (θ)	40.55°	44.88°
Line-of-sight angle (δ)	9.98°	9.24°
Line-of-sight versors (V)	0.76	0.709
Line-of-sight versors (N)	−0.113	−0.113
Line-of-sight versors (E)	−0.64	0.696

The measurements can be decomposed to retrieve the vertical and horizontal components of ground displacement velocities through the inversion of a linear system relating the LOS versors and angles (see Table 1) to the vertical and horizontal components.

Subsequent to the acquisition of the vertical and horizontal components, the displacement velocity along the steepest slope direction of the terrain (Vslope) can be calculated by projecting the 2D displacement versors along the slope versors, derived from a DEM. The Vslope provides a meaningful parameter for assessing slope stability, especially in landslide-prone regions.

Table 2 presents the information of the Sentinel-2 images and parameters exploited in this study for the implementation of the COSI-Corr method. The COSI-Corr methodology involves the comparison of two input images, acquired prior to and following the deformation event. Following the identification of stable areas through the use of Ground Control Points (GCPs), the software generates two displacement components for each image pair: the north–south (N/S) and east–west (E/W) displacement layers. These layers represent the horizontal components of surface movement and are used to analyze and quantify the deformation patterns across the scene. A quality parameter known as the signal/noise ratio (SNR) is also generated. Positive values for N/S displacement denote the north direction, while positive values for E/W displacement indicate the east direction.

Table 2: The Sentinel-2 dataset and the parameters employed in the COSI-Corr process.

COSI-Corr	
Optical imagery	Sentinel-2A
Band	Multispectral 13 bands
Number of scenes	2
Primary imagery	26 July 2016
Secondary imagery	29 August 2022
Initial window size	128 pixels
Final window size	64 pixels
Step	2 pixels

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

Following the definition of the procedure and methodology, next short-term step of the work will be elaboration of the satellite acquisitions (both radar and optical), with the purpose the analysis and interpretation of the landslide by using different satellites approaches and methods.

In a wider perspective and in a longer term, the focus will remain those landslides, whose remoteness makes in situ analysis difficult and deployment of ground sensors unfeasible.

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

Overall, this project provides 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, deriving from the activities performed within 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 "*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;

A chapter entitled "*InSAR data for the continuous monitoring of ground deformation at regional scale*" by Nicola Casagli *et alii*, has been published in the Book "*Advances in Remote Sensing for Infrastructure Monitoring*" edited by Springer. https://link.springer.com/chapter/10.1007/978-3-030-59109-0_3

The paper "*Spatial and temporal characterization of landslide deformation pattern with Sentinel-1*" by Poggi et alii has been published in the book titled Progress in Landslide Research and Technology (P-LRT) Volume 2 Issue, released in 2023. https://link.springer.com/chapter/10.1007/978-3-031-39012-8_15

The paper "Integration of satellite SAR and optical acquisitions for the characterization of the Lake Sarez landslides in Tajikistan" by Nardini *et alii* has been published on Landslides in 2024. https://link.springer.com/article/10.1007/s10346-024-02214-y

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