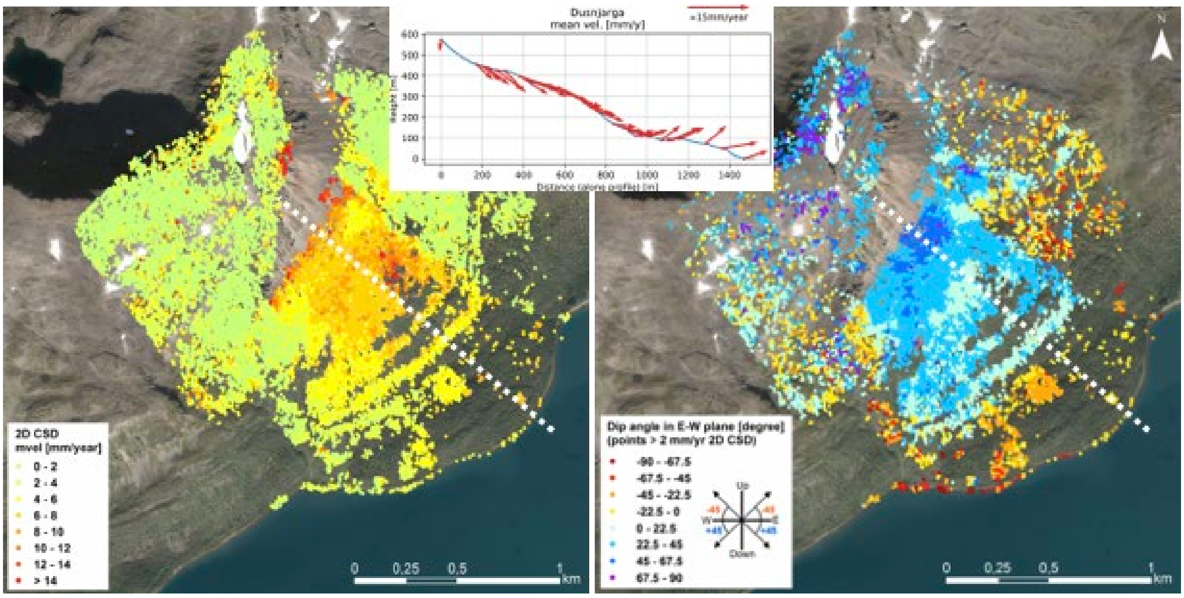
NORCE Norwegian Research Centre AS
www.norceresearch.no

Mapping and characterization of unstable slopes with Sentinel-1 multi-geometry InSAR (activity line 2: public sector applications)

Final report

Tom Rune Lauknes, Jakob Grahn, Line Rouyet, Yngvar Larsen, Martina Böhme, John Dehls, and Lene Kristiansen



REPORT 2 – 2020
NORCE Technology

Project title:	Mapping and characterization of unstable slopes with Sentinel-1 multi-geometry InSAR (activity line 2: public sector applications)
Project number:	101537
Institution:	NORCE Technology
Client/s:	ESA ESRIN
Classification:	Open
Report no.:	2-2020
ISBN:	978-82-8408-114-4
Number of pages:	43
Publication month:	November
Citation:	Tom Rune Lauknes, T.R., Grahn, J., Rouyet, L., Larsen, Y., Böhme, M., Dehls, J., Kristiansen, L. (2020). Mapping and characterization of unstable slopes with Sentinel-1 multi-geometry InSAR (activity line 2: public sector applications), Report 2-2020, Norce Tehnology, Tromsø.

Revisions

Rev.	Date	Author	Checked by	Approved by	Reason for revision
1	14.02.2020	Tom Rune Lauknes			Draft
	02.10.2020	Tom Rune Lauknes			Draft
	20.11.2020		Yngvar Larsen	Kjell Arild Høgda	

Tromsø, 20.11.2020

Tom Rune Lauknes	Yngvar Larsen	Kjell Arild Høgda
Project manager	*Quality assurance*	*Research director*

Contents

Distribution

Organization	Copies	Name
ESA	1 digital	Philippe Bally Nathalie Boisard
NORCE	1 digital	Tom Rune Lauknes Line Rouyet Yngvar Larsen Jakob Grahn
NGU	1 digital	Martina Böhme John F. Dehls
NVE	1 digital	Lene Kristiansen Lars Harald Blikra

The **custodian** of this document is Tom Rune Lauknes

The **authors** of this document are:

Tom Rune Lauknes, NORCE	Project's management, coordination of report
Jakob Grahn, NORCE	Head of algorithm and software development
Line Rouyet, NORCE	Review of report
Yngvar Larsen, NORCE	Review of report
Martina Böhme, NGU	Leading of user requirements & selection of sites
John Dehls, NGU	Review of report
Lene Kristiansen, NVE	Contribution to user requirements & selection of sites

List of figures

1 Introduction and scope

1.1 Executive summary

This is a high-level report that summarizes the main achievements and results of the research and development conducted in the project "Mapping and Characterization of unstable slopes with Sentinel-1 multi-geometry InSAR (activity line 2: public sector applications)", where multi-geometry Sentinel-1 Synthetic Aperture Radar Interferometry (InSAR) is used for improving characterization of unstable rock slopes in Norway.

In the project the objective was to demonstrate the added value of using higher-order InSAR-based earth observation (EO) products for landslide mapping and monitoring to the public sector in Norway, represented by the Geological Survey of Norway (NGU) and the Norwegian Water Resources and Energy Directorate (NVE).

The main scientific and technical objectives of the project were:

1. to develop higher-order Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) products that combines surface displacement measurements from all available InSAR geometries.
2. to increase the value of InSAR technology to map and characterize unstable landforms and provide a better understanding of slope processes that could relate to catastrophic failures.
3. to assess the added value of the developed, higher-order InSAR products for the public sector in Norway.

1.2 Scope

The Final Report is a deliverable in the project "Mapping and Characterization of unstable slopes with Sentinel-1 multi-geometry InSAR (activity line 2: public sector applications)" under ESA/ESRIN contract number 4000125274/18/I-NB.

1.3 Limitations and restrictions

It is assumed that the reader is familiar with advanced principles of InSAR and has a good overall understanding of methodologies for time-series deformation monitoring applications. Scientific references are given only where additional explanations are needed, and it is also assumed that reader is familiar with most of the used acronyms.

1.4 Mapping of landslides in Norway

The Norwegian Water and Energy Resources Directorate (NVE) is responsible for the national landslide mapping programs including susceptibility maps, hazard maps and risk maps. The Geological Survey of Norway (NGU) is responsible for hazard and risk classification of large rock slope instabilities in Norway. They also assist NVE with long term monitoring of high-risk instabilities. A very important factor in determining hazard is the determination of rates of movements. This is predominantly done using InSAR, although GNSS and in situ instrumentation (crack meters, tilt meters, borehole instrumentation, total stations etc.) are also applied at site level.

In Norway, there has been a significant interest from the public stakeholders (NGU and NVE) to use InSAR for mapping of landslides. Norut and NGU has collaborated over the last 12 years to develop a processing facility suited for Norwegian conditions. We have collected vast number of Radarsat-2 scenes for prioritized regions in Norway, as well as high-resolution TerraSAR-X data covering certain “hotspot” areas.

NGU launched a development project in 2016, with Norut a prime contractor, to set up a national InSAR-based deformation mapping service, based upon satellite data from Sentinel-1. The first national deformation map, produced by using Sentinel-1 Persistent Scatterer Interferometry (PSI), was publicly released in November 2018. The system, when in operational phase, will provide updated displacement maps at a national scale, and with an open data policy.

1.5 Hazard and risk classification of unstable slopes

When an unstable rock slope is detected, NGU is applying a standardized classification method in order to provide a hazard and risk assessment. The level of risk forms the basis for decisions regarding further actions.

The hazard level is based upon a series of geomorphological and structural geological criteria (development of back-scarp and flanks, morphological signs of the failure surface, kinematic analysis), as well as signs of activity (displacement rates and acceleration over time, increased rockfall activity and previous rock avalanche events). The result is a hazard score between 0 (very low hazard) and 12 (very high hazard). Due to the use of probabilities for each of the criteria, an uncertainty can be determined for the hazard score. The final score for a given area is a hazard level with minimum, average and maximum values. See (Hermanns et al., 2012) for details.

In order to classify an unstable slope, it is imperative that the geologist and NGU has as much knowledge as possible about the kinematics at each site.

1.6 Structure of the report

The structure in the report follows the work packages from the project. This Chapter present the background and the scope of the project. Chapter 2 describes the main user requirements, with algorithmic consolidation in Chapter 3. In Chapter 4 we describe the product design and the implementation chosen, with evaluation presented in Chapter 5. In Chapter 6 we present some results from the outreach and present demonstrations of the user uptake of the developed tool. Finally, Chapter 7 presents conclusions.

2 WP2: Consolidation of user requirements

2.1 Executive summary

This section defines the user requirements regarding the Combined Surface Displacement (CSD) product, generated by using multi-geometry Synthetic Aperture Radar Interferometry (InSAR) and the visualization, plotting and interpreting (VPI) software tool to map and characterize unstable rock slopes in Norway. We define the user requirements for the development of the VPI, as well as the criteria used for the selection of the pilot sites and describes the characteristics of each suggested site.

Two unstable rock slopes (Gamanjunni 3 and Osmundneset) are selected in areas with good understanding of the kinematics and with available validation datasets (sites for evaluation). Six unstable rock slopes are selected in areas of urgent interest for the public sector where further information is required for a better understanding of the slope processes. All sites are selected taking into account intrinsic limitations due to satellite radar layover and shadow.

The main output of this work package was *D1: Selection of pilot sites and consolidation of user requirements report (Rouyet et al., 2019)*.

2.2 Background

InSAR measurements are one-dimensional and correspond to changes in sensor-to-ground distance, i.e. displacements along the radar line-of-sight (LOS). Any displacement orthogonal to this direction is not possible to detect. By combining InSAR displacements from multiple ascending and descending satellite SAR geometries, it is possible to estimate 2D information (East-West horizontal and vertical displacement, expressed as length of 2D vector and dip angle of the deformation), called CSD hereafter. Combined horizontal and vertical information can be expressed as 2D displacement and dip of displacement relative to the vertical. This is valuable for geologists to understand the type of sliding mechanisms involved in specific unstable rock slopes. To fully take advantage of available datasets from InSAR Norway (insar.ngu.no), a user-friendly tool (called VPI thereafter), that calculates and visualizes 2D InSAR information in a Geographic Information System (GIS) will be developed in the project.

2.3 Consolidation of user requirements

The Geological Survey of Norway (NGU) and the Norwegian Water Resources and Energy Directorate (NVE) listed the following elements as requirements for development of the VPI:

- **Format:** The VPI tool has to be supported by ArcGIS Pro and implemented as a python plugin;

- **Generality:** The input products are multiple ascending and descending InSAR time series and mean velocity. If data is extracted from the InSAR Norway project (insar.ngu.no), it will be in the form of Persistent Scatterer (PS) points. The tool will be generic in the way that it can also support input in the form of distributed scatterers InSAR (e.g., input geocoded raster data from interferogram stacking or from Small Baseline Subset (SBAS) method). A digital elevation model is also needed as input. By importing time series and mean velocity information into ArcGIS and selecting a profile or area of interest, the tool has to be able to estimate CSD information and visualize the results in an intuitive and user-friendly way.

- **Priority 1:** Visualize 2D combined mean velocity and displacement dip angle as profile lines (Figure 1, left) or as vectors (Figure 1, right). Input data: topography (digital elevation model) and ascending/descending InSAR.

- **Priority 2:** Visualize 2D combined displacement for the entire time series for an area of interest (averaged CSD time series for a user defined area marked by using a chosen polygon.

- **Priority 3:** Along a profile as in Priority 1 but with additional kinematic or geological information: other displacement data e.g. GNSS, geological composition structure (fractures, foliation, scarps, etc.).

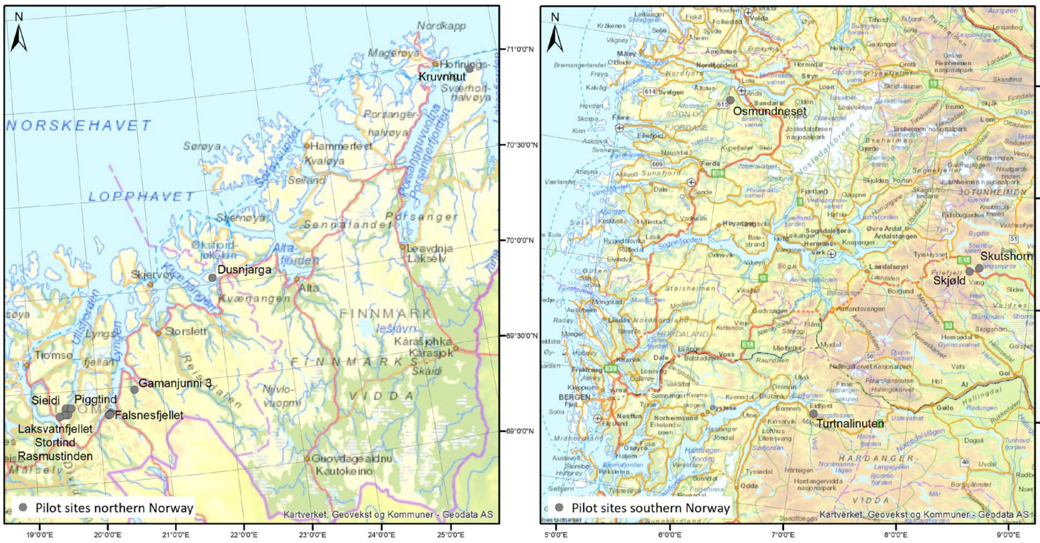


Figure 1. Study areas in northern Norway (left) and south western Norway (right).

2.4 Implementation of CSD in NGU's landslide workflow

NGU is coordinating a project with NORCE as prime contractor, to set up a national InSAR-based deformation mapping service, based upon satellite data from Sentinel-1. The first nation-wide InSAR deformation dataset was released in November 2018. This dataset is currently being used by NGU for mapping of landslides. The system, when in operational phase, will provide updated displacement maps at a national scale, and with an open data policy.

The current version of (insar.ngu.no) supports download of deformation data as Comma Separated Value (csv) files, however at a limitation of 50.000 points. An Application Programming Interface (API), allowing expert-users to directly download InSAR deformation products from the *InSAR Norway* portal to their client work stations, has been completed.

The VPI ArcGIS implementation should be generic, meaning it will support both manual import of deformation data, produced by different sources, as well as automatic extraction of data from the "insar.ngu.no" portal using the API.

The workflow will be such that the geologist who is responsible for mapping an area will use the VPI tool as an integrated part within the ArcGIS framework. This allows seamless integration with other datasets already included in the ArcGIS Project. Examples here are detailed orthophotos, field-mapped lineaments, Terrestrial Laser Scanning, geologic and geomorphologic maps, etc.

2.5 Tests to be performed during evaluation

The InSAR-derived higher order (CSD) products will be compared to other in-situ observations obtained by using either periodic or permanent GNSS stations, repeated Terrestrial Laser Scanning (TLS), and using a ground-based radar. Furthermore, the CSD products will be evaluated in the field where the observed deformation direction and magnitude will be compared to observed structures in the field. Where permanent GNSS stations exist, we will compare the estimated CSD time series with 3D deformation time series obtained from GNSS.

2.6 Selection of pilot sites

2.6.1 Criteria for selection

The criteria for the selection of the pilot sites can be divided into two groups:

1. Criteria related to InSAR data availability and properties;
2. Criteria related to geographical and geological considerations.

1. **InSAR criteria:**
   - Include sites with good common InSAR coverage from ascending and descending SAR geometries, i.e. sites not affected by extensive layover or shadow, with low vegetation coverage, and not too fast displacement, etc. Use data from InSAR Norway;
   - Avoid nonoptimal slope orientations (N-S facing slopes).

2. **Geographical and geological criteria:**
   - Include unstable rock slopes in several regions of Norway to test CSD under different conditions. over the country;
   - Consider unstable rock slopes in areas with estimated large consequences in case of catastrophic failure;
   - Include both rockslides already well understood and documented by previous studies and recently detected ones as future priority (field investigation planned in summer 2019);
   - Prefer unstable rock slopes with available in-situ displacement measurements (already available or planned) to validate the InSAR results;
   - Include unstable rock slopes with different slope settings and orientations to represent a large set of conditions and potentially identify InSAR limitations in specific contexts;
   - Include areas involving different movement mechanism (e.g. surficial versus deeper displacement) to test the value of CSD InSAR to differentiate geological processes based on the orientation of the displacements.

Based on these criteria, we selected eight pilot sites further described in (Rouyet et al., 2019), including **sites for evaluation** (good understanding of the unstable rock slopes, intensive previous investigation and other displacement data existing), and **sites for investigation** (recently detected areas, not well understood yet but prioritized by NGU/NVE for future work due to large consequences). Figure 1 shows the distribution of the sites over the country.

3 WP3: Algorithmic consolidation

3.1 Executive summary

The consolidation was based on a review of three state-of-the-art methods for computing Combined Surface Displacement (CSD). The methods primarily differ in the constraints used for regularising the inversion from a set of single geometry InSAR datasets to a CSD dataset. The consolidation concluded that two of the reviewed methods were suitable candidates for this project. These were: (i) the simple reprojection method and (ii) the Minimum Acceleration (MinA) combination technique (see *D2: Algorithmic consolidation report* for details). Given these methods, a corresponding processing flow, as shown in Figure 2, was proposed. The whole processing chain can be decomposed in three steps and are summarised below.

The main output of this work package was *D2: Algorithmic consolidation report* (Grahn et al., 2019).

3.2 Pre-processing

A key difference between the three methods reviewed in *D2: Algorithmic consolidation report* (that is the simple reprojection method, MinA combination technique and MSBaS method), is that the simple reprojection method and MinA combination technique are applied on LoS displacement data, that is after a conventional single-track inversion step has been applied. MSBaS on the other hand jointly inverts the interferometric phases and CSD in one step. While it is unclear what this difference means in terms of robustness and processing speed, taking the input as LoS displacements rather than interferometric phases leaves the choice of phase inversion method up to the user. The ”generality”-user requirement (see *D1: Consolidation of user requirements and selection of pilot sites report*) moreover states that the algorithm should handle input from single-track methods such as SBaS, interferogram stacking or Persistent Scatterer Interferometry (PSI), making the simple reprojection method and MinA combination technique favourable over the MSBaS method in the context of this project. The MSBaS method will therefore not be considered further. Remaining pre-processing steps include calibration across the multi-tack datasets. This is done by choosing a point or area of known displacement, typically where the ground can be considered stable. This choice will be done manually by the user before the algorithm is initialised. Secondly, the multi-tack datasets need to be co-located, which will be done by interpolation. Since the LoS displacements may result from any single-track method, they can be represented either as rasters as typical for Distributed Scatterers (DSs), or point clouds as typical for Persistent Scatterers (PSs), thus the interpolation needs to handle both cases. Thirdly, in the case of the simple reprojection method, the multi-tack datasets need to be resampled temporally to a set of shared times by means of interpolation.

In summary, pre-processing steps including: (i) displacement calibration (needs manual input of calibration point or region), (ii) spatial interpolation and (iii) temporal interpolation (only for simple reprojection).

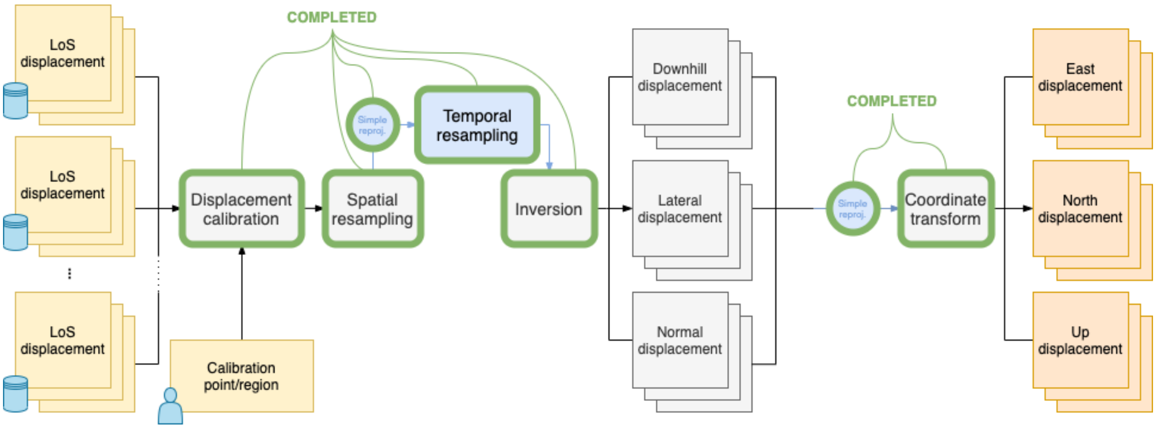


Figure 2 The proposed processing chain as of D2, including status of elements.

3.3 CSD estimation

CSD inversion consists of matrix inversion of equation 13 in D2 (simple reprojection) or equation 31 in D2 (MinA combination technique) in a weighted least squares sense using SVD.

Rank deficiency of the matrix is identified as the main challenge. This is caused by: (i) the sensor geometries being almost co-planar, (ii) the multi-track acquisitions not being co-incident and (iii) by temporal de-correlation (only in the case of MSBaS which includes phase inversion*). Rank deficiency is avoided by constraining the inversion by temporal resampling and/or regular*isation. Specifically, the temporal behaviour is constrained by interpolation in simple reprojection and by regularising the displacement velocity or acceleration to a minimum in the MinA and MSBaS methods. Rank deficiency due to the sensor geometries being almost co-planar is controlled by dismissing the north displacement altogether (simple reprojection and MSBaS) or by assuming the north displacement velocity to be minimal and constant (MinA).

Considering rockslides, it is natural to assume that the motion is dominant along the steepest and/or normal directions (with respect to the slope). It is therefore natural to constrain the lateral component with respect to the slope instead of the north component, given that the lateral component is significantly aligned with the north direction. This however restricts the inversion to slopes with a significant easterly or westerly aspect.

The inversion will be done in a local coordinate system, consisting of coordinates pointing: (i) along the gradient in the steepest downhill direction, (ii) tangentially in the lateral direction and (iii) in the normal direction. This enables adaptive regularisation by constraining the lateral direction.

3.4 Post-processing

For the MinA combination technique, the displacement velocities are integrated to obtain displacements. Finally, the CSD is then transformed from the local coordinate system to the East-North-Up coordinate system.

4 WP4: Product design and implementation

4.1 Executive summary

This section describes the interface and design of the VPI toolbox. The toolbox contains a set of tools for computing and visualising CSD in ArcGIS Pro. The main tools are:

- ***Import tool(s)*** - for importing LOS data from the InSAR-Norway web API, CSV files and raster files
- ***Profile tool*** - for analysing the spatial variation of the CSD, in terms of vectors along a user defined profile
- ***Time series tool*** - used for analysing the temporal variation of the CSD given a user defined area of interest

In addition, a set of utility tools are provided for computing CSD datasets without visualisation, for calibrating LOS datasets and for complementing ground-based datasets with LOS vectors.

Below the representation and import of input data is described, as well as the algorithmic implementation where parameters associated to data alignment and regularisation are described. The section ends with descriptions of the user interfaces to the main tools, illustrated with examples.

The main deliverable of this work package was the VPI toolbox.

4.2 Input data

4.2.1 Data representation

The input data is represented as ArcGIS feature classes of point type. Estimation of CSD can be done, given information about:

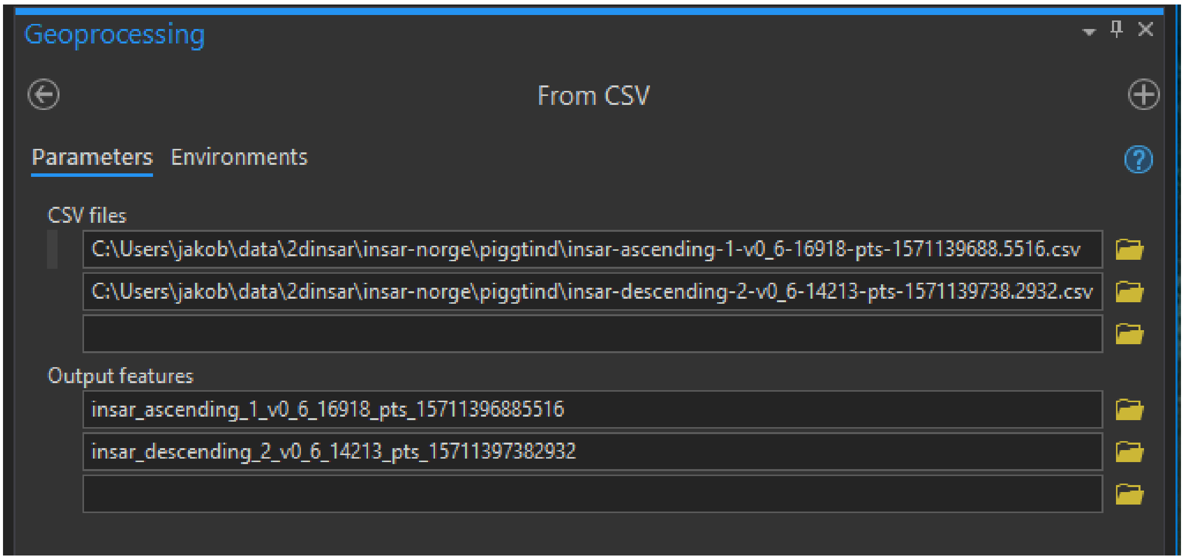
1) Point coordinates (with the corresponding coordinate reference system)
2) LoS unit vector (in an East, North and Up coordinate system)
3) LoS measurement (e.g. mean displacement velocity or displacement time series)

Required information about the LoS unit vectors and LoS measurement are assumed to be stored as arbitrarily named feature attributes.

4.2.2 Importing data

ArcGIS Pro provides import utilities for a great number of data types, such as shape files, text tables or GeoTIFFs, as well as a great variety of tools for converting between data types.

It thus enables the user to import InSAR data from a variety of sources, as long as the data can be represented as point type feature classes as described in the previous section. Although ArcGIS Pro provides multiple import utilities, two specialised import tools have been implemented.

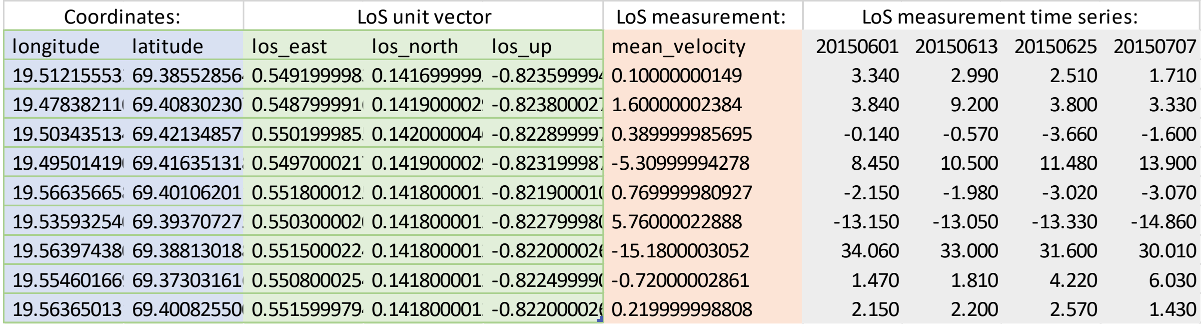


CSV files
C:\Users\jakob\data\2dinsar\insar-norge\piggtind\insar-ascending-1-v0_6-16918-pts-1571139688.5516.csv
C:\Users\jakob\data\2dinsar\insar-norge\piggtind\insar-descending-2-v0_6-14213-pts-1571139738.2932.csv

Output features
insar_ascending_1_v0_6_16918_pts_15711396885516
insar_descending_2_v0_6_14213_pts_15711397382932

Figure 3 Graphical user interface of the CSV import tool.

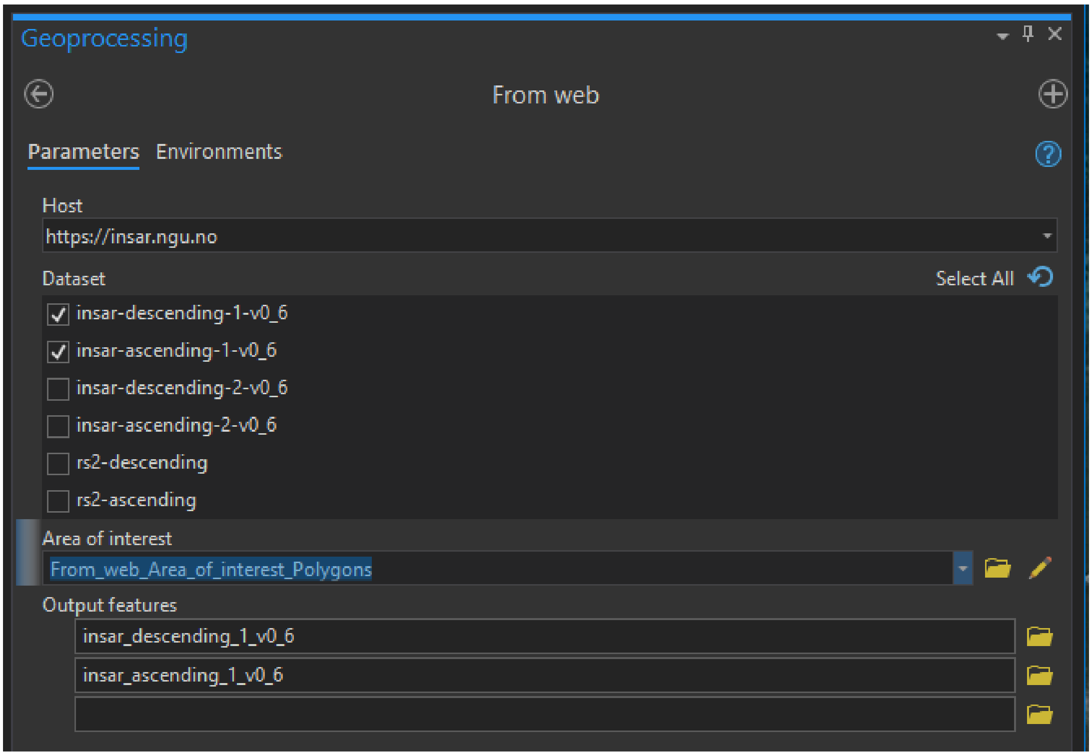
The first import tool imports CSV-files containing point like data. The graphical user interface is shown in Figure 3. An example of a tabulated CSV file is shown in Table 1. The file contains point coordinates, LoS unit vector components and two types of LoS measurements (mean displacement velocity and a displacement time series).



Coordinates:		LoS unit vector			LoS measurement:	LoS measurement time series:			
longitude	latitude	los_east	los_north	los_up	mean_velocity	20150601	20150613	20150625	20150707
19.51215553	69.38552856	0.549199998	0.141699999	-0.823599999	0.10000000149	3.340	2.990	2.510	1.710
19.47838211	69.40830230	0.548799991	0.141900002	-0.82380002	1.60000002384	3.840	9.200	3.800	3.330
19.50343513	69.42134857	0.550199985	0.142000004	-0.82289999	0.389999985695	-0.140	-0.570	-3.660	-1.600
19.49501419	69.41635131	0.549700021	0.141900002	-0.82319998	-5.30999994278	8.450	10.500	11.480	13.900
19.56635665	69.40106201	0.551800012	0.141800001	-0.82190001	0.769999980927	-2.150	-1.980	-3.020	-3.070
19.53593254	69.39370727	0.550300002	0.141800001	-0.82279998	5.76000022888	-13.150	-13.050	-13.330	-14.860
19.56397438	69.38813018	0.551500022	0.141800001	-0.82200002	-15.1800003052	34.060	33.000	31.600	30.010
19.55460166	69.37303161	0.550800025	0.141800001	-0.82249999	-0.72000002861	1.470	1.810	4.220	6.030
19.56365013	69.40082550	0.551599979	0.141800001	-0.82200002	0.219999998808	2.150	2.200	2.570	1.430

Table 1 A table representation of a CSV file containing all required fields for CSD estimation.

The second import tool uses the InSAR Norway API for direct download of data from the InSAR Norway web portal. The web import tool takes a user defined area of interest and a selection of datasets as input and imports data tiles intersecting the area of interest. The graphical user interfaces for the two tools are shown in Figure 4.



Host
https://insar.ngu.no

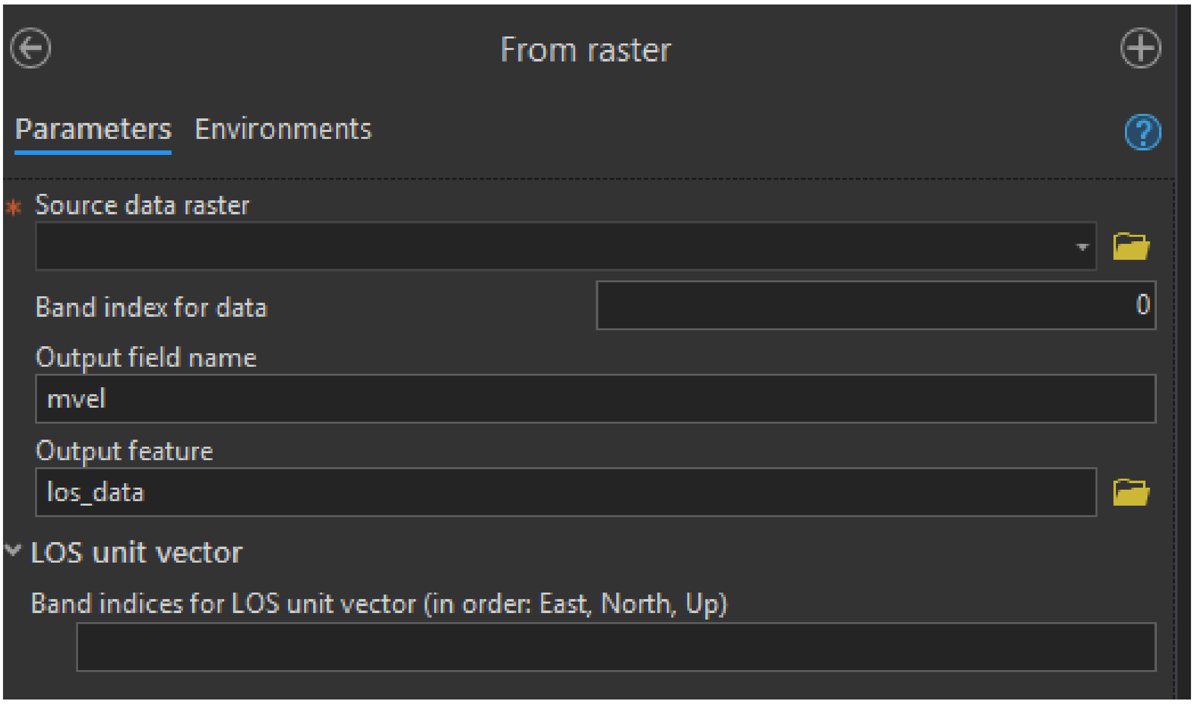
Dataset
☑ insar-descending-1-v0_6
☑ insar-ascending-1-v0_6
☐ insar-descending-2-v0_6
☐ insar-ascending-2-v0_6
☐ rs2-descending
☐ rs2-ascending

Area of interest
From_web_Area_of_interest_Polygons

Output features
insar_descending_1_v0_6
insar_ascending_1_v0_6

Figure 4 Graphical user interface of the web import tool.

The third import tool imports raster-files. The graphical user interface is shown in Figure 5.



* Source data raster

Band index for data 0

Output field name
mvel

Output feature
los_data

LOS unit vector

Band indices for LOS unit vector (in order: East, North, Up)

Figure 5 Graphical user interface for the raster import tool.

Using Sentinel-1 InSAR products from InSAR Norway

InSAR Norway provide LoS displacement products as point clouds for a set of different satellite geometries. For a given satellite geometry, each data point contains information about the *LoS unit vector* and the *LoS displacement* (as well as other parameters that will not be considered here). Given overlapping data points from distinctly different satellite geometries, the InSAR Norway data can thus be used for CSD estimation. The LoS displacement is provided as *mean displacement velocity* in mm/year and as *displacement time series* in mm. Data from InSAR Norway can be accessed through the web-portal insar.ngu.no. It can either be downloaded as CSV files and imported using the CSV import tool or downloaded directly through the InSAR Norway API using the web import tool. Figure 6 shows two Sentinel-1 datasets (ascending and descending) imported from insar.ngu.no.

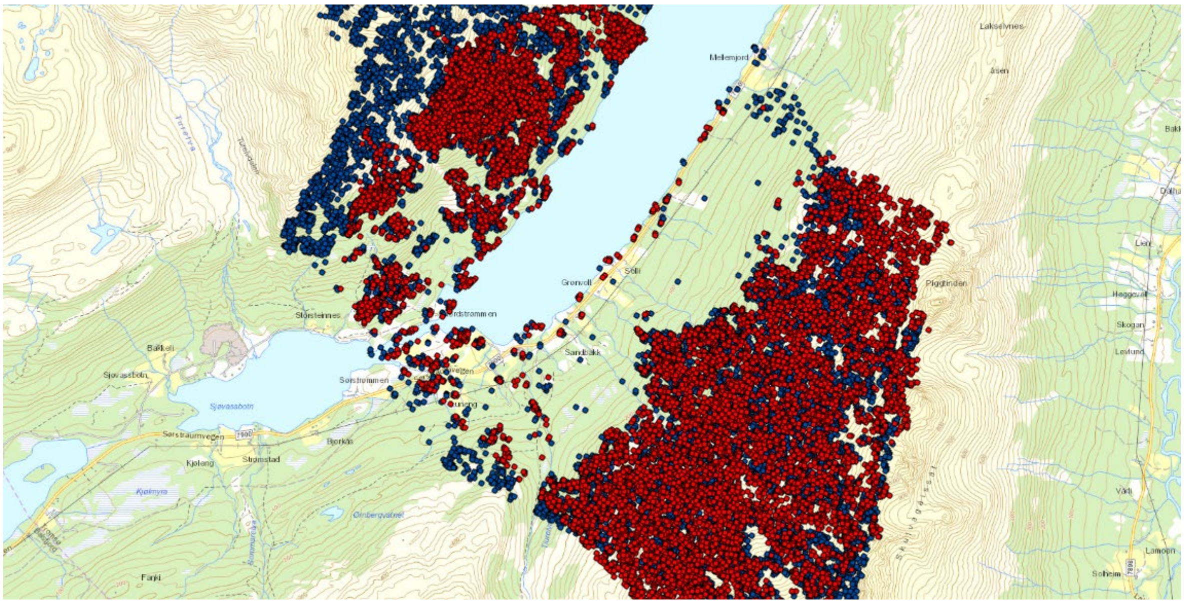


Figure 6 One ascending and one descending Sentinel-1 dataset imported from InSAR Norway.

4.3 Algorithmic implementation

4.3.1 Data alignment

Prior to CSD estimation, the multi-geometry datasets must be aligned spatially. A set of target points are chosen onto which all datasets are interpolated. Specifically, the target points are chosen as the set of points that intersects at least one point in each other dataset. Two points are moreover considered intersecting if the distance between them is less than a critical threshold. Pairwise distances between points in different datasets are computed using space partitioning in 2D (using a K-D tree algorithm) restricted to 1000 neighbours which enable fast calculations of point intersections. An example of two datasets being aligned, illustrated with stars (blue) and circles (yellow), is shown in Figure 7. The resulting set of intersecting points are illustrated with crosses (red).

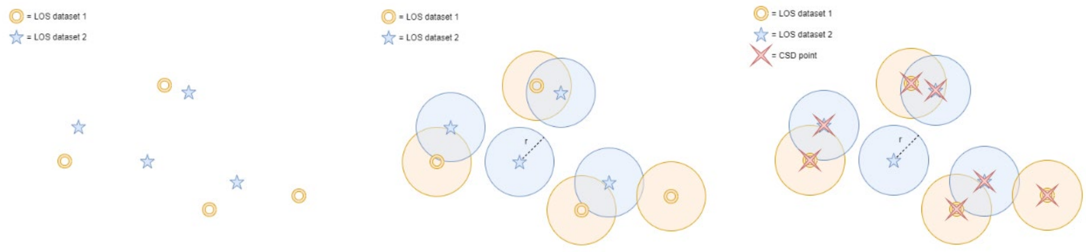


Figure 7 Illustration of two datasets being aligned (left). Point intersections are computed by assigning a radius r to each point (middle). Points that intersect at least one point in the other dataset are selected for interpolation (right).

The attributes representing the LoS vector components and the LoS measurements of the datasets are then interpolated onto the target points such that all datasets are spatially aligned. For interpolation, three options are supported: nearest neighbour, weighted nearest neighbour or Gaussian process regression.

4.3.2 Calibration

It is important that the individual InSAR datasets are calibrated with respect to each other. Prior to CSD estimation, calibration is therefore made. Two calibration methods have been implemented, one which calibrates the input datasets relative to a used defined polygon in which the mean displacement is assumed to be zero. The second method calibrates the data relative to a percentile, such that the displacement at the percentile is set to zero.

4.3.3 Alignment and regularisation

For CSD estimation, the simple reprojection method described in D2 has been implemented with optional regularisation. Extensive details about the simple reprojection method can be found in D2.

Regularisation here means that some assumption or constraint based on a-priori knowledge is imposed on the CSD estimation. If the InSAR line-of-sight vectors does not span all spatial dimensions, the InSAR data does not contain enough information to estimate the full 3-dimensional displacement. Specifically, the line-of-sight vectors from the Sentinel-1 satellites are roughly confined to a plane, due to the way their orbits and imaging modes are configured. Information about the displacement is thus missing in one direction, which typically is approximately the north direction. Regularisation is thus needed to impose information about the displacement in this direction.

The VPI-toolbox supports several regularisation options. It is set by type and direction. Currently, the available type are “None” for no regularisation and “Constant zero”, meaning that one direction is constantly fixed to zero. The direction can be set by:

- A user defined compass bearing

- The tangential direction of a user defined line
- The lateral direction of a user defined DEM

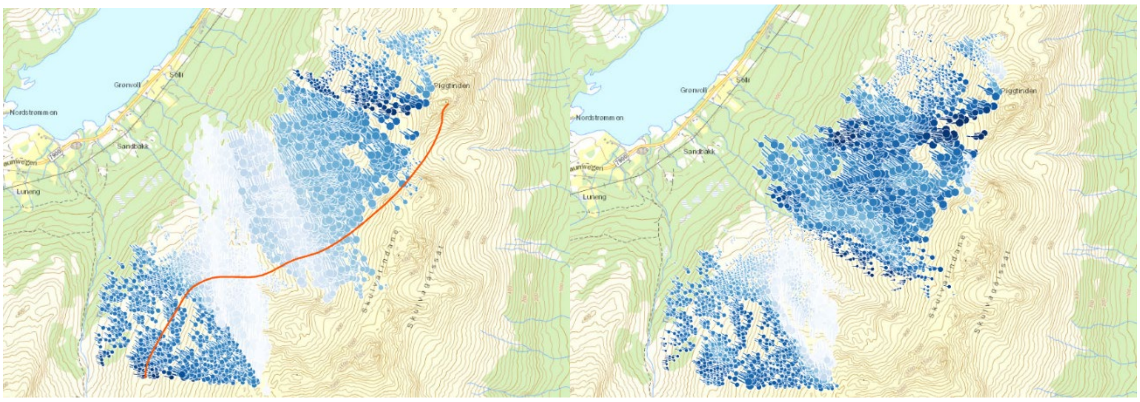


Figure 8. Examples of defining the regularisation direction from the tangent of a line (left) or the lateral direction of a DEM (right). The colours indicate the how well the regularisation constrains the inversion problem in terms of a conditioning number (blue indicates good conditioning, white indicates bad conditioning).

Figure 8 shows an example of using regularisation based on a line versus a DEM.

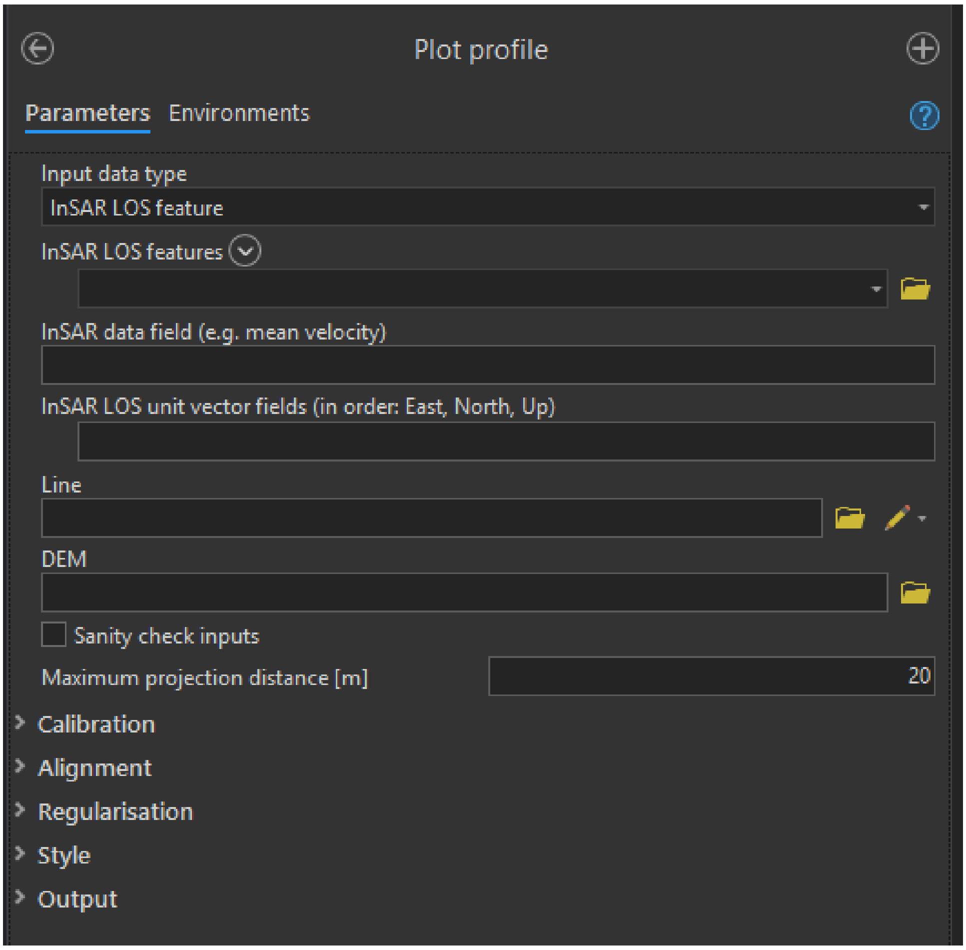
If datasets with LOS vectors spanning all three dimensions are available, regularisation is not needed. This situation occurs for instance if ground-based radar data is available in a north-south direction, in addition to Sentinel-1 data. Then, CSD is not confined to 2D but is fully 3D.

VPI implementation

In addition to the import tools described in section 4.1.2, the VPI toolbox contains two plotting tools: a profile tool and a time series tool.

4.3.4 Profile tool

The profile tool is designed to fulfil “Priority 1” in the user requirements. The tool takes a set of overlapping InSAR datasets, a line feature and a digital elevation model as input and returns a profile plot and (optionally) CSD products along the profile returned as a point type feature class or saved to a CSV file. The graphical user interface is displayed in Figure 10.



Input data type: InSAR LOS feature

☐ Sanity check inputs

Maximum projection distance [m]: 20

Figure 9 The graphical user interface of the profile tool.

As an example, a one ascending and one descending dataset has been imported from InSAR Norway as displayed in Figure 11. A westward line has been drawn, following the westerly slope of Piggtinden in Northern Norway and a digital elevation model is selected (here using the Norwegian 10m resolution DEM). The tool outputs the plot shown in Figure 12.

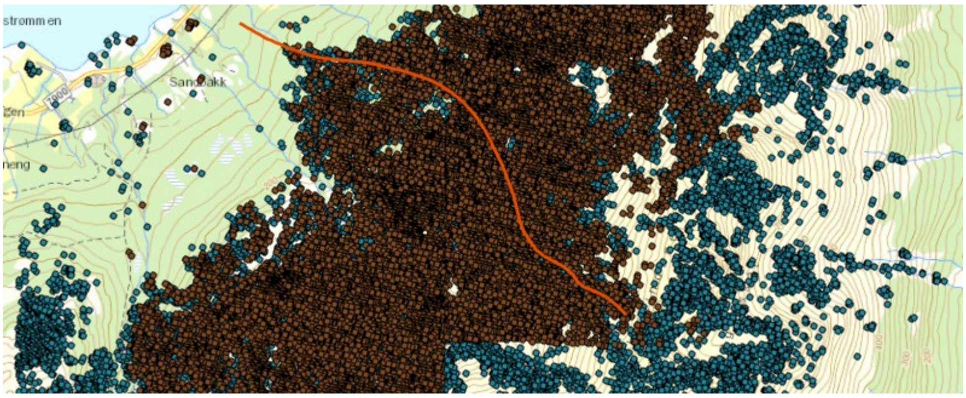


Figure 10 A user defined profile used as input to the profile tool.

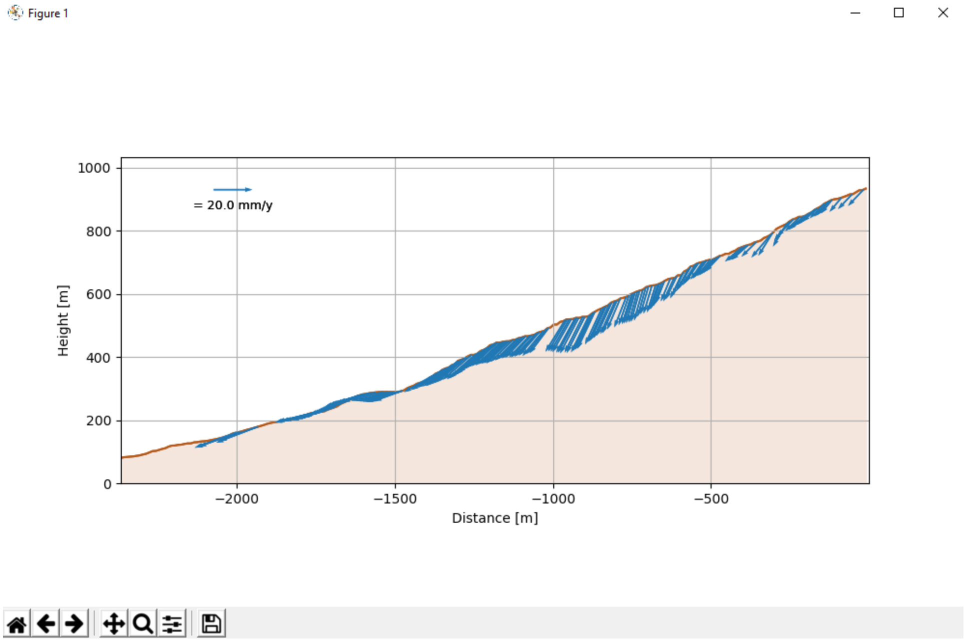
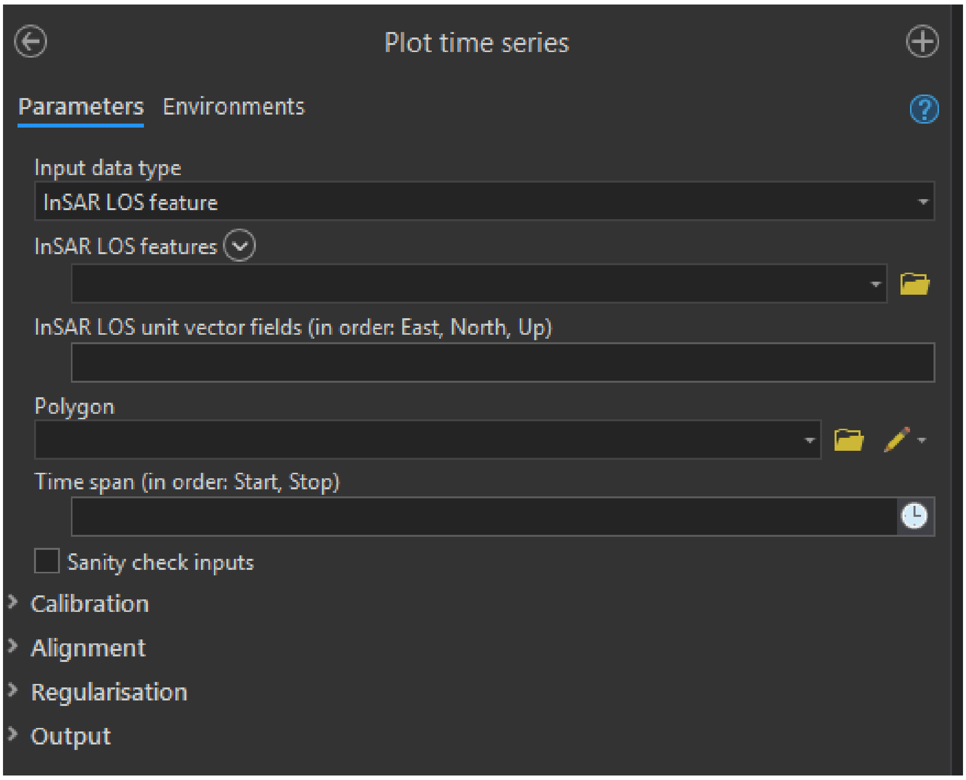


Figure 11 An output profile plot from the profile tool.

Time series tool

The tool takes a set of overlapping InSAR datasets containing time series data (for example as in Table 2), a polygon feature and an optional time span as input and returns a time series plot of desired CSD products. The graphical user interface is shown in Figure 13.



Plot time series

Parameters Environments

Input data type

InSAR LOS feature

InSAR LOS features

InSAR LOS unit vector fields (in order: East, North, Up)

Polygon

Time span (in order: Start, Stop)

☐ Sanity check inputs

Calibration

Alignment

Regularisation

Output

Figure 12 The graphical user interface of the time series tool.

As an example, one ascending and one descending dataset has been imported from InSAR Norway as displayed in Figure 14. A polygon has been drawn on the westerly slope of Piggtinden in Northern Norway. The tool outputs the plot shown in Figure 15, where the eastward, upward and absolute displacements are shown.

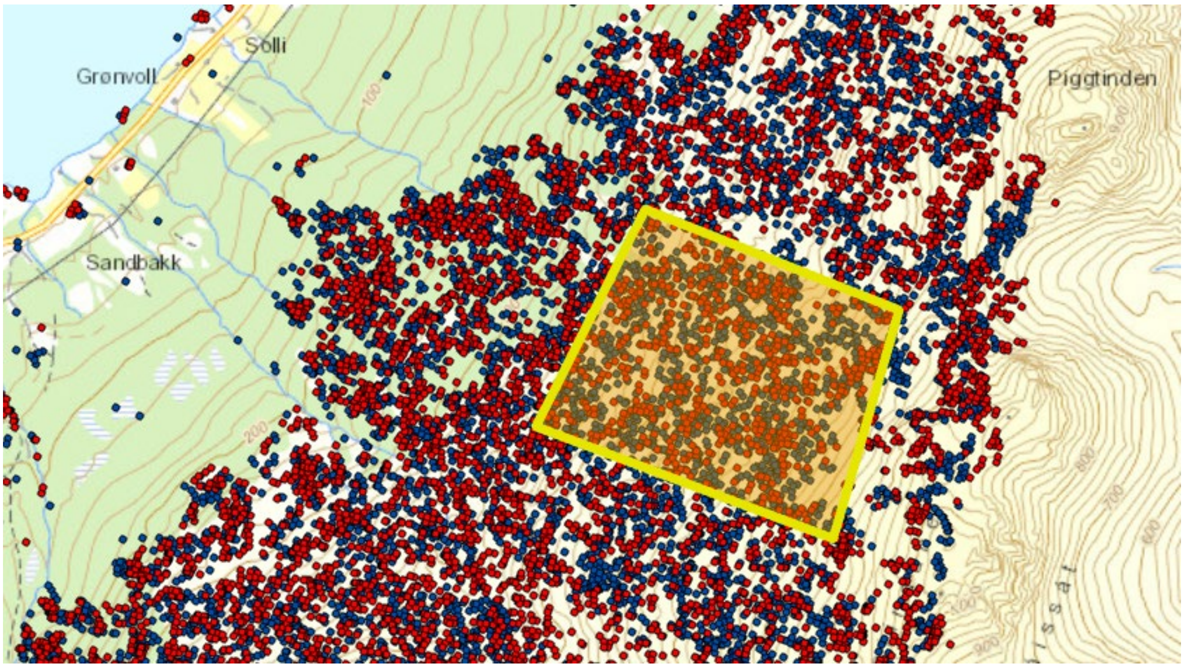


Figure 13 A polygon drawn on top of two InSAR datasets for input to the time series tool.

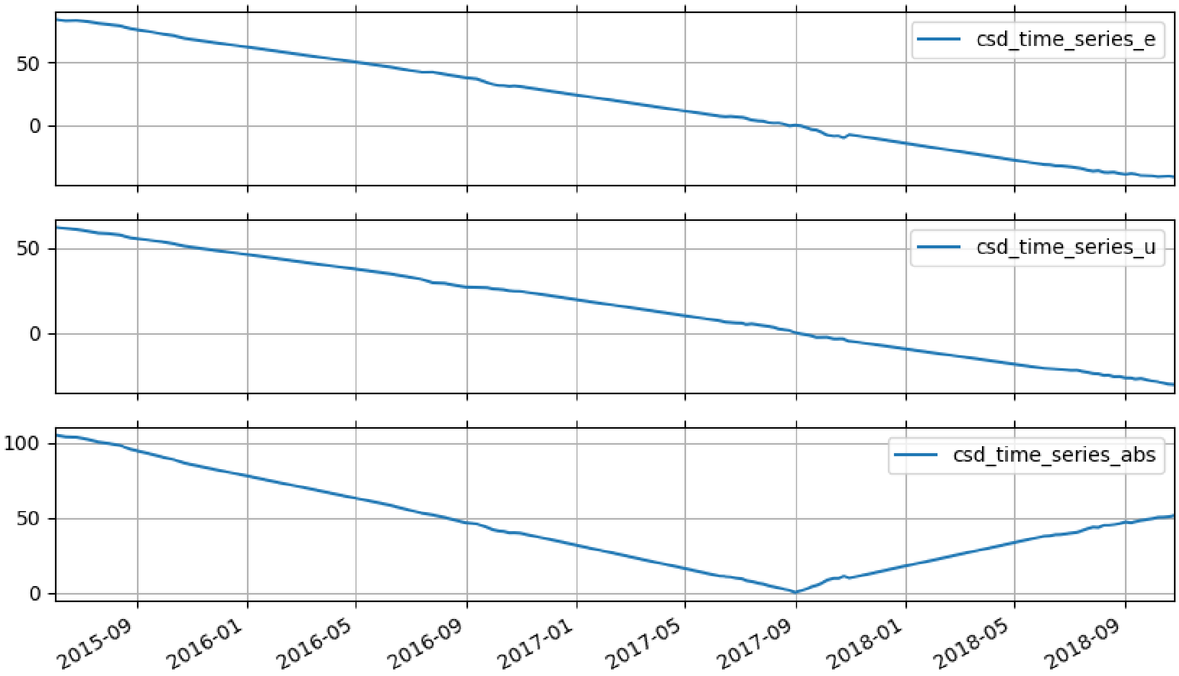


Figure 14 A time series plot showing the eastward, upward and absolute displacement of the west slope of Piggtinden.

Utility tools

In addition to the import tools and the visualisation tools described above, there are a set of utility tools. These include:

- A tool for only generating CSD points without any type of visualisation, given a set of input LOS features.
- A tool for calibrating line-of-sight data.
- A tool for generating line-of-sight vectors for ground-based radar data.

4.3.5 Optional settings

All tools in the VPI toolbox aligns a set of InSAR datasets and estimates CSD. These operations depend on several settings that can be set in the settings pane of the tools (this pane exists in all above mentioned CSD tools). Specifically, these include:

- **Calibration (None/Area/Percentile):**
  Either a polygon or a percentile can be provided for calibration (see section 4.2.2).
- **Point intersection radius:**
  The point radius used for identifying mutually intersecting points in the input InSAR datasets (see section 4.2.1).
- **Interpolation method (Nearest neighbour/Weighted nearest neighbour/Gaussian process regression):**
  Interpolation method for aligning mutually intersecting points in the input InSAR datasets (see section 4.2.1).
- **Regularisation type and direction:**
  Regularisation type (None or constant-zero) and direction (by compass bearing, user defined line or user defined DEM, see section 4.2.3)

5 WP5: Product evaluation

5.1 Executive summary

Combined Surface Displacement (CSD) products have been generated by using multi-geometry Synthetic Aperture Radar Interferometry (InSAR) and the visualization, plotting and interpreting (VPI) software tool developed within this project in order to map and characterize unstable rock slopes in Norway. This report evaluates the usefulness of the VPI-tool and the validity of CSD products for two evaluation sites as defined in report "D1: Selection of pilot sites and consolidation of user requirements." The two unstable rock slopes (Gamanjunni 3 and Osmundneset, Fig. 1 and 2) are selected due to the good understanding of the kinematics and the availability of other validation datasets.

The main output of this work package was *D3: Product evaluation report.* (Böhme et al., 2020).

5.2 Background

InSAR measurements are one-dimensional and correspond to changes in sensor-to-ground distance, i.e. displacements along the radar line-of-sight (LOS). Any displacement orthogonal to this direction is not possible to detect. By combining InSAR displacements from multiple ascending and descending satellite SAR geometries, it is possible to estimate 2D information (East-West horizontal and vertical displacement, expressed as length of 2D vector and dip angle of the deformation), called CSD hereafter. Combined horizontal and vertical information can be expressed as 2D displacement and dip of displacement relative to the vertical. This is valuable for geologists to understand the type of sliding mechanisms involved in specific unstable rock slopes. To fully take advantage of available datasets from InSAR Norway (insar.ngu.no), a user-friendly tool (called VPI thereafter), that calculates and visualizes 2D InSAR information in a Geographic Information System (GIS) has been developed in the project.

5.3 Evaluation sites

5.3.1 Gamanjunni-3

County, municipality, locality	Troms, Kåfjord, Manndalen
Coordinates (WGS 84)	69.48N, 20.53E

Gamanjunni 3 is situated on a west-facing slope in Manndalen valley, Troms county. With bedrock displacement rates of up to 54 mm/yr (Böhme et al., 2016), it is among the five fastest-deforming rock slopes in Norway. Owing to the relatively fast displacement and related consequences of a potential catastrophic failure, that would impact several farms, it has been classified as a high risk object (Böhme et al., 2016) and is permanently monitored by the Norwegian Water Resources and Energy Directorate (NVE).

5.3.1.1 Existing data and observed displacement

Gamanjunni 3 has been subject to detailed investigations, leading to good knowledge about the sites displacement pattern and mechanics behind.

- Differential global navigation satellite system (dGNSS) surveys yearly since 2011
- InSAR data from TerraSAR-X and Radarsat 2 satellites available
- CSD vector datasets derived from TerraSAR-X data (2009–2014 data, Eriksen et al., 2017).
- Several ground based radar surveys

Differential GNSS measurements show yearly displacements in between 40 and 54 mm, where the lower points have slower displacement rates than the upper (Figure 18, Figure 19). The movement direction is varying in between 252° and 262° and the dip in between 37° and 44°.

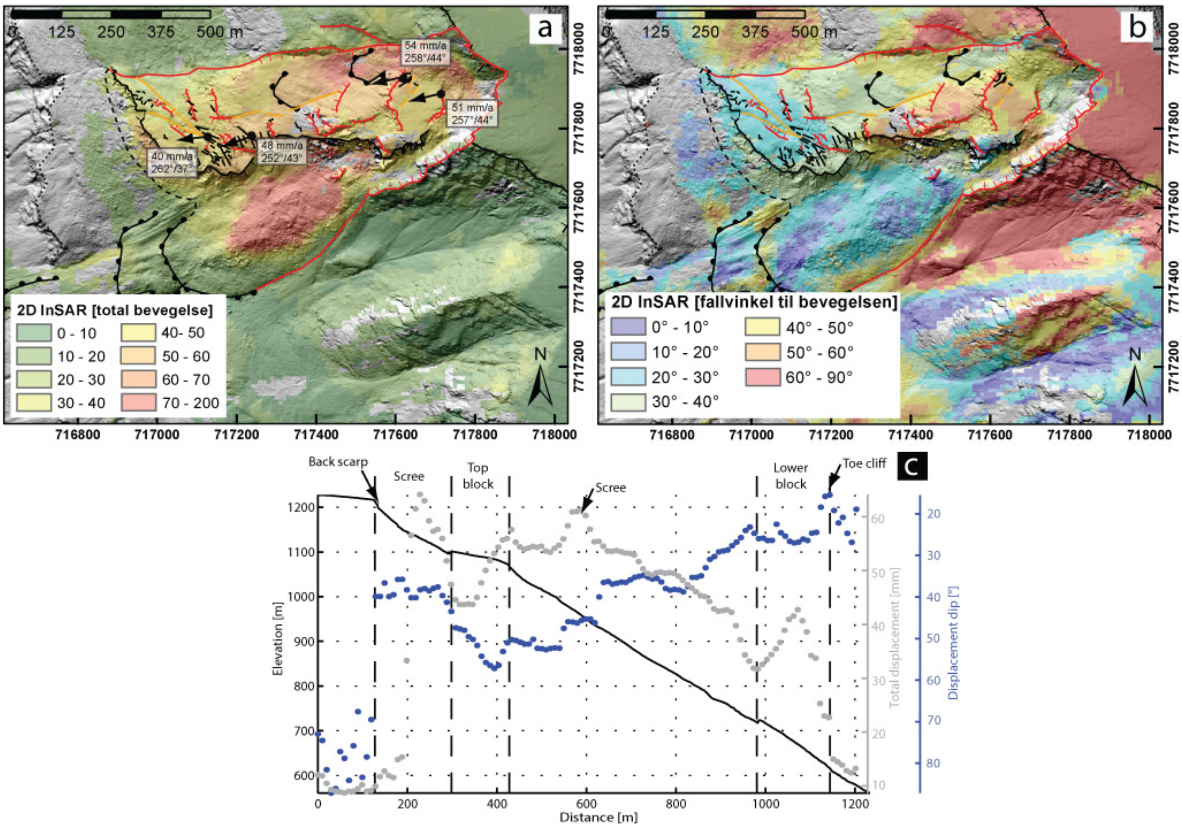


Figure 15. 2D InSAR data from TerraSAR-X. Observed displacement vectors from dGNSS are displayed.

InSAR data from TerraSAR-X (2009-2014) have an average displacement of 27 mm/yr at the top and 16 mm/yr at the toe of the unstable rock slope. CSD vector datasets derived from TerraSAR-X data of the same time period give larger displacments that are very similar to the dGNSS measurements: 47 mm/yr (dip 53 °) at the top and 42 mm/yr (dip 25°) at the toe (Figure 18). Radarsat 2 data gives much lower displacements with a different trend, 19 mm/yr at the top and 23 mm/yr at the toe.

Sentinel-1 data

Sentinel-1 data has limited coverage at Gamanjunni-3. Due to coverage only one of the ascending datasets can be used.

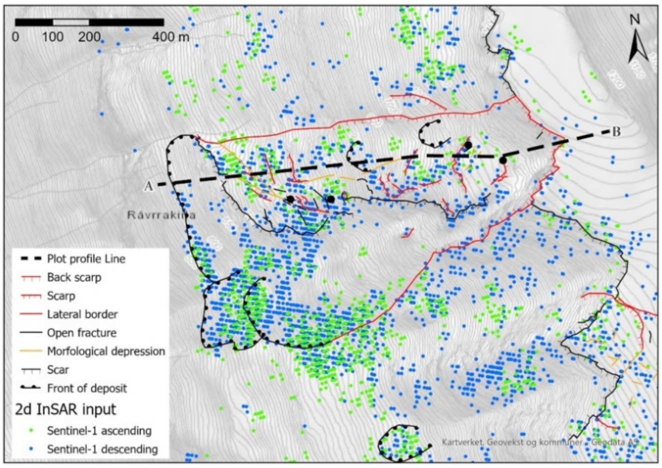


Figure 16. Sentinel-1 data coverage for Gamanjunni 3. Profile line A-B for extracted CSD vectors. Black dots are installed dGNSS points.

5.3.1.2 CSD vector results

Profiles with different extracted CSD vectors have been produced (Figure 20). For this different parameter choices have been tested. Furthermore, CSD data has been calculated for the entire unstable rock slope Gamanjunni 3 (Figure 21). The CSD average total displacement at the top is 48 mm/a with an average dip angle of 42°. At the bottom, the CSD average total displacement is 24 mm/a with an average dip angle of 14°.

5.3.1.3 Evaluation of CSD vector results

CSD data show the same trend as other displacement data with steeper and faster displacement at the top and shallower and slower displacement further down. CSD results at the top are very similar to dGNSS measurements, but they differ at the toe showing slower and shallower displacement.

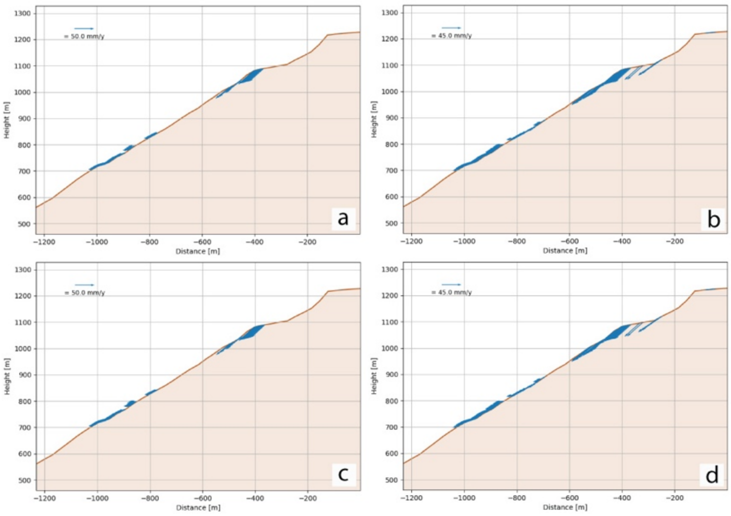


Figure 17. CSD profiles from Gamanjunni 3 produced with different parameters. a) Projection distance of 30 m and buffer radius 5 m; b) Projection distance of 40 m and buffer radius 5 m; c) Projection distance of 30 m and buffer radius 10 m; d) Projection distance.

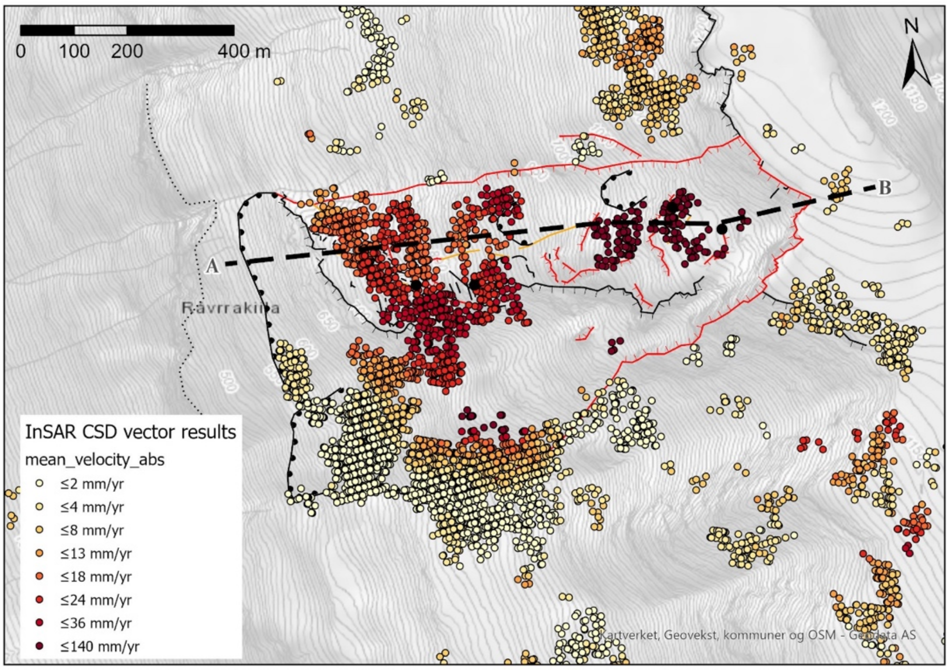


Figure 18. CSD map for Gamanjunni 3.

5.3.2 Osmundneset

County, municipality, locality	Vestland, Gloppen, Hyefjorden
Coordinates (WGS84)	61.78N, 6.01E

The unstable rock slope Osmundneset is situated on a west-facing slope above Hyefjorden, Sogn & Fjordane county. Observed bedrock displacements vary in between 2 to 4 mm/yr. A catastrophic failure would likely reach the subjacent fjord, causing a displacement wave and may result in loss of lives also in some distance to the location of the unstable rock slope. Because of those consequences, Osmundneset has been classified as a middle to high risk location.

5.3.2.1 Existing data

Osmundneset has been subject to detailed field investigations. Failure mechanisms and displacement rates are discussed in detail by (Booth et al., 2014). Differential GNSS surveys have been undertaken since 2008. Ground based InSAR data was also collected in 2018.

Differential GNSS measurements show yearly displacements in between 1 and 4 mm. The movement direction is varying in between 238° and 305°. Vertical displacements are not significant. Ground based InSAR measurements did not show significant displacements.

Sentinel-1 data

Sentinel-1 data has good data coverage for the unstable rock slope Osmundneset (Figure 22a).

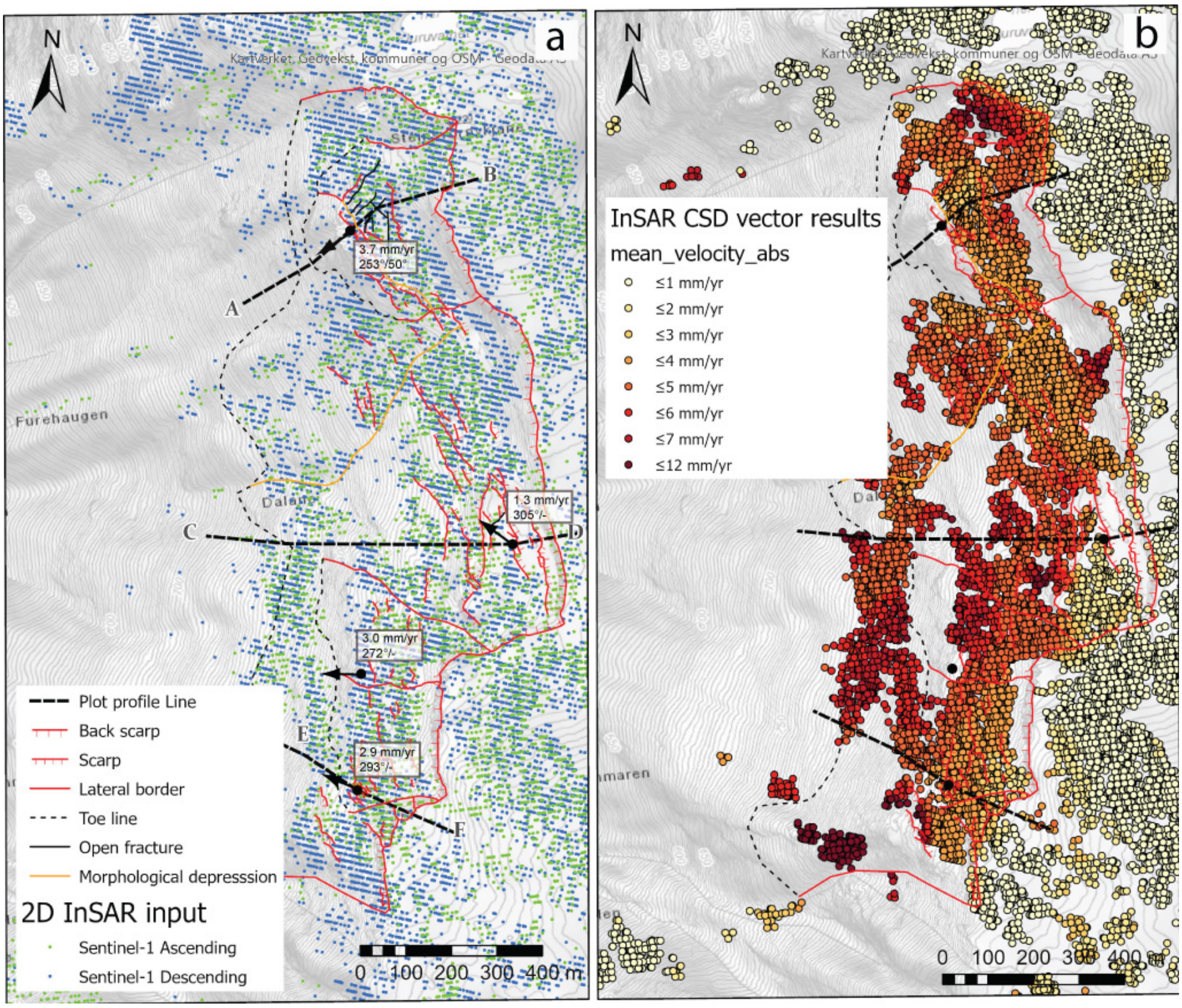


Figure 19. a) Sentinel-1 data coverage for Osmundneset. Profile lines for extracted CSD vectors. Black dots are installed dGNSS points. B) CSD map for Osmundneset.

5.3.2.2 CSD vector results

Three profiles at different locations with extracted CSD vectors have been produced (Figure 23). Furthermore, CSD data has been calculated for the entire unstable rock slope Osmundneset (Figure 22b).

Calculated displacements are in general much slower than those observed at Gamanjunni 3. The displacement rates are varying over the unstable area from a few mm up to 1.2 cm/yr.

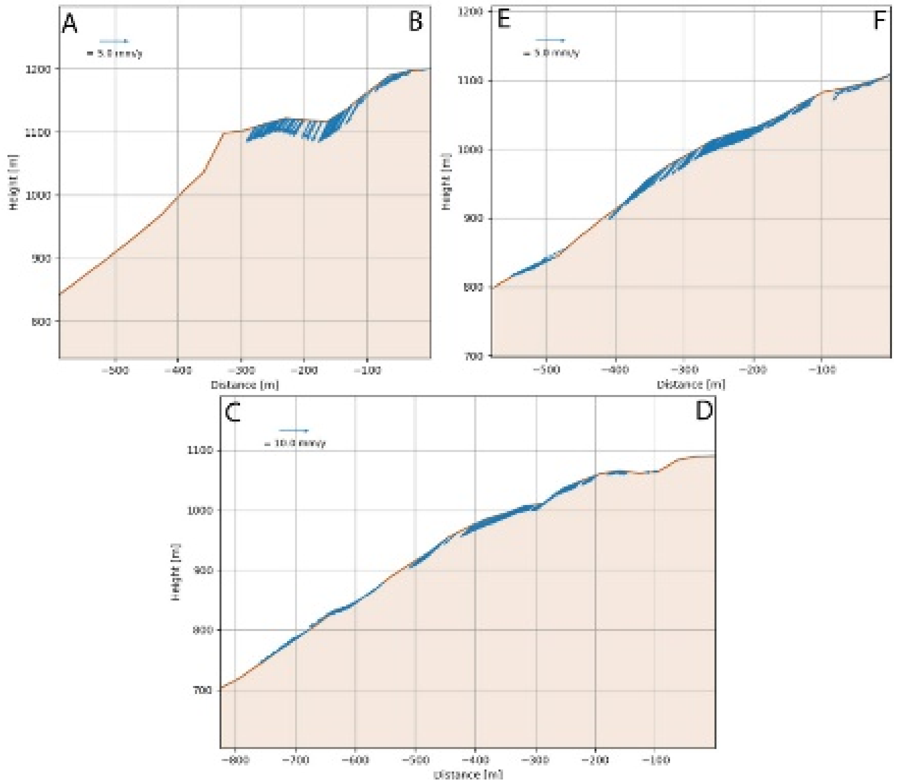


Figure 20. CSD profiles from the unstable rock slope Osmundneset. Profile locations are shown in Figure 22.

5.3.2.3 Evaluation of CSD vector results

The CSD average vectors have been calculated around the 4 dGNSS points. Those are fitting very well with measured dGNSS displacements (Table 1).

Table 2. Comparison of differential GNSS measurement results and averaged CSD vectors close to each GNSS point.

dGNSS vectors			CSD vectors	
Total [mm/yr]	**Direction [°]**	**Dip [°]**	**Total [mm/yr]**	**Dip [°]**
2.9	293	-	3.6	51
3	272	-	4.7	43
1.3	305	-	1.7	39
3.7	238	50	3.2	55

5.4 Evaluation of the VPI-tool

The VPI-tool has been tested of different users and is working good for all of them. It is easy to use and user friendly. The following list summarizes the feedback from NGU as part of the evaluation carried out in WP5:

Tool: Import from web:

- Imported files will always save in the ArcGIS Default-gdb, but not the specified database. Sometimes they did not save at all, just were displayed, but could not be used in further calculations.

Tool: Plot profile:

- Input files are not found, when they are moved to another “Group layer” that is located within a “Group layer” in the “Contents” pane (depth dependence of path)
- Tool is not working when DEM file is located in a database.
- Not able to use predefined shapefiles as input for the profile, when this is not located in a database
- Using “Lateral” as constrained direction under Regularization does not work for certain DEMs

Recommended improvements:

- Tool: Import from web
  - Possibility to load all online available datasets, without the necessity of updating the tool
  - Area of interest: possibility to choose “data frame”
  - It would be beneficial to be able to save at specified locations.
- Tool: Plot profile
  - Adjust minimum height to DEM, it is now always set to “0”. This looks strange for a profile just starting at 600 m
- Tool: Plot profile and Combine
  - It would be good to be able to use a constant direction value for a regularisation with a constrained direction.

All these issues have now been solved and implemented in the final version of the VPI tool.

6 WP6: Outreach and sustainability

The results from the project has been presented during several meetings and workshops where stakeholders from NGU and NVE has been present, and at American Geophysical Union (AGU) Fall meeting 2019 with contributing authors from both NORCE and NGU.

The VPI toolbox has gained high interest from the stakeholders and there are already plans for extension with new features, and tighter integration with the services and products from *InSAR Norway.*

NGU and NVE are now using the tool as part of their routines for analysis of unstable landslides. We have also implemented support for additional deformation observations from e.g. terrestrial radar interferometry (TRI), that can provide information about north-south oriented displacement and thus allows to produce full three-dimensional (3D) deformation maps. Figure 24 and Figure 25 shows an example of a landslide in south western Norway where Sentinel-1 observations have been combined with terrestrial observations using a radar to provide 3D displacement vectors.

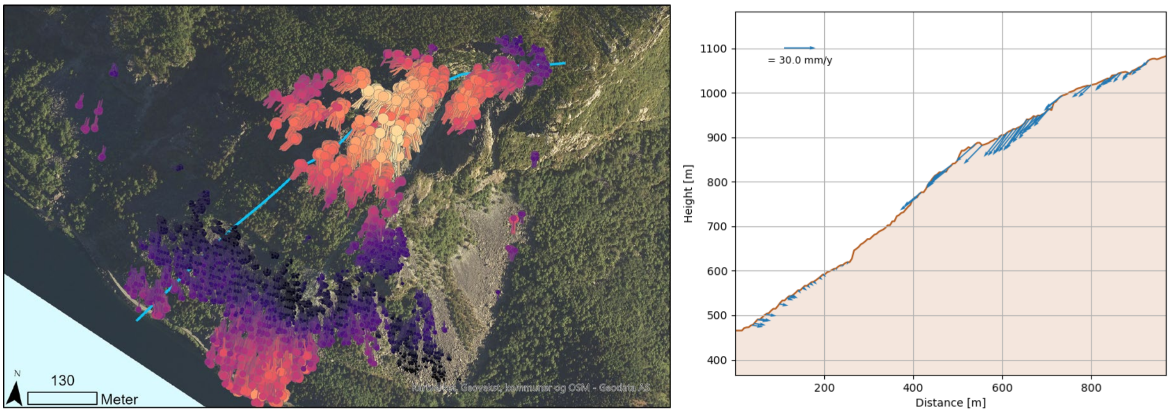
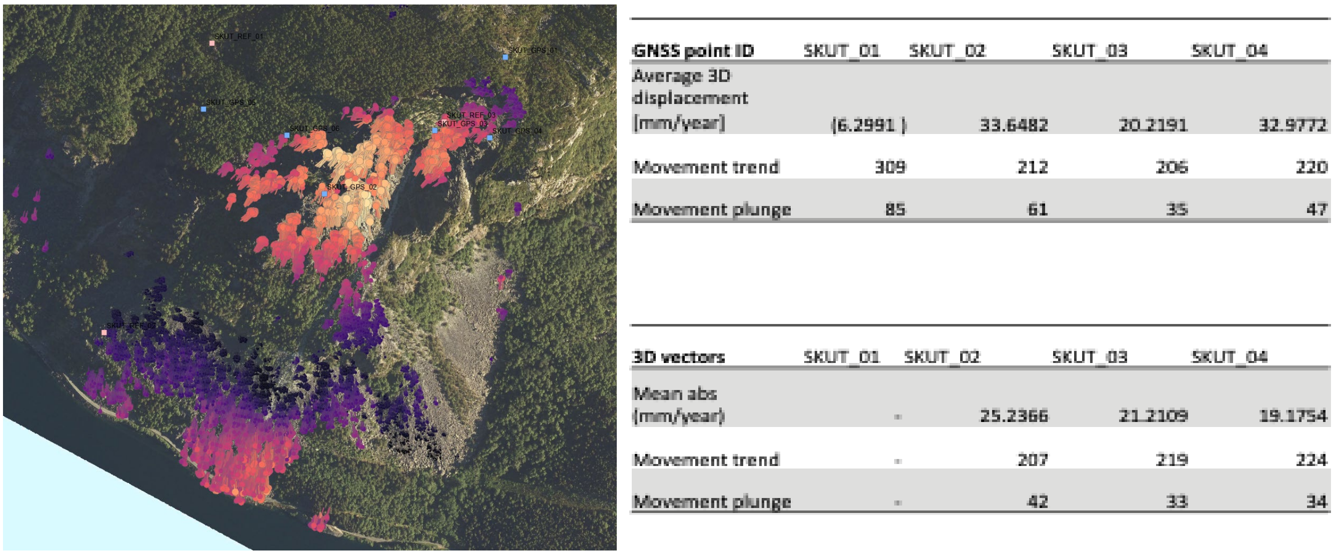


Figure 21. Example of landslide and CSD results produced by NGU using the VPI toolbox developed as part of this project. Source: M. Bredal, NGU.



GNSS point ID	SKUT_01	SKUT_02	SKUT_03	SKUT_04
Average 3D displacement [mm/year]	(6.2991)	33.6482	20.2191	32.9772
Movement trend	309	212	206	220
Movement plunge	85	61	35	47

3D vectors	SKUT_01	SKUT_02	SKUT_03	SKUT_04
Mean abs (mm/year)	-	25.2366	21.2109	19.1754
Movement trend	-	207	219	224
Movement plunge	-	42	33	34

Figure 22. An in-house evaluation is ongoing and preliminary results show good correlation between the estimated CSD 3D vectors and GNSS measurements. Source: M. Bredal, NGU

7 Conclusion

This report concludes the work in the project “Mapping and characterization of unstable slopes with Sentinel-1 multi-geometry InSAR (activity line 2: public sector applications)”.

The main objectives of the project were defined as:

1. to develop higher-order Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) products that combines surface displacement measurements from all available InSAR geometries.
2. to increase the value of InSAR technology to map and characterize unstable landforms and provide a better understanding of slope processes that could relate to catastrophic failures.
3. to assess the added value of the developed, higher-order InSAR products for the public sector in Norway.

The workflow has been implemented such that the geologist at NGU or NVE who is responsible for mapping an area can use the implemented VPI tool as an integrated tool within the ArcGIS framework. This allows seamless integration with other datasets already included in the ArcGIS Project. Examples here are detailed orthophotos, field-mapped lineaments, Terrestrial Laser Scanning, geologic and geomorphologic maps, etc.

The fulfilment of the project objectives has been demonstrated by deliverables D1–D3 and this report. The implemented VPI toolbox has been implemented into operational use by the involved stakeholders and expert users from NGU and NVE and based on the continuous feedback from these users we have already updated the VPI toolbox several times. In addition, the VPI is now also being used by a Master student at NORCE and the Arctic University of Norway that is working on characterizing landslides in Norway using Sentinel-1.

In summary, the feedback has been very positive, and the use of the toolbox has stimulated increased use of Copernicus Sentinel-1 data for landslide use in Norway.

8 References

Booth, A. M., Dehls, J., Eiken, T., Fischer, L., Hermanns, R. L., and Oppikofer, T., 2014, *Integrating diverse geologic and geodetic observations to determine failure mechanisms and deformation rates across a large bedrock landslide complex: the Osmundneset landslide*, Sogn og Fjordane, Norway: Landslides, p. 1-12.

Böhme, M., Bunkholt, H., Dehls, J., Oppikofer, T., Hermanns, R. L., Dalsegg, E., Kristensen, L., Lauknes, T. R., and Eriksen, H. Ø., 2016, *Geologisk modell og fare- og risikoklassifisering av det ustabile fjellpartiet Gamanjunni 3 i Manndalen, Troms*, Norwegian Geological Survey, 2016.031

Böhme, M., Hermanns, R., Gosse, J., Hilger, P., Eiken, T., Lauknes, T., and Dehls, J., 2019, *Comparison of monitoring data with paleo–slip rates: Cosmogenic nuclide dating detects acceleration of a rockslide*, Geology.

Böhme, M., Dehls, J. F., Rouyet, L., Grahn, J., and Lauknes, T. R., 2020, *Mapping and characterization of unstable slopes with Sentinel-1 multi-geometry InSAR (activity line 2: public sector applications): Selection of pilot sites and consolidation of user requirements, Product evaluation report D3*, issue 1.0, June 2020.

Eriksen, H. Ø., Lauknes, T. R., Larsen, Y., Corner, G. D., Bergh, S. G., Dehls, J., and Kierulf, H. P., 2017, *Visualizing and interpreting surface displacement patterns on unstable slopes using multi-geometry satellite SAR interferometry (2D InSAR)*, Remote Sensing of Environment, v. 191, p. 297-312.

Grahn, J, Lauknes, T. R., Larsen, Y, and Rouyet, L., 2019, *Mapping and characterization of unstable slopes with Sentinel-1 multi-geometry InSAR (activity line 2: public sector applications): Selection of pilot sites and consolidation of user requirements, Algorithmic consolidation report D2*, issue 1.0, July 2019.

Hermanns, R., Oppikofer, T., Anda, E., Blikra, L. H., Böhme, M., Bunkholt, H., Dahle, H., Devoli, G., Eikenæs, O., Fischer, L., Harbitz, C., Jaboyedoff, M., Loew, S., Molina, F. Y., and Xavier, F. ,2012, *A hazard and risk classification system for catastrophic rock slope failures in Norway*.

Rouyet, L., Böhme, M., Kristiansen, L., Lauknes, T. R., Larsen, Y., and Grahn, J., 2019, *Mapping and characterization of unstable slopes with Sentinel-1 multi-geometry InSAR (activity line 2: public sector applications): Selection of pilot sites and consolidation of user requirements, Technical report D1*, issue 1.0, March 2019.

9 Appendix 1: Data package description

9.1 Git repository

The toolbox is version controlled and maintained in a git repository. The repository contains the source code as well as documentation and usage examples. The repository can be found here:

https://gitlab.itek.norut.no/jakob/vpi-toolbox

9.2 Software dependencies

The VPI toolbox require the source codes, ArcGIS Pro version 2.5 or higher and a Python environment with the following dependencies:

Package	Version	Homepage
fiona	1.7.10	https://github.com/Toblerity/Fiona
affine	2.3.0	https://github.com/sgillies/affine
geopandas	0.8.1	https://geopandas.org/
scikit-learn	0.23.1	https://scikit-learn.org/stable/

9.3 Input/output description

The toolbox consists of three tools for computing and/or visualizing combined surface displacements from line-of-sight (LOS) measurements at different lines-of-sights. Below are the defined inputs and outputs for these tools:

	Combine tool	**Profile plotter**	**Time series plotter**
Required inputs:	- LOS measurements (CSV/Shapefile/raster) - LOS vectors (CSV/Shapefile/raster)	- LOS (mean/static) measurements (CSV/Shapefile/raster) - LOS vectors (CSV/Shapefile/raster) - Line feature (Shapefile) - DEM (Raster file)	- LOS time series measurements (CSV/Shapefile) - LOS vectors (CSV/Shapefile) - Polygon feature (Shapefile)

Optional inputs:	- DEM (Raster file) for lateral regularization		- DEM (Raster file) for lateral regularization
Outputs:	CSD components (CSV/Shapefile)	CSD vector profile plot (PNG/JPEG/EPS/…)	CSD time series plots (PNG/JPEG/ EPS/…)

NORCE Norwegian Research Centre AS
www.norceresearch.no