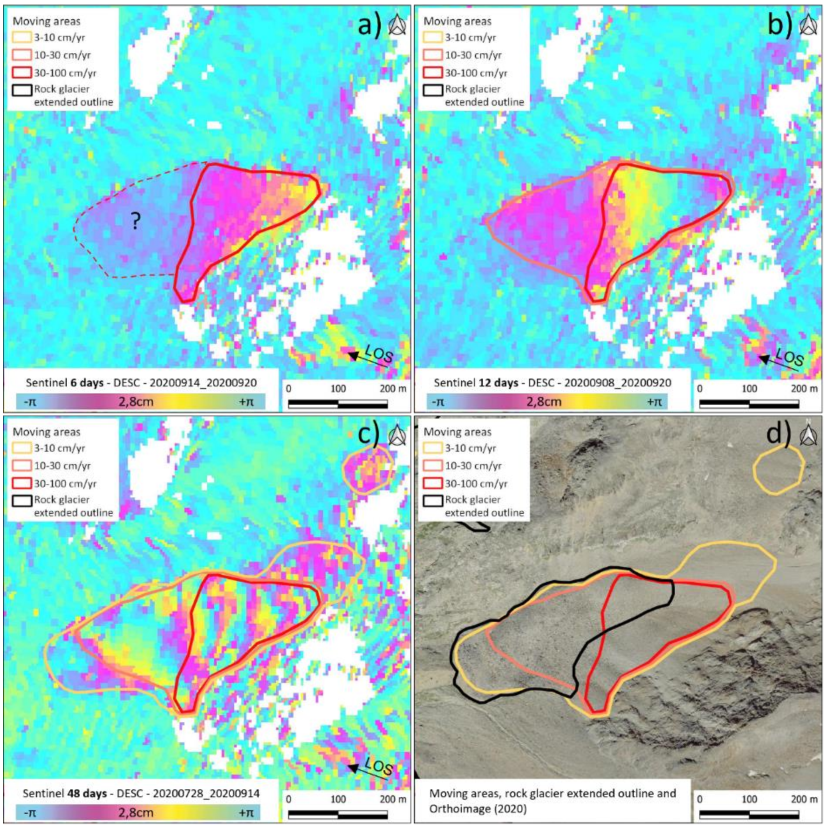
InSAR-based kinematic attribute in rock glacier inventories

Practical InSAR Guidelines v.4.0



RGIK Action Group

31.05.2023

To the attention of RGIK community

The Practical InSAR Guidelines (InSAR-based kinematic attributes in rock glacier inventories) is a document describing the recommendations for using Synthetic Aperture Radar Interferometry (InSAR) to assign kinematic attributes in rock glacier inventories.

This is not a standalone document. It is a complement to the following reference documents of the IPA Action Group on rock glacier inventories and kinematics (RGIK):

- Baseline concepts: Towards standard guidelines for inventorying rock glaciers
- Practical guidelines: Towards standard guidelines for inventorying rock glaciers
- Baseline concepts: Kinematics as an optional attribute of standardized rock glacier inventories

Useful methodological background information and additional examples on the interpretation of InSAR data can be found in Bertone et al. (2022). In the following document, we provide the basics necessary to use InSAR for the production of a rock glacier inventory (RoGI) (*Section 1. Basics*) and recommendations to perform the work in a standardized GIS-based tool (*Section 2. Practical guidelines*). We recommend to read this document as a complement of the tutorial of the RoGI exercise in the Goms valley (Switzerland).

To the attention of ESA CCI+ Permafrost external partners

In the framework of the European Space Agency (ESA) Climate Change Initiative (CCI+) Permafrost Project Phase 1 (2018–2021), several partners worked on assigning kinematic attributes in rock glacier inventories (RoGIs) produced in several regions worldwide. A past version of this document (v.3.0) was used to generate comparable RoGIs using a kinematic approach based on Synthetic Aperture Radar Interferometry (InSAR).

In ESA CCI+ Permafrost Phase 2 (2022–2025), a cross-validation exercise in subareas of the 12 initial regions has been designed to identify potential discrepancies between multiple operators, adjust the guidelines and evaluate the quality of the final products. The selected regions and involved partner institutions are shown in Annex C.

The present document is an updated version (v.4.0) of the Practical InSAR Guidelines. The objective is to define standard rules to assign an InSAR-based kinematic attribute to the rock glacier units and generate comparable RoGI products. This is not a standalone document. Consequently, we recommend that each operator read carefully the following documents before starting the inventorying process:

- Baseline concepts: Towards standard guidelines for inventorying rock glaciers
- Practical guidelines: Towards standard guidelines for inventorying rock glaciers
- Baseline concepts: Kinematics as an optional attribute of standardized rock glacier inventories

The inventorying process follows the procedure explained in the subfolder INSTRUCTION (*1_RoGI_practice_instructions.pdf*) of the project made for each Permafrost_cci subarea. The practical InSAR guidelines focus on delineating moving areas using InSAR and assigning InSAR-based kinematic attributes to inventoried rock glacier units.

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Main acronyms

CCI	Climate Change Initiative
ESA	European Space Agency
InSAR	Synthetic Aperture Radar Interferometry
IPTA	Interferometric Point Target Analysis
KA	Kinematic Attribute
LOS	Line-of-sight
MA	Moving Area
PSI	Persistent Scatterer Interferometry
RGU	Rock Glacier Unit
RoGI	Rock Glacier Inventory
SAR	Synthetic Aperture Radar
SBAS	Small Baseline Subset

1. InSAR basics

1.1 InSAR to map surface movement

Differential Synthetic Aperture Radar Interferometry (InSAR) is a satellite remote sensing technique used to measure surface movement over large areas. The approach consists of analysing **the phase differences between two SAR images taken at different times**, after removal of unwanted phase components (e.g. associated with the topography or the atmosphere).

The resulting map of phase differences is referred to as an "interferogram". It contains **one-dimensional information about the surface displacement**, corresponding to the **projection of the real displacement along the sensor view angle, i.e. the SAR line of sight** (**LOS**) (*Figure 1a*). A single SAR interferometric observation therefore does not allow to fully determine the magnitude and direction of a surface deformation. The three-dimensional displacement vector can only be computed if one assumes a certain displacement direction when focusing on a specific process, e.g. creep occurring along the steepest slope direction for the rock glaciers.

A Synthetic Aperture Radar (SAR) is not able to measure displacements that are fully perpendicular to its LOS and detects an underestimated displacement if the LOS deviates from the real displacement orientation. We therefore need **to know the measurement geometry of the available datasets to correctly interpret the interferograms**. SAR satellites are polar orbiting and imaging the Earth's surface at a specific incidence angle. With a right-looking sensor, a satellite crossing the Equator from South to North (**ascending passes**) looks **towards East**. When crossing the Equator from North to South (**descending passes**), it looks **towards West** (*Figure 1a*).

The SAR geometry has an impact on the achieved spatial coverage in mountainous terrain. North- and South-facing slopes are difficult to analyse, because creeping landforms include a displacement component perpendicular to the LOS orientation. **Back-facing slopes** (*D–I, Figure 1b*), defined as the western slopes when viewing in descending mode (eastern slopes in ascending mode), **are the most appropriate configurations**. The local spatial resolution is less affected by geometric distortions and the displacement orientation is more or less aligned with the LOS. The slopes facing the radar (*A–D, Figure 1b*) are less favourable for an InSAR analysis. In addition, the difference between the slope steepness and the radar incidence angle has to be considered. A steep incidence angle reduces shadow effects observed in back-facing slopes (*F–H, Figure 1b)* but increases layover effects in slopes facing the SAR (*B–D, Figure 1b*). Consequently, it is important to **use a combination of interferograms with different view angles and geometries (ascending/descending) to investigate different slopes in a region**.

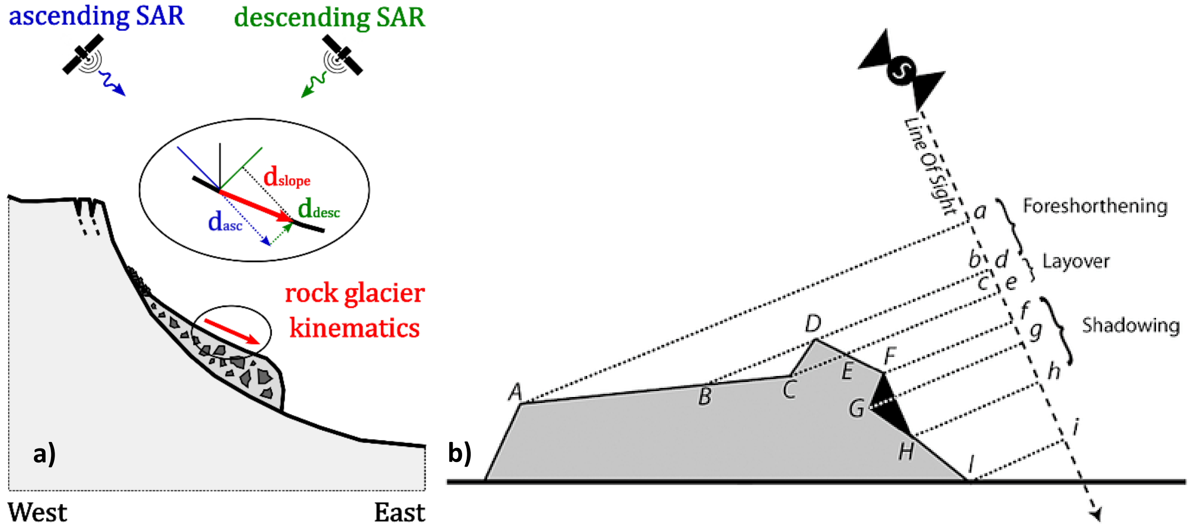


Figure 1. ***(a)*** *A displacement (d) vector along the slope (d_{slope}) and the line of sight (LOS) components measured by InSAR when using SAR images from ascending (asc) and descending (desc) geometries: d_{asc} and d_{desc}.* ***(b)*** *Geometric distortions from the SAR measurement geometry in mountainous regions.*

1.2 Visual interpretation of interferograms

The displacement that occurs between the two image acquisitions can be estimated by **visually interpreting the interferograms**. The results are spatially relative to a reference area selected outside the studied moving area. The spatial change of colour in the interferogram expresses the surface displacement projected onto the LOS direction. **An entire colour cycle (fringe) is equivalent to a change of half the SAR wavelength (λ/2) along the LOS during the time interval between the two images**. One phase cycle represents half the wavelength as the radar signal travels to the ground and back to the sensor. The direction of the change can be interpreted using the key in *Figure 2*. Considering back-facing slopes, clockwise colour changes mean that the radar beam has travelled further in the second acquisition and thus corresponds to a downslope process or subsidence. In the opposite case, it will be interpreted as an upslope displacement or uplift.

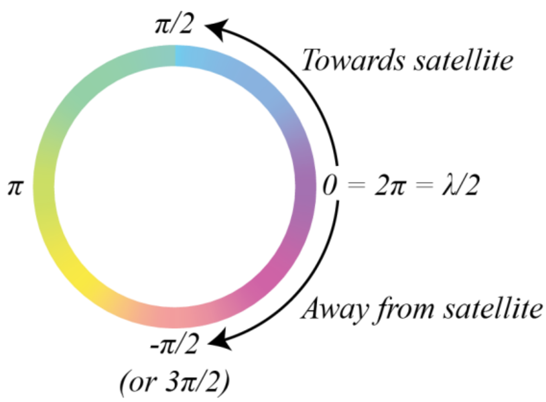


Figure 2. *The difference in displacement rate between locations with the same colour is a multiple of λ/2. When the colour changes in clockwise direction, the ground has moved away from the satellite. In the opposite direction, the ground has moved towards the satellite.*

The minimum and maximum displacement rates that can be detected depend on the time interval, the resolution and the SAR wavelength of the interferograms (*Figure 3* and *Table 1*). The interferometric SAR signal will become ambiguous when the displacement gradient between adjacent pixels is higher than half of the wavelength during the selected time interval. It will decorrelate when the changes occurring during the selected time interval are too large within the pixels. Temporal decorrelation can also occur due to changes in surface properties (e.g. vegetation, snow and wetness).

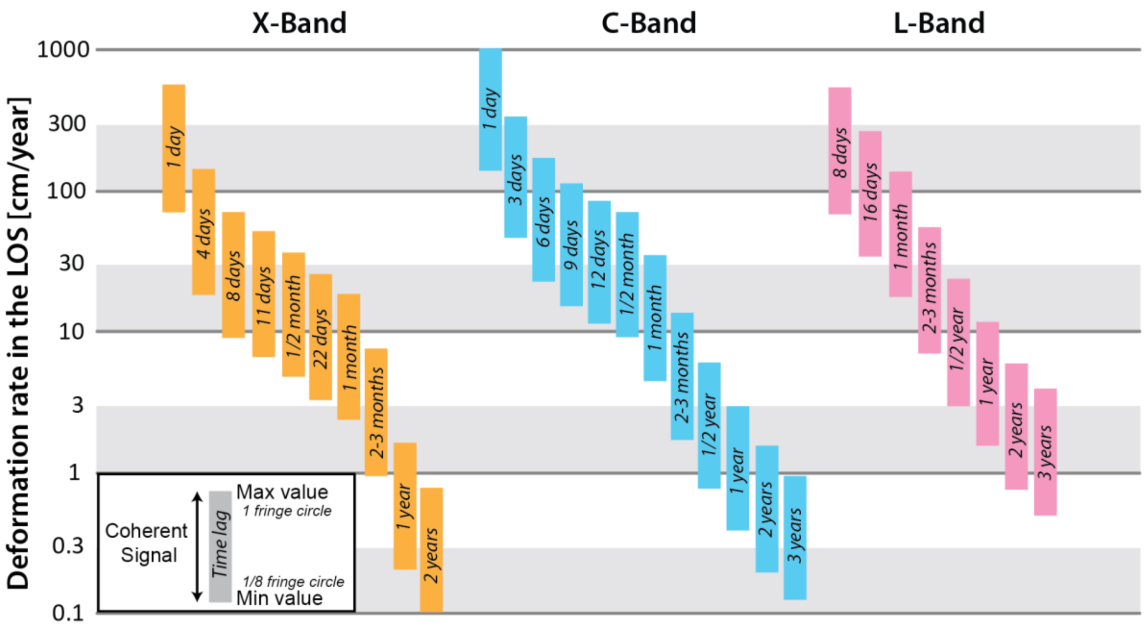


Figure 3. *Deformation rate observed by SAR sensors for the most commonly used time interval. A bar defines the interval of deformation rate in cm/yr for which a coherent signal can be identified and interpreted on an interferogram generated with a certain time interval. It shows the detection capability of different InSAR data. The lower limit corresponds to the minimal detectable velocity (1/8 of fringe cycle). The upper limit corresponds to the maximum velocity (one entire fringe). A movement lower than the minimum value of the bar is not detectable. A movement higher than the maximum value of a bar may decorrelate on the interferogram (adapted from Barboux et al. 2014).*

Table 1. *Radar characteristics of the main SAR systems used in the exercise.*

Satellite	*Terrasar-X*	*Cosmo-SkyMed*	*Sentinel-1*	*Radarsat-2*	*ALOS-2*	*SAOCOM*
Date	from 2007	from 2007[2]	from 2014	from 2007	from 2014	from 2018
Agency	DLR	ASI	ESA	CSA	JAXA	CONAE
Wavelength (cm)	3.1	3.1	5.5	5.6	24.3	23.5
Band	X	X	C	C	L	L
Incidence angle (°)	20–45	25–40	20–45	35	30–40	18-50
Range resolution (m)[1]	1–16	1–100	5–25	3–100	3–60	5-10
Azimuth resolution (m)[1]	1–16	1–3–100	5–40	3–100	3–60	10-50
Scene width (km)	10–100	10–200	80–400	50–500	70	10-400
Repeat cycle (day)	11	1–4–8–16	(6)–12[3]	24	14	(8)–16[3]

[1] The resolution in range and azimuth depends on the image acquisition mode. Common modes are the Spotlight mode (extra precise), Stripmap/Standard mode and Wide/ScanSAR mode (extended).

[2] Constellation of small Satellites for Mediterranean basin Observation (1st and 2nd satellites launched in 2007, 3rd in 2008 and 4th in 2010)

[3] With both satellites operating, the repeat cycle is 6 days for Sentinel-1 and 16 days for SAOCOM.

1.3 Interpretation of averaged velocity maps

To automatically obtain displacement maps (e.g. with units in cm), a processing step called **phase unwrapping** is required. This step allows to convert the cyclic phase differences (that range between -π and +π) into the absolute phase values and subsequently into displacements.

An advantage of adding an automated unwrapping step is that it allows for including and combining the information from a large amount of interferograms. All interferograms (with a chosen time interval depending on the expected velocity, see *Figure 3*) can be generated, unwrapped and then averaged to provide **average velocity maps** that are easily interpretable. **This process is called InSAR Stacking**. Such maps are usually expressed in m/yr along the LOS, with negative values (typically in red) showing areas moving away from the satellite and positive values (typically in blue) showing areas moving towards the satellite.

To take advantage of the redundancy of temporally overlapping interferograms and improve the measurement accuracy (e.g. in areas affected by significant atmospheric noise), more advanced multi-temporal InSAR techniques can be applied. These are typically divided into two main groups:

- Methods based on locating Persistent Scatterers (PSs), referred to as **Persistent Scatterer Interferometry (PSI)** or **Interferometric Point Target Analysis (IPTA)**. A stack of interferograms is generated at full resolution using a single reference scene, i.e. including long (interannual) interferograms. PSI is typically designed for linear and slow-moving features, and thus does not allow for correctly quantifying velocities higher than a few cm/yr. PSI can be useful for slow-moving landforms, e.g. to discriminate transitional and relict rock glaciers. For most active rock glaciers, PSI must be complemented by single interferogram analysis and/or distributed scattering InSAR.
- Methods based on Distributed Scattering (DS), referred to as **Small BAseline Subset (SBAS)**. These methods incorporate a large number of interferograms (multiple reference scenes) below chosen spatial and temporal baseline thresholds to reduce geometric and temporal decorrelations. The maximum detection capability depends on the chosen threshold of temporal intervals used to build the interferograms, following the same logic as *Figure 3*.

Phase unwrapping and resulting averaged products based on a large amount of interferograms (InSAR stacking, PSI or SBAS maps) are widely used to produce one single output and automate the processing over large regions. However, this step may introduce **data gaps from decorrelation and potential errors over fast-moving areas, as well as in areas with snow or vegetation. Results from InSAR Stacking, PSI/IPTA or SBAS must therefore be interpreted carefully and in combination with single wrapped interferograms.**

2. Practical guidelines

InSAR data can be used to characterize rock glacier kinematics. The following recommendations are stated for a systematic procedure based on the **interpretation of wrapped interferograms from a large InSAR dataset in order to locate moving areas related to rock glaciers, and estimate their displacement rates**. Similar recommendations could be applied to other InSAR methods, such as unwrapped interferograms, InSAR stacking, PSI/IPTA or SBAS, but the results must be interpreted carefully (see Section 1.3).

The objective is to provide the following outputs:

- **The moving areas (MAs)**, a polygon vector layer containing the outlines of MAs identified on the available InSAR data.
- **The kinematic attributes (KAs)** associated with primary markers (and optionally the outlines) of the **rock glacier units (RGUs)**.

2.1 InSAR data and GIS structure

2.1.1 Interferograms, velocity maps and normalization factors

Different SAR sensors can be selected according to their availability and accessibility. To obtain a comprehensive overview of slope movements in a given region and to prevent focusing on unrepresentative signals from one single interferogram, it is essential to **use a large set of valid interferograms** produced with time intervals from days to years in both orbit modes (ascending and descending). The major obstacles limiting the successful use of InSAR in alpine mountain environments are the slope orientation/steepness and the presence of (wet) snow. **Selected SAR scenes must be mostly snow-free** (e.g. usually between June–July and September–October in the Northern Hemisphere). SAR scenes with a short (daily) time interval can also be used in wintertime, when the snow is still dry in periods without strong precipitation or wind. Estimating the extent of old or fresh snow and the weather conditions (rain events) occurring on or up to 2 days before each SAR acquisition on the basis of available meteorological data has proven to be a helpful step in evaluating the quality of an interferogram. Additionally, the influence of phase noise and residual unwanted phase components remaining after InSAR processing (e.g. atmospheric effects) must be considered when interpreting an interferogram.

Different types of InSAR data and associated files are useful to investigate the region(s) of interest:

- **Interferograms:** MAs have to be identified by analysing several interferograms and combining different time periods (start, middle and end of snow-free seasons), different sensors and wavelengths (e.g. Sentinel-1, TerraSAR-X and ALOS) and different time intervals (from day(s) to year(s)). Both ascending and descending modes are required to document areas with different slope orientations. Areas affected by geometrical distortions should be masked in the analysed interferograms.
- **Velocity maps, e.g. InSAR stacking** (when available): Velocity maps based on short time intervals (6–12 days for Sentinel-1) are used to provide the highest detection capability (up to 84 cm/yr for 6 days / 42 cm/yr for 12 days due to potential phase aliasing). After unwrapping and averaging, the maps are expressed in m/yr (+/- depending on the movement directions in respect to the LOS: negative values show areas moving away from the satellite, positive values show areas moving towards the satellite. To enable a large range of detection capabilities, a multiple stacking procedure based on different time intervals can also be used. For a higher accuracy in areas with

low velocity, PSI/IPTA can also be used. As for single interferograms, areas affected by geometrical distortions should be masked out.

- **Normalization factors or N-S slopes layer:** The normalization factor is an index to re-project the LOS displacement (i.e. displacement measured along the LOS) along the direction of the steepest slope. It ranges between 1 and ∞. The value 1 means that the LOS and the slope are parallel (ideal case). By increasing the angle between the LOS direction and the steepest slope direction, the normal factor increases. In areas with a normalization factor greater than 5, LOS measurements from single interferograms or velocity maps are no longer reliable and should not be used. Normalization factors are used to identify the most appropriate geometry (ascending or descending) or exclude non-reliable pixels. When a MA is visible in InSAR data from both geometries, the data with the lowest normalization factor should be considered as more reliable. If the normalization factor is not available, west-facing slopes should be analysed in descending mode, while east-facing slopes should be analysed in ascending mode. As an alternative to normalization factors, a layer highlighting the North- or South-oriented slopes can be used with the similar objective to identify areas where InSAR data must be interpreted carefully.

Additional kinematic data (e.g. measurements from GNSS stations or airborne optical photogrammetry) can be used to complement the InSAR data and consolidate the assignment of a velocity class to the MAs.

The sources of InSAR data and the additional data used in the inventorying process (e.g. DEMs and orthophotos) should not have been acquired more than a decade apart, and the spatial resolutions of additional data sets should be comparable or higher than the spatial resolution of the InSAR data.

2.1.2 InSAR database in GIS

The InSAR data are organized in different groups and subgroups. **The first group level** discriminates between the sensors (e.g. Sentinel-1 and ALOS). **The second group level** discriminates between the geometries (ascending ASC and descending DESC). It may also include the layers documenting the normalization factors and the velocity maps (InSAR stacking, PSI/IPTA). **The third group level** discriminates between the time intervals used to generate the interferograms (e.g. 6D, 12D and 24D).

Example of GIS structure:

- INSAR
  - SENTINEL
    - ASC
      - 6D
        - 10_SENT1_ASC_20190903_20190909_0006_tflt.tif
        - …
      - 12D
        - 10_SENT1_ASC_20160906_20160918_0012_tflt.tif
        - …
      - 366D
        - 10_SENT1_ASC_20180902_20190903_0366_tflt.tif
        - …
      - 10_SENT1_ASC_norm_factor.tif
      - 10_SENT1_ASC_stacking_2018_2019.tif
    - DESC
      - 12D
        - 10_SENT1_DES_20160910_20160922_0012_tflt.tif
        - …
      - 24D
        - 10_SENT1_DES_20160910_20161004_0024_tflt.tif
        - …
      - 366F
        - 10_SENT1_DES_20180918_20190919_0366_tflt.tif
        - …
      - 10_SENT1_DES_norm_factor.tif
      - 10_SENT1_DES_stacking_2018_2019.tif

The file name of the interferograms has the following format:
Subarea-number_SARsensor_SARgeometry_AcqusitionDay1_ AacqusitionDay2_TimeInterval_tflt.tif
Ex: *15_SENT1_ASC_20180212_20180320_036_tflt.tif*

The file name of a stacking map has the following format:
Subarea-number_SARsensor_SARgeometry_FirstYear_LastYear.tif
Ex: *10_SENT1_DES_stacking_2018_2019.tif*

2.2 Identify, delineate and characterize moving areas (MAs)

The MA identification is an initial step to assign a KA to each inventoried RGU (Section 2.3). All MAs related to rock glaciers should be compiled in the **polygon vector layer "MovingAreas_*"**.

We recommend proceeding to **MA identification in parallel with the RGU identification with primary markers (iterative process).** Firstly, InSAR-based MA identification may contribute to detect RGUs that may have been missed in a geomorphological assessment. Secondly, comparing InSAR with the location of the primary markers contributes to discard MAs that are related to processes other than rock glacier creep.

2.2.1 MA definition

A MA is defined as an **area at the surface of a rock glacier in which the observed direction and velocity of the flow field are spatially consistent and homogeneous during a documented time**. It must represent the downslope movement rate of the rock glacier (permafrost creep). Any confusion with movements related to other processes (e.g. melt-induced subsidence or subjacent landslide) should be avoided, based on geomorphological criteria. MA definition is described in detail in the Baseline concepts document: Kinematics as an optional attribute of standardized rock glacier inventories.

Detecting and quantifying MAs is **technology dependent**. The present document provides **recommendations for deriving standardized MAs using InSAR**, that will then be used to assign a KA to the inventoried rock glaciers (Section 2.4).

2.2.2 MA identification

The MA detection is performed by looking at the textural features visible from wrapped interferometric phase differences (hereafter just named "interferograms"). **Three types of InSAR patterns can typically be identified: (1)** no change defined by a plain pattern, **(2)** smooth change characterized by a (partly) fringe pattern and **(3)** decorrelated signal expressed by a noisy pattern (Figure 4 and Figure 5c). The texture is evaluated around the considered pixel depending on the size of the landform that has to be detected in the neighbouring environment. The minimal MA extent is based on the operator's judgment and depends on the spatial resolution of the interferogram, the filtering applied to reduce noise, as well as the effective size of the landform. We recommend to delineate a MA only if at least 20–30 pixels show a clear InSAR pattern.

The MA detection is based on the combined visualization of **a set of wrapped interferograms of various time intervals**. The error sources (e.g. due to processing, snow cover or atmospheric artefacts) must be as low as possible to ensure that the resulting data is confidently exploitable for characterizing surface movement related to rock glacier creep. The combined visualisation of several wrapped interferograms avoids focusing on unrepresentative patterns and isolated artefacts. These effects are sometimes identifiable with a noisy pattern or with a fringe pattern extended over very large areas. Atmospheric or snow artefacts often occur only on a few interferograms, and therefore can be discriminated from movement by analysing a large dataset. Noise patterns related to vegetation or glaciated areas are persistent over all interferograms and can often be identified by comparing the interferograms with orthophotos. When available, **InSAR stacking, SBAS or PSI velocity maps** are also valuable to detect MAs, especially when the objective is to inventory large regions**.**

An estimation of the LOS velocity is possible when the MA is characterized by a fringe pattern (Section 2.3.3). When a MA is characterized by a noisy pattern, i.e. when the rate of surface movement is too fast for the selected time interval and the signal is decorrelated, the identification of the position, extent and outline of fast MAs is still possible. **Slow displacement rates (velocities below 3 cm/yr)** can be detected but are often difficult to delineate with enough precision based on single interferograms. Multi-temporal InSAR techniques including interferograms with long temporal intervals (e.g. PSI) are better suitable for detecting slow movements, as they exploit the redundancy of temporally overlapping interferograms and improve the measurement accuracy (e.g. in areas affected by significant atmospheric effects).

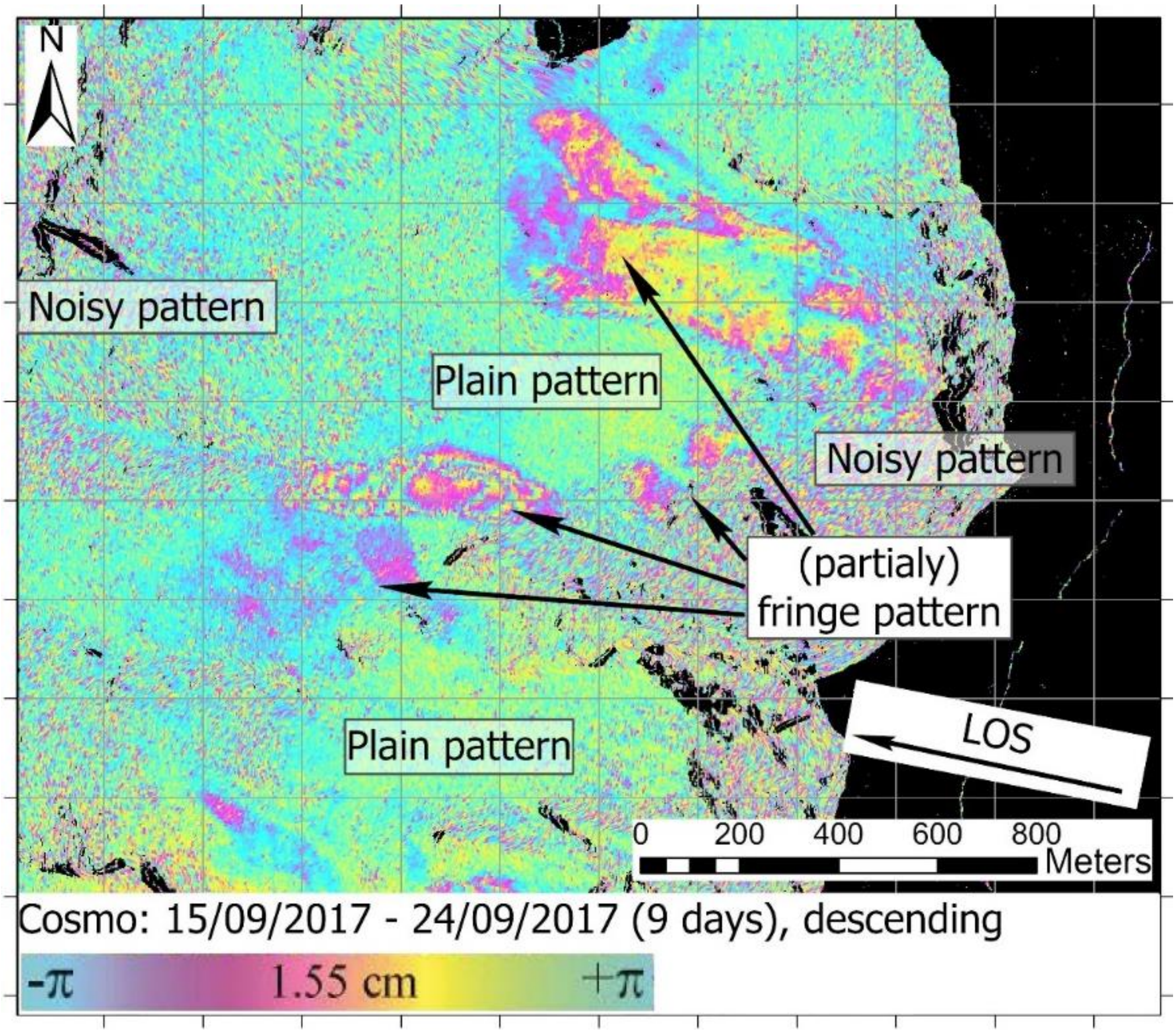


Figure 4. *Example of InSAR signal patterns. Data where layover and shadowing are masked out and shown in black.*

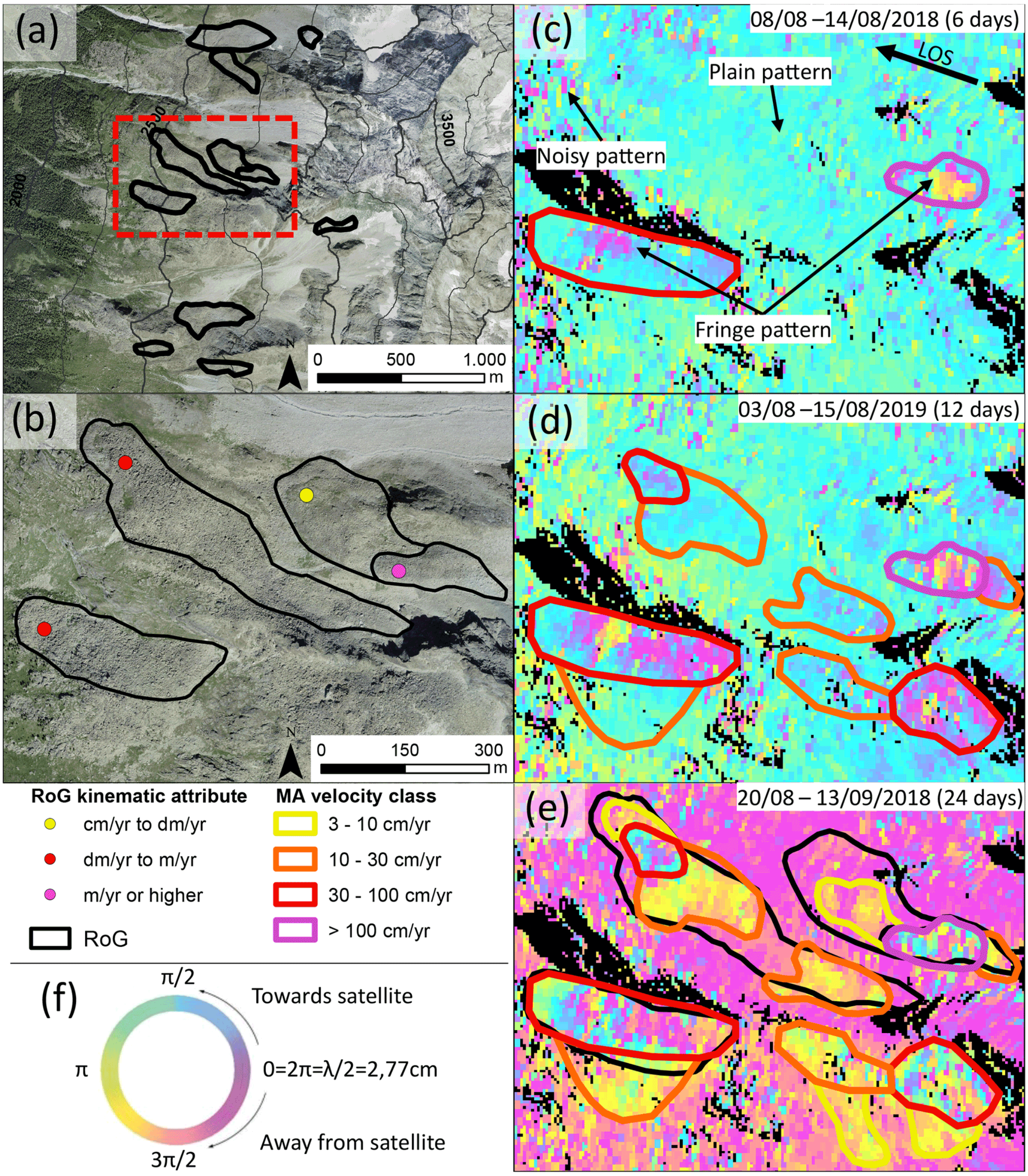


Figure 5. *Example of RoGI in the Arolla region (location: 46° 2′ 24′′ N, 7° 30′ 36′′ E, 2750 m a.s.l.), Swiss Alps.* ***a)*** *outlines of the rock glaciers are in black, and the location of an investigated area is highlighted in red. Orthoimages from © Google Earth 2019.* ***c–e)*** *Sentinel-1 interferograms from the descending orbit, including examples of InSAR signal patterns; layover and shadow areas are masked out (black).* ***(c)*** *Two MAs are detected on the 6d interferogram.* ***d–e)*** *Using 12d and 24d, additional MAs are visible. This is an example where the MA outlines do not fully match the geomorphological outline of the rock glaciers. MAs (SE-border) not related to rock glaciers are visible and mapped.* ***b)*** *Based on MAs, the kinematic attributes are assigned to rock glaciers.* ***f)*** *Fringe cycle related to the change of colour: a complete fringe cycle is equivalent to a change of half a wavelength (2.77 cm for Sentinel-1) in the LOS direction (Bertone et al., 2022).*

2.2.3 MA delineation

The detected MA is delineated using a polygon that is manually drawn around the relevant InSAR pattern. The polygon describes an area where a given InSAR signal is detected in most of the available interferograms.

MAs have to be outlined according to the following requirements:

- **Outlines should be drawn starting from interferograms with small time intervals (and small wavelengths).** Subsequently, by increasing the time intervals, the outlines can be refined and additional outlines (landforms with lower velocities) can be identified and drawn. As the extent of a MA could partly vary depending on the observation time and the velocity patterns, the final outline should delineate a MA with homogeneous velocity, and the velocity range within a MA should fit the classes of velocity defined in Section 2.3.3.
- **The outline does not necessarily fit the geomorphological outline of the related RGU.** It has to match the limits of the detected InSAR pattern (*Figure 5e*).
- **A MA can override the geomorphological limits of the related RGU** (*Figure 5e*), e.g. when two overlapping landforms are moving at rates, that are not significantly different.
- **Several polygons can be related to the same landform and several MAs can be overlapping.** Slower MAs can embed faster ones (*Figure 5e*).
- **The minimum extent of a MA depends on the spatial resolution of the data inputs and the size of the landform.** Interferograms with high spatial resolution allow for higher detail when drawing outlines. It is recommended that a fixed precision of the drawn outline is applied (e.g. fitting the size of one or two image pixels of the highest resolution InSAR data available).
- **Isolated movements, unreliable areas and unrepresentative parts have to be avoided.** In case of uncertainty, we recommend not to delineate the MA.

For the following steps, two important elements have to be considered:

- The border of a MA is often non-sharp, depending also on the detection capability of the used technique, making a precise delineation difficult. In this case, a low to medium reliability has to be noted (Section 2.3.4).
- Areas outside of any delineated MA refer either to the absence of movement, to a movement under the detection limit or to unreliable data. The lack of an identifiable MA does not mean necessarily mean that no movement occurs. With no additional information, the kinematic attribute must remain undefined (Section 2.4.2).

An example of the MA delineation procedure is showed in *Figure 6*.

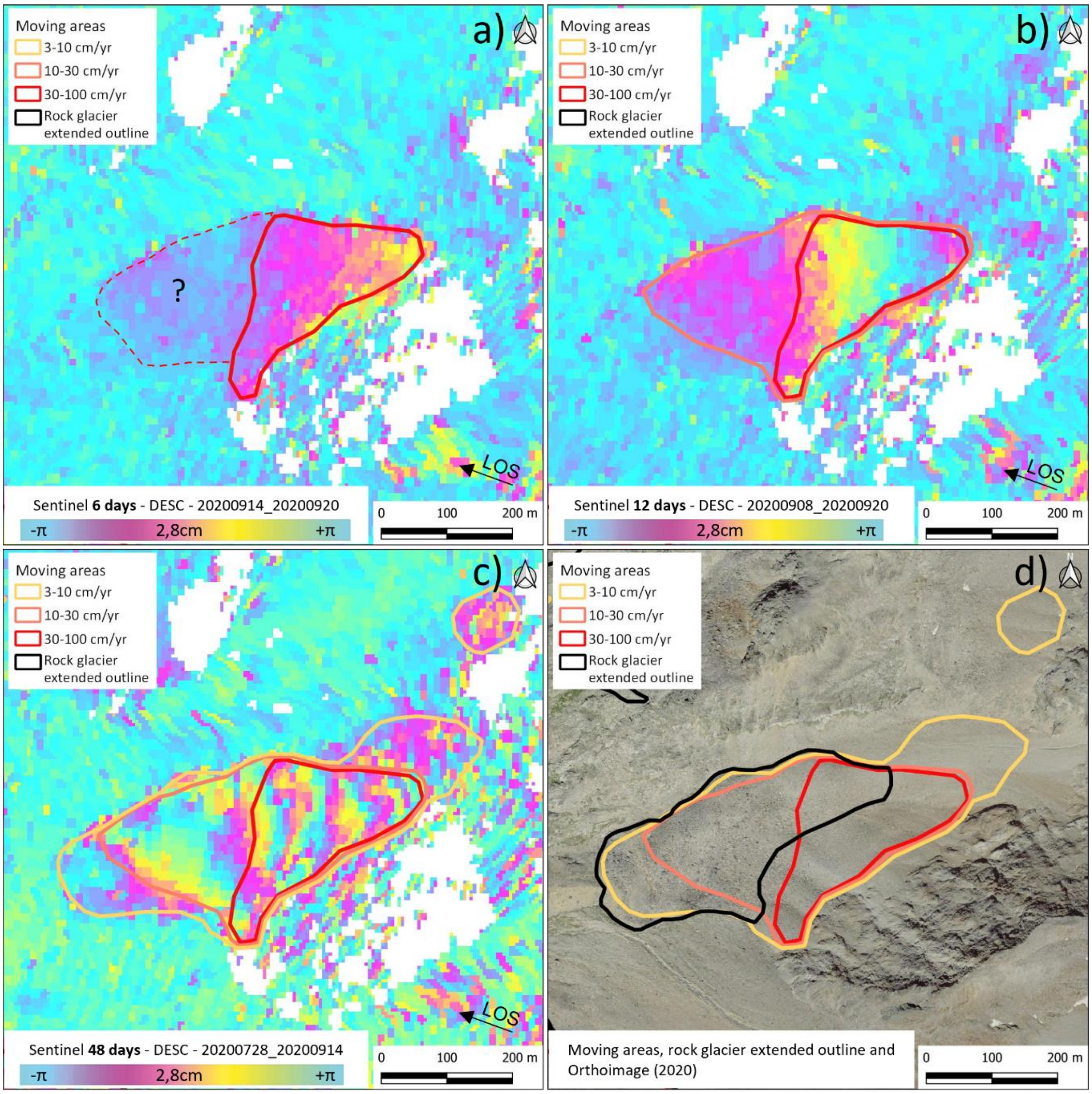


Figure 6. *MA identification using Sentinel-1 interferograms. A large set of interferograms with different time intervals is required to confirm the delineation/characterization of the MAs.* ***a)*** *A signal is detected on a 6-day interferogram (red line) and a small signal could be detected on the left (dashed line).* ***b)*** *Using a 12-day interferogram, a signal could again be seen on the upper part and the small signal detected on the 6-days interferogram is now clearly visible.* ***c)*** *On a 48-day interferogram, the frontal and upper parts are well detected and confirm the delineation of the previous polygons. The upper part becomes partially decorrelated.* ***d)*** *Orthoimage with rock glacier outline and MAs. New MAs become visible (orange polygons). Three MAs have been drawn on the rock glacier (velocity: 30-100cm/yr in red, 10-30 cm/yr in orange and 3-10 cm/yr in yellow). Note that the MAs do not follow the delineation of the rock glacier (black polygon: extended footprint).*

2.2.4 MA velocity classification

The MA velocity classification is recommended to determine the KA of each inventoried RGU (Section 2.3). The use of velocity classes intends to facilitate the assignment of a homogeneous simplified velocity information to the rock glaciers.

The velocity class of InSAR-derived MAs ("Vel.class" attribute of the MovingAreas_* layer) refers to the **1D LOS InSAR displacement rate on back-facing slopes**. It is **strictly stamped by time characteristics** ("Time.Obs" attribute of the MovingAreas_* layer):

- The **observation time window**, i.e. the period during which the detection and characterization is computed/measured (e.g. multi-annual, annual, intra-annual). The minimum required duration is **one month** (several months are preferable) **in snow-free periods**.
- The **temporal frame**, i.e. the duration during which the periodic computations/measurements are repeated and aggregated for defining the MA (i.e. during which year(s)).

The velocity class should reflect the spatio-temporal averaged displacement rate of the landform and neither a brief intra-annual variation nor an extreme. When MAs are detected/characterized using time intervals shorter than one month (e.g. 6 days for Sentinel-1), several pairs should be used in order to cover the minimal observation time window of one month (e.g. at least two 6-day interferograms within a month). When periodic measurements are available during a temporal frame of several years (consecutive years are preferable), the same observation time window must be applied (e.g. always August–September in 2018 and 2019).

The categorization of the velocity is performed exploiting two main approaches:

a) **Classification using the InSAR colour scheme** by comparing the phase signal inside and outside a detected MA at different time intervals (*Figure 2*). This is done in two steps: first, by counting the entire fringe cycles from a point assumed to be stable relative to the detected MA (using *Figure 2*); second, by converting the fringe cycle into velocity per year (use Annex A for conversion).

b) **Classification based on the detection limits according to the time intervals between images**, i.e. identifying the time intervals at which a moving feature is coherent or decorrelated. This is done by comparing the signal of each interferogram with the detection capability of each sensor and time interval (bars on *Figure 3*). Decorrelated patterns indicate that the displacement rate is greater than the maximum detectable limit within that interferogram (i.e. more than the upper limit of the bar). No visible fringe patterns indicate that the displacement rate is less than the minimum detectable limit with that interferogram (i.e. less than the lower limit of the bar). Visible fringe patterns indicate that displacement is detectable within that interferogram and can be used to categorize the MA velocity.

In areas where additional datasets are available, **a third approach can be used, ideally in combination with the two previous ones:**

c) **Averaged velocity maps based on unwrapped interferograms and multi-temporal InSAR techniques (when available).** InSAR stacking, SBAS or PSI maps are valuable to spot areas with movement when mapping large regions**.** In areas with very low velocity (typically over transition/relict landforms with mm/yr to a few cm/yr) and in areas with major atmospheric effects, these products are also more robust than single interferogram analyses. However, data gaps can occur on fast-moving landforms, especially on datasets based on interferograms with long time intervals (such as PSI). No data does not mean that there is no movement, but can mean indicate the exact opposite. In areas where the velocity is high with a large gradient of velocity between neighbouring pixels, the results can also be affected by major errors. These are generally often easy to identify: the area is covered by a random combination of decorrelated areas (no data) and patches with various colours: blue (movement towards the sensor) and red (movement away from the sensor).

<u>1D LOS velocity classes:</u>

- Undefined
- < 1 cm/yr (no movement up to some mm/yr)
- 1–3 cm/yr
- 3–10 cm/yr
- 10–30 cm/yr
- 30–100 cm/yr
- > 100 cm/yr

The additional attribute named "Comment" can be used to give more detail to the classification (e.g. heterogeneity inside the MA, etc.). More detailed information about very fast landforms (> 100 cm/yr), e.g. from GNSS, optical photogrammetry or very high temporal resolution interferograms) can also be explained in this field.

An example of velocity classification is showed on *Figure 7* for seven MAs delineated based on different SAR sensors and time intervals. Looking at Sentinel-1 6-day interferograms (*Figure 7b*), two MAs can be identified with fringe pattern (labels 1 and 3 on *Figure 7a*). When increasing the time interval (i.e. 12-day interferogram, *Figure 7c*), additional MAs become visible (label 2, 4 and 6 on *Figure 7a*). More details can be observed with Cosmo-SkyMed (*Figure 7d, 7e* and *7f*), due to the higher spatial resolution. By observing the 9-day interferogram (*Figure 7d*), two MAs characterized by many fringes can be identified (labels 1 and 3 on *Figure 7a*), while others have a partial fringe pattern (labels 2, 4 and 6 on *Figure 7a*). When increasing the time interval (i.e. to 16 days), MA 3 becomes completely decorrelated (noisy pattern), and the MA 1 become partially decorrelated. Fringe patterns can be well identified in MA 4, and two additional MAs can be detected (labels 5 and 7 on *Figure 7a*). When further increasing the time interval (i.e. 32 days), MA 1 also becomes completely decorrelated (noisy pattern) and fringe patterns become well visible in MAs 4, 5 and 7.

Based on this example, the two following main velocity classification methods can be applied:

<u>a) Classification using the InSAR color scheme:</u>

According to the color cycle shown in *Figure 2*, MA 3 is classified as > 100 cm/yr because a complete fringe cycle is visible on the Sentinel-1 6-day interferogram (i.e. 2.8 cm in 6 days). In the Cosmo-SkyMed 9-day interferogram, at least two complete fringe cycles are visible, referring to a full wavelength (3.1 cm) occurring in 9 days. MAs 1, 2 and 6 are classified as 30–100 cm/yr, as a complete fringe cycle (2.8 cm) is measured in the Sentinel-1 12-day interferogram. In the Cosmo-SkyMed 9-day interferogram, a complete fringe cycle is equally visible, indicating movement of 1.55 cm in 9 days. MAs 4, 5 and 7 are classified as 10–30 cm/yr, as a complete fringe cycle is not visible in the Sentinel-1 6-day and 12-day interferograms. In the Cosmo-SkyMed 32-day interferogram, a complete fringe cycle is visible, which indicated movement of 1.55 cm in 32 days.

<u>b) Classification based on the detection limits according to the time intervals between images:</u>

Based on *Figure 3*, MA 3 is classified as > 100 cm/yr, as the fringe pattern is visible only in the 6-day (Sentinel-1) and 9-day (Cosmo-SkyMed) interferograms, i.e. the interferograms with time intervals of more than 15 days become decorrelated. MAs 1, 2 and 6 are classified as 30–100 cm/yr, as the fringe pattern is visible in the 6-day and 12-day Sentinel-1 interferograms, as well as in the 9-day and 16-day Cosmo-SkyMed interferograms. It becomes decorrelated in the 32-day Cosmo-SkyMed interferogram.

MAs 4, 5 and 7 are classified as 10–30 cm/yr, as the fringe pattern is not visible in the 6-day Sentinel-1 interferogram, but becomes visible in the 9-day Cosmo-SkyMed interferogram.

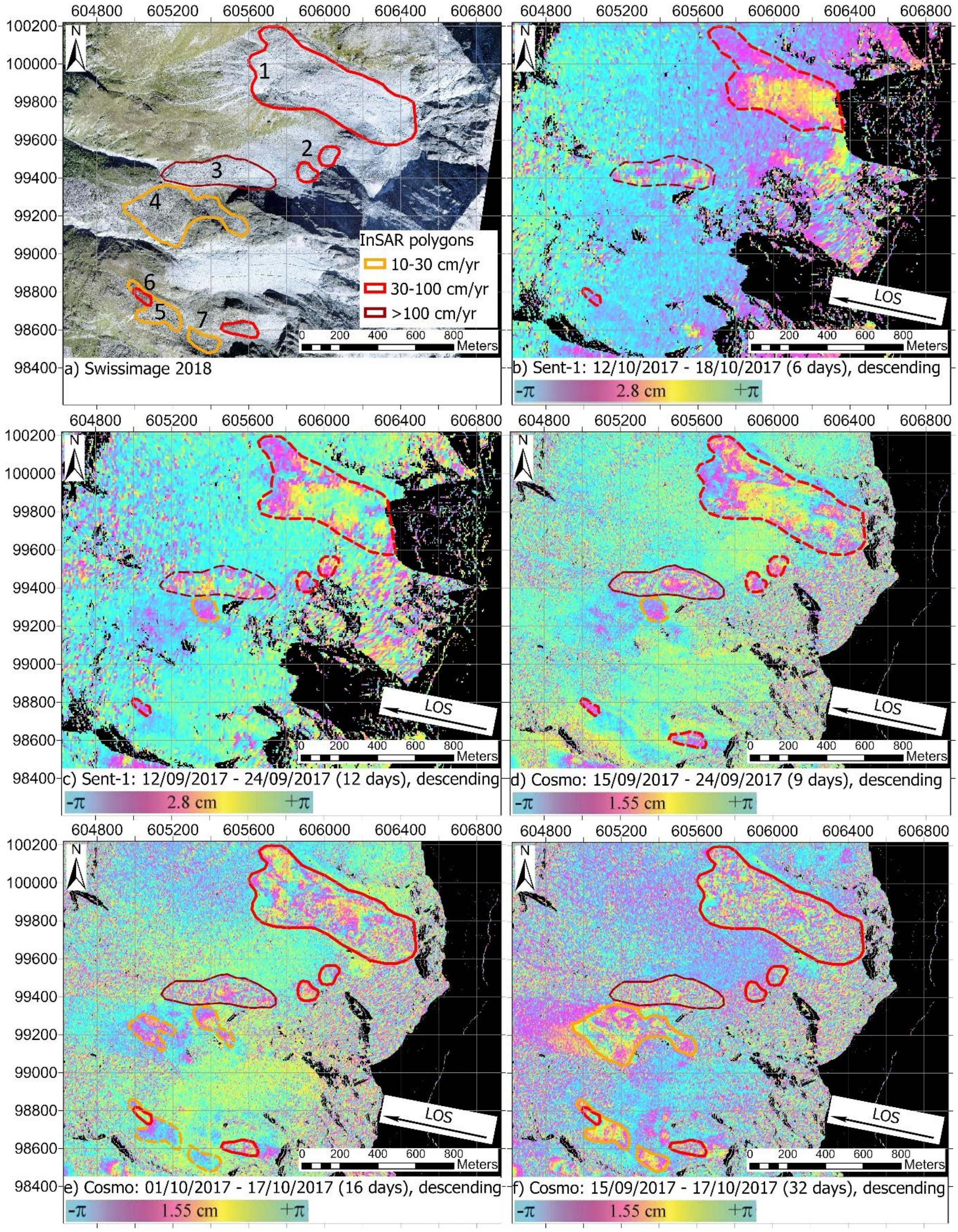


Figure 7. *Example of MA outlining and classification (Arolla area, Western Swiss Alps).* ***a)*** *Orthoimage.* ***b-f)*** *Sentinel-1 (b-c) and Cosmo-SkyMed (d-f) interferograms. Areas affected by layover and shadow have been masked out (black). Dashed lines are the temporary outlines of MAs detected on an interferogram. Solid lines are the final outlines of MAs based on all interferograms.*

When available, **averaged velocity maps based on unwrapped interferograms** can also be used. The averaged results are expressed in mm/yr, cm/yr or m/yr and can therefore be categorized using the standard velocity classes as shown in *Figure 8* and *Figure 9*. The KA attribute is then based on the criteria described in Section 2.3. Note that depending on the maximum time interval used to build the interferograms exploited to generate such averaged products, the detection capability is highly variable. When using PSI/IPTA techniques based on several years of SAR images, areas moving more than a couple of cm/yr are likely to become decorrelated (*Figure 10a*). To document areas moving up to dm–m/yr, averaged products based on short temporal baseline interferograms (only 6- and 12-day intervals using Sentinel-1) must be used (*Figure 10b*). It is recommended to use these maps **in combination with the single interferogram approaches** described previously.

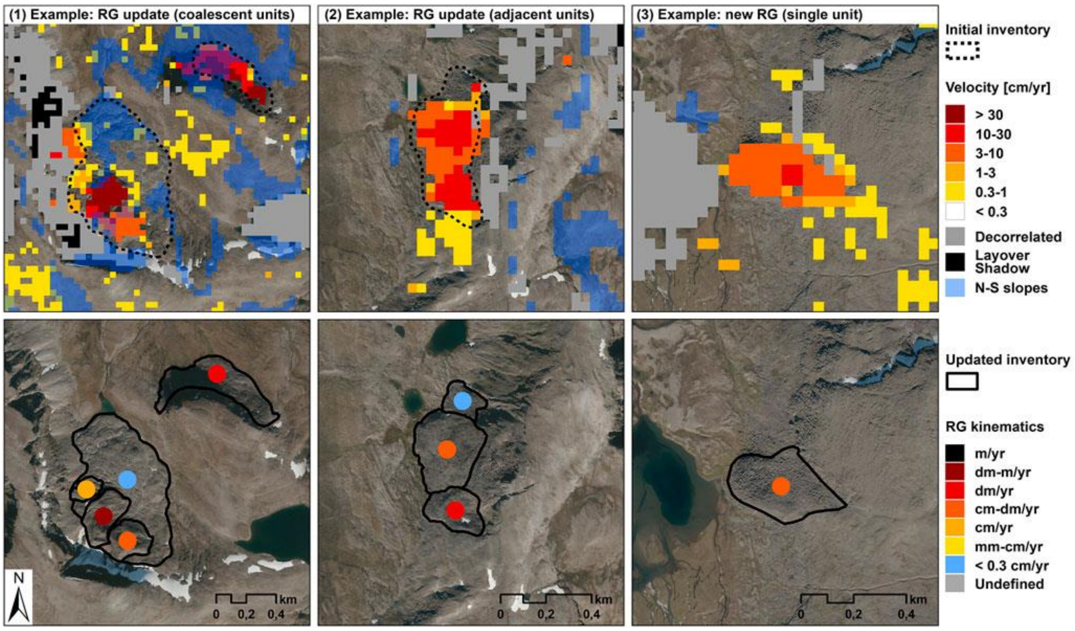


Figure 8. *Example of categorized InSAR stacking based on unwrapped interferograms with variables time intervals (short intervals for high velocity, long intervals for low velocity) (Rouyet et al., 2021).*

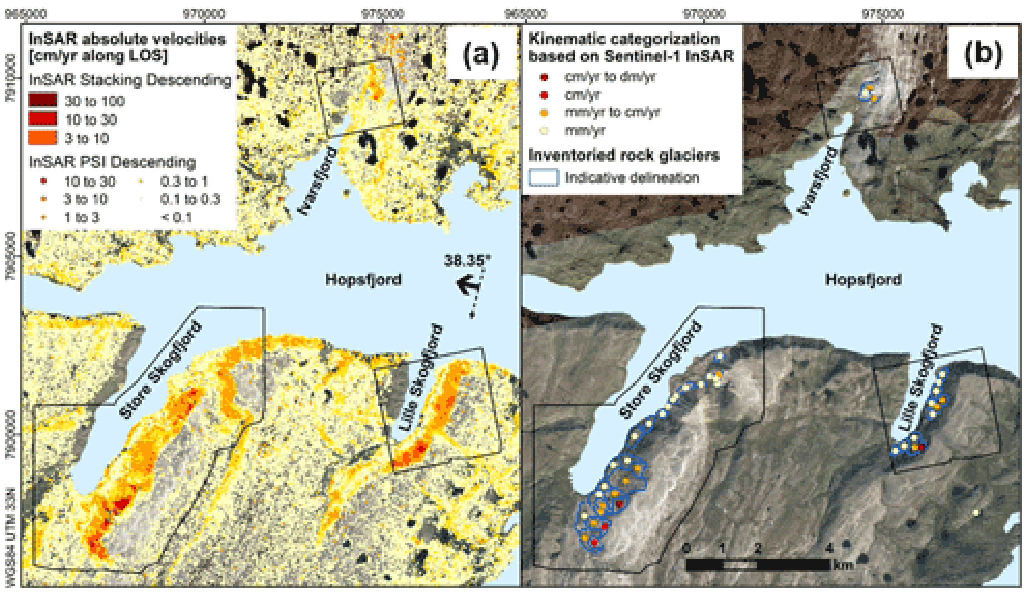


Figure 9. *Example of categorized InSAR stacking and PSI results based on unwrapped interferograms with variables time intervals (short intervals for high velocity, long intervals for low velocity) (Lilleøren et al., 2022).*

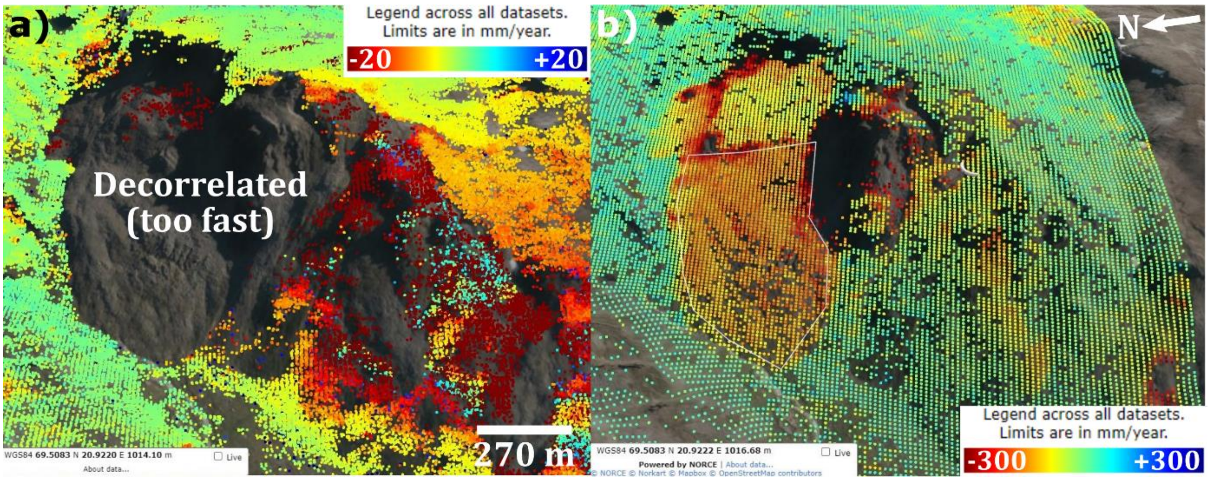


Figure 10. *Comparison between two types of averaged velocity maps based on unwrapped interferograms.* ***a)*** *PSI averaged velocity maps over a fast-moving rock glacier showing that the technique fails to document the fastest part of the lobe. Areas moving more than a couple of cm/yr are decorrelated (no data).* ***b)*** *Averaged velocity map (InSAR stacking) based on 6-days and 12-days Sentinel-1 interferograms over the same rock glacier. Velocity up to several dm/yr is detected.*

2.2.5 MA reliability

The reliability (or the degree of confidence) of the detected MA has to be qualitatively assessed (low, medium, high) according to the quality of both the outline detection and the velocity class assignment ("Rel.MA" attribute of the MovingAreas_* layer).

Reliability categories:

- **Low:** A MA can be identified but both the outline and the signal interpretation (velocity categorization) are uncertain.
- **Medium:** A MA can be identified but either the signal interpretation (velocity categorization) or the outline is uncertain.
- **High:** A MA can be identified and characterized based on a clear signal. The geometry is well appropriate (back-facing slope) and the data has high quality, allowing for reliable outlining and signal interpretation (velocity categorization).

When analysing North- and South-facing slopes, or when the number of interferograms is low, the reliability of the detection decreases. When the reliability in classifying velocity is too low due to specific technical limitations, the velocity class must be set as "undefined".

When available, the comparison can be performed using other kinematic data (e.g. in-situ measurements). This approach allows for consolidating the assignment of the velocity class of the InSAR-based MA and improving the KA reliability (Section 2.4.2).

2.3 Assign a kinematic attribute (KA) to a rock glacier unit (RGU)

2.3.1 KA definition and categories

The KA documents the overall kinematic state of the rock glacier unit (RGU) at the time of the inventory. It is defined in detail in the Baseline concepts document: Kinematics as an optional attribute of standardized rock glacier inventories.

The KA consists of **semi-quantitative categories expressing the multi-annual downslope velocity of an entire RGU**, defined as followed:

Category	Label	Comment	Related activity
0.	Undefined	(default category)	
1.	< cm/yr	(no up to very few movement)	relict
2.	cm/yr	(order of magnitude ≈ 0.01 m/yr)	transitional
3.	cm/yr to dm/yr	(order of magnitude ≈ 0.05 m/yr)	transitional
4.	dm/yr	(order of magnitude ≈ 0.1 m/yr)	active
5.	dm/yr to m/yr	(order of magnitude ≈ 0.5 m/yr)	active
6.	m/yr	(order of magnitude ≈ 1 m/yr)	active
7.	> m/yr	(more than ≈ 3 m/yr per year)	active

The default category is 0 "Undefined". The RGU falls into this category when:

- No (reliable) kinematic information is available,
- The rock glacier is mainly characterized by an identified MA of undefined or unreliable velocity,
- The kinematic information is too heterogeneous.

When InSAR-based MA have been delineated and characterized, the activity assessment ("Acti.Ass" attribute in RGU_PrimaryMarker_* or RGU_Outlines_* layers) can follow a kinematic approach. In this case, the KA ("Kin.Att") can in that case be filled.

Three others elements associated with the KA must be documented:

- The KA reliability ("Rel.Kin"):
    - NULL: if the KA is undefined.
    - Low: low reliability of the MAs and/or heterogenous coverage.
    - Medium: medium or high reliability of the MAs and/or heterogenous coverage.
    - High: clear KA assignment based on high MAs reliability quality and unambiguous distribution over the rock glacier.
- Multi-year validity time period ("Kin.Period" attribute) used to assign the KA.
- The type of data ("TypeOfData" attribute) used to assign the KA ("Radar" category in this case).
- Additional information regarding the datasets and the quality of the attribution (spatial representativeness: percentage of surface documented by MA) are documented in the field "Kin.Comment".

2.3.2 Translation rules: from MA to KA

The MA velocity should be transferred to the proper KA category in order to indicate the overall multi-annual rate of movement observed on a dominant part of the rock glacier surface. **Manual transfer from a velocity class of an InSAR-derived MA to the rock glacier KA is recommended** instead of applying an automated way to extract the value.

The two following **cases a) and b)** present recommendations based on two different observation time windows. They are applicable if the following conditions are fulfilled:

- 1D LOS InSAR measurements are performed on back-facing slopes.
- A dominant part of the RGU is covered by one single MA.

In the case of several variable MAs:

- The assigned category should represent **the dominant velocity class of the RGU**.
- If two equally dominant, but directly adjoining KA categories (e.g. 4 and 5) are present on a RGU, **the category of the area closer to the front is favoured for the attribution**.
- In case of a larger spread of equally dominant categories on the same RGU (e.g. 4 and 6), **the median category** (e.g. 5) **should be used, with a comment about the heterogeneity and a medium to low reliability.**
- If MAs show a large heterogeneity over the unit (e.g. more than three MAs with velocity classes falling into various categories), **the category "0. Undefined"** should be chosen. A large heterogeneity can also indicate the need to refine/redefine the delineation of the initial units (if confirmed by geomorphological evidences).

An additional field named "Kin.Comments" can be used to provide more detail about the categorization, e.g. additional information about the data properties and the quality of the attribution (spatial representativeness: percentage of surface documented by MA, information about where the movement is faster/slower, etc.)

<u>Case a: Annual or multi-annual observation time window</u>

A dominant part of the RGU is depicted by a single MA, whose associated velocity class is reliably characterized at an annual or multi-annual observation time window (i.e. annual interferograms). This typically concerns MAs with the following velocity classes:

1. < 1 cm/yr
2. 1–3 cm/yr

(Note that larger movement is decorrelated using annual interferograms)

The KA of the considered RGU can be assigned as following (only for back-facing slope in 1D LOS InSAR measurements):

<u>Velocity classes (annual)</u>	<u>Kinematic attribute</u>
1. < 1 cm/yr	1. < cm/yr
2. 1–3 cm/yr	2. cm/yr

<u>Case b: Observation time window shorter than 1 year</u>

A dominant part of the RGU is covered by a single MA, whose associated velocity class is reliably characterized at an observation time window shorter than 1 year (at least one month in snow-free periods). This typically concerns MAs with the following velocity classes:

3. 3–10 cm/yr
4. 10–30 cm/yr
5. 30–100 cm/yr
6. > 100 cm/yr

(Note that smaller movement remains undetected using short time intervals)

The order of magnitude of the rock glacier creep rate is estimated per default as 20% lower than the summer time velocity. The KA of the considered RGU can be assigned as following (only for back-facing slope in 1D LOS InSAR measurements):

Velocity classes (summer)	Velocity classes (annual)	Kinematic attribute
3. 3–10 cm/yr	4–8 cm/yr	3. cm/yr to dm/yr
4. 10–30 cm/yr	8–24 cm/yr	4. dm/yr
5. 30–100 cm/yr	24–80 cm/yr	5. dm/yr to m/yr
6. > 100 cm/yr	> 80 cm/yr	6. or 7. m/yr or > m/yr *

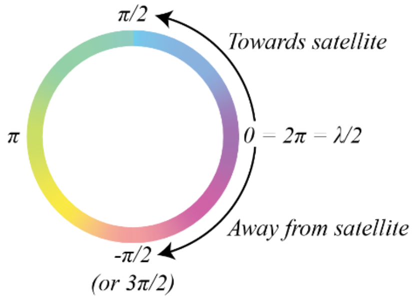
* the category "m/yr" or "> m/yr" should be selected and a note "m/yr or higher" should be indicated in the field "Kin.Comment".

If additional kinematic information is available (GNSS, aerial photogrammetry, very high temporal resolution interferograms) and allows for detailing velocities that exceeds m/yr, this must be specified in the field "Kin.Comment"):

Velocity classes (summer)	Velocity classes (annual)	Kinematic attribute
6. 100–300 cm/yr	80–240 cm/yr	6. m/yr
7. > 300 cm/yr	>240 cm/yr	7. > m/yr

ANNEX A: Converting fringe patterns (colour cycle) to velocity (cm/yr)

Annual velocity (cm/yr) is calculated as *disp / time* * 365, where *disp* is the displacement shown on the interferogram and *time* is the interval used to generate the interferogram. A displacement for an entire fringe cycle is half the wavelength of the SAR sensor.



For example, with one entire fringe cycle on a Sentinel-1 12 days interferogram, we calculate the corresponding annual velocity as: $\frac{\lambda/2}{12} * 365 = \frac{2.75}{12} * 365 = 84$ cm/yr.

C-band SAR: SENTINEL-1/RADARSAT-2. Wavelength lambda = 5.5 cm

Fringe pattern (fraction of half a wavelength)	Velocity (cm/yr) based on **6 days** interferograms	Velocity (cm/yr) based on **12 days** interferograms	Velocity (cm/yr) based on **18 days** interferograms	Velocity (cm/yr) based on **24 days** interferograms
1/5	33	17	11	8
1/4	42	21	14	10
1/3	56	28	19	14
1/2 (half)	84	42	28	21
2/3	112	56	37	28
3/4	125	63	42	31
4/5	134	67	45	33
1 (entire)	167	84	56	42

L-band SAR: ALOS-2/SAOCOM. Wavelength lambda = 23.6 cm

Fringe pattern	**8 days**	**16 days**	**70 days**	**364 days**
1/5	108	54	12	2
1/4	135	67	15	3
1/3	179	90	21	4
1/2	269	135	31	6
2/3	359	179	41	8
3/4	404	202	46	9
4/5	431	215	49	9
1	538	269	62	12

X-band SAR: TerraSAR-X/Cosmo-SkyMed. Wavelength lambda = 3.1 cm

Fringe pattern	**9 days**	**11 days**	**16 days**	**22 days**
1/5	13	10	7	5
1/4	16	13	9	6
1/3	21	17	12	9
1/2	31	26	18	13
2/3	42	34	24	17
3/4	47	39	27	19
4/5	50	41	28	21
1	63	51	35	26

ANNEX B: Technical advice

This annex shows some examples of discrepancies between operators that have been identified in the results of an exercise performed during a RGIK workshop in February 2020.

Note that this is based on a past version of the InSAR guidelines, resulting in different colours of the MA and RGU outlines, compared to the other figures of this document.

Case 1) Two or more MA outlines (related to the same RGU) with different velocity classes

Case 2) Two or more MA outlines (related to the same RGU) with different velocity classes observed in very different time observation windows

Case 3) Two or more MAs superimposed with different velocity classes

Case 4) RGU not covered by MA(s)

Case 5) Two adjacent MAs cover the same RGU

Case 6) RGU partly covered by MA(s)

Case 7) MA velocity class > 100 cm/yr

Case 8) Complex RGU with diverse InSAR signal

For each case, a brief description and a possible solution is provided, followed by one or more practical examples with explanations.

Case 1) Two or more outlines of MAs (related to the same RGU) with different velocity classes

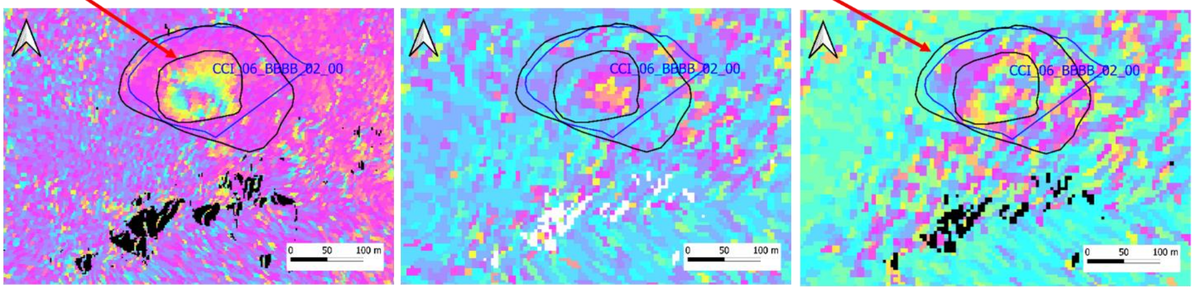
>> Rules:

- MAs related to the same RGU should be detected and outlined using all available InSAR data.
- The faster MA visible on summer interferograms should also be visible on the annual interferograms that include the summer periods.

>> Example from operator A:

30 – 100 cm/yr
Time_obs_win: Summer 2014, 2016 and 2017
Reliability: high
Remarks:

3 – 10 cm/yr
Time_obs_win: Annual 2016 – 2017
Reliability: low
Remarks: low reliability especially into the rooting zone

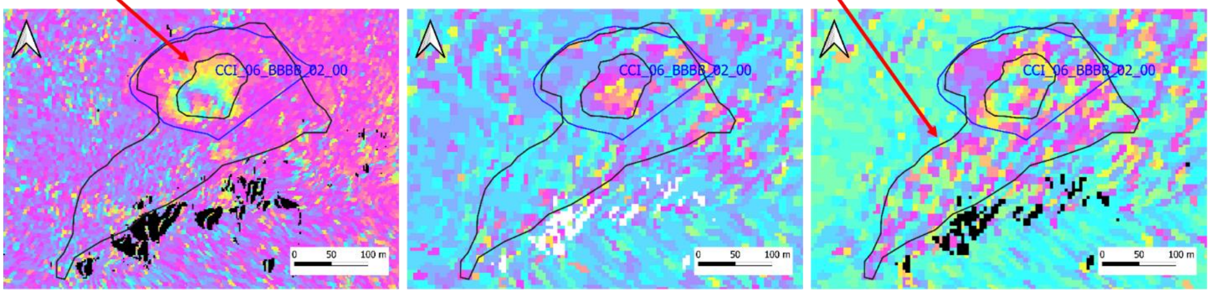


TERRA_20140723_20140814_22d_desc_diff | ALOS2_20160712_20160920_70d_desc_diff | ALOS2_20160712_20170808_392d_desc_diff

>> Example from operator B:

10 – 30 cm/yr
Time_obs_win: Summer 2014, 2016 and 2017
Reliability: high
Remarks:

3 – 10 cm/yr
Time_obs_win: Annual 2016 – 2017
Reliability: low
Remarks: low reliability especially into the rooting zone



TERRA_20140723_20140814_22d_desc_diff | ALOS2_20160712_20160920_70d_desc_diff | ALOS2_20160712_20170808_392d_desc_diff

>> Notes:

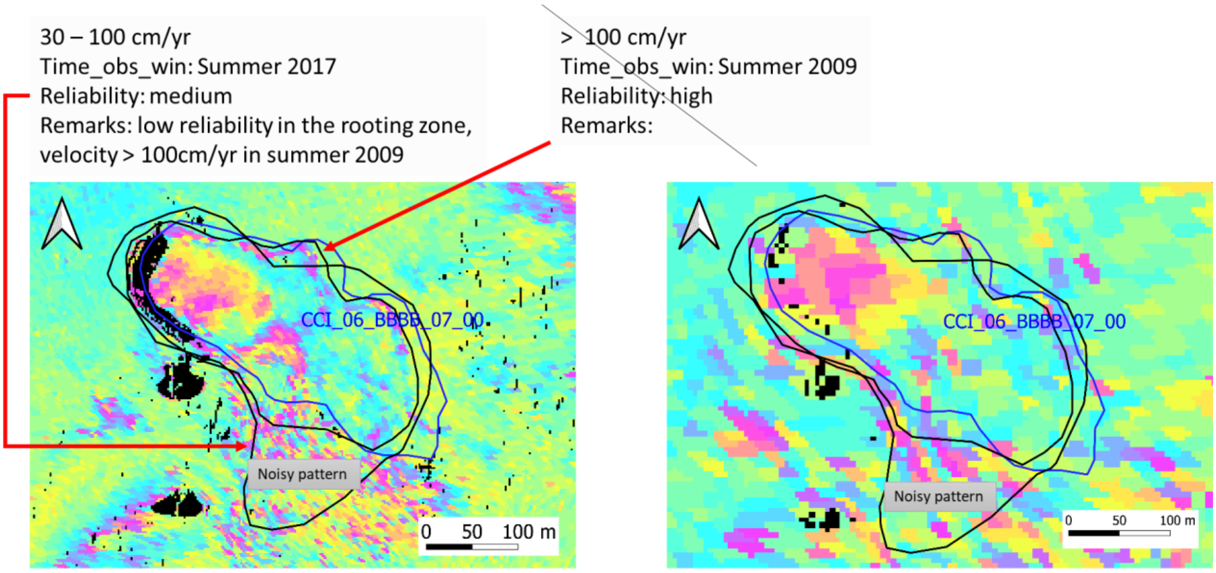
- *As the faster MA is visible on summer 2016 and 2017 interferograms, it should also be visible on an annual 2016 – 2017 interferogram (e.g. with decorrelation).*
- *Faster MA is visible in all summer interferograms. Reliability should be set to "high".*
- *Slower MA is visible only in one annual interferogram. Reliability should be set to "low", with additional Comment: "low reliability especially into the rooting zone".*

Case 2) Two or more outlines of MAs (related to the same RGU) with different velocity classes observed in very different time observation windows

>> Rules:

- If a long period separates the time observation windows of two analysed interferograms (e.g. summer 2009 and summer 2017), only the MA detected in the latest period should be outlined and classified. In the field "Comment", information about the previous detected velocity (e.g. in 2009) can be added.
- If the two time observation windows are very close (e.g. summers 2016 and 2017), only one MA should be mapped and classified, according to the mean velocity observed in both summers. Indicate in the field "Comment" that there is variability between the years and document which summer was the fastest.

>> *Example:*



TERRA_20090924_20091005_11d_asc_diff   SENT1_20170913_20170925_12d_asc_diff

>> *Notes:*

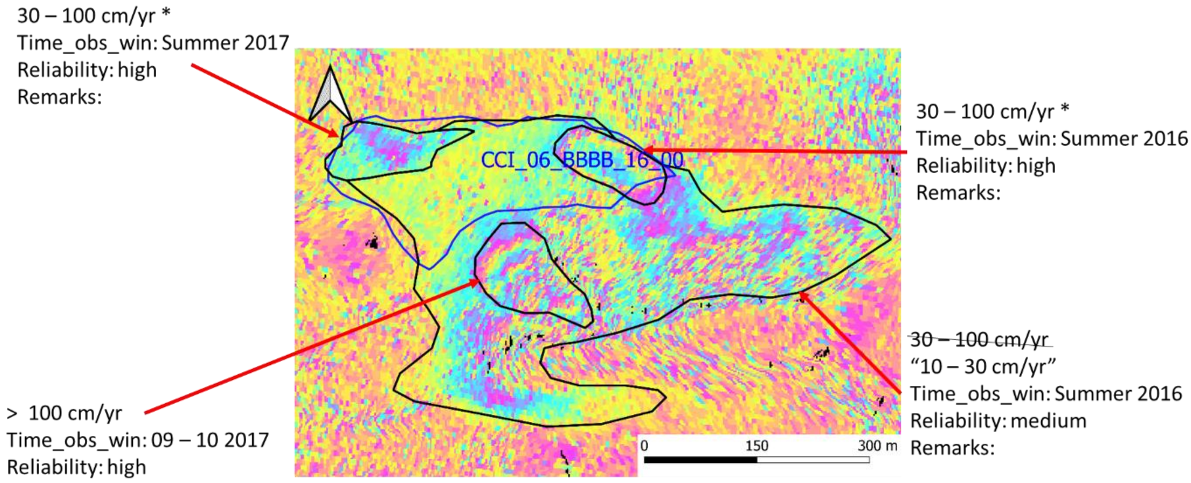
- *MA with velocity class 30–100 cm/yr includes a part with noisy pattern in the rooting zone (southern part) detectable in all interferograms. It is certainly related to artefacts, and should be excluded.*
- *A long period separates the two time observation windows (i.e. summer 2009 and summer 2017), then only MA detected in summer 2017 should be outlined and classified. In the field "Comment", information about the previous detected velocity in summer 2009 can be added.*

Case 3) Two or more MAs superimposed with different velocity classes

>> Rules:

- Different outlines should be drawn when <u>faster</u> MA(s) are included in <u>slower</u> MA. If smaller MA(s) included in larger MA(s) have the same velocity classes, the smaller MA(s) should be removed or the velocity classes should be redefined.
- Note that a large heterogeneity can also indicate the need to refine/redefine the delineation of the initial geomorphological units (iterative process combining geomorphological and kinematic approaches).

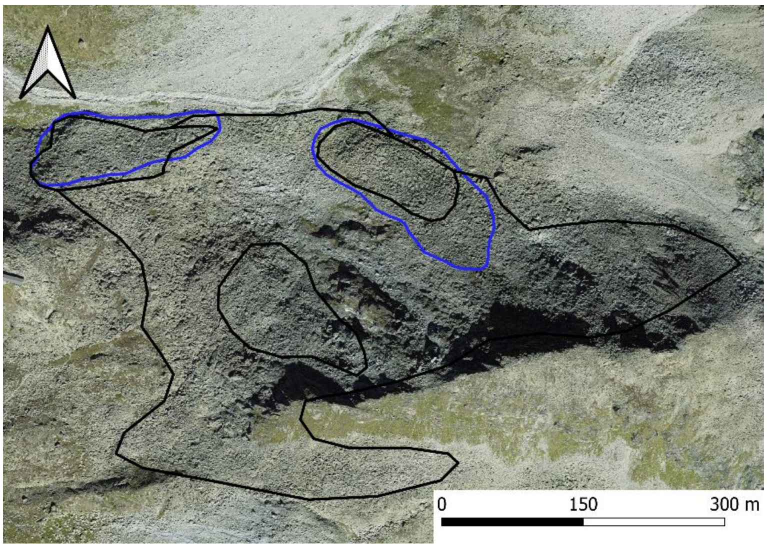
>> *Example:*



COSMO_20171001_20171017_16d_desc_diff

>> *Notes:*

- *The velocity classes should be verified. Either the velocity classification is correct and the small MAs (*) should be removed (included in the largest MA), or the velocity classes should be redefined (e.g. here change the velocity class of the largest MA)*
- *The RGU(s) may need to be refined. An example is shown below:*



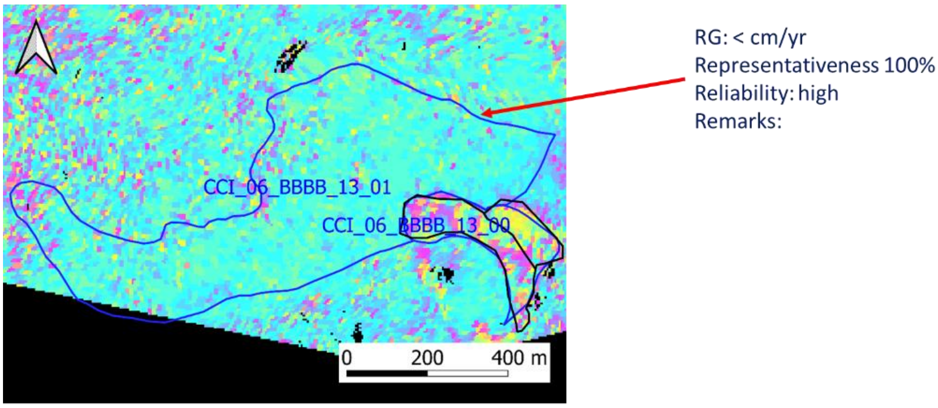
Case 4) RGU not covered by MA(s)

>> Rules: Check the available annual InSAR interferograms:

- If a similar plain pattern is visible both inside and outside the RGU, it means that no movement occurs. Therefore, the KA can be set to "< cm/yr", and the reliability is "high".
- If a decorrelation (noisy pattern) is visible on the RGU, it means that an estimation of a reliable velocity is not possible. The KA has to be set to "undefined". Comments about the decorrelation patterns can be added in the field "Comment".

When a plain or noisy pattern is visible on the entire RGU, the spatial representativeness is 100%.

>> Example for CCI_06_BBBB_13_01 RGU:



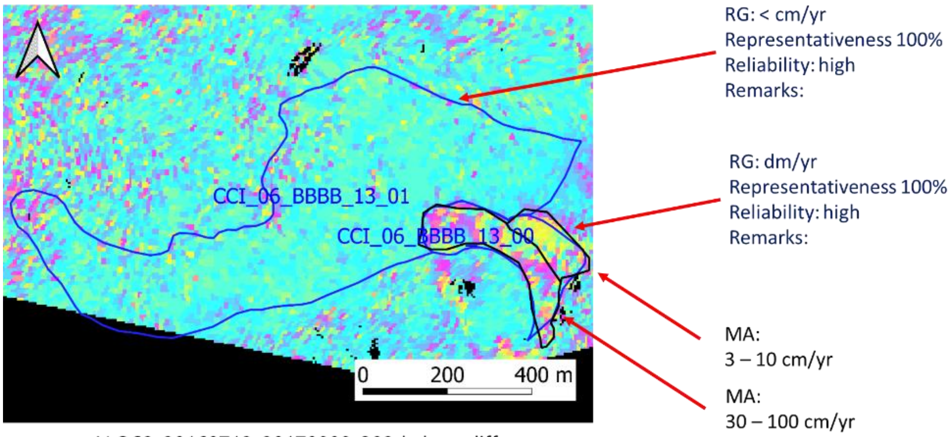
ALOS2_20160712_20170808_392d_desc_diff

>> Notes: A plain pattern on the CCI_06_BBBB_13_01 RGU is visible in an annual interferogram, it indicating that no movement is detected. Therefore, the KA can be set to "< cm/yr" and the reliability to "high".

Case 5) Two adjacent MAs cover the same RGU

>> Rule: The KA can be assigned using a mean value between the MAs.

>> Example for CCI_06_BBBB_13_00 RGU:



ALOS2_20160712_20170808_392d_desc_diff

>> Note: CCI_06_BBBB_13_00 is covered by two MAs. For the KA, a mean value of dm/yr is chosen.

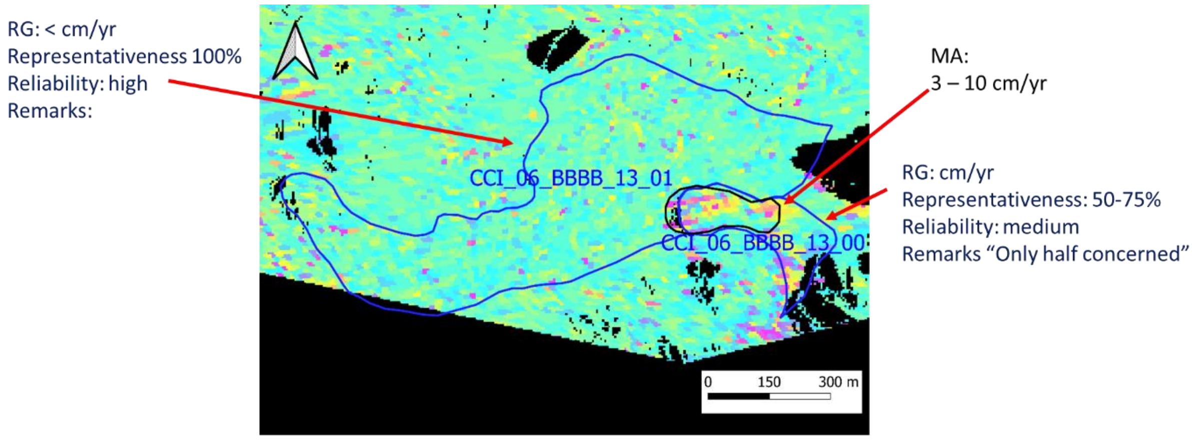
Case 6) RGU partially covered by MA

>> Rules:

Check the available annual InSAR interferograms on the remaining part of the RGU not covered by a MA, in order to understand if a plain or noisy pattern is visible (as Case 4):

- If a plain pattern on the RGU not covered by MA(s) is visible, no movement is detected and velocity is "< cm/yr". The KA can be assigned using a mean value between the detected MA(s) and the area with velocity "< cm/yr". The spatial representativeness can be documented considering the MA(s) extension and the area with velocity "< cm/yr" (i.e. area with plain pattern). Information about the limited MA(s) extension can be added in the field "Comment" (e.g. "only half concerned"). A large heterogeneity can also indicate the need to refine/redefine the delineation of the initial geomorphological units.
- If a decorrelation (noisy pattern) on the RGU not covered by MA(s) is visible, it is not possible to estimate a reliable velocity. The KA has to be set to "Undefined" if the spatial representativeness is < 100. Additional information about the detected decorrelation and an estimated KA can be added into the field Comments. If the spatial representativeness is between 50–75% the KA can be assigned depending on the detected velocities of MA(s), but the reliability should be set to "low".

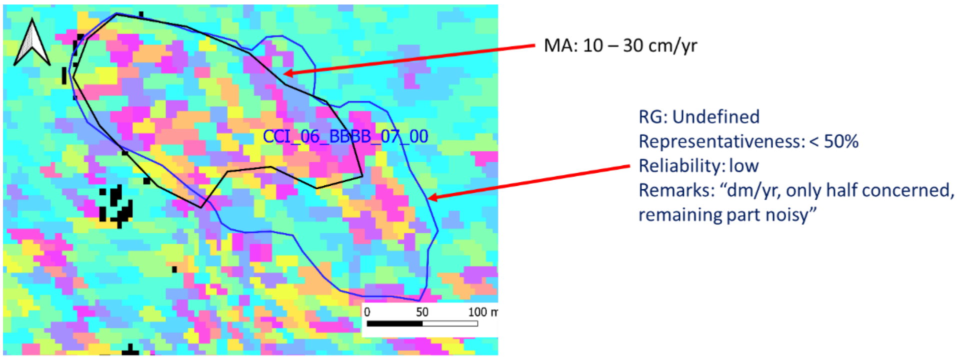
>> Example for CCI_06_BBBB_13_00 RGU:



ALOS2_20140911_20150910_364d_asc_diff

>> Notes: if a plain pattern is partially visible on the annual interferogram, in a part of the RGU that is not covered by an initially delineated MA, the KA must be attributed accordingly. CCI_06_BBBB_13_00 RGU can be classified as "cm/yr" considering the MA velocity class of 3–10 cm/yr and the velocity < cm/yr visible on the RGU not covered by MA.

>> Example for CCI_06_BBBB_07_00 RGU:



ALOS2_20140911_20150910_364d_asc_diff

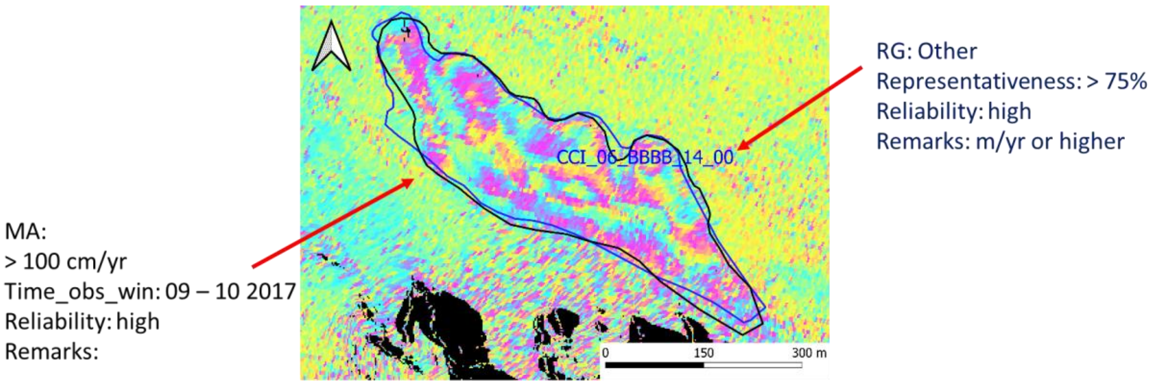
>> Notes: on annual interferograms, a noisy pattern is visible on the RGU not covered by a MA. In this example, the representativeness is near 50%: CCI_06_BBBB_07_00 should be classified as “undefined”. The detected noisy pattern and the estimated KA can be added in the field “Comment”.

Case 7) MA velocity class > 100 cm/yr

>> Rules:

- MA velocity class assignment: when it is possible to distinguish between the additional velocity classes 100–300 cm/yr and > 300 cm/yr, the velocity class is set to > 100 cm/yr but additional information can be added in the field “Comments”. This distinction is only possible very high temporal resolution (1–4 days) InSAR data or other kinematic data (e.g. GNSS) is available.
- KA assignment:
  - If the MA velocity class is “> 100 cm/yr”, with a comment “100–300 cm/yr” or “> 300 cm/yr”, the KA should be set to “m/yr” or “> m/yr” respectively. A description of how the velocity has been assessed (e.g. “validated by GNSS”, “optical photogrammetry”, “high temporal InSAR data”, etc.) can be added in “Comments”.

>> Example:

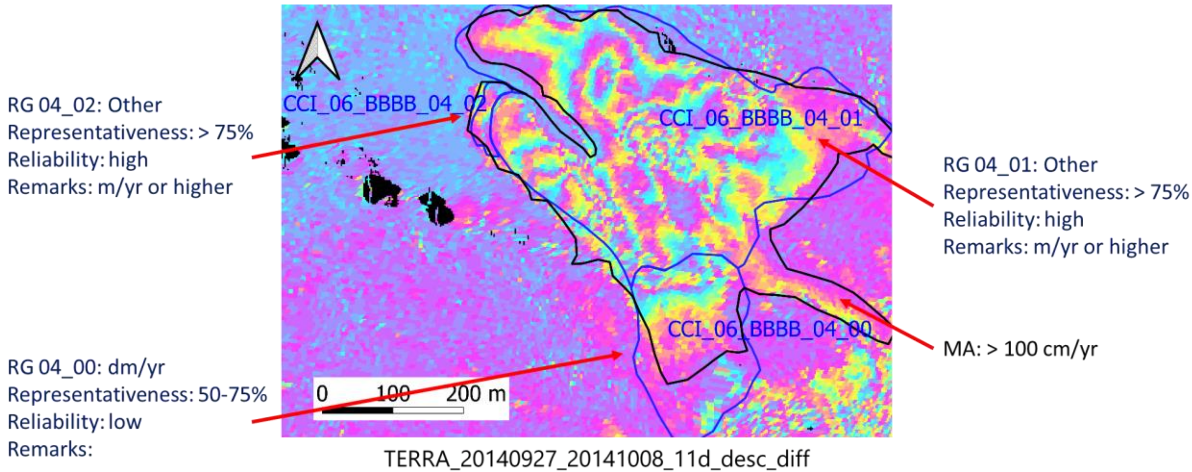


COSMO_20170915_20170924_9d_desc_diff

>> Note: If the MA velocity class is > 100 cm/yr, the KA is “m/yr” <u>or</u> “> m/yr”. Write a comment in “Kin.Comment”: m/yr <u>or</u> higher.

Case 8) Complex RGU with diverse InSAR signal

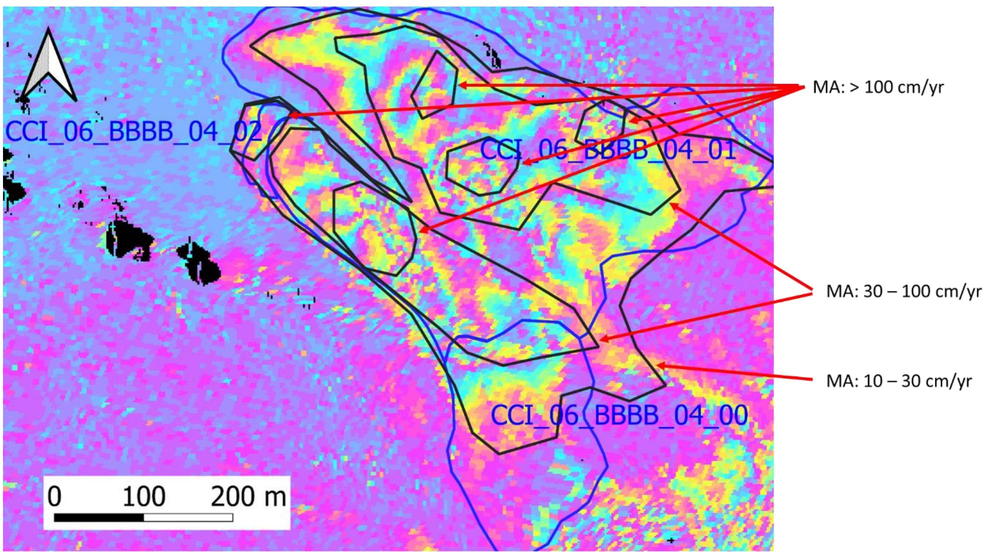
>> Example:



TERRA_20140927_20141008_11d_desc_diff

>> Notes:

- *RGU CCI_06_BBBB_04_00: a decorrelation (noisy pattern) on the RGU not covered by MA(s) is visible on annual interferograms. The RGU is classified as dm/yr with spatial representativeness between 50–75%, but the reliability is low (see Case 6).*
- *RGU CCI_06_BBBB_04_01: MA with velocity class > 100 cm/yr (see Case 7).*
- *RGU CCI_06_BBBB_04_02: MA with velocity class > 100 cm/yr (see Case 7). However, the small RGU (not related to a specific MA) suggests the need to renew the InSAR analysis to possibly detect specific movement. If a movement separated from the other MA is visible, re-outline the MA(s) at this location (see the example below).*



TERRA_20140927_20141008_11d_desc_diff

ANNEX C: CCI+ Permafrost project: selected regions and partner institutions

RoGI region	Responsible institution
Western Alps (Switzerland)	University of Fribourg (Switzerland)
Disko Island (Greenland)	Gamma Remote Sensing (Switzerland)
Troms (Norway)	NORCE Norwegian Research Centre (Norway)
Finnmark (Norway)	NORCE Norwegian Research Centre (Norway)
Nordenskiöld Land (Svalbard)	NORCE Norwegian Research Centre (Norway)
Southern Venosta (Italy)	University of Bologna (Italy)
Carpathians (Romania)	WUT and Terrasigna (Romania)
Vanoise Massif (France)	University of Savoie / University Grenoble Alps (France)
Brooks Range (Alaska)	University of Alaska Fairbanks (USA)
Central Andes (Argentina)	IANIGLA (Argentina)
Tien Shan (Kazakhstan/Kirghizstan)	University of St. Andrews (UK) / TU Graz (Austria)
Southern Alps (New Zealand)	University of Lausanne (Switzerland)