VALIDATION AND COMPARISON OF ICE VELOCITY FIELDS FROM SAR DATA - RESULTS OF THE ESA GLACIERS_CCI ROUND ROBIN EXPERIMENT

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ABSTRACT

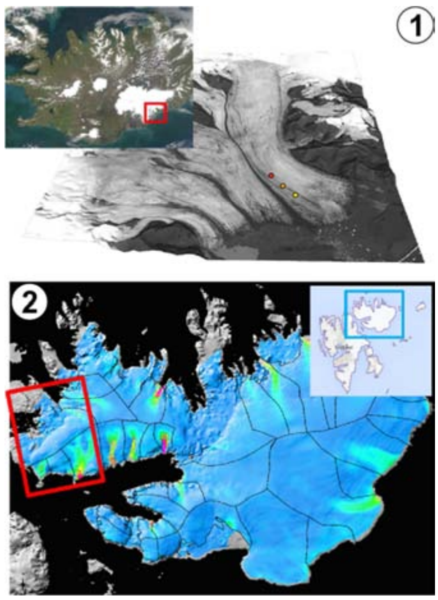
Ice velocity is an important parameter to evaluate the dynamic response of glaciers to climate change. Repeat pass SAR data enable the measuring of ice motion with high accuracy through differential processing techniques, including SAR interferometry and offset tracking.
In order to validate and inter-compare ice velocity maps generated by various techniques at different institutions, Round Robin Exercises were initiated in the frame of the ESA Glacier Climate Change Initiative (CCI) project. Standardised datasets (SAR and optical repeat pass satellite scenes) were prepared for three different test sites. The participants were invited to select a data set, apply their software/technique of choice for ice flow mapping, and return the results together with a feedback form describing the processing steps and selected parameters in detail. Here we summarise the results of the comparisons only for the SAR data sets over three test sites.

1. THE GLACIER_CCI ROUND ROBIN EXPERIMENT

ESA's Climate Change Initiative (CCI) is a programme aimed at generating a set of validated, Essential Climate Variables (ECVs) from existing satellite observations [1], including accuracy measures for the individual data products. The Glaciers_cci project aims at producing ECV data sets including glacier area, elevation change and surface velocity derived from different data types and techniques. In order to learn about the performance of the different algorithms and implementations of techniques for deriving the different ECV parameters, a Round Robin (RR) experiment was performed within the project. Here we focus on the results for ice velocity retrieval with SAR data. The Round Robin experiments are intended as benchmark tests in order to support the selection of the algorithm which is most suitable for automatic production of ice velocity fields [1]. A more detailed description of the RR experiments and the outcomes for all ECV parameters can be found in [2]

1.1. Round Robin sites

Three test sites with different characteristics and different SAR data sets were chosen for the Round Robin experiments, namely Breiðamerkurjökull (Iceland), Vestfonna ice cap (Svalbard), and Baltoro glacier (Karakoram) (Fig. 1).
Breiðamerkurjökull is an outlet glacier of Vatnajökull ice cap in Iceland draining towards the Atlantic Ocean. The glacier front terminates in a proglacial lake. In-situ GPS measurements provided by the University of Iceland coincidently acquired with the RR datasets, enable independent validation.
The second area is the Vestfonna ice cap in the high Arctic region of Svalbard. Several in-situ velocity measurements (stakes and repeat GPS) are available on Vestfonna to validate the ice motion products of the RR participants [3]. The Baltoro glacier in the Karakorum region (Pakistan) comprises several tributaries and has a length of 63 km. Approximately 70% of the lower glacier is debris-covered. Therefore, it is representative for the Himalayan glacier type with both, debris covered and debris-free tongues [4]. A pair of Landsat images acquired over a similar time interval is used for comparison.



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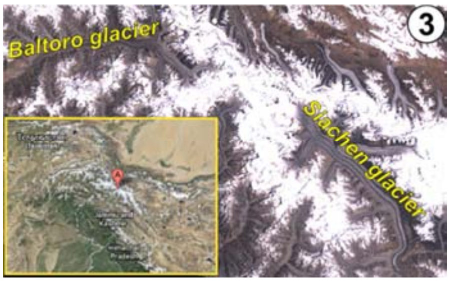

Figure 1. Panel (1) Location of Breiðamerkurjökull and the GPS stations BMJ1-3 (coloured dots) used for validation.

Panel (2) Svalbard, Nordaustlandet, with the ice cap Vestfonna. Velocity map derived from ERS-1/2 1-day repeat InSAR (Winter 95/96), colour coded. Coverage of RR data is marked by the red frame.

Panel (3) The Baltoro test site in the Karakoram region. The two main glaciers in the region are the Baltoro and Siachen glaciers.

1.2. Round Robin datasets

At Breiðamerkurjökull, two repeat pass TerraSAR-X images acquired on 26/08/2008 and 06/09/2008 with a temporal separation of eleven days were provided. Two repeat pass ALOS PALSAR images acquired on 01/02/2008 and 18/03/2008 with a temporal separation of 46 days were provided for Vestfonna, and two repeat pass ENVISAT ASAR images acquired on 04/04/2004 and 24/04/2005 with a temporal separation of about one year for the Karakoram site.
All SAR data were made available as Single-Look Complex (SLC) images and as full scene. TerraSAR-X data were processed in COSAR format [5] and ASAR/PALSAR in GAMMA format [6]. Specifications of the datasets are summarised in Tab. 1.

2. EVALUATED TECHNIQUES FOR GLACIER VELOCITY RETRIEVAL

Recently, two primary methods evolved to retrieve fields of surface ice motion and were tested in this RR experiment [7, 8]:

- Interferometric repeat-pass SAR (InSAR) analysis, delivering the velocity component in radar line-of sight (LOS). InSAR requires coherent image pairs

- Feature tracking in SAR images including various approaches like cross-correlation of templates in amplitude or complex SAR images, or coherence optimization.

Feature tracking techniques do not require coherence between the two SAR images, but are less sensitive to displacement than InSAR. Feature tracking relies on distinct features like crevasses. If coherence is preserved in both SAR images, the complex signal (speckle) can be utilised. Feature tracking provides 2-dimensional displacements in SAR geometry, i.e. in the azimuth and slant-range (LOS) sensor geometry, while radar interferometry provides 1-dimensional displacements in the line-of-sight (LOS) direction of the SAR sensor.

3. OVERVIEW ON RETURNED RESULTS

For Vestfonna, we received seven results applying different techniques; five groups returned results for Breiðamerkurjökull, and four groups participated in RR exercise over Karakorum using the ENVISAT ASAR data.
In general, the received data sets over the RR sites provide a good basis for inter-comparisons as the results were derived by different software packages and/or different processing parameters.
Tab. 2 gives an overview of all RR results (raw displacements without post-processing) for all three RR sites, together with the most important processing parameters applied by the different groups.

Table 1. Overview of the standardised datasets provided to the RR participants for the different test sites.

Study Site	Sensor	Date	Specification	Description
Karakorum	ENVISAT-ASAR	4-Apr-2004	IS2, desc VV	SLC image in GAMMA format
	ENVISAT-ASAR	24-Apr-2005	IS2, desc VV	SLC image in GAMMA format
Vestfonna	ALOS-PALSAR	1-Feb-2008	FBD, asc HH/HV	SLC image in GAMMA format
	ALOS-PALSAR	18-Mar-2008	FBD, asc HH/HV	SLC image in GAMMA format
Breidamerkurjökull	TerraSAR-X	26-Aug-2008	desc HH	SLC image in COSAR format
	TerraSAR-X	6-Sep-2008	desc HH	SLC image in COSAR format

Table2. Overview on the received results and the main processing parameters by different participants.
* search chip interferogram size 32

RR site	No	Algorithm	Matching window Size	Matching spacing	Oversampling factor	Quality measure
Vestfonna	**1**	FT	128 x 256	5 x 50	2 x 4	SNR
	2	FT	64 x 64	10 x 20	16 x 16	CC
	3	FT	64 x 192	6 x 36	2 x 2	SNR
	4	FT	12 x 54	6 x 29	4 x 4	Contrast measure
	5	Fringe-visibility	32 x 32*	6 x 36	2 x 2	SNR
	6	InSAR	N.A.	2 x 8	N.A.	Coherence
	7	MAI	N.A.	6 x 36	N.A.	Coherence
Breiðamerkurjökull	**1**	FT	128 x 128	25 x 25	2 x 2	CC
	2	FT	128 x 128	25 x 25	16 x 16	CC
	3	FT	128 x 128	50 x 50	2 x 2	SNR
	4	FT	64 x 64	6 x 6	16 x 16	CC
	5	FT	44 x 40	22 x 20	4 x 4	Contrast measure
Baltoro	**1**	FT	40 x 40	4 x 4	2 x 2	CC
	2	FT	64 x 192	5 x 25	2 x 2	CC
	3	FT	64 x 256	12 x 48	2 x 2	CC
	4	FT	32 x 64	5 x 25	16 x 16	CC

4. ANALYSES OF RESULTS

Despite the wide application of SAR data, only a few systematic studies comparing different algorithms and procedures for glacier surface velocity estimation have been reported, based on repeat optical [9] or radar image data. Here we compare the results returned by the RR participants and validate the derived glacier surface velocities using GPS measurements at the test sites Vestfonna and Breiðamerkurjökull. The common pre-processing for InSAR and feature tracking applications includes data import and accurate co-registration. Offsets due to image misalignment are measured using similar image matching techniques as the computation of displacements in the actual feature tracking; however, often with different parameterizations (e.g. with a reduced sampling to decrease the computational effort). InSAR results were received only for the Vestfonna and Breiðamerkurjökull sites, feature tracking results are available for all three test areas including Baltoro glacier in the Karakoram (Tab. 2).

4.1. Interferometry

Several different processing techniques utilising the phase information of SAR data were applied by the RR participants (Tab. 2, Fringe-visibility, InSAR and Multi Aperture Interferometry MAI) over Vestfonna. However, both slant-range and multiple-aperture interferograms at the Vestfonna site have low

coherence, in particular over the outlet glaciers. Therefore, unwrapping was not successful for these data sets (Fig. 2).
A similar result can be seen for Breiðamerkurjökull test site where interferograms were largely decorrelated with fringes visible only over the non-glaciated areas. Due to the lack of coherence, intensity cross-correlation clearly performs better compared to the interferometric SAR methods with these data sets (with the current sensors).

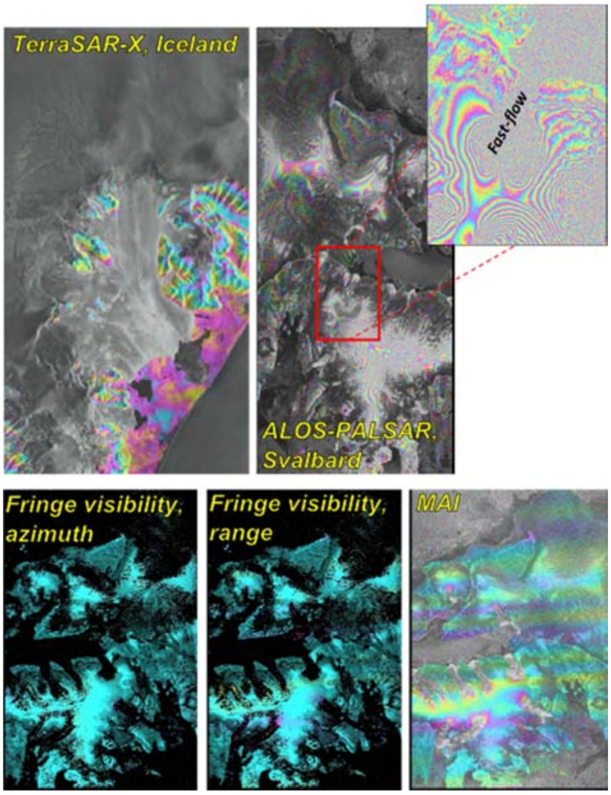

Figure 2. Upper panel :InSAR processing examples over Breiða-merkurjökull (left) and Vestfonna (right). Either the entire glaciated area (Breiðamerkurjökull), or the fast flowing outlet glaciers (Vestfonna) are decorrelated and therefore not suitable for velocity retrieval.
Lower panel: Fringe visibility and MAI results over Vestfonna. All results suffer from decorrelation.

4.2. Offset tracking

As a first step, the "raw" matching output (slant range displacement, azimuth displacement) of the different feature tracking processing chains had to be harmonised. The different groups chose different settings during the tracking procedure (template size, template spacing, multi-looking), resulting in different pixel sizes and x/y extents. Therefore, accurate co-registration of the datasets was required before an inter-comparison between the results of the different groups could be carried out. Here, we considered the offset introduced by the different starting points for placing the first matching window, as well as the different template sizes and spacing. All RR participants were asked to deliver the offset tracking results in "pixel displacement" units. Therefore, no adjustment of the pixel values was required.
Generally, the different intensity cross-correlation results are similar in terms of coverage regarding valid information and displacement values, although they are derived by different software packages. Fig. 3 shows a qualitative comparison of the results over Breiðamerkurjökull where the pattern of ice motion on the glacier is well captured by the different datasets. The acceleration of ice flow close to the calving front as well as the flow band stretching up to the higher reaches of the ice cap can be clearly seen in all results. The datasets have similar magnitudes, except for dataset 2 which appears to have a slight shift compared to the other results. However, the datasets show large differences in coverage of retrieved motion, especially in the upper parts of the glacier.

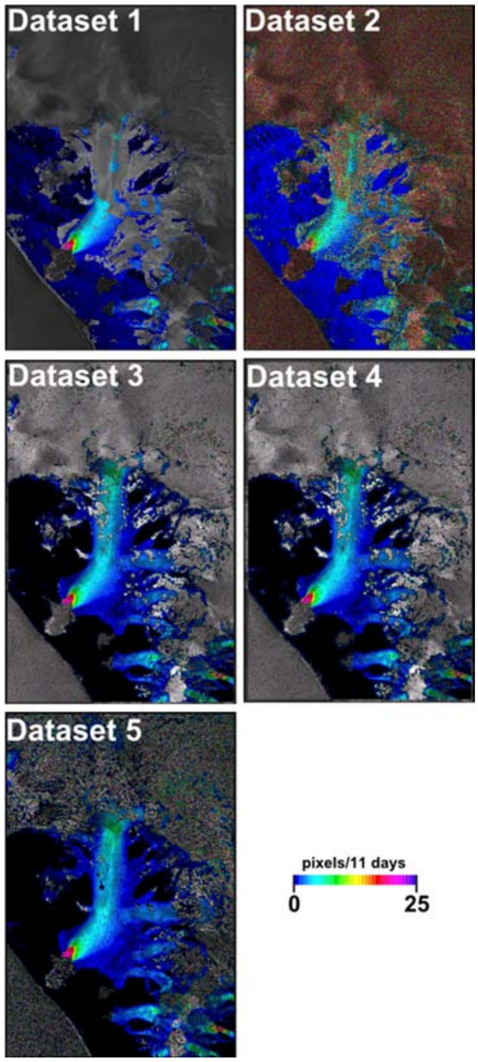

Figure 3. The displacement magnitude of the five RR results over Breiðamerkurjökull in slant range geometry stretched to the same colour scale, super-imposed on the TerraSAR-X amplitude image from 26/08/2008.

A comparison of SAR and optically derived velocities over the Baltoro site shows, that the Landsat (panchromatic channel) results outperform the Envisat-ASAR results under these high-mountain conditions, due to the higher noise level (speckle) and comparatively low spatial resolution of the Envisat-ASAR images (Fig. 4).

This becomes especially clear from the small glaciers successfully (though with some noise) matched using the optical methods, but not using the ASAR data. High resolution SAR (e.g. TerraSAR-X) data are required for this type of glaciers. Also, layover effects within radar images of mountainous terrain may hide some regions of interest, which in this example (Fig. 4) affects the entire northern branch of Baltoro glacier. However, SAR feature tracking provides better results in the accumulation areas, where visual contrast in optical images is limited.

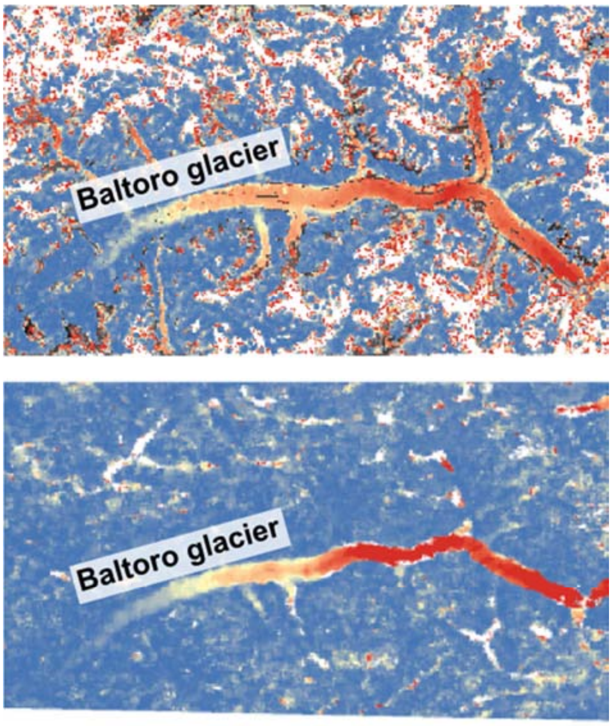

Figure 4. Displacements over Baltoro glacier from Landsat pan (upper), and ENVISAT-ASAR (lower). Both results derived with the same software and stretched to the same colour scale.

For a more quantitative comparison, we extracted a cross section from the results received from five of the RR participants over Breiðamerkurjökull. The profile crosses the glacier tongue close to the terminus in order to capture both, high and low velocities with a strong gradient towards the margin (Fig. 5, first panel). This profile stretches well over bedrock on both sides of the glacier, allowing a reference with non-moving areas.

The cross-section plot (Fig. 5, second panel) shows that all participants obtain rather similar values. Only Dataset 2 shows a large noise level. This algorithm fails especially in the fast flowing part of the glaciers where the displacement is up to 14.5 pixels. All algorithms perform very well over stable ground. Mean values for the first 40 pixels of the profile (bedrock only) range between 0.108 (Dataset 1), and 0.003 (Dataset 5) pixels. Excluding Dataset 2 we calculate a mean profile of all other data sets and investigate the deviation from the resulting average velocity for every data set (Fig. 5, third panel). This comparison shows that all results range between ± 1 pixel, i.e. better than the spatial resolution of the sensor. Largest deviations can be found in the centre of the profile coinciding with the fast-flowing part of the glacier tongue (except for the outliers in Dataset 1).

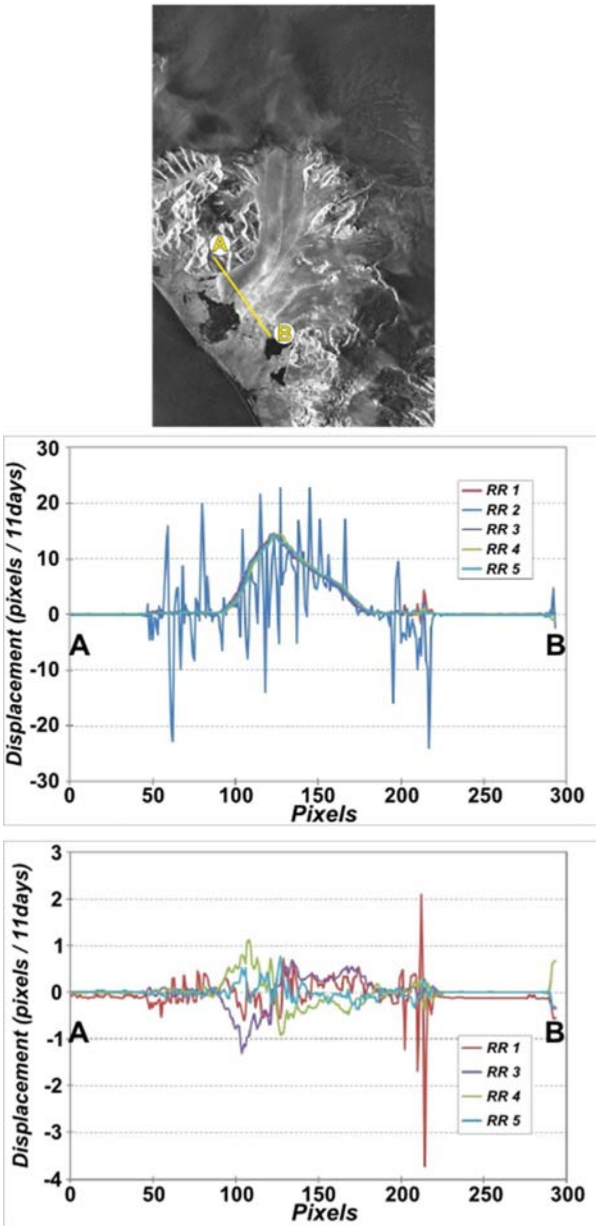

Figure 5. Cross section profiles A-B (middle) and deviation from reference mean displacement for the results at Breiðamerkurjökull.

Additionally, we show the comparison with DGPS surveys from [3] at the Vestfonna site for two selected results as they used similar processing parameters (Fig. 6, upper panel). The average of the absolute difference between DGPS and ALOS PALSAR results are 9.6 m/yr and 7.6 m/yr for the same two datasets, respectively. Maximum differences are 40.9 m/yr and 25.2 m/yr.
Further, we compared the two data sets with similar processing parameters over two areas on stable ground (Fig. 6, lower panel). Standard deviations are 0.69 m and 0.48 m in ground-range (i.e. about 1/20th of the range pixel dimension), 0.52 m and 0.53 m in azimuth direction (i.e. about 1/10th of the azimuth pixel size), respectively.

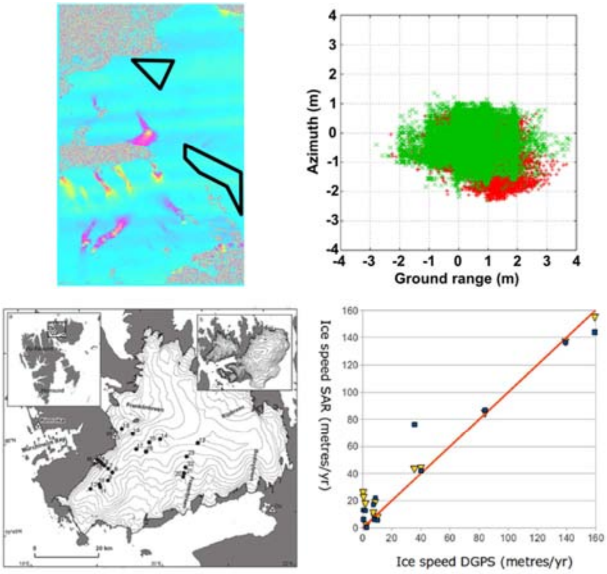

Figure 6. Comparison of displacement values over stable ground (black polygons) of two selected results (upper) and with DGPS surveys on the glacier from [2] at the Vestfonna site (lower). Upper left image shows azimuth displacement derived by offset tracking.

5. DISCUSSION

The criteria used for algorithm selection within the Glaciers_cci project are robustness, reliability and accuracy. For the Vestfonna and Breiðamerkurjökull sites, intensity cross-correlation performs better compared to the other SAR methods (fringe-visibility, InSAR and MAI), because of poor coherence. With the currently available SAR sensors feature tracking, not requiring coherent signals, is wider applicable for retrieval of glacier motion.
In terms of algorithm efficiency, the participants of the round robin were asked to include also computational times. These statistics provide a general overview, but are however not directly comparable because of different hard- and software applied. While pre- and post-processing are very efficient procedures with processing durations of a few minutes, main processing for template matching can be computationally intense. For a whole SAR scene, feature tracking processing durations of all RR results range from about one hour in the best case (Baltoro with a window size of 40x40, 4 pixels spacing and an oversampling factor of 2) to 6 days in the worst case (Breiðamerkurjökull with a window size of 64x64, 6 pixels spacing and an oversampling factor of 16).

6. CONCLUSION

In conclusion, we consider the application of the intensity-cross correlation algorithm to be the most robust and efficient algorithm for SAR data extending over time spans of several days. We estimate the reliability of this algorithm to return co-registration parameters as accurate as 1/10th of a SAR image pixel. This corresponds for the ALOS PALSAR and TerraSAR-X data separated by a temporal interval of 46 respectively 11 days to an accuracy of about 10 m/yr and for the ENVISAT ASAR data separated by a temporal interval of 35 days to an accuracy of about 20 m/yr. In terms of algorithm implementation, further development is required to automatically tune the matching window size, as in the RR this step was based on the participant experience. Further development is also suggested for post-filtering of the matching outcomes. The cross-correlation of templates in amplitude SAR images has thus a very high potential to be efficiently implemented for routine processing of satellite data to generate maps of ice surface displacement as ECV within the Glaciers_cci project.

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