Performance assessment of the glacier outline products, and description of the evaluation methodology

Issue 1.0

SEN3APP

Processing Lines And Operational Services Combining Sentinel And In-Situ Data For Terrestrial Cryosphere And Boreal Forest Zone

FP7 Grant agreement No 607052

Document History

Date	Update	Contributor	Organization
22/09/2016	Initial document	Gabriele Schwaizer	ENVEO

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Introduction

Glacier outline products are generated on user demand from Sentinel-2 data. The main focus during the SEN3APP project was on glaciers in the Alpine area, due to limited availability of other usable Sentinel-2 scenes acquired in late summer during the development and demonstration phase.

Regular updates of glacier outlines are an important information for climate change studies. Further, the melt water from glaciated areas is also important for water supply management and for hydropower companies, particularly when the seasonal snow cover is gone. Information on the uncertainty of the glacier outline products is important for the users for interpreting the provided information. The purpose of the document is to provide information for the user to estimate the suitability of the product.

1. Document Identifier

SEN3APP_ENVEO_GLO_VR_V1.0

2. Title

Performance assessment of the glacier outline products, and description of the evaluation methodology

3. Authority and Contact Information

ENVEO IT GmbH

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4. Abstract

The uncertainty information related to the glacier outline products are presented. The performance of selected glacier outlines is assessed by comparison with selected glaciers outlines generated from other very high resolution optical satellite data, by courtesy provided by the Copernicus Data Warehouse within the EU FP7 project SEN3APP.

5. Keywords

#glacier outlines, #Alps, #Alpine area, #optical satellite, #Sentinel-2, #MSI

6. Key terminology

Glacier outlines	Glacier outlines include all snow, clear ice and debris covered areas on glaciers. Internal rocks or water bodies on or before the glacier ice are mapped and identified separately.
NDSI	The Normalized Difference Snow Index is often used to separate snow and clear ice from other surface classes
Orthophoto	Very high resolution photography (often ~ 0.5 m pixel size) acquired from an airplane over a small region. Data is only available for a selected date.

7. Background, Context and Scope

Glacier outline products were generated on user demand for selected glaciers within the SEN3APP project based on Sentinel-2 data. Key users were interviewed in the beginning of the project period to identify if the product specifications fulfil their requirements or if changes are needed.

Evaluation of glacier outlines is challenging, as usable reference data are rare, and ground truth data available for some single spots are not suitable for an overall spatial validation. A Sentinel-2 scene acquired on 13 August 2015 during the commissioning phase over the Austrian Alps was selected for generating glacier outline products within SEN3APP. Four neighboured WorlView-2 scenes, with 2 m pixel size for the VNIR bands and 0.5 m pixel size for a panchromatic band, were acquired exactly on the same date over some of the selected glaciers. This very high resolution satellite data was by courtesy provided by the Copernicus Data Warehouse free of charge within the project. Unfortunately, for the orthorectification of the WorldView-2 scenes a different DEM was used than for the orthorectification of the Sentinel-2 scene. Also the orthorectification of the four neighboured WorldView-2 scenes does not match, but irregular shifts are obvious at overlapping regions. As both datasets, the WorldView-2 and the Sentinel-2 are only available as “ortho ready”, and the digital elevation models used for the orthorectification are not available to the public, it is not possible to correct for this spatial mismatch.

In order to roughly assess the performance of the Sentinel-2 based glacier outlines, glacier outlines generated from other satellite data or orthophotos from former years are overlaid with the products generated within SEN3APP. It is known from regular mass balance measurements and field measurements that the Austrian glaciers are retreating since years. Thus, the glacier outlines of previous years must extend a larger area than the glacier outlines retrieved from the Sentinel-2 scene of 2015.

Additionally, the preliminary glacier outlines, generated by automated processing but before applying any manual corrections for debris covered glacier parts or cast shadowed areas, are compared with the preliminary glacier outlines by courtesy provided by the University of Zürich, Switzerland, generated within the ESA project Glacier CCI. This intercomparison allows a performance assessment of the automated pre-processing chain. The manual post-processing strongly mainly depends on the quality of the used satellite image, as well as on the experience and the knowledge of the place of the analyst.

The QA4EO framework was selected as an example of a template for reporting the performance of the glacier outline products and as an information package for the user to easily assess the suitability of the data for the purpose.

8. Product performance and uncertainty

The overall local classification accuracy of the glacier outline product is assessed to be within about 50 m using Sentinel-1 data with 10 m pixel size. The global accuracy, i.e. the spatial accuracy due to the geolocation of the Sentinel-2 satellite data used as input is excluded from this estimation. Assessing the global accuracy of the orthorectification of Sentinel-2 data would be the work for a new project.

9. Inputs

Input	Description	Link
ENVEO glacier outline products	Glacier outlines generated from a Sentinel-2 scene of 13 August 2015 acquired over the Austrian Alps	https://scihub.copernicus.eu/dhus/#/home
Glacier outlines from orthophotos	Glacier outlines generated from orthophotos of 1998/99, by courtesy provided by A. Lambrecht and M. Kuhn (Univ. of Innsbruck), and 2007/09 for the Austrian Alps, by courtesy provided by B. Seiser (ÖAW/IGF)	(Lambrecht & Kuhn, 2007) (Fischer, Seiser, Stocker Waldhuber, Mitterer, & Abermann, 2015)
RGI5.0	Randolph Glacier Inventory 5.0 (published in 2015), glacier outlines for Central Europe (for the region Hohe Tauern mapped from satellite data of 2003)	http://www.glims.org/RGI/
GIUZ preliminary glacier outlines	Preliminary glacier outlines resulting from the automated pre-processing of the Sentinel-2 scene of 13 August 2015 by the Geographical Institute of the University of Zurich, courtesy provided by F. Paul within the ESA project Glacier CCI	
ENVEO preliminary glacier outlines	Preliminary glacier outlines resulting from the automated pre-processing of the Sentinel-2 scene of 13 August 2015 by ENVEO	

10. Standards and Traceability

Standard/ Documentation	Description	Link
GLIMS	Internationally accepted standard for mapping and storing glacier outlines retrieved from remote sensing data	http://www.glims.org/

11. Methodology, Processing

1) Prepare all glacier outlines in a common map projection
2) Overlay each preliminary and final glacier outlines in a GIS software (e.g. QGIS)
3) Visual comparison of preliminary and final glacier outlines
4) Comparison of final glacier areas from Sentinel-2 scene with glacier extents from orthophotos from former years

12. Evaluation of Performance

The uncertainty of the glacier outline product depends on different parameters:

- Geolocation accuracy: Sentinel-2 scenes are provided as Level 1C data only, i.e. the data are already projected to a specific coordinate system using ground control points and a digital elevation model.
- Automated classification accuracy: an automated processing chain is used to retrieve preliminary glaciers, including snow areas and clear ice areas. The mapping accuracy of this preprocessing step depends on the applied method.
- Manual classification accuracy: debris covered areas of regions in cast shadowed areas cannot be classified correctly as glacier areas in most cases. Thus, such areas have to be manually mapped in a post-processing step. The accuracy of the resulting glacier outlines mainly depends on the expertise of the analyst.

The accuracy of the geolocation of the Sentinel-2 scene used as basis for all glacier outline analyses is crucial, but is currently done at ESA. The user of Sentinel-2 data cannot influence the accuracy of the associated geolocation. For the orthorectification, the PlanetDEM with 90 m pixel size is used by ESA, which might be sufficient for Sentinel-2 data in flat terrain, but can be very critical in terms of accuracy in steep, complex terrain, where most of the Alpine glaciers are located. This is particularly crucial, when a high resolution DEM is used for the pre-processing of the Sentinel-2 scene, which does not match exactly the DEM used for the orthorectification. Thus, a topographic correction, usually applied to reduce the illumination effects caused by topography and atmospheric propagation, can significantly decrease the quality of the Sentinel-2 top of atmosphere reflectance used as input for the automated pre-classification of glacier areas. But, assessing the overall accuracy of the geolocation of the Sentinel-2 data would be a task for a new project.

The accuracy of the automated pre-classification of glacier areas depends on the used method to classify snow and clear ice areas. Many commonly used pre-classifications are based only on the Normalized Difference Snow Index, but this results in partly significant misclassifications of open water bodies as glacier areas. We used additional bands to get rid of such areas before performing any manual corrections. A comparison of the preliminary glacier outlines generated by ENVEO within SEN3APP with the preliminary glacier outlines by courtesy provided by the Geographical Institute of the University of Zurich, generated within the ESA project Glacier CCI (Figure 12.1), shows, that the main glacier areas are mapped by both methods, but the approach of ENVEO excludes already water bodies, as well as small snow patches outside of glaciers, which are both manually corrected by GIUZ in the post-processing. But, based on the available results from the automated pre-processing chains, the overall accuracy of the main glacier areas is assessed to be within two pixels at 10 m pixel size.

After the automated pre-classification, usually a manual post-processing step is required to correct for misclassified snow patches outside of glacier areas, or to add debris covered or cast shadowed areas to glacier areas. This correction introduces the major uncertainty, as the correct manual delineation depends on the experience of the analyst with the used satellite data base, as well as with the analysed region. Local knowledge of the places can help to improve the analysed glacier outlines significantly. Debris covered glacier tongues are the most challenging part of the manual correction, and can sometimes only very hardly be discriminated from surrounding moraines. Thus, the accuracy of the glacier product is lowest in such areas, up to three pixels at 10 m pixel size.

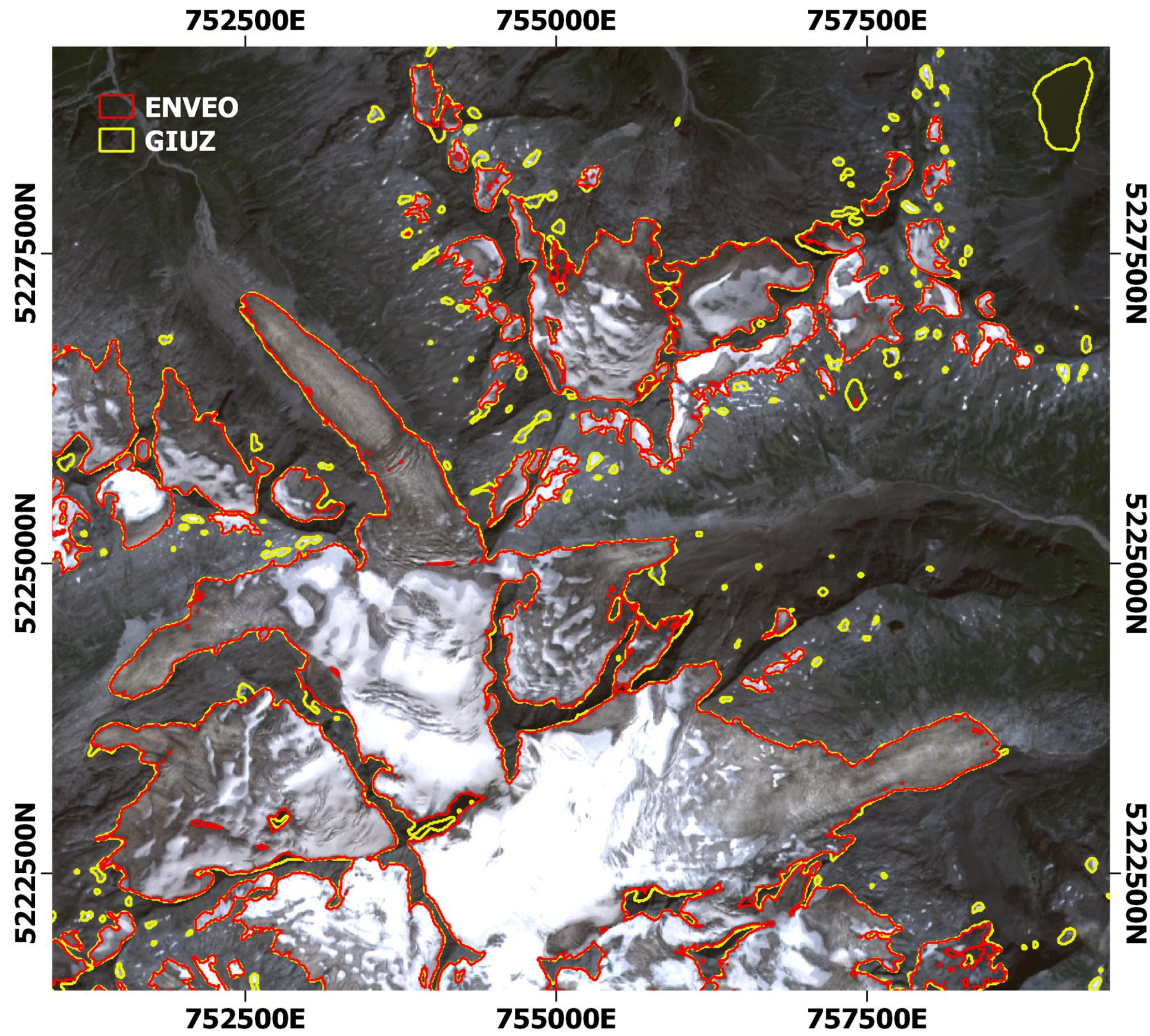

Figure 12.1: Comparison of preliminary glacier outlines retrieved by automated processing chains of ENVEO (red) and Geographical Institute of University of Zurich (GIUZ, yellow) from the same Sentinel-2 scene of 13 August 2015. Based on this outcome the outlines are manually corrected for debris covered glacier areas or glacier areas in cast shadowed regions.

But also glaciers having a common accumulation zone, as shown in Figure 12.2, are difficult to discriminate. For such cases, a DEM is required, which should ideally have the same spatial resolution as the used spectral bands of Sentinel-2. Unfortunately, the accuracy of the overall geolocation is also problematic for this processing step, when for instance a national DEM is used for the separation of common accumulation areas, which does not match exactly the geolocation of the Sentinel-2 scene. In case of the Austrian glaciers, glacier inventories of previous years are available, which are used as basis information to make the glacier areas comparable. The right graphic in Figure 12.2 shows the differences on a debris covered glacier tongue, as well as the difficulties of common accumulation areas, when different data sets are used for the classification.

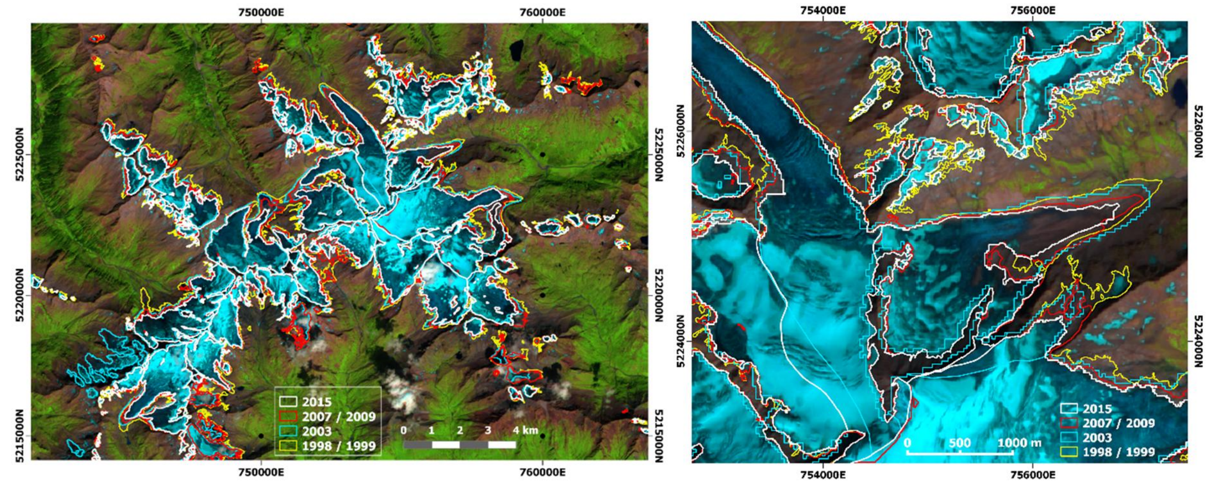

Figure 12.2: Glacier outlines of the generated within SEN3APP from a Sentinel-2 scene of 13 August 2015 (white) compared with glacier outlines from the Austrian Glacier Inventory of 2007 / 2009 from orthophotos (red, by courtesy provided by B. Seiser from ÖAW/IGF), glacier outlines of the Randolph Glacier Inventory from satellite data of 2003 (RGI5.0, cyan), and the glacier outlines of the Austrian Glacier Inventory of 1998 / 1999 from orthophotos (yellow, by courtesy provided by A. Lambrecht and M. Kuhn, 2007, University of Innsbruck). Left: All Austrian glaciers of the region Venedigergruppe. Right: Subset of selected glaciers of the Venedigergruppe to illustrate the mapping differences in the products.

Based on the analyses of the left graphic in Figure 12.2, the derived glacier areas of the Austrian glacier inventories (AGI) of 1998 / 99 and 2007 / 09, each based on orthophotos, are compared with the glacier areas derived from the selected Sentinel-2 scene analysed within SEN3APP. As all larger glaciers in this region are retreating since years, this investigation is used to assess if the retrieved SEN3APP glacier outlines are plausible at all. The results, shown in Table 12.1, show that all glaciers had a negative area change, i.e. retreated since 1998 / 99 and since 2007 / 09, as has been expected. The overall accuracy of the retrieved glacier areas might be improved in some cases using time series of satellite data for the analysis, in particular if parts of a glacier are heavily debris covered or affected by remaining seasonal snow. The glacier areas of the Randolph Glacier Inventory were not considered in these intercomparisons, as glacier outlines show partly severe deviations from the AGI outlines in common accumulation areas.

Table 12.1: Comparison of selected glacier areas derived from the Austrian Glacier inventories of 1998/99 and 2007/09 with the glacier areas generated within SEN3APP from the Sentinel-2 scene of 13 August 2015. The total areas are provided in km², and areal changes are provided in percentages.

	Area [km²]			Area change [%]	
Glacier name	1998 / 1999	2007 / 2009	2015	1998 / 99 - 2015	2007 / 09 - 2015
Untersulzbach Kees West	0,237	0,208	0,156	-34,18	-25,00
Kratzenbeg Kees	0,310	0,203	0,169	-45,48	-16,75
Maurer Kees W	1,409	1,347	1,331	-5,54	-1,19
Simony Kees	2,565	2,193	1,620	-36,84	-26,13
Käferfeld Kees	2,493	2,106	1,682	-32,53	-20,13
Viltragen Kees	2,127	1,850	1,698	-20,17	-8,22
Maurer Kees M	2,117	1,808	1,732	-18,19	-4,20

	Area [km²]			Area change [%]	
Glacier name	1998 / 1999	2007 / 2009	2015	1998 / 99 - 2015	2007 / 09 - 2015
Frosnitz Kees	2,734	2,444	2,103	-23,08	-13,95
Habach Kees	3,289	2,781	2,366	-28,06	-14,92
Mullwitz Kees	3,244	2,931	2,806	-13,50	-4,26
Dorfer Kees	3,798	3,401	2,848	-25,01	-16,26
Untersulzbach Kees	3,721	3,459	3,125	-16,02	-9,66
Rainer Kees	3,511	3,216	3,179	-9,46	-1,15
Krimmler Kees	4,883	4,208	3,948	-19,15	-6,18
Umbal Kees	4,728	4,315	4,057	-14,19	-5,98
Schlaten Kees	9,316	8,274	7,713	-17,21	-6,78
Obersulzbach Kees	11,007	9,752	8,768	-20,34	-10,09

13. References

Fischer, A., Seiser, B., Stocker Waldhuber, M., Mitterer, C., & Abermann, J. (2015). Tracing glacier changes in Austria from the Little Ice Age to the present using a lidar-based high-resolution glacier inventory in Austria. *Cryosphere*, *9*(2), 753–766. http://doi.org/10.5194/tc-9-753-2015

Lambrecht, A., & Kuhn, M. (2007). Glacier changes in the Austrian Alps during the last three decades, derived from the new Austrian glacier inventory. *Annals of Glaciology*, *46*(1), 177–184.

Information on snow and ice area products on glaciers

Issue 1.0

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Introduction

Maps of snow and ice areas on selected glaciers are generated as demonstration products on demand during the EU FP7 project SEN3APP. The main focus during the SEN3APP project was on selected glaciers in the Alpine area, due to limited availability of other usable Sentinel-2 scenes during the development and demonstration phase of the project.

Regular updates of the snow and ice areas on glaciers are important indicators for climate change studies, and can be used as proxy for assessing a glacier's mass balance. Information on the uncertainty of the snow and ice areas on glaciers is important for the users for interpreting the provided information.

1. Document Identifier

SEN3APP_ENVEO_GLS_PR_V1.0

2. Title

Information on snow and ice area products on glaciers

3. Authority and Contact Information

ENVEO IT GmbH

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4. Abstract

Snow and ice areas were generated for selected glaciers in the region Hohe Tauern, Austria, from a Sentinel-2 scene acquired during the commissioning phase on 13 August 2015. A coincidently WorldView-2 scene was ordered and by courtesy provided by the Copernicus Data Warehouse. Unfortunately, the geolocation of the Sentinel-2 and the WorldView-2 data does not match at all, probably due to different ground control points and digital elevation models used for the orthorectification. But both products are only available from the products providers as "ortho ready". Due to lack of other reference data, the performance of the snow and ice products on glaciers from Sentinel-2 data can currently not be assessed.

5. Keywords

#snow and ice area, #glacier, #Alps, #Alpine area #optical satellite, #Sentinel-2, #MSI

6. Key terminology

Glacier facies	Surface types of glaciers, including typically snow, bare ice, neve, debris cover, nunataks (internal rocks), and sometimes melt water bodies

7. Background, Context and Scope

The snow and ice area products on selected glaciers were generated on demand during the EU FP7 project SEN3APP (No. 607052) based on Sentinel-2 data. Key users were interviewed in the beginning of the project period to identify if the product specifications fulfil their requirements or if changes are needed.

Evaluation of snow and ice areas on glaciers is very challenging, as the spatial extent of the snow areas can change rapidly, even within a few hours, and thus, usable reference data are very rare. Ground truth data are only available for some single spots on selected glaciers, but these were not necessarily measured coincidently with the satellite acquisition.

A Sentinel-2 scene acquired on 13 August 2015 during the commissioning phase over the Austrian Alps was selected for generating the snow and ice areas on selected glaciers within SEN3APP. Four neighboured WorlView-2 scenes, with 2 m pixel size for the VNIR bands and 0.5 m pixel size for a panchromatic band, were acquired exactly on the same date and nearly at the same time over some of the selected glaciers. This very high resolution satellite data was by courtesy provided by the Copernicus Data Warehouse free of charge within the project. Unfortunately, for the orthorectification of the WorldView-2 scenes a different DEM was used than for the orthorectification of the Sentinel-2 scene. Also the orthorectification of the four neighboured WorldView-2 scenes does not match, but irregular shifts are obvious at overlapping regions. As both datasets, the WorldView-2 and the Sentinel-2 are only available as “ortho ready”, and the digital elevation models used for the orthorectification are (so far) not available to the public, it is not possible to correct for the mismatch in the geolocation.

The QA4EO framework was selected as an example of a template for reporting the current status information on the product snow and ice on glaciers.

8. Product performance and uncertainty

An accuracy assessment for the generated product cannot be provided due to lack of reference data.

Performance assessment of the glacier ice velocity products for Greenland, and description of the evaluation methodology

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Introduction

Glacier ice velocity maps are generated from Sentinel-1 data for Greenland during the SEN3APP demonstration phase.

The glacier ice velocity information is important for climate change studies, as the ice velocity provides dynamic information about a glacier. Information on the uncertainty of the glacier ice velocity products is important for the users for interpreting the provided datasets.

1. Document Identifier

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Performance assessment of the glacier ice velocity products for Greenland, and description of the evaluation methodology

3. Authority and Contact Information

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4. Abstract

The uncertainty information related to the Sentinel-1 derived glacier ice velocity products are presented for selected outlet glaciers of Greenland. The performance of the ice velocity products is assessed by comparison with ice velocity maps derived from TerraSAR-X and ALOS PALSAR data.

5. Keywords

#glacier, #ice velocity, #Greenland, #Sentinel-1, #C-SAR

6. Key terminology

Glacier ice velocity	Ice surface velocity of a glacier
Offset tracking	Method applied to retrieve ice surface velocity for glaciers from repeat-pass satellite images

7. Background, Context and Scope

The ice velocity products for glaciers in Greenland from Sentinel-1 (S1) data were regularly generated during the EU FP7 project SEN3APP (No. 607052). Key users were interviewed in the beginning of the project period to identify if the product specifications fulfil their requirements or if changes are needed.

For assessing the performance of the S1 based ice surface velocity products, ice surface velocity maps were generated for selected glaciers in Greenland based on TerraSAR-X (TSX) and ALOS PALSAR (AP) data. Ice velocities were then inter-compared in selected test regions and along pre-defined central flowlines of glacier tongues.

The QA4EO framework was selected as an example of a template for reporting the performance of the satellite data products and as an information package for the dataset user to easily assess the suitability of the data for the purpose.

8. Product performance and uncertainty

No in-situ validation data are available for the region and time period of the generated IV products presented here. For estimating product performance and uncertainty of S1 derived velocities, we therefore compare the velocity products with ice velocity maps retrieved from TSX and AP data (Figure 8.1). The comparisons are performed with velocity maps retrieved from single SAR repeat pass pairs. For S1 velocity data acquired from single image pairs and velocity data from a velocity mosaic (multiple merged & averaged tracks) are used. Because of possible temporal velocity variations, the lower sections of glacier tongues are not used for the comparison. We computed the root mean square error (RMSE) of velocity magnitude between TSX and S1 for 28 areas with mean velocities ranging from 1 m d^{-1} to 10 m d^{-1}. The RMSE for this data set corresponds to 7.4% of the mean velocity for S1 velocities from a single image pair and to 4.8 % for the merged S1 velocity map.

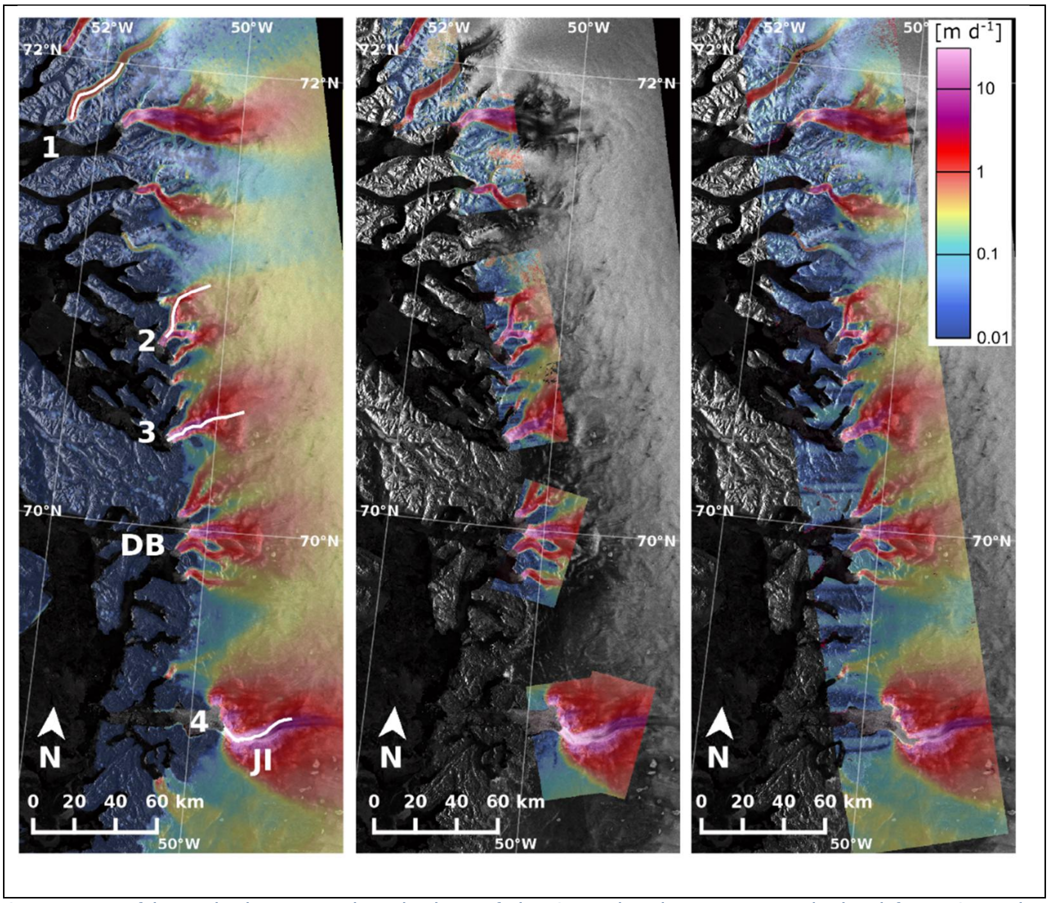

Figure 8.1: Maps of ice velocity on outlet glaciers of the Greenland west coast, derived from SAR data of (a) Sentinel-1, 3-15 January 2015, (b) TerraSAR-X, 11 days repeat pass from different epochs in December 2014 and February 2015, (c) PALSAR, 20 November 2009 - 5 January 2010. DB – northern Disco Bugt; JI – Jakobshavn Isbrae. White lines show profiles of Figure 12.1: 1 - Umiammakku Isbrae, 2-Sermeq Silarleq, 3-Store Gletsjer, 4-Jakboshavn Isbrae. (from Nagler et al., 2015)

9. Inputs

Input	Description	Link
ENVEO glacier ice velocity products	Glacier ice velocity products from Sentinel-1	http://cryoportal.enveo.at/
Glacier ice velocity products from TerraSAR-X & ALOS PALSAR	Glacier ice velocity maps used as reference data set	http://cryoportal.enveo.at/

10. Standards and Traceability

Standard/ Documentation	Description	Link
Glacier CCI	Standards defined in the ESA project Glacier CCI	http://www.copernicus.eu/projects/glaciers-cci

11. Methodology, Processing

1) Determine in-situ site locations used for validation/inter-comparison: Select TSX & AP data covering same area and time period (if available) as S1 ice velocity map
2) Derive ice velocity maps from feature tracking using TSX & AP data
3) Resample to same grid spacing in order to match the product size of the S1 ice-velocity map
4) Computed the root mean square error (RMSE) of velocity magnitude between TSX and S1 for different test areas with mean velocities ranging from 0.1 m d^{-1} to 10 m d^{-1}
5) Extract profiles along glacier central flowlines for inter-comparison and quality assesment

12. Evaluation of Performance

The inter-comparison of the S1 ice velocity maps with velocities derived from TSX show high agreement. The reported RMSE value includes the total uncertainties both for the S1 velocities and the TSX velocities. The uncertainty for slow moving areas was calculated by deriving the RMSE for 12 areas with mean velocities between 0.1 m d^{-1} to 0.5 m d^{-1}. For S1 velocities retrieved from a single image pair the RMSE is 0.068 m d^{-1}, and for the merged S1 ice velocity map the RMSE is 0.047 m d^{-1}. The higher relative error at slow velocities is due to the impact of ionospheric noise in the total error budget.

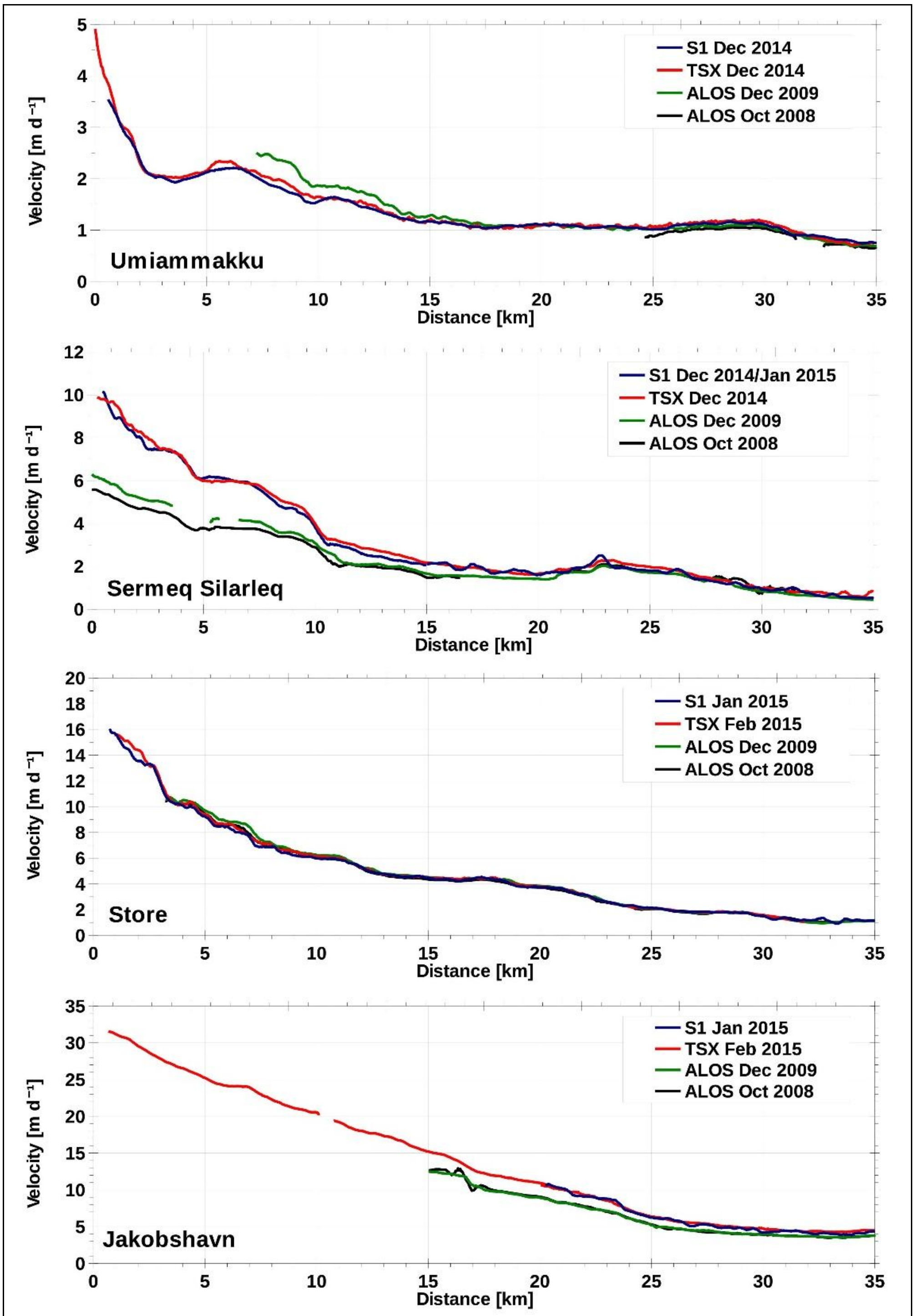

Figure 12.1: Ice velocity along central flowlines for Umiammakku Isbræ, Sermeq Silarleq, Store Gletsjer, Jakobshavn Isbræ. Distance upstream of ice front in January 2015. Location of profiles in Figure 8.1. (Nagler et al., 2015)

Figure 12.1 shows the velocities along the central flowlines on the lower terminus of four outlet glaciers (location in Figure 8.1), derived from S1, TSX and AP data. The velocity profiles in *Figure 12.1* are from the cold season when short term fluctuations in velocity are modest compared to the melting period. For three of the glaciers the S1 analysis provides velocities all along the terminus. For Jakobshavn Isbrae S1 and AP are not able to track the motion down to the front because of the sharp velocity gradients across the ice stream. The S1 and

TSX velocity profiles shown in *Figure 12.1* are separated in time up to one month. On Umiammaku Isbrae, Sermeq Silarleq and Store Gletsjer the S1 and TSX velocity profiles show close agreement, indicating on one hand comparatively stable velocities during December 2014 and January 2015, on the other hand similar performance of the two sensors for tracking velocities along the central flowlines. A comparison between S1 and AP indicate that Sermeq Silarleq and Jakboshavn Isbrae show significant acceleration, increasing towards the calving front, while Umiammakku shows a deceleration. Store Gletsjer shows good agreement between all datasets, also indicating stable velocities and similar performance for all three sensors.

13. References

Nagler, T.; Rott, H.; Hetzenecker, M.; Wuite, J.; Potin, P. The Sentinel-1 Mission: New Opportunities for Ice Sheet Observations. Remote Sens. 2015, 7, 9371-9389.

Assessment of performance of the Ice surface Velocity (IV) product and description of the evaluation methodology

Issue 1.0

SEN3APP

Processing Lines And Operational Services Combining Sentinel And In-Situ Data For Terrestrial Cryosphere And Boreal Forest Zone

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Introduction

Satellite SAR missions make it possible to operationally map and monitor glacier flow on a nearly global scale using offset-tracking methods. With Sentinel-1 Level 1 SLC data, downloaded from the Scientific Data Hub, the retrieval of ice surface velocity maps over the Svalbard Archipelago is possible since August 2014 every 12 days. Knowledge on glacier ice velocity provides a better understanding of a wide range of processes related to glacier dynamics, for example glacier mass flux, flow modes and flow instabilities (e.g. surges), sub-glacial processes (e.g. erosion), and the development of glacier lakes and associated hazards. In addition, the comparison of the spatio-temporal variations of glacier velocities both within and between regions will improve understanding of climate change impacts.

In order to apply this satellite derived data product the user needs information on the uncertainty related to the interpretation and understanding how the uncertainty information was derived. The purpose of the document is to provide information for the user to estimate the suitability of the product (in the view of performance characteristics) to the purpose in hand.

1. Document Identifier

SEN3APP_GAMMA_IV_VR_V1.0

2. Title

Assessment of performance of the Ice surface Velocity (IV) product and description of the evaluation methodology.

3. Authority and Contact Information

Gamma Remote Sensing

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4. Abstract

The uncertainty information related to the Ice surface Velocity (IV) product is presented. The derivation of the quantitative measures of uncertainty is presented in detail that the user can track back the procedure and repeat the analysis or use the same procedure to similar satellite data product.

The overall uncertainty for the ice surface velocity (IV) product derived from Sentinel-1 data with a time interval of 12 days in areas far from glacier's calving fronts and shear zones is typically between 20 and 30 m/yr (0.05 to 0.08 m/d).

5. Keywords

#ice surface velocity, #SAR satellite, #Sentinel-1

6. Key terminology

Ice surface velocity	While radar methods detect a mixture of surface and sub-surface features (penetration depth in dry snow and ice up to >100 m depending on the radar frequency and snow and ice purity and structure), they are generally referred to as measurement of ice glacier surface velocity flow
SAR	Radar with synthetic aperture antenna to achieve high spatial resolution

7. Background, Context and Scope

The Ice surface Velocity (IV) satellite data product has been developed in the SEN3APP EU-FP7 projectt. The project aim was to develop existing or new satellite data products in collaboration with potential service users and to establish data processing and delivery services for these products. In the beginning of the project a comprehensive list of satellite data products generated by the project partners. Then key users were identified and focus was given to the data products that met their needs. Other satellite data products were also developed further in the project for potential new users.

The QA4EO framework was selected as an example of a template for reporting the performance of the satellite data products and as an information package for the dataset user to easily assess the suitability of the data for the purpose. Each product was validated during the course of the project against in-situ or other independent data source and the results were reported as part of the validation report.

This is the first version of the documentation that should be made easily available where the IV data is also made accessible and delivered together with the data.

8. Product performance and uncertainty

The uncertainty of the ice surface velocity product is estimated as the mean and standard deviation between the differences from the “true” velocity to the velocity measured with Sentinel-1 data. Three product performance evaluations were performed on Svalbard glaciers using Radarsat-2 Wide Ultra Fine Mode acquisitions with a spatial resolution of about 3 m and a coverage of approximately 50 km x 50 km, GPS stakes, and ground-based radar measurements with a spatial resolution of about 2 m x 16 m. In our analysis we make a difference between regions close to glacier's calving fronts and shear zones, where spatial and temporal variability of ice surface velocity is large, and regions far from glacier's calving fronts and shear zones. The validation results are summarized in Table x.

Ice surface velocity maps computed from Radarsat-2 Wide Ultra Fine Mode acquisitions of February 1 and February 25, 2016 and February 25 and March 20, 2016 over Basins-2 and 3 (Austfonna) were inter-compared with ice surface velocity maps computed from Sentinel-1 on February 9 and February 21, 2016 and March 4 and 16, 2016, respectively. Ice surface velocity maps computed from Radarsat-2 Wide Ultra Fine Mode acquisitions of February 4 and February 28, 2016 and February 28 and March 23, 2016 over Stonebreen (Edgeøya) were inter-compared with ice surface velocity maps computed from Sentinel-1 on February 9 and February 21, 2016 and March 4 and 16, 2016, respectively. On average, the mean difference and standard deviation between the Radarsat-2 and Sentinel-1 ice velocity records for areas far from the glacier's calving fronts and shear zones were 17 m/yr and 26 m/yr, respectively. For areas close to the glacier's calving fronts and shear zones the mean difference and standard deviation between the Radarsat-2 and Sentinel-1 ice velocity records were on average 38 m/yr and 64 m/yr, respectively. Ice surface velocities during winter 2016 over Basin-2 and Basin-3 were over 2,000 m/yr, over Stonebreen up to 1,000 m/yr.

Three GPS stake records over a period of almost one year over Hansbreen and Storbreen in South Spitsbergen are compared to Sentinel-1 velocity values computed every 12 days and averaged over the same long time interval. The mean velocities of the three GPS stakes were 70 m/yr, 92 m/yr and 460 m/yr, those averaged from the Sentinel-1 records 112 m/yr, 81 m/yr and 450 m/yr. Mean difference and standard deviation between the two records for the three stakes were 11 m/yr and 30 m/yr, respectively.

Ice surface velocities for a continuous GPS stake far from the calving front of Hansbreen were compared with six Sentinel-1 products over periods of 12 days between September 2015 and April 2016. The mean velocities over the whole period were 87 m/yr for the GPS records and 71 m/yr for the Sentinel-1 records, respectively. Mean difference and standard deviation between the two records for the six periods were 16 m/yr and 18 m/yr, respectively.

Ice surface velocities for a continuous GPS stake close to the calving front of Hansbreen were compared with three Sentinel-1 products over periods of 12 days between August and October 2015. The mean velocities over whole period were 229 m/yr for the GPS records and 111 m/yr for the Sentinel-1 records, respectively. Mean difference and standard deviation between the two records for the three periods were 118 m/yr and 76 m/yr, respectively.

Ground-based radar measurements of ice surface velocity around the front of Kronebreen were performed with Gamma Portable Radar Interferometers on August 27, 2016 from two locations during 3 hours simultaneously and the two line-of-sight measurements combined to derive horizontal ice surface velocity. Inter-comparison with the Sentinel-1 ice surface velocity map computed with acquisitions of the 20 August and 1 September, 2016 for a region away from the calving front and shear zones indicated a mean difference and standard deviation between the two records of 8 m/yr and 22 m/yr, respectively. Mean velocities over this homogeneously moving area were 417 m/yr from the GPRI-2 records and 405 m/yr for the Sentinel-1 records, respectively. Close to the calving front mean difference and standard deviation between the two records were of 67 m/yr and 268 m/yr, respectively, and mean velocities were 581 m/yr from the GPRI-2 records and 552 m/yr for the Sentinel-1 records, respectively.

Table x. Results of the validation of IV products.

Regions far from glacier's calving fronts and shear zones		
Inter-Comparison Experiment	*Mean Difference*	*Standard Deviation*
Radarsat-2 WUF Mode Basin-2, Basin-3 and Stonebreen	17 m/yr	26 m/yr
Yearly GPS Hansbreen and Storbreen	11 m/yr	30 m/yr
Continuous GPS Hansbreen (12 days)	16 m/yr	18 m/yr

GPRI-2 Kronebreen (3 hours)	8 m/yr	22 m/yr

Regions close to glacier's calving fronts and shear zones		
Inter-Comparison Experiment	*Mean Difference*	*Standard Deviation*
Radarsat-2 WUF Mode Basin-2, Basin-3 and Stonebreen	38 m/yr	64 m/yr
Continuous GPS Hansbreen (12 days)	118 m/yr	76 m/yr
GPRI-2 Kronebreen (3 hours)	67 m/yr	268 m/yr

9. Inputs

Input	Description	Link
SEN3APP ice surface velocity	Horizontal ice surface velocity data over the Svalbard Archipelago from Sentinel-1 SAR data since August 2014	SEN3APP (http://sen3app.fmi.fi)
Radarsat-2 ice surface velocity	Horizontal ice surface velocity data from Radarsat-2 Wide Ultra Fine Mode data (~3 m spatial resolution) for 2016.02.01_2016.02.25 and 2016.02.25_2016.03.20 over Basin-3 and 2016.02.04_ 2016.02.28 and 2016.02.28_2016.03.23 over Stonebreen (Svalbard)	Images available from Copernicus for SEN3APP (http://sen3app.fmi.fi)
DGPS stake measurements	Differential GPS stake measurements in 2015 and 2016 on Hansbreen and Storbreen, South Spitsbergen (Svalbard)	Courtesy Centre for Polar Studies, University of Silesia, Sosnowiec, Poland (http://www.polarknow.us.edu.pl)
GPRI-2 ice surface velocity	Ground-based radar measurements of ice surface velocity over Kronebreen (Svalbard) performed with the Gamma Portable Radar Interferometer on August 27, 2016 (spatial resolution 0.75 m x ~16 m)	Courtesy CalvingSEIS Project (http://www.mn.uio.no/geo/english/research/projects/calvingseis)

10. Methodology, Processing

Satellite-derived displacements can be compared to field measurements (e.g. DGPS stakes) provided that the temporal and spatial representativeness of these measurements is valid. In addition, satellite-derived displacements can be compared to products derived from independent image data of equal or better resolution, accuracy, and precision. In these cases, the discrepancy between the products is a function of the accuracy of both matches, the representativeness of the displacement compared to the “real” displacement, and the temporal variations between the acquisition dates of the two sets of images.

The methodology for derive uncertainties for ice surface velocity products include:
1) Determine site locations used for validation;
2) Align ice surface velocity measurements form space and in-situ to the same geographical projection, time interval and velocity component;
3) Extract ice surface velocity values for different areas;
4) Compute statistics of uncertainty.

11. Evaluation of Performance

The overall uncertainty for ice surface velocity derived from Sentinel-1 data with a time interval of 12 days in areas far from glacier's calving fronts and shear zones is between 18 and 30 m/yr (0.05 to 0.08 m/d). Close to glacier's calving fronts and shear zones the Sentinel-1 ice surface velocities are underestimated and the uncertainty gets larger, because regions of fast and slow flowing are within the large region used for the space measurements while in-situ records are typically on much smaller areas, including fast-moving spots.

For every individual Sentinel-1 frame a header file provides statistical measures (mean and standard deviation) of ice surface velocity on ice-free regions as a further performance indicator. Typical standard deviation values are also between 20 and 30 m/yr.

Validation of ice surface displacements measured from satellite sensors is inherently difficult, because glacier surface velocities are variable temporally, with diurnal, seasonal, and inter-annual cycles, and spatially, so that motion estimated for large areas from space is not necessarily representative of the motion of individual features or points in the field. Thus, direct comparison to point measurements are suitable only for the same time interval and areas with homogeneous velocity fields. In addition, in-situ surface ice velocity is measured by DGPS at stakes, representing the 3D displacement of the surface due to several processes (horizontal, displacement, ablation, movement along slope, etc.), while from space SAR sensors measure line-of-sight and along-track displacement. To validate or compare products from these different methods requires first transforming measurements to the same velocity component (usually horizontal).

12. Evidence to Support Performance Indicator

Similar ice surface velocity products derived from Sentinel-1 image pairs were compared with ice velocity maps retrieved from TerraSAR-X data on the Greenland west coast by Nagler et al. (2015). The RMSE between the two data sets was 7.4% of the mean velocity for values ranging from 1 to 10 m/d. The uncertainty for slow moving areas between 0.1 and 0.5 m/d of Sentinel-1 velocities retrieved from single image pairs was 0.068 m/d (25 m/yr).

13. References

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