

EVALUATING THE IMPACT OF RADIOMETRIC
CALIBRATION AND THERMAL NOISE REMOVAL ON
GLACIER VELOCITY ESTIMATES FROM SENTINEL-1
SAR DATA: A CASE STUDY ON LIVINGSTON ISLAND

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Abstract

This study evaluates whether applying pre-processing to Sentinel-1 GRD (Ground Range Detected) SAR images alters the accuracy of glacier surface velocity estimates obtained with an offset-tracking algorithm. The pre-processing includes applying thermal noise removal and radiometric calibration deriving sigma0 type products. The research focuses on glaciers near the Bulgarian research base on Livingston Island (Antarctica), using available in-situ GNSS velocity measurements as ground truth. Three nearly identical processing chains were implemented in ESA's SNAP software: one including radiometric calibration (producing sigma0) and thermal noise removal, one with only thermal noise removal, and one with neither. All other processing steps and parameters were held constant to isolate the effect of calibration and thermal noise removal.

Key words: remote sensing, SAR, glacier, velocity maps, radiometric calibration

Introduction. Remote sensing, and SAR in particular is indispensable for glacier monitoring in polar regions where field data are sparse [1]. Offset-tracking

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on Sentinel-1 GRD products is widely used to estimate surface velocities [2–4]. The radiometric calibration converts raw pixel values to physically meaningful backscatter (σ_0), potentially influencing the cross-correlation used in offset-tracking. Previous studies have shown mixed sensitivity to calibration and thermal noise removal. Both steps are part of the processing chain developed by ESA [5] and are recommended for improving reliability of the end result. This work quantitatively evaluates the effect on a localized Antarctic setting with GNSS validation.

Study area. Livingston Island is part of the South Shetland Islands archipelago, located northwest of the Antarctic Peninsula, and is among the actively studied polar regions in West Antarctica. The island covers an area of approximately 798 km², of which the majority (87.6%) is covered by an ice cap and outlet glaciers. The terrain is predominantly mountainous, with central ridges and plateaus from which numerous glacier streams flow radially towards the northern and southern coasts. In situ measurements of surface ice velocities reveal a wide range – from near-zero values to tens of m a⁻¹ – with pronounced seasonality and short-term accelerations.

This study presents results from field observations on the Balkan and Contell glaciers, located in close proximity to the Bulgarian Antarctic Base St. Kliment Ohridski (Fig. 1).



Fig. 1. Point locations for both glaciers and time periods

The coordinates of the observed points were determined through GNSS measurements conducted with Trimble Alloy GNSS and Trimble R8s receivers. The Trimble Alloy receiver was used as a base station (positioned at site KOH2), while the Trimble R8s served as a rover station. Long-term measurements in the frontal part of Balkan Glacier were carried out between 2 and 26 January 2023 at a fixed point attached to the ice, located about 100 m from the glacier front and 1318 m from the permanent GPS station KOH2. The coordinates were obtained through static one-hour measurements. The study of ice-flow velocities on Contell Glacier was conducted in January 2025 by repeated measurements (once per week) of stakes arranged in two rows in the upper part of the glacier. The coordinates were determined using 15-minute static sessions.

Methods. This study applies the offset-tracking method to Sentinel-1 Ground Range Detected (GRD) images using three distinct processing chains, all three implemented within the SNAP software environment. All three processing chains are illustrated in Fig. 2 and are designed to enhance co-registration accuracy and subsequently generate high-quality glacier velocity maps. They are based on the general processing for creating glacier velocity maps provided by ESA [5].

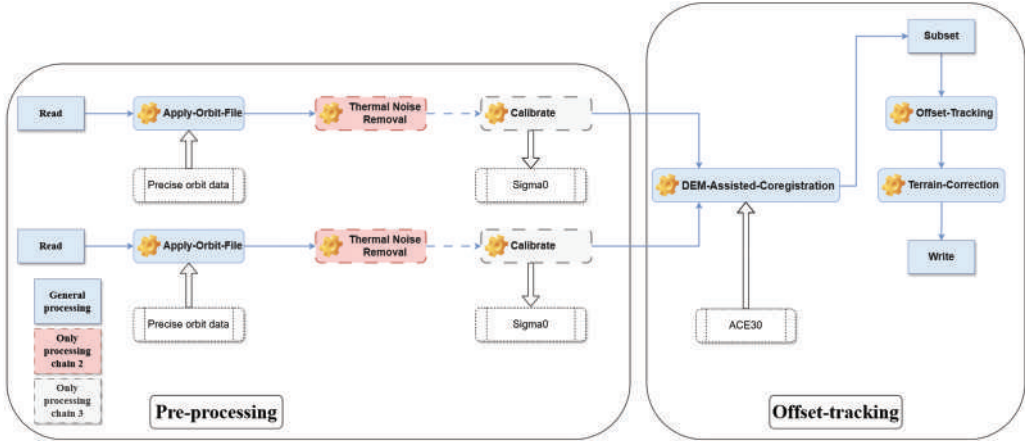


Fig. 2. Processing chains for SAR images

The workflow begins with updating the orbit files, which introduces precise ephemerides and thereby improves the accuracy of the co-registration process. Then in processing chain 1 – named “general processing”, the next step includes DEM-assisted co-registration, while the other two processing chains include additional pre-processing. Important note for processing chain 1 is that the non-processed GRD products contain information about the amplitude of the back-scattered signal which can be used to calculate intensity. Using unmodified products leads to keeping the amplitude as the main source of information, and it is the one being used for the offset-tracking method. This is not true for the other two processing chains since applying thermal noise removal (TNR) converts

the amplitude to intensity using the following equation

$$(1) \quad \text{intensity} = \text{amplitude}^2.$$

In order to compare both products, the intensity band must be converted to become a permanent band of the product and the amplitude band must be removed, otherwise the product metadata is not updated, and amplitude persists as the main band and is included in the co-registered product. Trying to remove it from this point in the processing causes the offset-tracking algorithm to crash since the band mentioned in the metadata is missing (the amplitude band). This led to performing this conversion and complete removal of the amplitude band, so the end products are comparable.

The second processing chain includes addition step – TNR. This process aims to correct pixel values affected by system-induced artifacts [6]. In the third chain, this step is followed by radiometric calibration before the co-registration. The ACE30 dataset was employed [7]. A spatial subset is then created to restrict the analysis to the area of interest, after which the offset-tracking algorithm is applied. This method requires several parameters including grid size (set to 30 m), oversample coefficient (set to 16), cross-correlation threshold (0.1) and maximum velocity (2.5 m/day according to results of previous studies of the region [3]).

The final step of all three chains is terrain correction, which projects the output data into the UTM projection based on WGS 84 coordinate system. This correction accounts for distortions introduced by imaging geometry, ensuring consistency with in-situ measurements also collected in UTM. Radiometric calibration procedure corrects the backscattered signal values registered by the sensor. In this study, sigma0 was selected as it provides terrain-normalized backscatter values. The calibrated sigma0 values were calculated according to the following equation [8]:

$$(2) \quad \sigma^0 = \frac{DN^2}{A_{\text{dn}}^2 \cdot K} \cdot \frac{1}{G_{\text{eap}}^2} \cdot \left(\frac{R}{R_{\text{ref}}} \right)^3 \cdot \sin \alpha,$$

where $\frac{1}{G_{\text{eap}}^2}$ is the antenna height correction (EAP), $\frac{R}{R_{\text{ref}}}$ is the range signal lost (RSL), A_{dn} is the final product scale, and α is the local incident angle.

Results. Comparison was performed for both January of 2023 and January of 2025. All images were downloaded from the Copernicus Eco System.

All SAR-derived velocities were compared to in-situ data to compute absolute errors (reported in m/d) (Table 1). Large discrepancies appeared in the first 12-day period (0.361 m/d), while the second 12-day period showed smaller differences (0.132 m/d). The 24-day interval also showed notable differences (0.155 m/d). All comparisons used one in-situ point measured via continuous GNSS over 580 hours.

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Difference between SAR velocities from different processing chains for 2023

	Product type	Cross- corr. coeff.	GNSS [m/d]	Satellite [m/d]	Difference [m/d]
12 days	Calibrated	0.1	0.06292	0.42412	0.36119
04.01.23–	Non-calibrated	0.1	0.06292	0.42437	0.36145
16.01.23	No thermal noise removal, intensity	0.1	0.06292	0.42447	0.36155
12 days	Calibrated	0.1	0.06213	0.19530	0.13318
16.01.23–	Non-calibrated	0.1	0.06213	0.19530	0.13318
28.01.23	No thermal noise removal, intensity	0.1	0.06292	0.19530	0.13238
24 days	Calibrated	0.1	0.06292	0.21703	0.15410
04.01.23–	Non-calibrated	0.1	0.06292	0.21703	0.15410
28.01.23	No thermal noise removal, intensity	0.1	0.06292	0.21950	0.15658
Period	Reference/ Difference	Calibrated [mm/d]	Non-calibrated [mm/d]	No TNR	[mm/d]
12 days	cal, cross 0.1	0.00000	0.00026		0.00036
04.01.23–	nocal, cross 0.1	−0.00026	0.00000		0.00010
16.01.23	noTNR, cross 0.1	−0.00036	−0.00010		0.00000
12 days	cal, cross 0.1	0.00000	0.00000		−0.00079
16.01.23–	nocal, cross 0.1	0.00000	0.00000		−0.00079
28.01.23	noTNR, cross 0.1	0.00079	0.00079		0.00000
24 days	cal, cross 0.1	0.00000	0.00000		0.00247
04.01.23–	nocal, cross 0.1	0.00000	0.00000		0.00247
28.01.23	noTNR, cross 0.1	−0.00247	−0.00247		0.00000

For more detailed product comparison, the difference between the errors was also calculated. The comparison is presented in Table 1, where all negative values mean that the error is smaller and conversely – positive ones indicate bigger error. Due to the extremely low values of the differences, all errors are presented in mm/d. These results show that the error with the calibrated images is smaller compared to the non-calibrated images and the no TNR images – the difference is around 0.25 mm/d compared to non-calibrated images and 0.35 mm/d for no TNR images. The non-calibrated images are also better in terms of error compared to the no TNR images, difference is around 0.1 mm/d, and are worse than the calibrated ones for the first 12-day period. The second period shows no significant difference between calibrated and non-calibrated images while the no TNR images have bigger errors, around 0.8 mm/d. The same holds for the 24-day period, where the difference between calibrated and non-calibrated images is 0 while the no TNR images have an error of 2.5 mm/d.

Comparisons for 2025 were made using nine in-situ points for the first 12-day period and five of the same points for the second 12-day period and the 24-day period. Comparison between in-situ measurements and SAR is performed similarly to the 2023 analysis (Table 2). Important note is that not all points were measured exactly every 12 days. First four points (C01 to C04) were measured on 06.01.2025, then on 20.01.2025 and finally on 04.02.2025 (only for points C01 and C02). The same holds for the rest of the points which were measured on 12.01.2025, then on 19.01.2025 and finally on 04.02.2025. All velocities were calculated using the coordinates of the points and the time between measurements as base. Then a consistent velocity was assumed for the days when measurement data were not available.

For the first 12-day period the difference varies between 28 cm/d to around 4.8 cm/d. The average error is around 16.7 cm/d which is caused mainly by the slow-moving points C01, C02, C13, and C14 which are difficult to register using the offset-tracking method. The difference for the faster points with velocity above 3 cm/d is around 12 cm/d. The smallest error is achieved for point C16 and is around 4.7 cm/d which is moving at around 6 cm/d. Unfortunately, this point was unreachable for the second and third measurements and is therefore not measured with the GNSS receiver.

The second 12-day period shows bigger errors for all five points. The biggest error is around 32 cm/d and the average is 23.7 cm/d. This is mainly caused by the very low velocity of the remaining points. All points are nearly stationary moving at a rate of 1 cm/d except point C14 which moves at around 4 cm/d but still keeps the high error due to higher velocity derived from the SAR there. Low speed points are difficult to detect using offset-tracking on GRD images at this resolution. This is also confirmed by the results for the 24-day period where the errors are significantly smaller, averaging around 10 cm/d. All points show a homogeneous error with very little difference. This is the longest available period for which in-situ measurements were possible so increasing the time period between acquisitions was impossible.

A precise comparison between product types was also performed (Table 2). For this purpose, the difference between errors for all product types was calculated. All negative values mean the error is smaller, and vice versa – positive values mean bigger error.

Results for the first period show that the errors for the calibrated images compared to non-calibrated images are worse for point C14 at around 0.4 mm/d, for the rest of the points all differences are insignificant. The same is true for calibrated images compared to images with no TNR. Comparison between non-calibrated and no TNR images show no significant differences.

The second time period shows no difference between calibrated and non-calibrated images. Comparing calibrated and no TNR images shows 0.5 mm/d difference for points C12 and 0.2 mm/d for point C1 – the rest of the points have

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Comparison of velocities in m/d for 2025 using all three processing chains and methods

Period	Name	Calibrated [m/d]	Non- calibrated [m/d]	NOTNR [m/d]	V(XYH) [m/d]	V(XYH)- Calibrated [m/d]	V(XYH)- Non- calibrated [m/d]	V(XYH)- NOTNR [m/d]
12 days 05.01.25–17.01.25	C01-1	0.22634	0.22634	0.22634	0.01382	0.21253	0.21253	0.21253
	C02-1	0.20722	0.20722	0.20722	0.01609	0.19341	0.19341	0.19341
	C03-1	0.18436	0.18432	0.18432	0.04530	0.17054	0.17051	0.17051
	C04-1	0.16310	0.16308	0.16308	0.08269	0.14929	0.14927	0.14927
	C12-1	0.29499	0.29499	0.29499	0.02202	0.28117	0.28117	0.28117
	C13-1	0.19044	0.19044	0.19044	0.02190	0.17663	0.17663	0.17663
	C14-1	0.18116	0.18072	0.18072	0.03959	0.16735	0.16691	0.16691
	C15-1	0.11696	0.11691	0.11691	0.05830	0.10315	0.10310	0.10310
12 days 17.01.25– 29.01.25	C16-1	0.06133	0.06135	0.06135	0.05906	0.04752	0.04753	0.04753
	C01-1	0.18190	0.18190	0.18209	0.02176	0.16809	0.16809	0.16827
	C02-1	0.22069	0.22069	0.22071	0.01553	0.20688	0.20688	0.20690
	C12-1	0.22955	0.22955	0.23007	0.00619	0.21574	0.21574	0.21626
	C13-1	0.28580	0.28580	0.28580	0.01246	0.27199	0.27199	0.27198
24 days 05.01.25– 29.01.25	C14-1	0.33547	0.33547	0.33546	0.04000	0.32165	0.32165	0.32165
	C01-1	0.12405	0.12406	0.12405	0.03318	0.11024	0.11024	0.11024
	C02-1	0.11106	0.11108	0.11106	0.02993	0.09724	0.09726	0.09724
	C12-1	0.13856	0.13858	0.13856	0.01721	0.12475	0.12477	0.12475
	C13-1	0.10537	0.10538	0.10537	0.02158	0.09155	0.09156	0.09155
24 days 05.01.25– 29.01.25	C14-1	0.10693	0.10694	0.10693	0.05722	0.09311	0.09313	0.09311
Period	Name	Cal.–non- calibrated [mm/d]		Cal.–no TNR [mm/d]		Non-calibrated–no TNR [mm/d]		
12 days 05.01.25–17.01.25	C01-1	–0.00001		0.00001		0.00003		
	C02-1	0.00022		0.00022		0.00000		
	C03-1	0.03631		0.03631		0.00000		
	C04-1	0.02302		0.02301		–0.00001		
	C12-1	–0.00012		0.00027		0.00039		
	C13-1	0.00124		0.00122		–0.00001		
	C14-1	0.44098		0.44091		–0.00007		
	C15-1	0.04931		0.04926		–0.00004		
12 days 17.01.25– 29.01.25	C16-1	–0.01459		–0.01453		0.00006		
	C01-1	–0.00043		–0.18175		–0.18132		
	C02-1	–0.00006		–0.01957		–0.01951		
	C12-1	–0.00140		–0.52017		–0.51877		
	C13-1	–0.00012		0.00530		0.00542		
24 days 05.01.25– 29.01.25	C14-1	0.00000		0.00516		0.00516		
	C01-1	–0.00381		–0.00010		0.00371		
	C02-1	–0.02131		–0.00001		0.02130		
	C12-1	–0.02094		0.00000		0.02094		
	C13-1	–0.00850		0.00002		0.00852		
24 days 05.01.25– 29.01.25	C14-1	–0.01740		0.00004		0.01743		

no significant differences. The same holds for non-calibrated and no TNR images with the non-calibrated being more accurate with the same differences.

Finally, the longer period shows that calibrated and no TNR images have the same error which is smaller compared to non-calibrated images. The biggest difference is in points C2 and C12 with difference at 0.02 mm/d which is not significant.

All observed differences between in-situ and satellite-derived velocities fall within ranges reported in previous studies [2], although discrepancies increase under low-velocity conditions. The largest errors occur over slow-moving glacier areas and short temporal baselines (12 days), where displacements approach the detection limit of the offset-tracking method. In such cases, the homogeneous surface texture – particularly during the 2025 campaign – limits stable backscatter features, reducing cross-correlation performance and leading to velocity overestimation.

The 10 m spatial resolution further constrains the detection of small displacements, amplifying uncertainties in slow-moving regions. Improved results for the 24-day period confirm the importance of sufficient displacement magnitude for reliable estimates. Additional errors arise during co-registration, especially due to the low-resolution DEM (ACE30, ~ 1 km). This is most evident in the 2023 dataset, where poor representation of the ice–sea boundary likely caused misregistration and inclusion of water pixels, producing unrealistically high velocities.

Conclusion. Across both study periods and processing setups, the influence of radiometric calibration and TNR on glacier velocity estimates derived from Sentinel-1 GRD data is generally limited and context-dependent. Radiometric calibration shows negligible impact on the final velocity values, with most comparisons yielding near-identical results. Thermal noise removal exhibits a slightly stronger effect, with some cases showing increased errors when it is omitted. However, these differences are typically small and not consistent across all observations.

The dominant source of error in the derived velocities can be attributed to the characteristics of the study area and data. Slow-moving glacier surfaces, combined with homogeneous backscatter conditions and short temporal baselines, significantly reduce the reliability of the offset-tracking method. This is particularly evident in the large discrepancies observed for low-velocity points in the 2025 dataset. Extending the temporal baseline to 24 days improves the agreement with in-situ measurements, confirming the sensitivity of the method to displacement magnitude.

Additional uncertainties are introduced during the co-registration stage, where the use of a low-resolution DEM (ACE30, ~ 1 km) may lead to geometric misalignments, especially in coastal zones where ice and water boundaries are not well defined. These factors can produce erroneous displacement vectors and contribute to the observed overestimation of velocities.

Overall, the obtained errors fall within the range reported in previous studies for this method. The results indicate that while radiometric calibration and thermal noise removal can be included as good practice, their impact on accuracy is secondary compared to scene conditions, temporal baseline, and co-registration quality. Consequently, acceptable velocity estimates can still be obtained without these preprocessing steps, provided that the inherent limitations of the method and data are properly considered.

REFERENCES

- [1] KÄÄB A., S. H. WINSVOLD, B. ALTENA et al. (2016) Glacier remote sensing using Sentinel-2. Part I: radiometric and geometric performance, and application to ice velocity, *Remote Sens.*, **8**(7), 598, <https://doi.org/10.3390/rs8070598>.
- [2] AMITRANO D., R. GUIDA, G. DI MARTINO, A. IODICE (2019) Glacier monitoring using frequency domain offset tracking applied to Sentinel-1 images: a product performance comparison, *Remote Sens.*, **11**(11), 1322, <https://doi.org/10.3390/rs11111322>.
- [3] ATANASOVA-ZLATAREVA M., H. NIKOLOV (2022) Creation of glaciers velocity maps in Livingston Island using Sentinel-1 data. In: *Proc. 8th Int. Conf. on Cartography and GIS*, Vol. 2, Nessebar, Bulgaria, 20–25 June 2022 (eds T. Bandrova, M. Konecny, S. Marinova), ISSN 1314-0604.
- [4] ATANASOVA M. (2023) Ice velocity monitoring of Livingston Island glaciers by time series SAR data. In: *Proc. XI Natl. Geophys. Conf.*, 9 June 2023, <https://doi.org/10.48368/bgs-2023.1.N14>.
- [5] Serco Italia SPA (2018) Glacier Velocity with Sentinel-1 – Peterman Glacier, Greenland (version 1.2), RUS Lectures. Available at: <https://rus-copernicus.eu/portal/the-rus-library/learn-by-yourself/>.
- [6] HAJDUCH G., N. MIRANDA, R. PIANTANIDA et al. (2017) Thermal denoising of products generated by the S-1 IPF, ESA Tech. Note (Sentinel-1 Mission Documentation).
- [7] Earth and Planetary Remote Sensing Laboratory (n.d.) ACE GDEM. Available at: https://www.cse.dmu.ac.uk/geomatics/products_ace_overview.html.
- [8] MIRANDA N., P. J. MEADOWS (2015) Radiometric calibration of S-1 Level-1 products generated by the S-1 IPF, ESA Tech. Note (Sentinel-1 Mission Documentation).

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