



PROGRAMME OF
THE EUROPEAN UNION



EGMS Validation Report

2018-2022 update

SERVICES SUPPORTING THE EUROPEAN ENVIRONMENT AGENCY'S (EEA) IMPLEMENTATION OF THE COPERNICUS EUROPEAN GROUND MOTION SERVICE – PRODUCT VALIDATION.



Date: 26/06/2024

Doc. Version: 2.0

Content ID: **SPECIFIC CONTRACT No 3506/R0-COPERNCA/EEA.59565**
Implementing Framework service contract No EEA/DIS/R0/21/009

**Document Control Information**

Document Title	EGMS Validation Report 2018-2022 update
Project Title	Services supporting the European Environment Agency's (EEA) implementation of the Copernicus European Ground Motion Service – Product validation.
Document Authors	Joan Sala Calero, Malte Vöge, Joana Esteves Martins, Daniel Raucoules, Marcello de Michelle, Amalia Vradi, Filippo Vecchiotti
Project Owner	Lorenzo Solari
Project Manager	Joan Sala Calero
Document Code	D7.2_Validation_Report.docx
Document Version	2.0
Distribution	Public
Date	26/06/2024

Document Approver(s) and Reviewer(s):

Name	Role	Action	Date
Lorenzo Solari	Project owner	Approved	26/06/2024

Document history

Revision	Date	Created by	Short description of changes
Draft	26/04/2024	Joan Sala Calero	Initial draft version
Final	26/06/2024	Joan Sala Calero	Final report version



Contents

EXECUTIVE SUMMARY	4
1 INTRODUCTION	5
1.1 The European Ground Motion Service.....	5
1.2 Validation concept	5
2 VALIDATION HIGHLIGHTS.....	7
2.1 Service validation objectives	7
2.2 Service compliance checks	9
2.3 Thematic areas (applications)	11
Landslides	11
Mining and post-mining	12
Urban.....	13
Groundwater exploitation.....	14
Volcanism	15
3 VALIDATION RESULTS	16
3.1 Applicability and Usability.....	16
3.1.1 Methodology overview	18
3.1.2 Index of Agreement (IoA) overview	19
3.1.3 Validation results per thematic area.....	22
Landslides	22
Mining and post-mining	31
Urban.....	46
Groundwater exploitation.....	58
Volcanism	60
3.2 Consistency/Accuracy	62
3.2.1 Methodology overview	63
3.2.2 Index of Agreement overview	65
3.2.3 Validation results per thematic area.....	68
Landslides	68
Mining and post-mining	77
Urban.....	84
Groundwater exploitation.....	101
Volcanism	107
REFERENCES	111
GLOSSARY	113
ANNEX: InSAR concepts summary	114



EXECUTIVE SUMMARY

- The validation exercise targeting the **2018-2022** EGMS update has been performed in 37 areas distributed across Europe, focusing on the comparison or agreement between site-specific datasets and EGMS products. A previous validation exercise is available [here](#) for the **2015-2021** update. As expected, the shorter time series analysis period yields higher Measurement Point (MP) density across all land cover classes.
- The EGMS Basic/L2a and Calibrated/L2b products (Line-of-Sight) are suitable to delimitate ground motion polygons representing **landslide** phenomena. Slope orientation and satellite acquisition geometry have to be considered. These moving areas can be used to complement the manually maintained national and regional inventories (i.e. Spain, France).
- EGMS is not only able to detect landslides but also **accurately follow** their deformation trend. This is seen in the comparison with Automatic Total Stations in Tyrol, Austria, despite that local **north-south** horizontal movements are greatly underestimated due to the geometry of the satellite acquisitions. This is an unsolvable problem, linked to the geometry of acquisition of the satellite.
- The EGMS portfolio can be used to detect large scale active **mining** and **post-mining** induced ground motion. One of the best examples that proves this is the comparison with piezometric in situ data in the Turow mine area, located in Poland at the border with Czech Republic and Germany. EGMS matches in situ-derived **linear** deformation rates; however, the EGMS struggles to follow deformations when they become **non-linear**. This is a known limiting factor of the technique applied (refer to [EGMS Product user manual](#) for the full technical description).
- EGMS products have been tested against in situ measurements in one of the most iconic **groundwater** over exploitation areas in Europe: Guadalentín basin (Lorca), in Spain. Both validation against GNSS and piezometric data provided high quality results, also highlighting a strong correlation between subsidence rates and the increase of the soft-soil layer's thickness.
- EGMS products have been tested in complex **active volcanic environments** such Mount Etna in Italy and La Palma in Spain. Despite the dynamism of these areas, EGMS has proven capable of reliably mapping the displacements at both sites.
- EGMS offers very high MP density in **urban areas**, fully complying with its technical specifications. Moreover, it effectively captures significant man-made construction settlements, as demonstrated by its performance at the test site near Oslo central station in Norway.



1 INTRODUCTION

1.1 The European Ground Motion Service

The Earth's surface is in constant motion, whether driven by natural phenomena such as tectonic activity or volcanism or influenced by human activities such as groundwater extraction or mining. This dynamic nature can have significant impacts on both infrastructure and natural ecosystems. The European Ground Motion Service (EGMS) was created in response to clear user needs raised from different perspectives of the ground motion community. Representing the forefront of space-based remote sensing technology, the EGMS uses Synthetic Aperture Radar Interferometry (InSAR) data derived from [Sentinel-1](#) radar images to detect and precisely measure ground movements across Europe. The EGMS provides three levels of products updated annually:

- **Basic/L2a:** Line-of-sight (LOS) velocity maps in ascending and descending orbits with annotated geolocalisation and quality measures per Measurement Point (MP). Basic products are referred to a local reference point.
- **Calibrated/L2b:** LOS velocity maps in ascending and descending orbits referenced to a model derived from global navigation satellite systems time series data. Calibrated products are absolute, being no longer relative to a local reference point.
- **Ortho/L3:** Components of motion (east-west and vertical) anchored to the reference geodetic model. Ortho products are based on the Calibrated/L2b product resampled to a 100m grid.

More information about the product levels is available [here](#).

1.2 Validation concept

According to Congalton and Russell (2001), validation is an integral component of mapping projects incorporating Earth Observation data. In this sense, the validation exercise synthetized in this report is understood as a measure of agreement between reference (ground-based and Earth Observation) data and the EGMS. This report concerns the EGMS second update, with reference period **2018-2022**. Future versions of the report will release validation outcomes after each annual product update.

The validation of the EGMS has the following goals and it is built upon the following concepts:

- It verifies the **usability** of the data for different applications according to *initial user requirements* and with respect to the *fields of application* foreseen by the [EGMS Product Specifications](#) and the [EGMS End User Requirements](#) documents.
- It determines if the **quality** of the products is consistent with the technical specifications for different areas and applications, and if the quality level is sufficient for supporting such applications. In parallel, it is used to confirm the conclusions of the [EGMS Quality Assurance and Control Report](#).



- It addresses the **completeness** and **consistency** of the data products together with their **accuracy**.
- The validation exercise has been designed to be **transparent** and **reproducible**, therefore the code and datasets used (depending on license agreements) will be published in the form of editable Jupyter **notebooks**. The expected time of publication is Q3 2024.
- The validation of EGMS products is based on the comparison of data of different nature. Therefore, a complete **agreement** is unlikely, and any differences observed may not be related to a quality issue.
- It is performed by the validation consortium led by Sixense and formed by NGI, TNO, BRGM, GeoSphere, and Terrasigna, with the following data providers: CNR-IREA, CSIC-IGME, CNIG, IGN, Geopartner, DTU, CGS, and LNEG.

The validation exercise is conducted across 37 areas distributed throughout Europe. The datasets used in this validation exercise are detailed in [D3-Validation Data Collection](#) along with the environmental and geological characteristics of each site as reported in [D5-Validation Areas](#).

Seven different validation activities were designed to establish the agreement between various local and regional data sources and the EGMS portfolio. The chosen high-level procedures and validation criteria are documented in [D6-Validation Methodologies](#). To ensure inter comparability and reproducibility, normalized IoAs (Index of Agreement) will be referenced throughout the validation documentation whenever quantitative comparisons can be performed (IoAs take values between 0 and 1, with 0= complete disagreement, 1= complete agreement). Activities assessing the usability of the EGMS product may involve expert based thresholds and qualitative assessment based on the available ancillary data.

This report is structured into two main sections, each targeting different types of readers. Section 2, “*Validation Highlights*”, is intended for readers seeking general and concise conclusions from the validation exercise. For readers new to EGMS and InSAR, appendices at the end of the document provide a list of abbreviations and describe fundamental concepts related to radar (interferometric) ground motion products. Also, the [Algorithm Theoretical Basis Document](#) complements and integrates this section.

Section 3, “*Validation results*”, is designed for readers familiar with EGMS and InSAR products, providing expert conclusions for each of the sites selected for the different thematic areas of application. Within this section, the analysis of results is divided into two categories: applicability/usability and accuracy/precision.



2 VALIDATION HIGHLIGHTS

In this section, the insights derived from Section 3 "Validation results" are summarized and simplified with a focus on applicability. The goal is to capture the significance of EGMS for potential applications within the defined thematic areas. This summary is targeted to users who may be relatively new to EGMS and InSAR.

2.1 Service validation objectives

Validation is the confirmation, through the provision of evidence, that the requirements for a specific intended use or application have been fulfilled. A set of validation activities were conducted to ensure and provide confidence that EGMS products can achieve its intended use, goals, and objectives, meeting stakeholder requirements.

Figure 1 on the next page summarizes the validation components and the processes involved:

- **Methodology:** Different procedures were implemented taking as inputs EGMS product levels and independent data available for selected sites. These methods enable the comparison of site data with EGMS subsets. Detailed descriptions can be consulted on [D6-Validation Methodologies](#).
- **Data:** Site datasets are crucial for validating EGMS product levels. Datasets were collected with a relevant temporal overlap with the EGMS time series (targeting >85%), and their properties (license, format, coverage) were documented in [D3-Validation Data Collection](#) and [D5-Validation Areas](#).
- **Criteria checked:** Different criteria were used to compare validation site datasets with the EGMS portfolio. For example, some methods focus on analysing velocity and displacement rates, while others examine the XYZ positioning of the EGMS MPs or their density. The method descriptions can be found in [D6-Validation Methodologies](#).
- **Index of Agreement (IoA):** The concept is documented in Section 2 of [D6-Validation Methodologies](#) and referenced throughout the EGMS validation documentation. A set of normalized IoAs is used to compare EGMS products with independent site datasets.
- **Thematic areas:** The main application areas or use cases of the EGMS were identified to evaluate the strengths and limitations of the products in addressing specific issues related to natural or anthropogenic ground deformation phenomena.

The **reproducibility** of the validation workflows is ensured by exploiting the Jupyter Notebook environment and scripts, which translate methodologies into code using validation site data as inputs. The Notebooks will be published in Q3 2024. The outputs are normalized **IoAs**, which, combined with expert knowledge and literature, provide a better understanding of the applicability of the EGMS ground motion portfolio to certain **Thematic Areas**.

Compliance with the service specifications, as detailed in section 2.2, has also been considered in the validation processes.

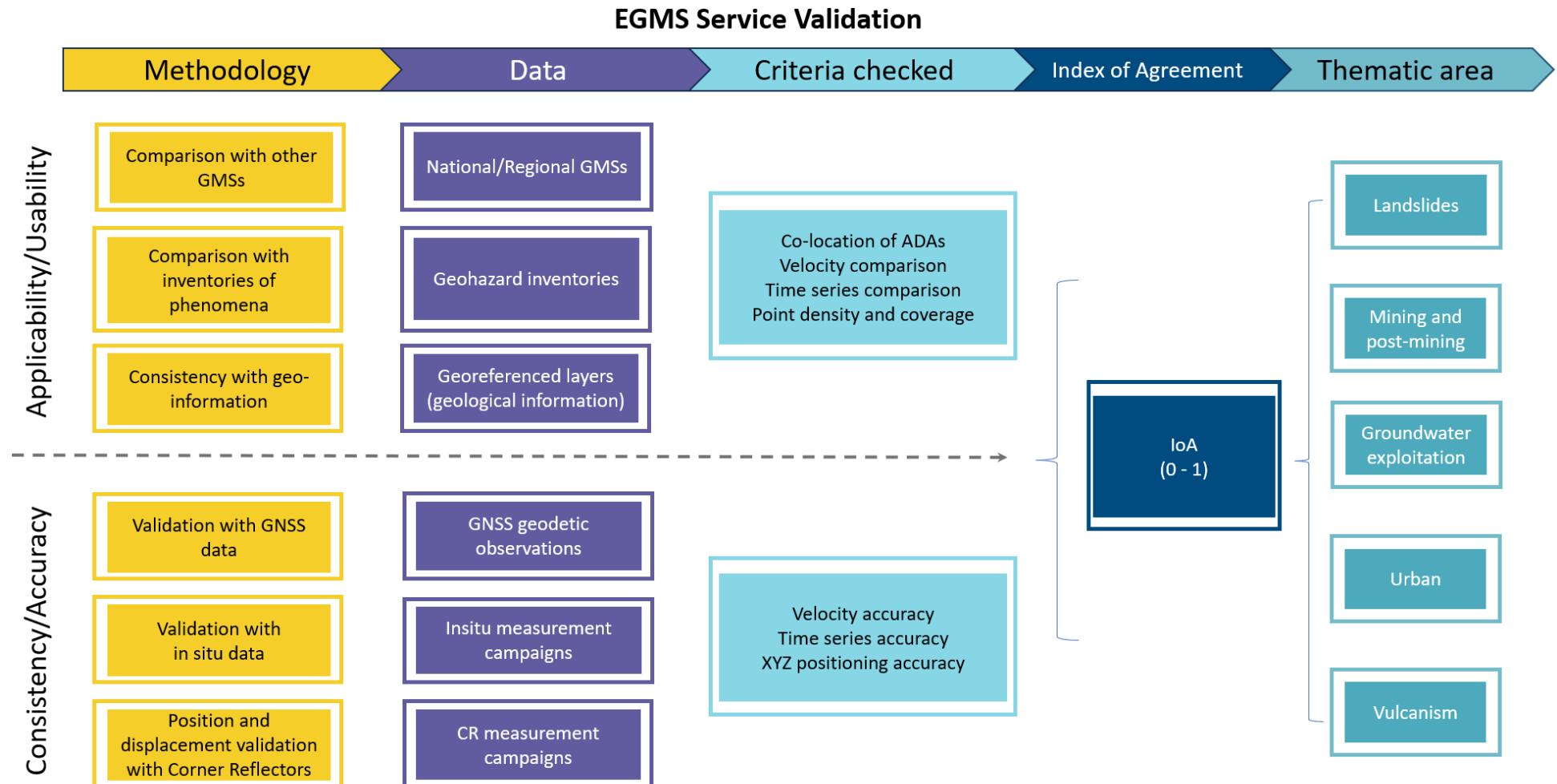


Figure 1: Graphical abstract for EGMS validation concept. CR, corner reflector. ADA, active deformation area. GNSS, global navigation satellite system. GMS, ground motion service. IoA, Index of Agreement.

2.2 Service compliance checks

An important aspect of the validation exercise involves assessing the compliance of EGMS product levels with their technical specifications based on user requirements. When assessing point-based datasets with associated coordinates, one of the most straightforward aspects to verify is the MP density.

The land cover data consists of quality-controlled polygons from the Urban Atlas, spanning over 12 urban areas and their surroundings at different latitudes. Figure 2 shows eight major urban areas and four mountainous sites, strategically included to enhance statistical representation. The compiled and averaged statistics span an area comparable to the size of Switzerland, making it a substantial and representative subset of the EGMS.

Figure 3 illustrates how the EGMS Basic/L2a and Calibrated/L2b products meet the established minimum requirements outlined in the [EGMS Product Specifications](#) document (e.g., > 5,000 MP/km² for the continuous urban fabric land cover class). Testing the density of the Ortho product was deemed unnecessary as it represents a resampling to a uniform 100x100 grid.

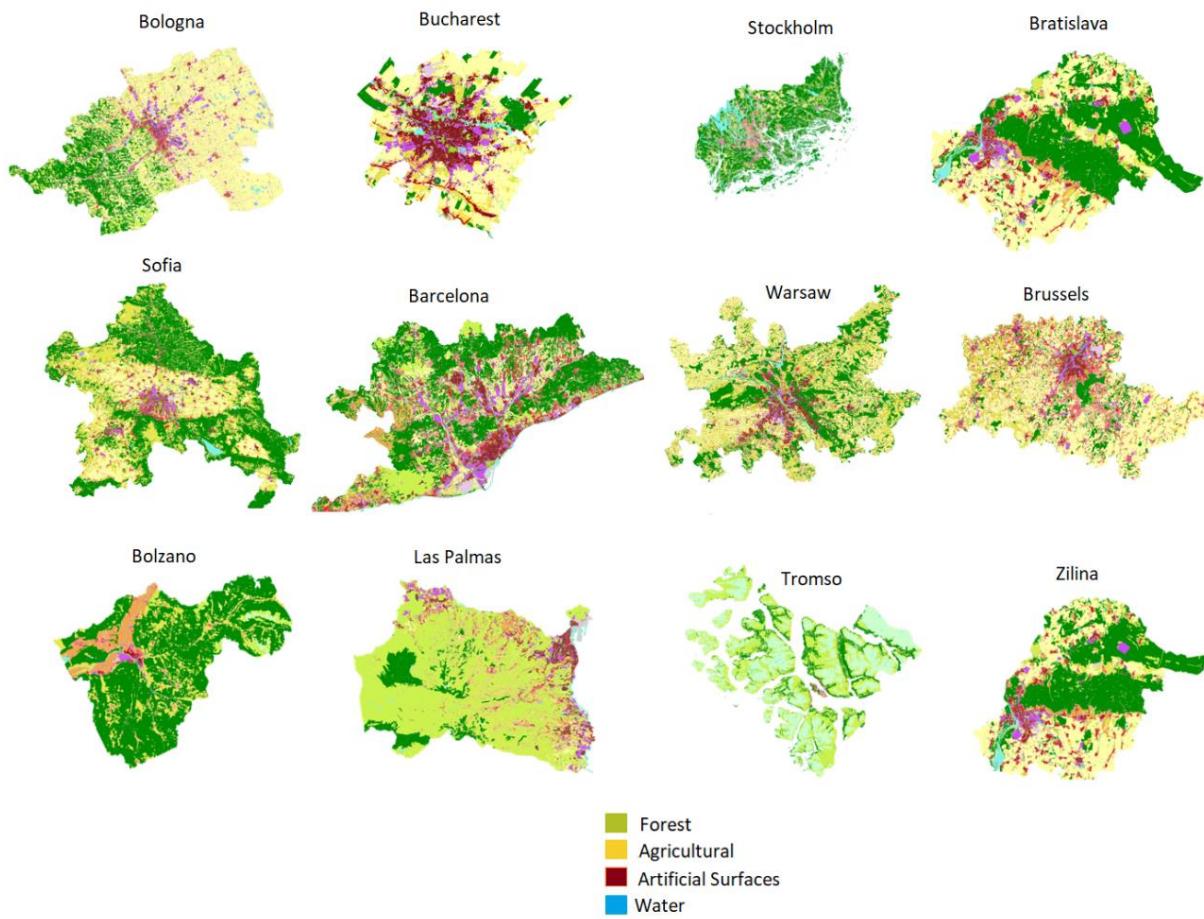


Figure 2: Land cover and land use classes for Urban Atlas 2018 at the 12 sites selected to verify MP density.

The outcome of this statistical analysis allows users to understand how MP density adapts to surface properties. In this context, Figure 3 clearly illustrates how artificial surfaces, such as the urban built-up environment, exhibit the highest densities, whereas surfaces characterized by consistent changes, such as agricultural areas and forests, yield lower MP densities.

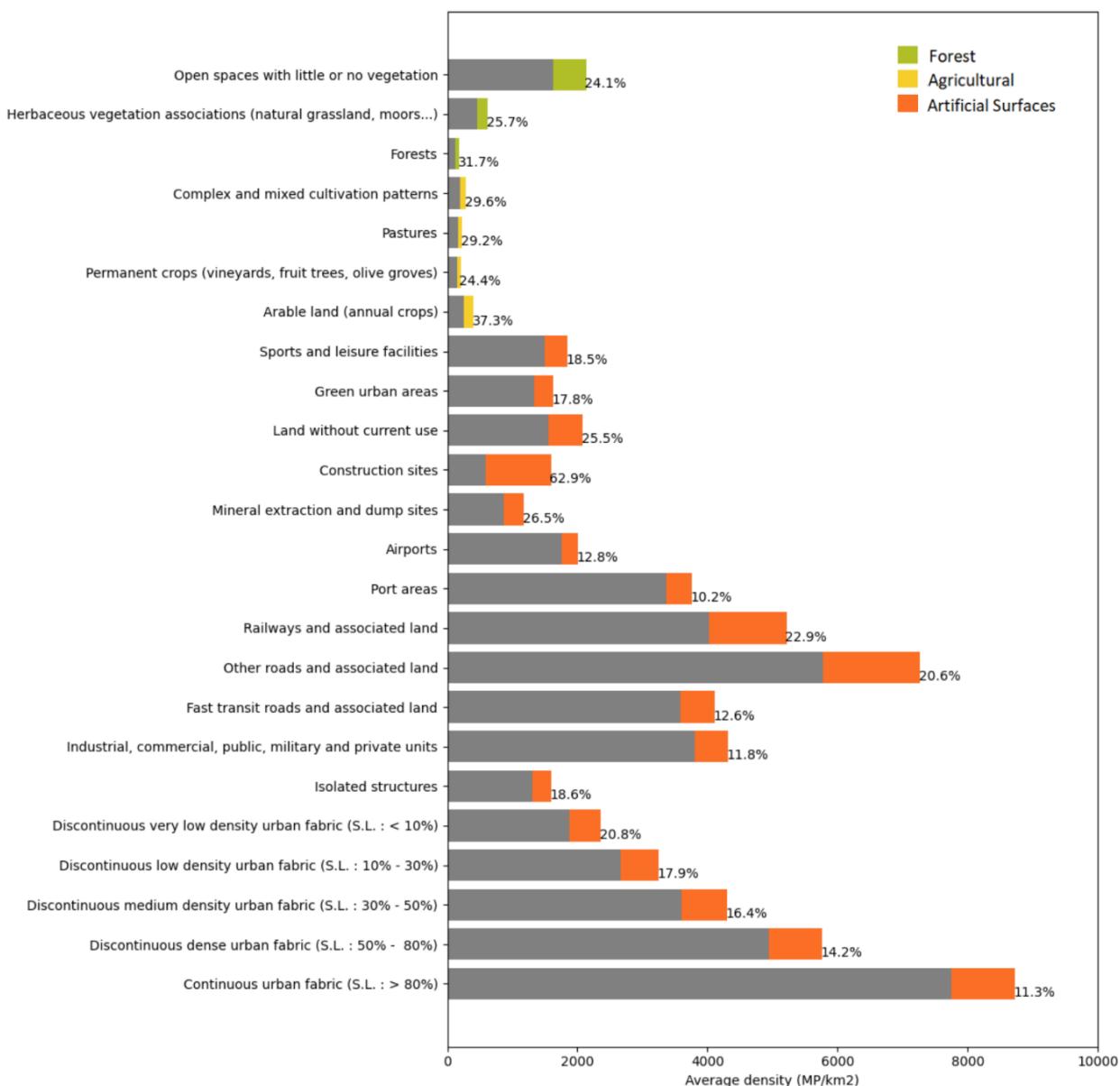


Figure 3: EGMS measurement point (MP) density for Basic/L2a and Calibrated/L2b products across 12 Urban Atlas sites. Previous release 2015-2021 density values (grey) and increase percentages (indicated by numbers and orange bars). The land cover/land use classes are grouped according to the first level of the Corine Land Cover nomenclature.

On the same figure, the EGMS 2018-2022 update densities per class are compared to the [2015-2021](#) release. A substantial increase in MP density (22.6% in average) is observed. The shorter study period reduces temporal decorrelation (fewer surface changes). This effect is particularly evident in land cover classes where changes occur more frequently.

2.3 Thematic areas (applications)

This section provides a concise summary of the expert validation insights reported in Section 3, focusing on each thematic area of application covered by the EGMS portfolio.

Landslides

Landslides encompass a wide range of phenomena involving downhill ground movement. EGMS products can measure surface deformation at the millimetre level over extended periods, making them well-suited for detecting and monitoring landslides characterized by cyclical and widespread movements. A key challenge in dealing with slope movements lies in the acquisition geometry (see Annex for details). EGMS L2 LOS products in combination with clustering algorithms that group MPs into Active Deformation Areas (ADAs) (Appendix-1 of [D6.1-Validation Methodologies](#)) provide valuable inputs for enhancing existing field-based landslide inventories. Ortho/L3 product is less suitable for landslide analysis due to its coarser resolution and dependency on the availability of both orbits.

Specific areas from the Spanish and French national landslide inventories were selected to assess the overlap of the EGMS products and the potential of enriching these field-based inventories using EGMS information. Figure 4 illustrates this approach focusing on the Alpes Maritimes region in France. A key element in landslide analyses involves the understanding of the relationship between slope orientation and the magnitude of displacement recorded by the EGMS. Section 3.1.3 demonstrates how EGMS can potentially be used to complement field observations and enrich national landslide inventories.

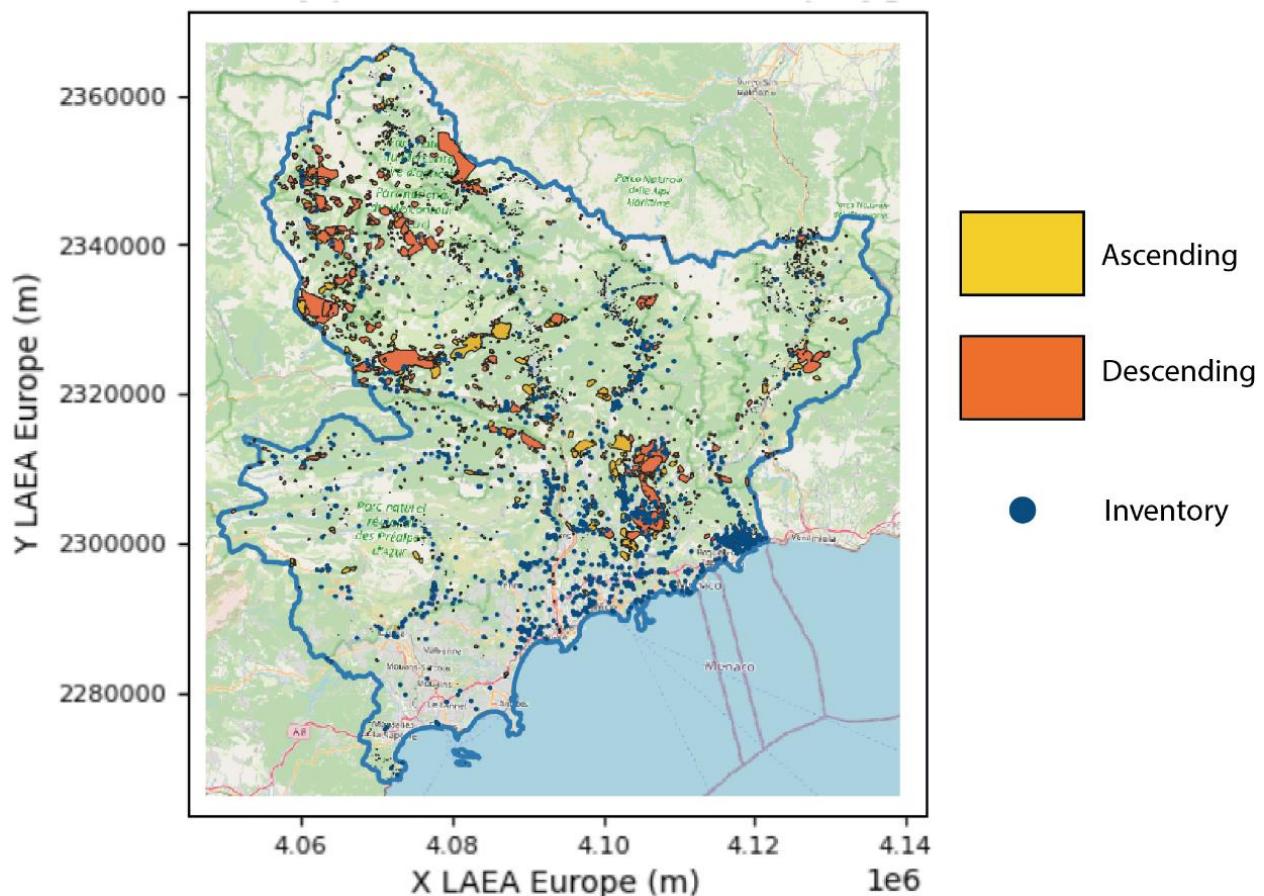


Figure 4: Alpes Maritimes landslides inventory and EGMS derived Active Deformation Areas for ascending and descending orbits.

EGMS Basic/L2a and Calibrated/L2b products have proven effective for studying slow-moving and medium/large landslides spanning several hectares. In terms of accuracy, the comparison with in situ Automatic Total Stations (ATS) in Navis, (Austrian Tyrol) yielded satisfactory results, except for those landslides moving in the North/South direction (see Annex for measurement limitations of InSAR). In conclusion, EGMS L2 products (Basic/L2a and Calibrated/L2b) prove to be suited for landslide detection, even in highly mountainous areas where the MP density is intrinsically linked to both the acquisition geometry and the orientation of topographic slopes.

Mining and post-mining

The EGMS has proven to be an effective tool for characterizing ground motion induced by mining and post-mining activity, including both open pit and underground mines. It is important to note that in some cases it faces limitations in monitoring active dumping/excavation areas and measuring fast motion or surface changes. These limitations are inherent to the INSAR technique rather than the EGMS itself (consult the [EGMS Algorithm Theoretical Basis \(ATBD\)](#) for a list of some known limitations of InSAR).

The investigation of post-mining effects in **Limburg** (Netherlands) revealed a clear overlap in the location of ADAs between the Dutch GMS and the EGMS, as depicted in Figure 5. Furthermore, the assessment of additional post-mining sites such as **La Unión** (Spain), specifically focusing on ‘tailings’ (i.e., the designated areas for mine waste storage) and their associated motion, revealed a clear correlation between the presence of tailings and ground motion. General agreement has been observed across all mining sites, proving that EGMS L2 products are a valuable tool for this application.

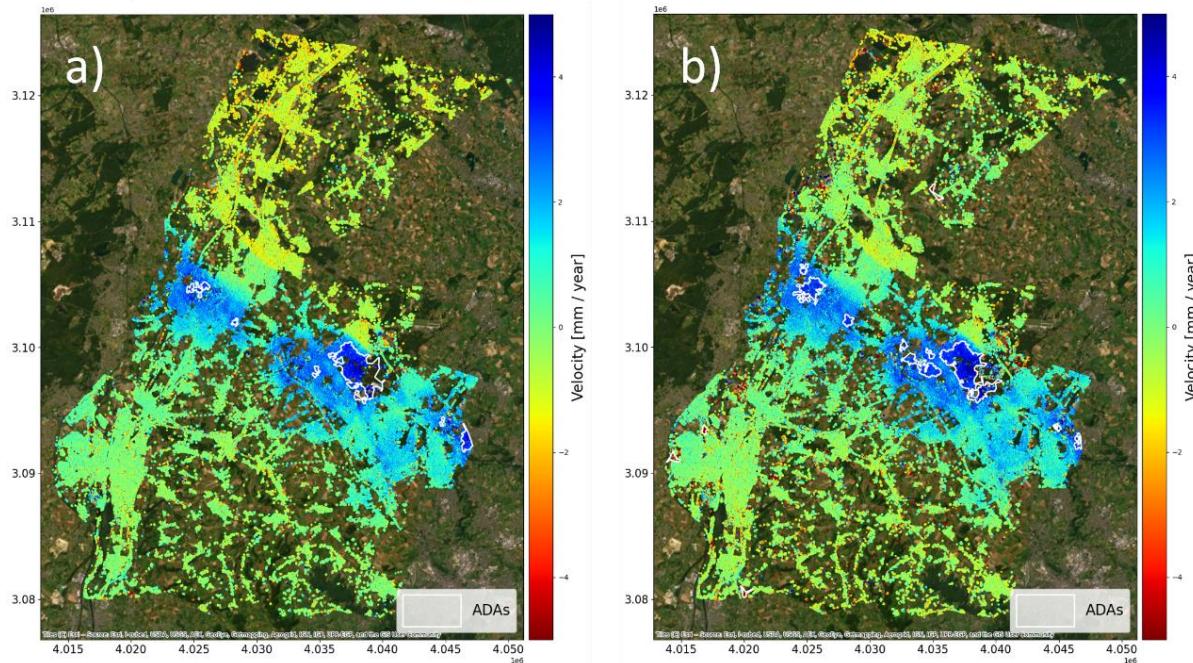


Figure 5: Comparison of velocities between the EGMS Calibrated/L2b product of orbit 88/ascending (a) and the Dutch GMS (b). Detected Active Deformation Areas are depicted by the white polygons. The minor difference between the two datasets is commented in chapter 3.1.3.

Freyming-Merlebach, located in the **Lorraine** region of France near the German border, faced growing concerns due to uplifts caused by natural water filling in formerly exploited underground coal mines (**post-mining**). To address this, over 850 annual levelling measurements

were used to validate the EGMS data. The goal was not to evaluate the different known accuracies of two measurement techniques (InSAR versus in situ) but to confirm their general agreement in characterizing the deformation phenomena. The result of this comparison demonstrated that the EGMS Basic/L2a and Calibrated/L2b products are well suited for monitoring this type of large-scale ground motion phenomena.

The mining operations in **Turow**, the second largest **active coal mine** in Poland, not only deplete water supplies but also trigger subsidence in the border areas of Germany and Czech Republic. An extensive network of water boreholes has been employed to evaluate the effectiveness of the EGMS for monitoring the impacts of Turow's mining activities in the vicinity of the open-pit lignite mine near the Czech-Polish border. All EGMS product levels scored IoAs above 0.8 when compared to piezometric data, indicating a strong correlation between EGMS results and ground information. These results confirm that the EGMS is capable of capturing such ground motion phenomena.

Urban

Oslo (Norway) was selected as a validation site for assessing urban subsidence and the impact of engineering works/construction. Over the past 10-15 years, the vicinity of the Oslo central station has undergone extensive building and infrastructure development. Construction activities have led to significant settlements in the area, primarily caused by the reduction of pore pressure, mainly resulting from leakage associated with drilling activities. A clear correlation between subsidence and anthropogenic activity was found across all EGMS products. In parallel, depth-to-bedrock and soil thickness maps exhibit a strong spatial correlation with EGMS deformation areas as depicted in Figure 6.

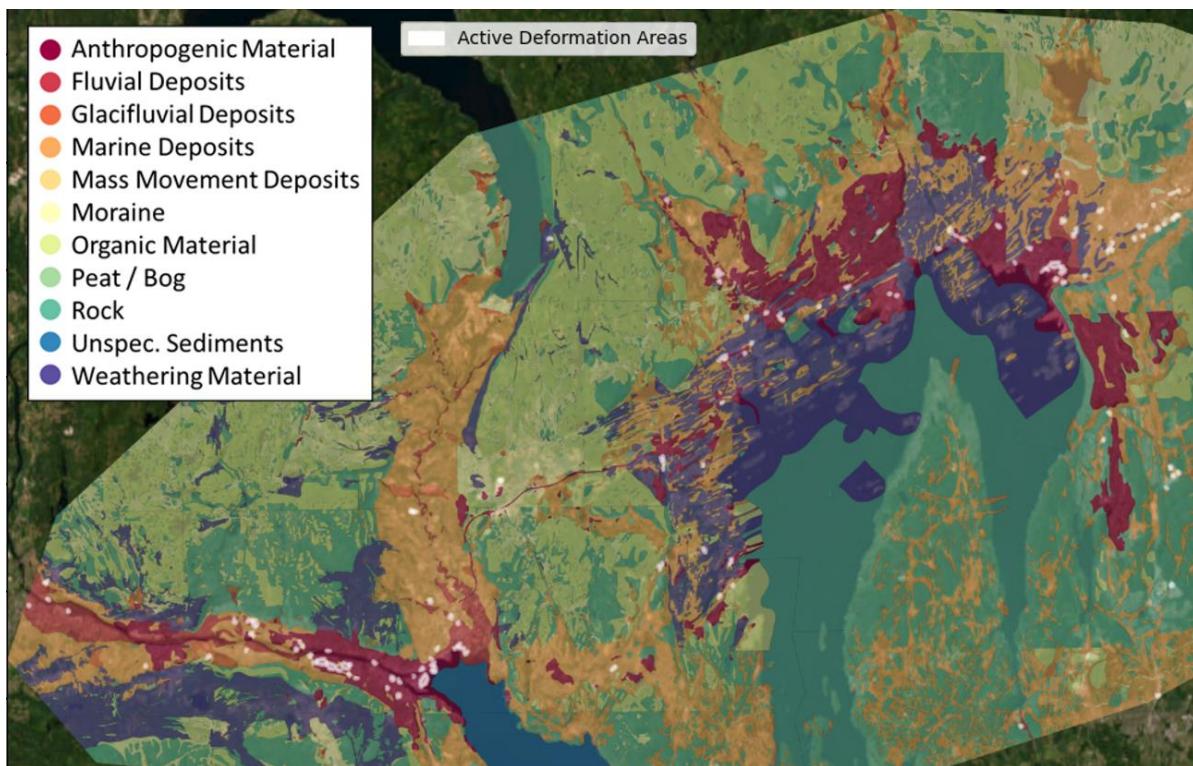


Figure 6: Comparison of detected Active Deformation Areas with the quaternary geology in the Oslo metropolitan area (Basemap: ESRI).

Thyborøn (Denmark) is located on a sandy barrier facing the North Sea and is vulnerable to flooding from the adjacent Linford due to its low elevation (1.0 – 2.5m). Coastal subsidence is believed to be a consequence of the overall sedimentary structure of the barriers and landfills, including the compaction of some highly compressible layers. In Thyborøn, the ADAs from a ground motion map produced by DTU and those obtained from EGMS show similarities in the harbour area. Corner Reflectors (CR) were used to determine the consistency of time series, location, and height measurements between CRs and EGMS MPs at and around the CRs' vicinity. The accuracy of satellite measurements met predefined EGMS specifications, allowing for the correct detection of the ground motion.

Groundwater exploitation

The **Guadalentín basin** in south-east Spain is one of the driest regions in Europe (Figure 7). The aquifer is located between the cities of Lorca and Puerto Lumbreras. The continuous extraction of groundwater, mainly for agricultural use, led to subsidence. EGMS products effectively capture this phenomenon, allowing for a comparison with GNSS and in situ measurements (including levelling campaigns and piezometers) to estimate accuracy/precision and assess soil characteristics. The non-linearity of the subsidence induced by the water table fluctuations poses a challenge for any PS analysis and the EGMS is no exception (see section 3.2). However, the spatial patterns of this deformation are successfully captured, as evidenced by comparisons with ancillary geodata such as a soft soil thickness map. Unfortunately, validation data is not available at the same weekly frequency as the EGMS, making direct comparisons for accuracy challenging. Despite that, a general sense of agreement between EGMS and in situ measures was found.

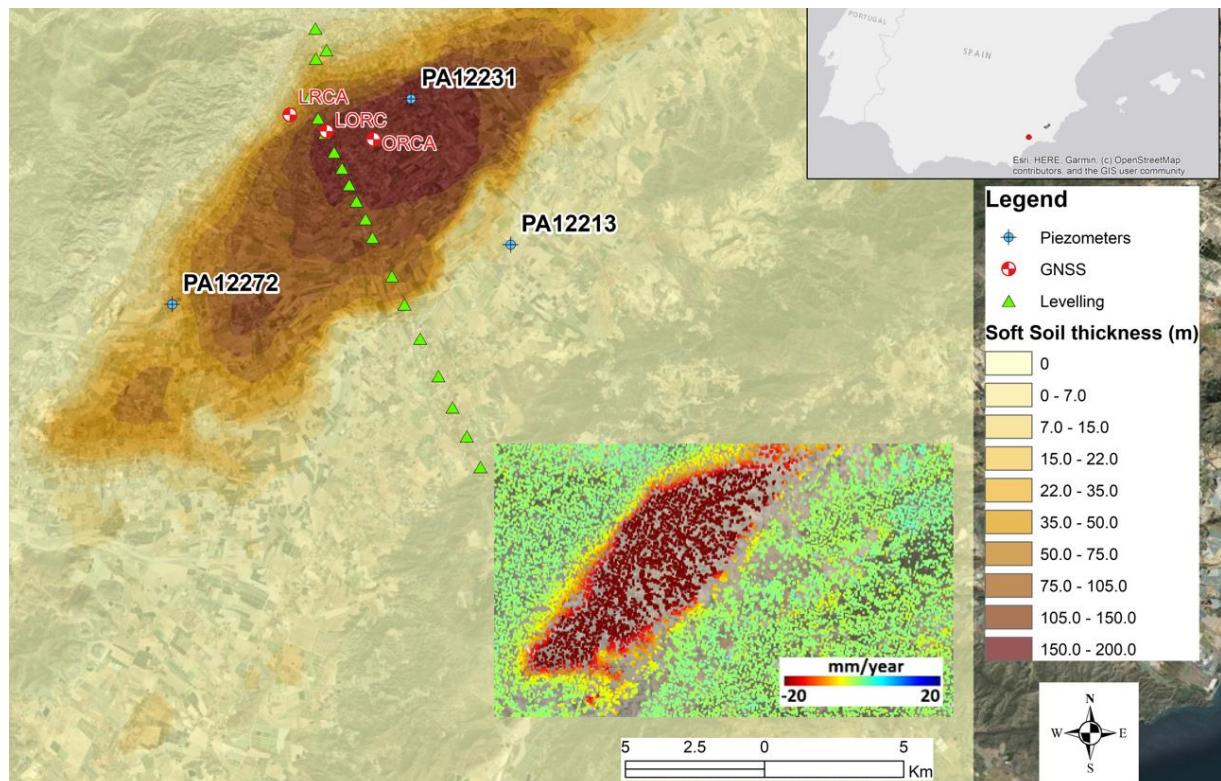


Figure 7: Ground water over exploitation area (soft soil layer) and induced subsidence in Lorca (Spain) as captured by the EGMS Ortho/L3 product. Locations of in situ measurements and GNSS stations inserted.

Volcanism

The validation site at **Mount Etna** was selected due to its active volcanism, making it the largest active volcano in Europe. An ad-hoc InSAR processing conducted by CNR-IREA provided all product levels for comparison with the EGMS products. The comparison revealed a general agreement between the two InSAR datasets as represented in Figure 8 (see Section 3 for details).

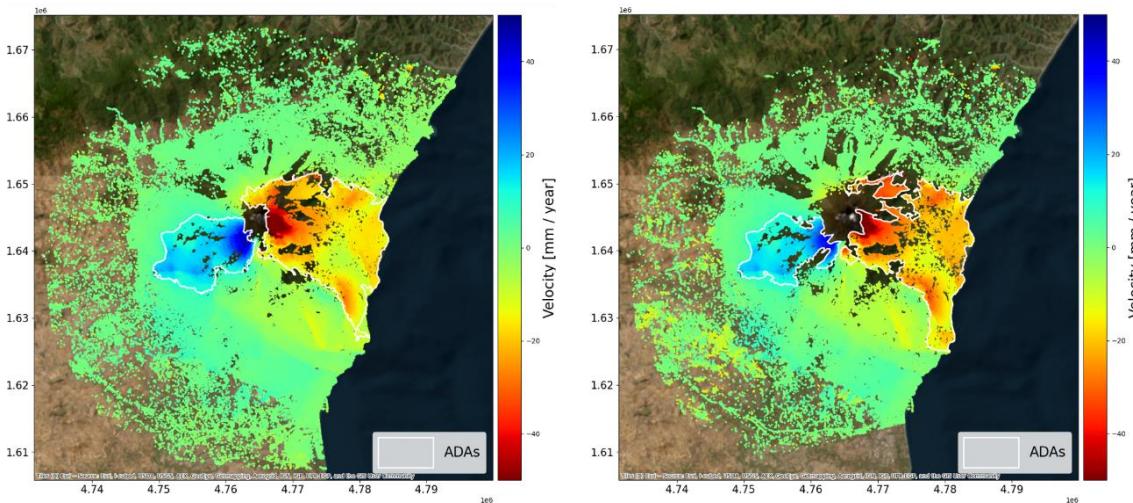


Figure 8: Intercomparison of the two main Active Deformation Areas obtained from EGMS Basic/L2a orbit 44 (left) and IREA InSAR processing (right).

For those new to EGMS and InSAR, it is important to note that LOS ascending and descending orbits produce different maps (Figure 9) due to the acquisition geometry, viewing Mount Etna from different points of view (refer to Annex for more details). In a few words, the volcanic edifice is recording a lateral spreading process with the east flank moving to the east and the western flank to the west. Moreover, a rather strong earthquake event (December 2018) can be observed in the time series in Figure 9 in addition to the volcanic activity.

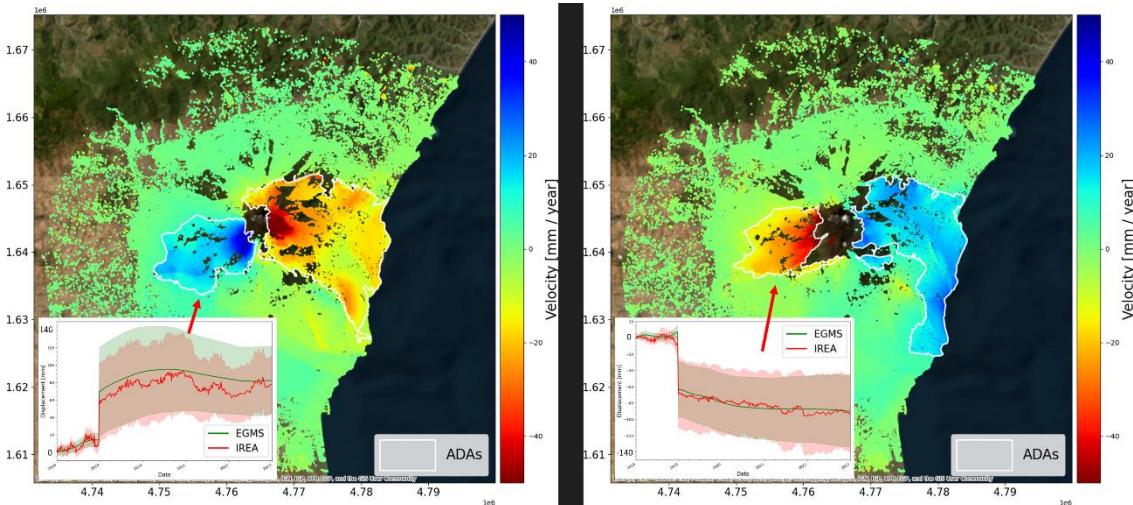


Figure 9: Intercomparison of EGMS velocity maps (Basic/L2a) for ascending orbit 44 (left) and descending orbit 124 (right) geometries. The time series represent the averaged time series for the Active Deformation Area detected on the western flank, showing both EGMS and IREA time series.

In conclusion, the comparison with the IREA products resulted in a strong correlation between both datasets. This high level of agreement is particularly noteworthy given the dynamic nature of the volcanic system and the highly non-linear time series. These results demonstrate that the EGMS is capable of reliably mapping displacements even under challenging conditions.



3 VALIDATION RESULTS

This section presents the validation results organized per thematic area, structured as a technical report tailored for readers already familiar with EGMS and InSAR processing results and seeking a comprehensive understanding of the usability, quality, consistency, and accuracy of the EGMS.

The results are categorized into two groups based on the nature of the site data, aiming to separate qualitative and quantitative analyses. The **IoA**, described in Section 3.1.2, have been considered to facilitate the intercomparison of results across different sites. The first section evaluates **applicability and usability** by thematic area, while the second assesses overall **consistency and accuracy** in comparison with other ground motion field measurement techniques.

3.1 Applicability and Usability

This section is designed to assess the applicability of the EGMS portfolio in characterizing specific phenomena within the defined thematic areas of the EGMS Service, adhering to its specifications. The EGMS portfolio for these sites is compared to other high-resolution and geo-localised data sources such as:

- Other operational and quality-controlled Ground Motion Services (GMS) or InSAR results, to study and compare EGMS's ability to capture known deformation trends and phenomena.
- High-resolution land cover layers, aimed at exploring the correlation between surface characteristics versus MP density as well as time series attributes quality.
- National inventories of geo-localised phenomena or geohazards, to aid in identifying the kind of phenomena most suitable for representation in the EGMS products.
- Geological, lithological, hydrogeological, geomorphological, and geotechnical maps to correlate observed deformation trends with soil characteristics.
- Aerial photography and high-resolution land cover layers, providing insights into MP density and sensitivity to changes.
- Digital elevation models and derived slope data, enhancing the interpretation of geometrical constraints in the 3D plane.
- Inventories of anthropic activities that can trigger surface motion including mining, quarrying, geothermal fluids extraction, oil and gas extraction, and water pumping. Matching these with observed EGMS deformation areas helps identifying the phenomena captured by the EGMS.

Table 1 and Figure 10 provide a summary of the validation sites, with descriptions available in the documents [D3-Validation Data Collection](#) and [D5-Validation Areas](#):

Table 1: Overview of validation sites (Applicability/Usability).

	Consistency with other GMS	Consistency with inventories of phenomena	Consistency with geo-information
Landslides	Aosta valley (IT) Tuscany (IT)	Rules / Arcos de la Frontera (ES) French Alps (FR)	<i>Not evaluated</i>
Mining and post-mining	Limburg (NL)	Lorraine region (FR)	Silesia (CZ) La Unión (ES)
Urban / Anthropogenic	Thyborøn (DK) Po delta (IT)	<i>Not evaluated</i>	Oslo (NO) Tagus valley (PT)
Groundwater exploitation	<i>Not evaluated</i>	<i>Not evaluated</i>	Lorca (ES)
Extra (Volcanism)	Mount Etna (IT)	<i>Not evaluated</i>	<i>Not evaluated</i>

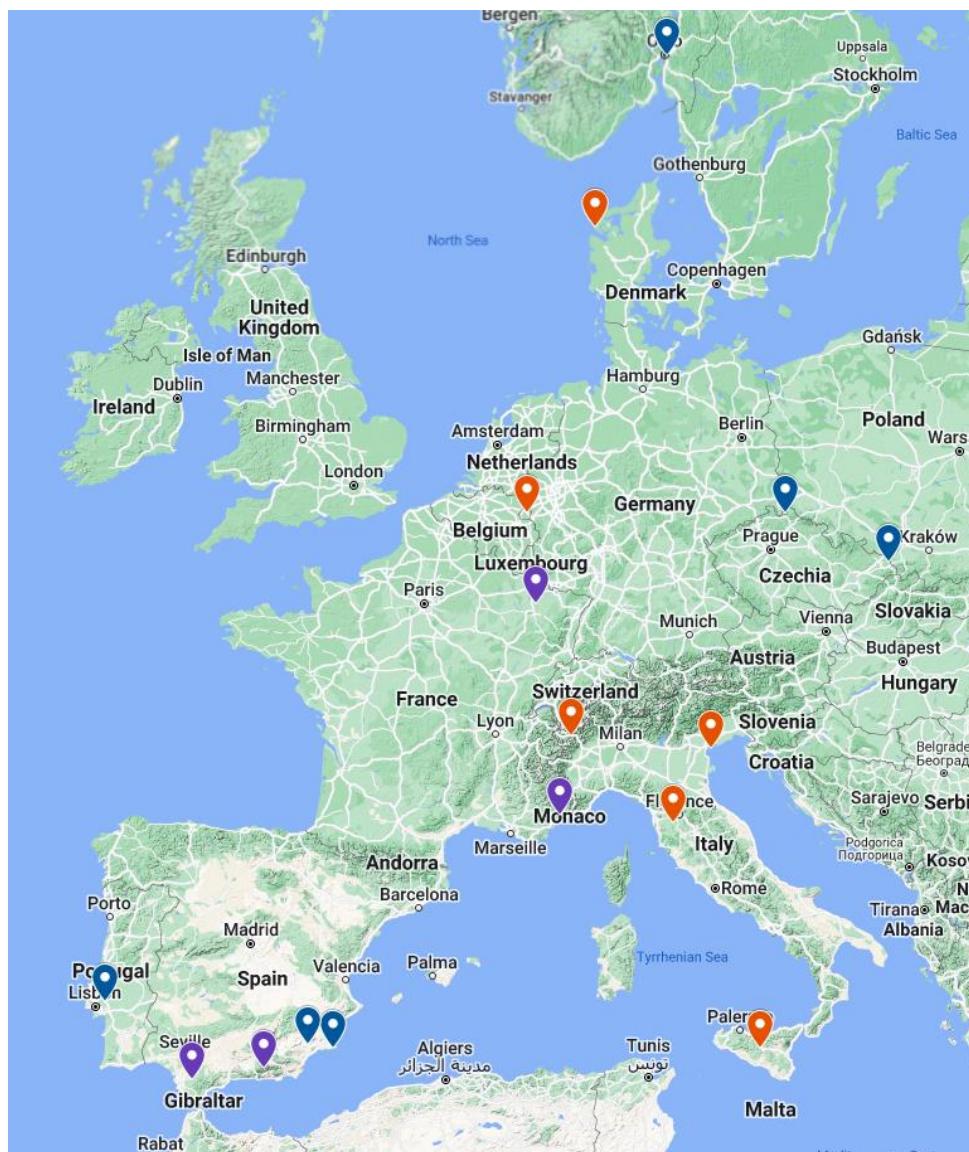


Figure 10: Objectives and thematic areas versus validation sites (Applicability/Usability). The colours refer to the validation activities reported in Table 10 (Basemap: Google).

3.1.1 Methodology overview

Three validation activities focused on applicability were conducted across various validation sites (Figure 10). Detailed methodologies for each activity can be found in document [D6-Validation Methodologies](#). The ADA approach has been used across the three validation methods. An ADA is a cluster of MPs exhibiting the same deformation pattern represented with a polygon (the concept and algorithms are explained in Appendix 1 of [D6-Validation Methodologies](#)).

- **Comparison with other GMS:** The EGMS portfolio is compared with quality-controlled and validated datasets from existing operational national/regional GMSs. The validation is conducted separately for each EGMS product level and acquisition geometry (ascending and descending). Due to varying availability of product levels in the respective public national/regional GMSs, the validation is limited to comparable datasets. Additionally, two independently quality-controlled and validated ad-hoc processing results (Mount Etna in Italy and Thyborøn in Denmark) are included in the analysis. Spatial resampling to 30x30m and automated detection of ADAs are performed to facilitate intercomparison of different GMSs.

It is important to understand that the other GMSs are prone to the same or similar sources for error, such as residual atmospheric phase, digital elevation model inaccuracies or phase unwrapping errors, just like the EGMS. Therefore, they cannot be regarded as “ground truth”. Therefore, the comparison focuses on usability rather than absolute accuracy.

Further, the comparison has some limiting factors:

- The two datasets are not re-referenced to a common reference point or GNSS model. This choice was made to avoid altering the datasets beyond the applied pre-processing described in [D6.1-Validation Methodologies](#). However, this needs to be considered when comparing datasets, especially for the uncalibrated Basic/L2a products.
- When calibrated data is compared, differences in the calibration methods and/or reference systems must be considered.
- Identification/detection of ADAs is an important aspect of this comparison. This detection, however, can be sensitive to differences in MP density, meaning some differences may arise from varying MP densities rather than measured velocity.
- The EGMS and the other GMSs use different processing strategies, which means that some differences are expected. While the EGMS is designed to map displacements over large areas, some GMSs focus on more localized phenomena such as landslides.
- **Comparison with inventories of phenomena:** The main goal of this validation activity is to compare the EGMS data with information provided by inventories such as points or polygons representing the geometry, expected velocity or qualitative characteristics of the phenomena, along with dates of geohazard events or recorded damage. This activity



aims to test EGMS's detection capabilities, particularly in geohazards management, by exploring the potential of EGMS data to complement or build inventories when they do not exist. The focus is on the capability to detect known phenomena and, when available, to assess the similarity between ADAs derived from both inventories and EGMS, which serves as a key validation indicator for mapping geohazards. The characteristics of the addressed phenomena, including size and velocity of movement, are considered to have an impact on the validation analysis. To identify landslide phenomena in EGMS products, a positive detection is determined if the EGMS velocities detected within the inventory polygons differ significantly from those in the surroundings (outside the inventory). A detection is deemed successful when the velocity difference between the "inside of the polygon" and "outside of the polygon." **exceeds 2 mm/year.**

- **Consistency checks with ancillary data:** This activity employs national inventories of geomorphological, geotechnical, and geological data, combined with expert judgement and automated procedures, to identify ADAs in the EGMS datasets based on radar interpretation. Ancillary data, such as information on landslides, active faults, or mining activity, supports the interpretation. While this approach does not directly translate to quantitative statistics or IoA values, it provides valuable insights into the alignment of EGMS products with geological and geotechnical considerations.

3.1.2 Index of Agreement (IoA) overview

For those cases where quantitative comparisons between EGMS products and in situ data can be performed, reproducible IoAs have been developed based on the summarized validation activities and methodologies mentioned above. Each IoA corresponds to a validation methodology applied to the different sites presented in Figure 10 (colour coded by methodology). Table 2 provides a summary of each IoA, specifying the EGMS product levels under evaluation:



Table 2: Index of Agreement (IoA) for Applicability/Usability

IoA	Methodology	Short description of how the index is calculated	EGMS product
Spatial overlap between moving areas (EGMS vs GMS)	Comparison with other GMSSs	ADA surface overlap: Overlap between ADA polygons obtained from two GMS sources. Formula: Maximum of: (Number ADAs with > 30% overlap) * 100 / Number ADAs OR (Total overlap area all ADAs * 100) / (Total area joined ADAs)	L2a/L2b/L3 (*)
Relative velocity difference (EGMS vs GMS)	Comparison with other GMSSs	Difference between measures: relative velocity difference calculated as follows: (abs(dVel) * 100) / maximum (absolute (Vel _{EGMS} + Vel _{validation})/2, 3.0)	L2a/L2b/L3 (*)
Velocity correlation coefficient (EGMS vs GMS)	Comparison with other GMSSs	Correlation: Spatial correlation of velocity values on a common grid using Pearson ¹ Correlation coefficient (linear correlation)	L2a/L2b/L3 (*)
Displacement correlation coefficient (EGMS vs GMS)	Comparison with other GMSSs	Correlation: Mean of Temporal correlation of time series using Pearson ¹ Correlation coefficient (linear correlation)	L2a/L2b/L3 (*)
Phenomena captured (yes/no)	Comparison with inventories of phenomena	Binary detection based on velocity threshold: This parameter is positive if the motion detected by EGMS inside the inventory polygons is significantly different (>2 mm/year) from all the EGMS MPs outside the inventoried phenomenon.	L2a/L2b
EGMS ADA and phenomena area intersection	Comparison with inventories of phenomena	Polygon intersection: Intersection between EGMS active deformation areas (ADA) polygons and inventory polygons representing phenomena/events.	L2a/L2b
EGMS ADA and phenomena location/point	Comparison with inventories of phenomena	Point within ADA: EGMS active deformation areas (ADA) polygons contain the inventories of phenomena represented with points.	L2a/L2b

1- Pearson correlation coefficient: <https://www.sciencedirect.com/topics/social-sciences/pearson-correlation-coefficient>



ADA detection vs land cover maps	Consistency with geo-information	Expert based assessment (qualitative): Correlation between anthropogenic land cover classes and active deformation areas (ADA) obtained from EGMS.	L2a/L2b/L3
ADA detection vs geological maps	Consistency with geo-information	Expert based assessment (qualitative): Correlation between depth to bedrock and deformation patterns (ADAs) derived from EGMS.	L2a/L2b/L3
ADA detection vs soil thickness maps	Consistency with geo-information	Expert based assessment (qualitative): Correlation between soil thickness maps and deformation patterns (ADAs) derived from EGMS.	L2a/L2b/L3
ADA Comparison with fault lines positions	Consistency with geo-information	Expert based assessment (qualitative): Correspondence between EGMS –active deformation areas (ADA) polygons and fault lines.	L2a/L2b/L3

(*) Product selection depending on availability in other GMS:

- Aosta Valley: Basic/L2a
- Tuscany: Basic/L2a
- Limburg: Calibrated/L2b
- Thyborøn: Basic/L2a
- Po River Delta: Basic/L2a
- Etna Basic/L2a + Calibrated/L2b + Ortho/L3

3.1.3 Validation results per thematic area

In this section, site descriptions and results are collectively presented, providing an overview per thematic area and validation strategy or objective. For a complete description of the sites, including metadata, please refer to [D3-Validation Data Collection](#) and [D5-Validation Areas](#).

Landslides

Aosta Valley (Italy)

This region, located in the Italian Alps, experiences a variety of gravitational phenomena including shallow landslides (e.g., debris flows, planar and rotational slides), rockfalls, large slope instabilities and deep-seated gravitational slope deformations.

Figure 11 shows a comparison of displacement velocities between the EGMS and the regional GMS of the Regione Valle d'Aosta (Valle d'Aosta Region, RVDA) for the Basic/L2a product ascending orbit 88. Since the most recent dataset from RVDA only contains acquisitions after April 2019, both datasets have been resampled to cover the same period from April 2019 to December 2022. The comparison reveals good agreement between the detected ADAs. However, the RVDA dataset identifies 147 ADAs, while the EGMS dataset results in 79 ADAs. This discrepancy can be at least partially attributed to differences in MP density and coverage. The RVDA dataset seems to have better coverage on many slopes, where vegetation reduces the coherence of scatterers (see Figure 11), which most likely causes the higher number of ADAs in the RVDA dataset. These differences are most likely due to different processing algorithms and strategies. While the EGMS is optimized for large scale mapping, the RDVA processing is optimized for landslide monitoring, i.e., to map local phenomena.

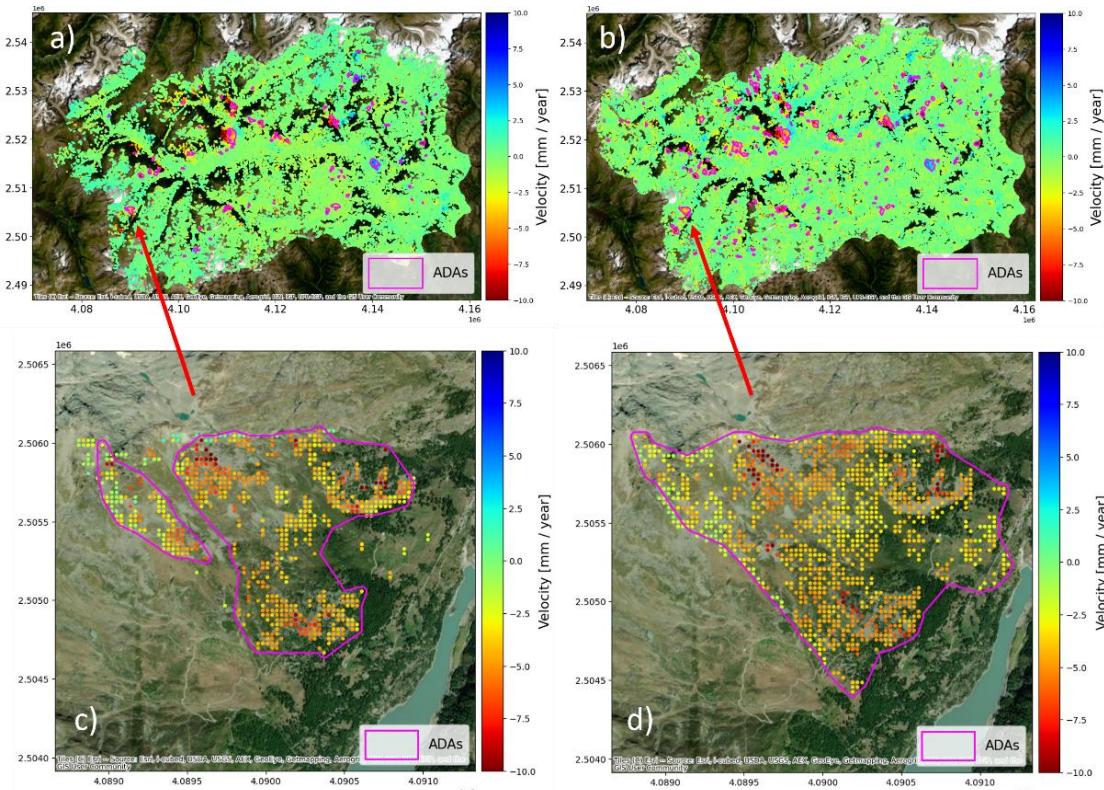


Figure 11: Displacement comparison for Aosta Valley (Italy): (a) Basic/L2a displacement velocities (EGMS, orbit 88/ASC); (b) RVDA displacement velocities. For the Active Deformation Area marked by red arrows: (c) and (d) close-ups of corresponding vel maps.

In the previous validation exercise for the EGMS [2015-2021](#) update, a difference between the velocity values of the two InSAR products (RDVA/EGMS) for the ascending orbit 88 was observed along the main valley cutting through the region. The EGMS showed a slight shift towards positive velocities in the main valley, that correlated with topography and, as it was evident only in the ascending data, was interpreted as a residual atmospheric signal. The 2018-2022 EGMS update (analysed in this document) does not show a similar difference, indicating an improvement. However, the impact of this effect on the IoA can be assumed to be small, as the discrepancy mostly affected the valley, while most ADAs are detected on the mountain sides.

Figure 12 (a) and (b) show the averaged time series and the velocity correlation for the ADA shown in Figure 11. It should be noted that for the ADA comparison, all MPs within the combined ADA area (merging ADAs detected in both datasets) have been considered. The time series show a good agreement in their general trend. The EGMS data exhibits a clear seasonal variation, which is not visible in the RDVA data. The velocity correlation in Figure 12 (b) also shows a good agreement, as evidenced by the elongated point distribution close to the diagonal (red line).

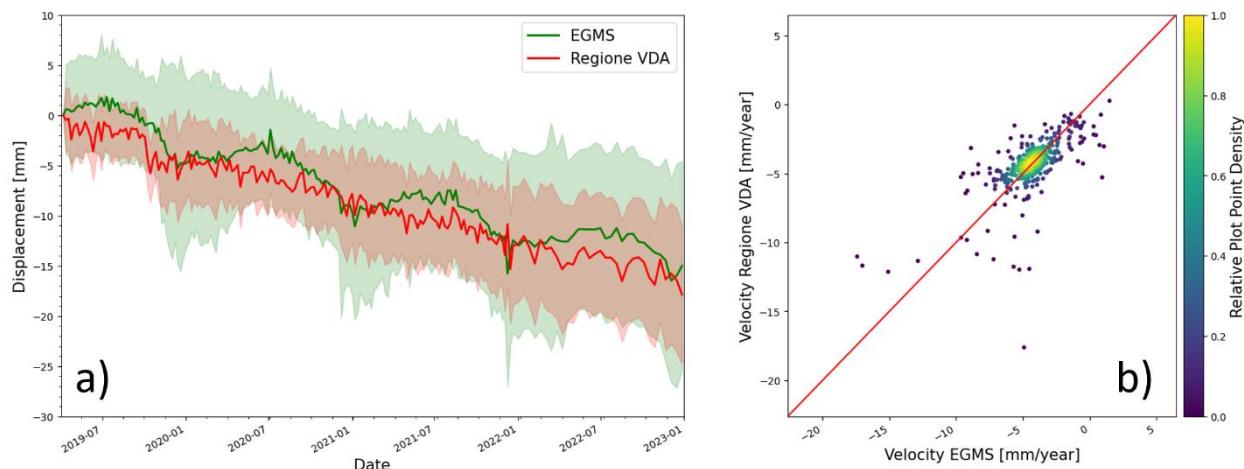


Figure 12: (a) Average and standard deviation of Active Deformation Area time series for EGMS and RVDA for the ADA shown in Figure 11; (b) velocity correlation for area the same ADA.

Table 3 presents the averaged validation measures (see [D6-Validation Methodologies](#)) for all Basic/L2a products that have been compared, along with the resulting IoAs. The relatively low IoA of 0.55 for spatial overlap can mostly be explained by the better coverage of the RDVA products on some of the mountain slopes, which is most likely due to the optimization of the RDVA products for landslide monitoring, while the EGMS is optimized for general large-scale mapping.

Table 3: Validation measures and IoAs for Aosta valley.

Vale d'Aosta	Validation Measure	IoA
Spatial overlap [%]	57.57	0.55
Relative Velocity Difference [%]	43.18	0.95
Velocity Correlation	0.61	0.68
Displacement Time Series Correlation	0.68	0.81
Total		0.75

Conclusion for the Aosta Valley area:

Although the comparison between the two datasets reveals some differences, all major landslide areas are identified, and the time series show an overall good agreement. Some discrepancies in ADA detection may be attributed to variations in MP coverage rather than differences in velocity. Additionally, the limited temporal overlap of just over three years may introduce some differences due to the necessary resampling of the data. Despite these factors, the resulting IoA of 0.75 indicates a reasonably good agreement between both datasets suggesting that the EGMS is useful for regional-level landslide mapping activities.

Tuscany (Italy)

The validation site in the Tuscany Region (Regione Toscana) covers the provinces of Massa Carrara, Lucca, and Pistoia. As Tuscany is an area particularly prone to landslides, this was the phenomenon of interest for this region. Tuscany is a new validation site and was not part of the previous validation exercise.

Figure 13 shows a comparison of displacement velocities between the EGMS and the regional GMS of the Regione Toscana (RT) for the Basic/L2a product descending orbit 168.

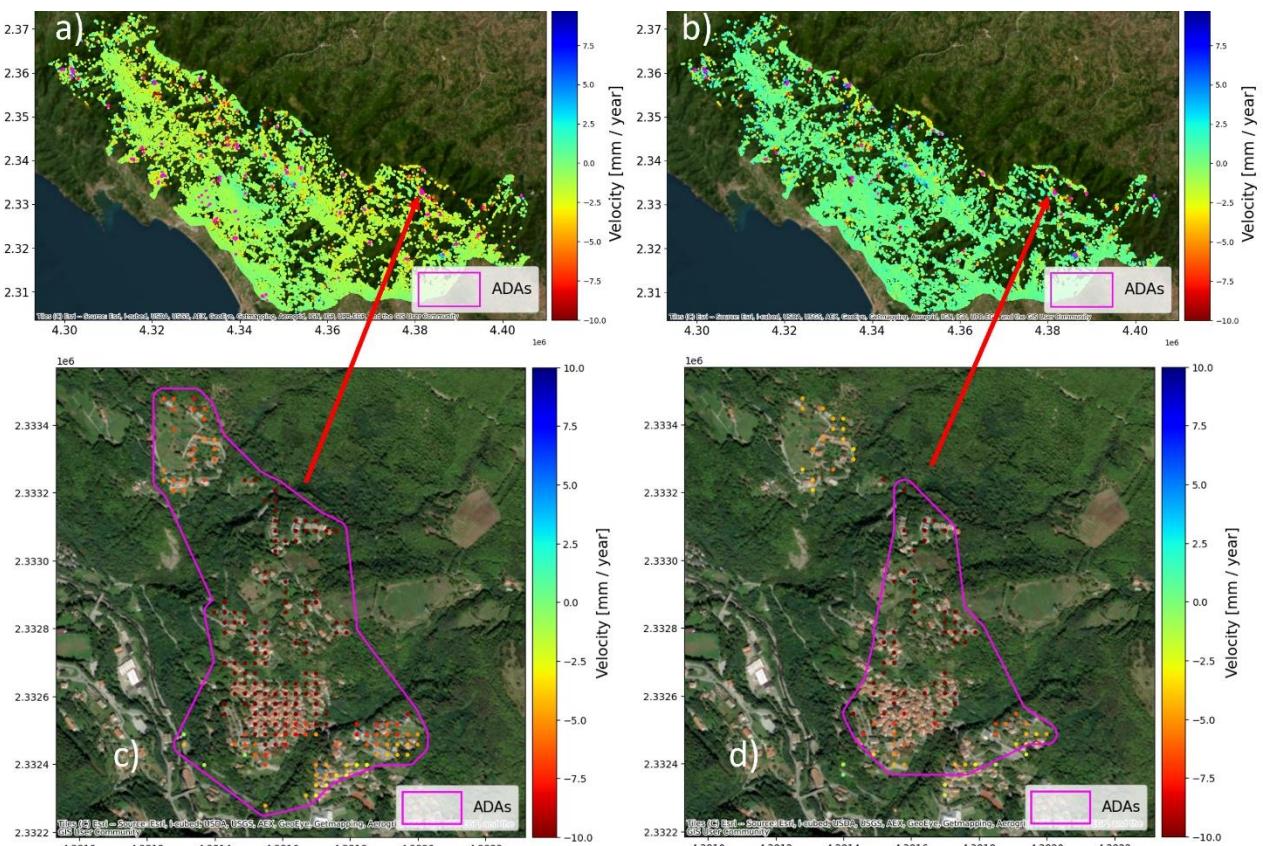


Figure 13: Displacement comparison for Tuscany (Italy): (a) Basic/L2a displacement velocities (EGMS, orbit 168, descending); (b) Regione Toscana displacement velocities. For the ADA marked by red arrows: (c) and (d) close-ups of corresponding velocity maps. Differences in MP density consequently affect ADA delimitation shown in (c) and (d).

The velocity maps reveal a general velocity offset of about 1.3 mm/year between the two datasets, with the EGMS providing velocities shifted to the negative compared to the measurements in the RT dataset. This difference is most likely due to the selection of different reference points in the two datasets. This discrepancy naturally affects the ADA detection. Additionally, the difference in MP density impacts ADA detection (see below), resulting in 74 ADAs detected in the EGMS dataset compared to only 32 ADAs in the RT dataset. Despite these differences, there is a good agreement between the datasets for larger ADAs, as demonstrated in Figure 13 (c) and (d).

Figure 14 (a) shows a comparison of the time series for the same ADA shown in Figure 13 (c) and d). Again, for the ADA comparison, all MPs within the combined ADA area (merging ADAs detected in both datasets) have been considered. Both time series exhibit a good match. Moreover, standard deviations for the displacement values are also very similar between the two datasets. Figure 14 (b) shows the spatial correlation of the velocity values. Ideally, the distribution of the points should align with the diagonal marked in red. While a clear linear correlation of the velocity values is observed, the points appear to be shifted from the diagonal towards the RT velocity axis, which is consistent with the observed general velocity offset of about 1.3 mm/year between the datasets.

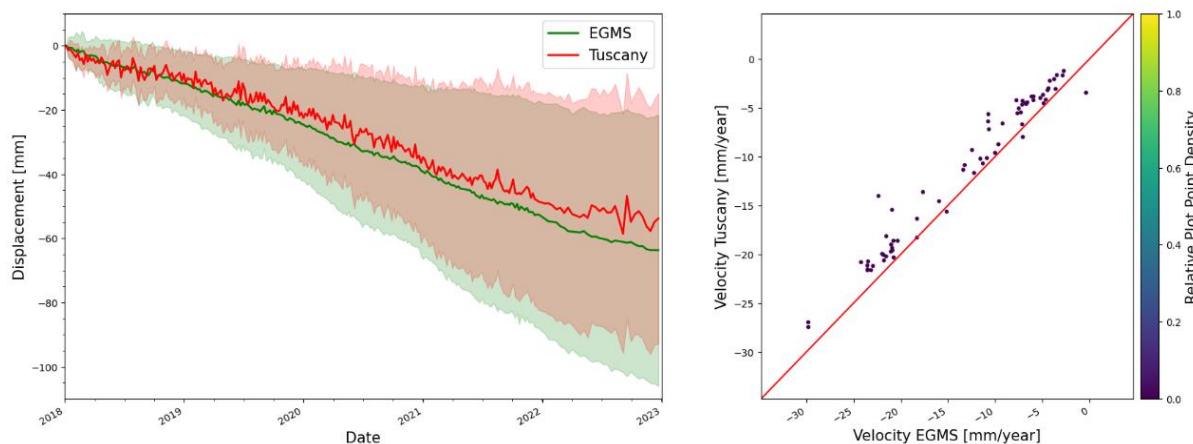


Figure 14: (a) Average and standard deviation time series calculated from all the MPs making the Active Deformation Area (ADA) shown in Figure 13, for EGMS and RT; (b) velocity correlation for the same ADA.

It has to be noted that the two ascending orbits (15 and 117) that have been compared also exhibit velocity offsets, although of much lower magnitude compared to the descending orbits (Orbit 15: ~0.2 mm/year; Orbit 117: ~0.7 mm/year). Similarly, in these cases, more ADAs are detected for EGMS compared to the RT dataset. It is likely that the higher MP density of the EGMS products (containing about four times as many MPs as the corresponding RT products before resampling to a common 30 m x 30 m grid) is mostly causing the difference in ADA detection, such that especially smaller ADAs that were detected in the EGMS product, are more likely to be rejected in the RT product because the limit of minimum 20 points is not met.

The ADA detection difference mostly being caused by different MP densities. A low velocity difference of 37% between the two datasets can be also observed. Therefore, the low spatial overlap of 0.39 should not be regarded as a negative outcome, as it shows, that the EGMS is able to detect more ADAs than the RT dataset.



Table 4: Validation measures and IoAs for Tuscany.

Tuscany	Validation Measure	IoA
Spatial overlap [%]	49.62	0.39
Relative Velocity Difference [%]	37.37	0.97
Velocity Correlation	0.65	0.75
Displacement Time Series Correlation	0.87	1.00
Total		0.78

Conclusion for the Tuscany area:

A general offset of about 1.3 mm/year is noticeable in the descending product between both datasets. While this affects the total number of detected ADAs, a good agreement is still observed for larger ADAs. The ADA time series exhibit a good temporal correlation, and velocity values also correlate reasonably well. The resulting IoA of 0.78 shows that, despite observed differences, the datasets show a good match, confirming the usability of the EGMS for regional-level landslide mapping activities.

French national landslide inventory (Alpes Maritimes)

The Alpes Maritimes department in the southeast of France has been chosen for the intercomparison of national landslide inventories with ADAs derived from EGMS products. Over the past two decades, the region has experienced numerous episodes of intense rainfall, with particularly notable events occurring in 2000, in February and November 2014, and October 2015. The most recent one in October 2020 during the Alex storm, triggered damaging landslides in the Vésubie, Roya and Tinée valleys. Moreover, the area is characterized by deep seated landslides.

National inventories are commonly created by field investigations, sometimes aided by aerial photos or optical satellite imagery. When ground motion is identified in the field, a georeferenced point is recorded in the inventory. The French national inventory has recently been updated (2022-2024) through the ANR (Agence National pour la Recherche) project "VIGIMONT" (VIGIlance MONTagne: service de prévision de risque glissement de terrain et laves torrentielles en territoire de montagne).

The subset of the national inventory in the Alpes Maritimes region contains a significant number of landslides (>500). Since these are mountainous areas, density of radar scatterers, and thus MP coverage, is expected to vary depending on factors such as slope, aspect, and land cover. MP density is also expected to change depending on the ascending/descending orbits.

The comparison between ADA polygons and inventory points (Figure 15 on the next page) serves to evaluate EGMS landslide detection capabilities in the Alpes Maritimes department. The Calibrated/L2b product has been chosen for this comparison given the negligible regional motion (less than 0.7 mm/year). In the ascending orbit, 36% of inventory points fall within an ADA, while 51% of ADAs host an inventory point. In the descending orbit, 22% of inventory points fall within an ADA, with 54% of ADAs containing an inventory point.

These results can be attributed to EGMS's ability to detect slow moving landslides that may not be visible on the ground, particularly in remote unmapped areas distant from built environment and assets, since national inventories rely on field observations (human based) and damage reports, usually in proximity to artificial surfaces. This disparity highlights positive results as observable in Figure 15.

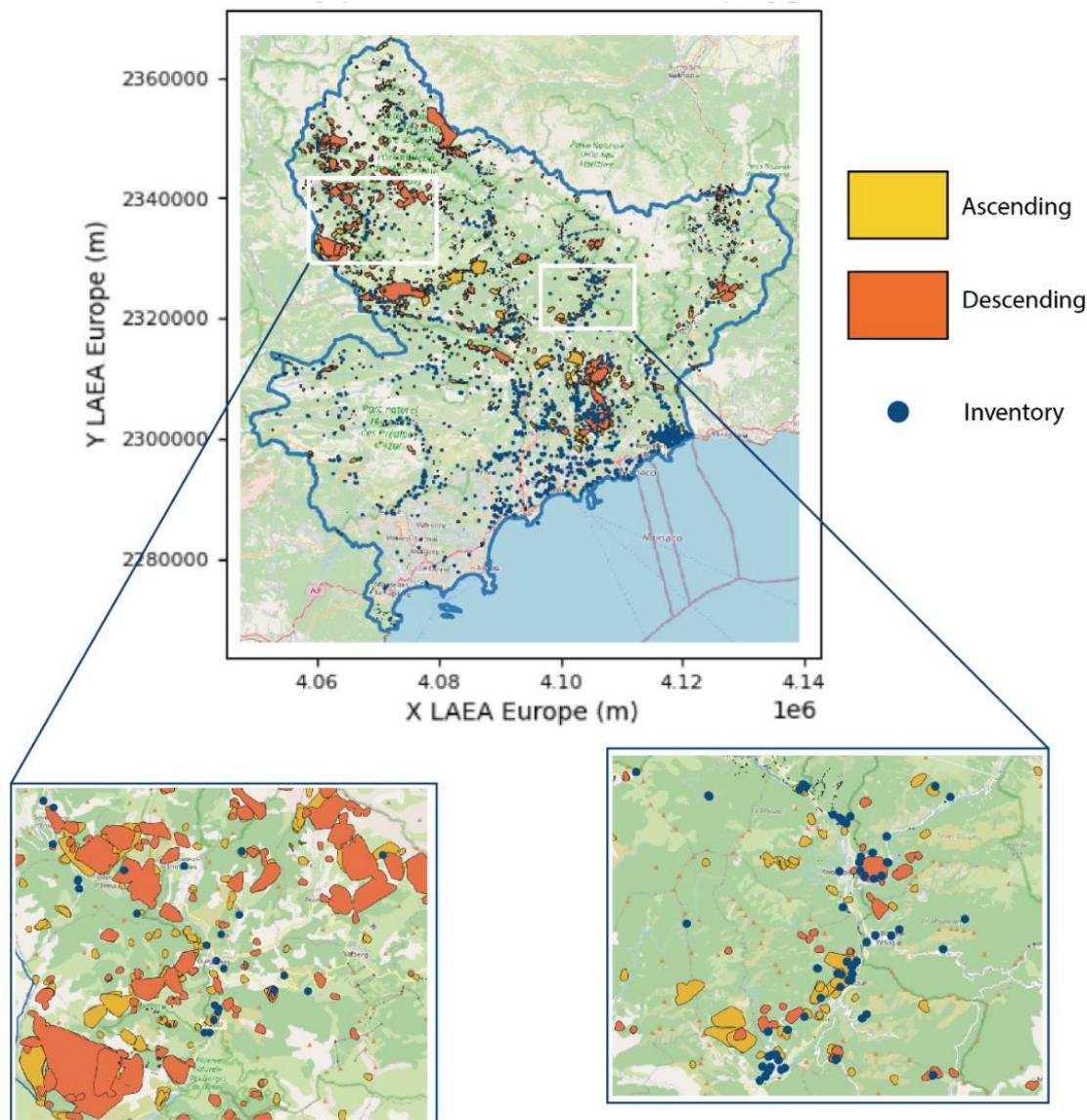


Figure 15: EGMS Calibrated/L2b Active Deformation Areas compared with updated national inventory (blue dots) on the French Alpes Maritimes department. Ascending and descending orbits.

More than half of the (potential) landslides identified by EGMS are not recorded in the national inventory. This presents interesting perspectives for improving national inventories. These findings align with those of the previous EGMS release validation (2015-2021).

Comparisons with inventories reveal that the number of EGMS MPs within landslide areas highly depends on the acquisition geometry (ascending/descending). The use of EGMS L2 products is recommended for landslide motion detection, especially in highly mountainous areas where MP density depends on both acquisition geometry and orientation of topographic slopes. It is

important to note that EGMS L2 products correspond to the LOS direction (1 dimension), making them suitable for detecting slow motions ranging from 1mm/year to approximately 20 cm/year, where the full 2D/3D components of the motion are not required. On the other hand, for landslide detection, the direction of motion can be inferred from the slope. Therefore, EGMS L2 results are adequate to detect changes in the ground motion regime (e.g. acceleration or deceleration).

Finally, North/South oriented landslides might go unnoticed or wrongly characterized when the magnitude of the vertical component of the movement is low. This is a well-known limitation of InSAR, as the technique is less sensitive to ground motion occurring along the flight direction of the satellite. In conclusion, in North/South oriented landslides, there might be confusion between vertical and horizontal motion components, leading to an underestimation of motion velocity in the Ortho/L3 product.

Do EGMS polygons contain points from national inventories?

In the Alpes Maritimes department, EGMS proves its value as a complementary tool to field observations and has the potential to enrich national inventories. In the ascending orbit, 36% of inventory points fall within an ADA, while 51% of ADAs host an inventory point. In the descending orbit, 22% of inventory points fall within an ADA and 54% of ADAs host an inventory point.

Spanish landslide inventory (Rules reservoir)

The Rules reservoir is located across the Guadalefeo river valley, downstream from its confluence with the Izbor river, in the municipality of Vélez de Benaudalla, and collects the water from the southern slopes of Sierra Nevada Mountain range, Sierra de Lújar and La Contraviesa. The 30 km² basin around the reservoir is affected by several landslides, most of them reported in the Spanish national inventory. An overview of EGMS products is illustrated in Figure 16.

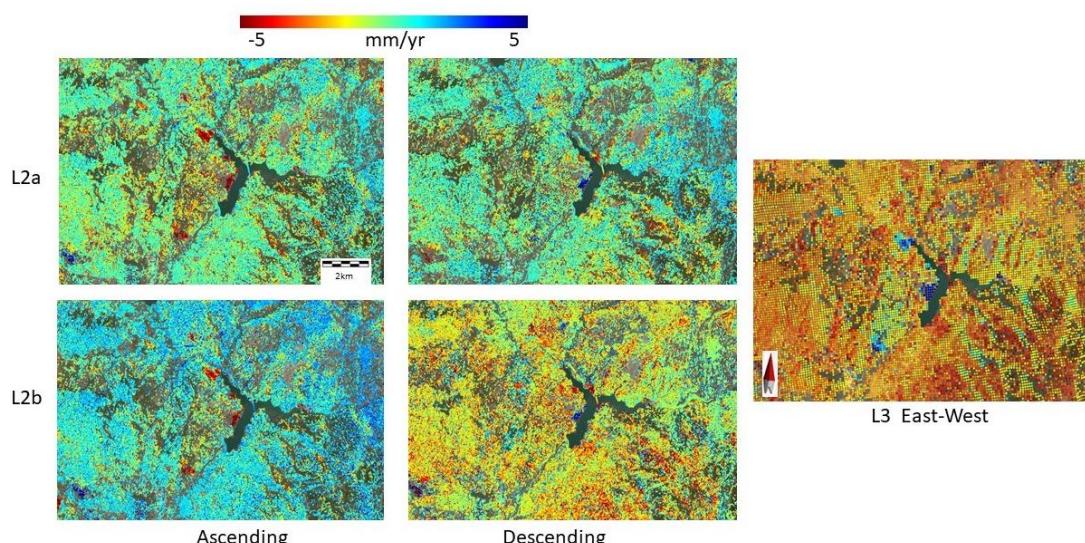


Figure 16: Basic/L2a and Calibrated/L2b ascending and descending orbits on the Rules validation area. Ortho/L3 East-West component is affected by a 3-4 mm/year regional horizontal motion towards the West, which results in an obvious difference with respect to the Basic/L2a orbits.

EGMS derived ADAs are compared to inventories derived from field mapping and an ad-hoc InSAR processing conducted by CSIC/IGME. A velocity threshold of 4 mm/year has been used to select relevant moving areas. The EGMS results in the test area are affected by a regional motion due to neotectonics (Piña-Valdés et al. 2022) of similar magnitude as the expected motion on the sliding slopes. For this reason, the Basic/L2a product (not calibrated on GNSS) is deemed more appropriate for the area of interest, as it provides motion data at local scale. Noteworthy is the fact that the area is located in a sector (South of Sierra Nevada) characterized by very large gravitational motions.

Figure 17 shows the comparison between the national inventory and EGMS ADAs. The low similarity found between inventories and EGMS products might be related to a potential decrease of activity of the inventoried landslides. In addition, a difference between ascending and descending ADAs can be observed resulting from the relative slope of the landslides with respect to the acquisition geometry position.

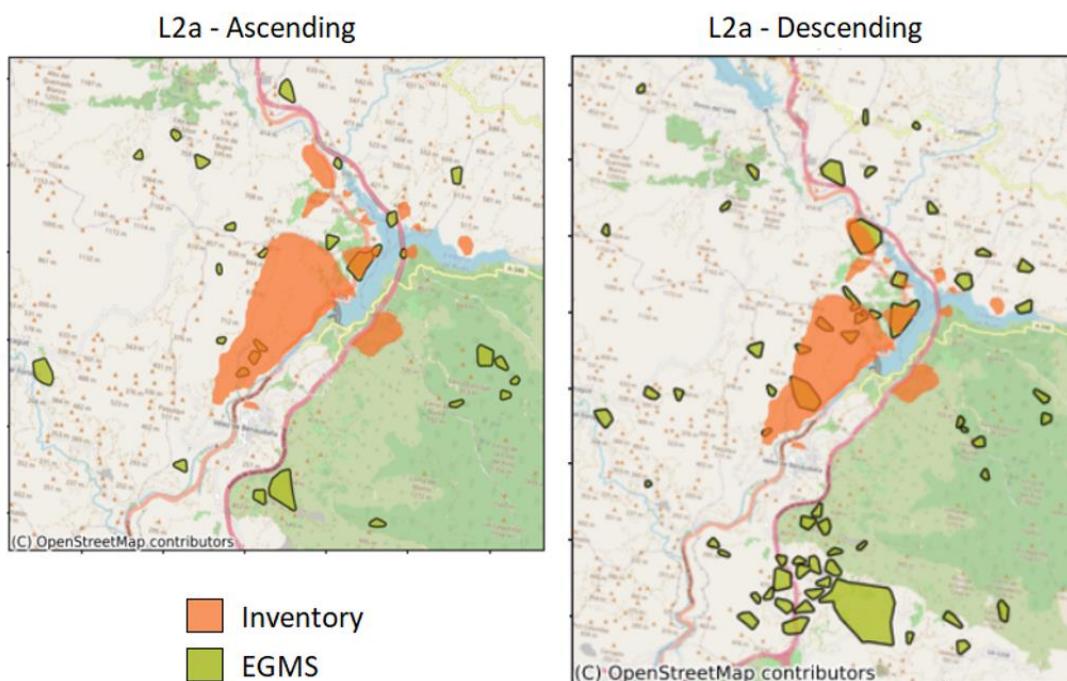


Figure 17: Basic/L2a ascending and descending Active Deformation Areas (green) and inventory polygons (orange).

A vast majority of the landslides available in the inventory (>90%) are covered at least by 3 EGMS MPs. Differences in velocities within the landslide polygon and within a 300-meter buffer have been analysed to assess EGMS landslide detection capabilities. Only a minority of landslide polygons exceed the 2mm/year difference threshold, indicating they are slow moving landslides.

Are EGMS polygons similar to polygons from national inventories?

In the Rules area, the proportion of EGMS Basic/L2a derived polygons that are considered consistent with the inventory represent 8% for ascending and 14% for descending orbits. Inventory polygons only partly match ADAs (Figure 17) most likely because the landslides activity has decreased since they were included in the inventory. Despite this, EGMS data successfully detects new landslide polygons.

Spanish national landslide inventory (Arcos de la Frontera)

The following example is focused on the Arcos de la Frontera landslide, Spain. In order to spot the landslide phenomena in the EGMS products, the detection is considered positive or matching if the velocities detected by EGMS inside the inventory polygons is significantly different from the EGMS surrounding MPs. The criterion is the mean velocity difference between MPs “inside the polygon” and “outside the polygon”. The detection is considered successful when the mean velocity difference is higher than 2 mm/year. Calibrated/L2b products, ascending and descending orbits, are evaluated (Figure 18) since the landslide LOS motion is ten times faster than the regional motion (Bru et al., 2017).

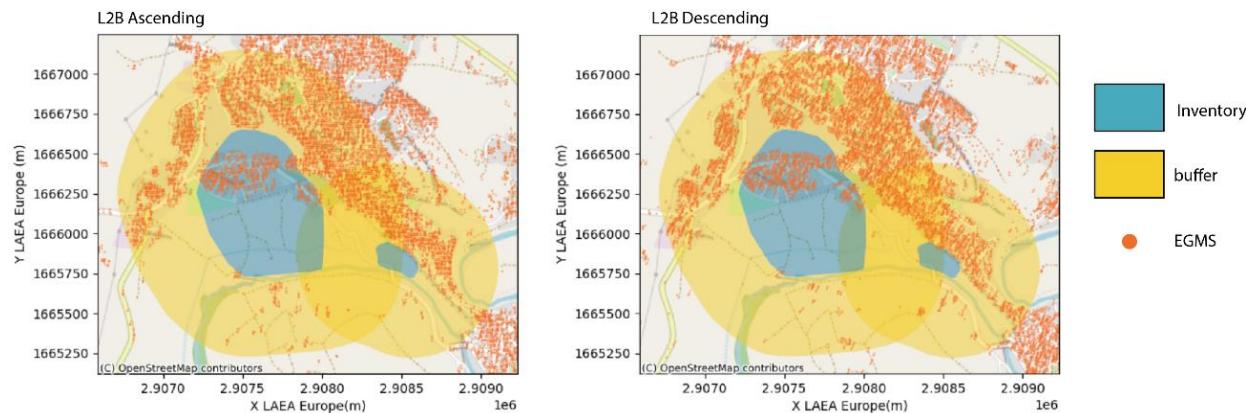


Figure 18: Inventory polygons with 300m buffer and EGMS Calibrated/L2b MP coverage for ascending (left) and descending (right) orbits.

The large-scale landslides are sufficiently covered by EGMS MPs (in both orbits). As expected, velocity differences between the inventory polygon and its stable surroundings show that EGMS is able to successfully capture the phenomena.

Table 5: Summary of findings for Arcos de la Frontera landslides.

EGMS product	Velocity difference between inventory polygon and its surrounding buffer	Average velocity in the surrounding buffer (stable)	Number of EGMS measurement points inside the inventory polygon
Calibrated/L2b/ASC	4.7 mm/year	1.2 mm/year	804
Calibrated/L2b/DESC	2.4 mm/year	1.3 mm/year	959

The Arcos de la Frontera landslide is partly covered by vegetation affecting MP density due to surface changes. Therefore, EGMS MPs on Arcos de la Frontera landslide are visible on the built area only, with respect to the entire inventory area. Compared to the previous EGMS update ([2015-2021](#)), the EGMS average velocity has lowered in Arcos de La Frontera. This is probably due to a deceleration (or change of displacement style/direction) of the landslide itself. Landslides velocity might change according to rainfall rates.

Does EGMS detect motion within the polygons from the national inventories?

The detection is considered successful because the average difference in EGMS values between the inside/outside the inventory polygons is higher than 2 mm/year.

Do EGMS polygons contain points from national inventories?

EGMS is complementary to field observations capturing inventoried events.

80% of inventory polygons fall inside an EGMS ADA polygon for both ascending and descending orbits.

Are EGMS polygons similar to polygons from national inventories?

In the ascending orbit, the intersection between EGMS ADA polygons surface and the national inventory is 55%, while 37% of EGMS ADAs are outside the national inventory polygons. In descending orbit, the intersection between EGMS ADA polygons surface and the national inventory is 47% of their average surface, while 11% of EGMS ADAs are outside the national inventory polygons. This is a positive result given that the shape of the inventoried phenomena depends highly on land cover.

Mining and post-mining

Limburg (Netherlands)

The **Limburg** area, situated in the southeast of the Netherlands, is a former coal mining region characterized by predominantly urban landscapes with gentle topography, reaching a maximum elevation of approximately 322m. Coal mining activities in the Limburg area were abandoned in the 1970s. In 1994, the hydrologically connected, neighbouring German mining operations were also terminated, leading to the cessation of all mining-related ground water pumping (Cuenca et al, 2012). The subsequent rise of the water table resulted in uplift across areas in the Netherlands, Germany, and Belgium.

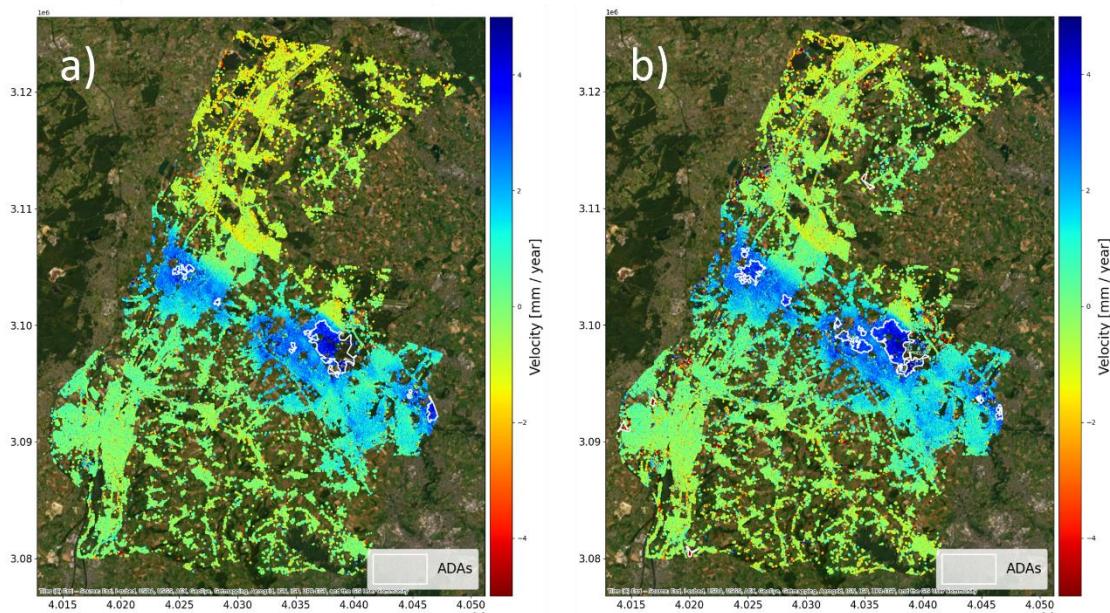


Figure 19: Comparison of velocities: (a) EGMS Calibrated/L2b product ascending orbit 88 (b) Dutch GMS. Detected Active Deformation Areas are depicted by the white polygons.

Figure 19 shows a comparison of the velocities between the EGMS and the Dutch GMS for the Calibrated/L2b product of ascending orbit 88. The white polygons indicate the detected ADAs. Given the small ground motion rates, the velocity threshold for ADAs detection have been set to 3 mm/year.

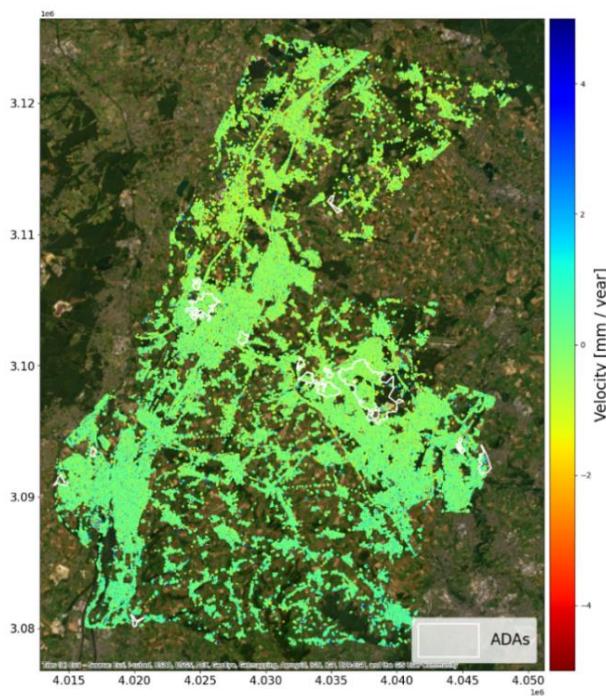


Figure 20: Velocity difference ($dvel = velEGMS - velDutch GMS$) between the EGMS and the Dutch GMS for Calibrated/L2b products of ascending orbit 88. Detected Active Deformation Areas are depicted by the white polygons.

The overall patterns in the velocity maps appear highly consistent between the two datasets. North of the uplift area, the amplitude of the EGMS velocities appears slightly higher than those of the comparative dataset, but the difference is below 1mm/year (Figure 20) and does not seem to affect ADA detection in the uplift area.

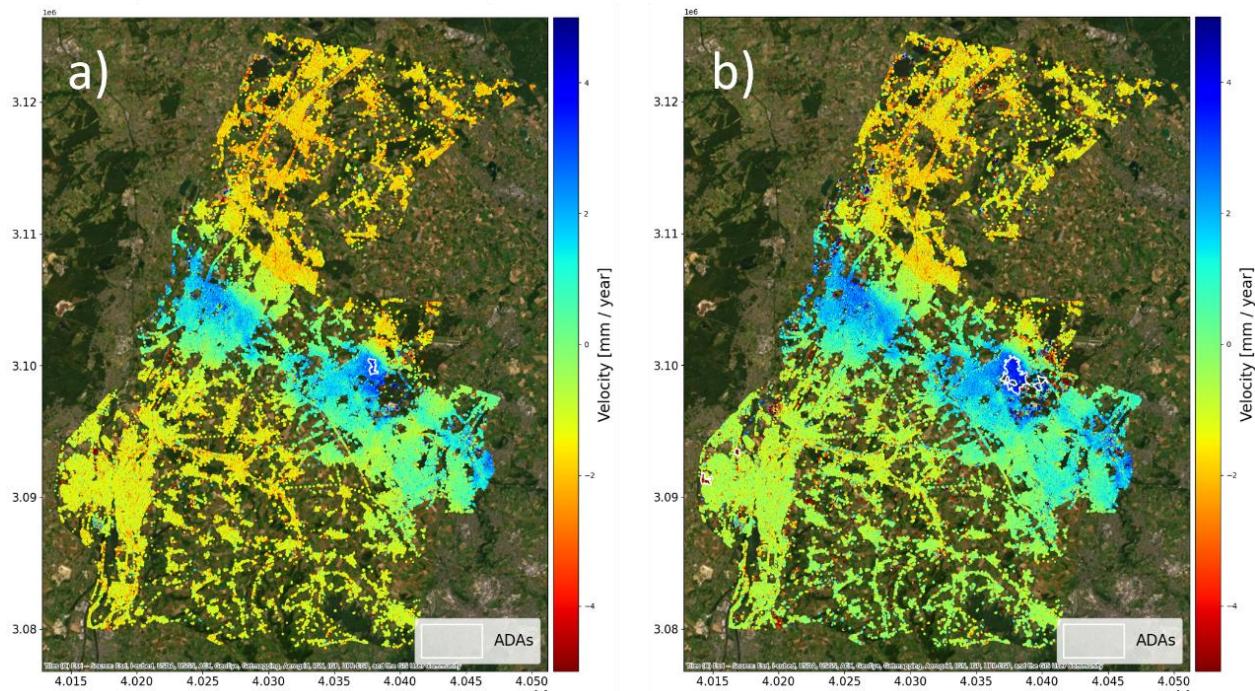


Figure 21: Comparison of velocities between the EGMS Calibrated/ L2b product descending orbit 37 (a) and the Dutch GMS (b). Detected Active Deformation Areas are depicted by the white polygons.

Figure 21 shows the comparison of the velocities between the EGMS Calibrated/L2b product of descending orbit 37 and the Dutch GMS. A general offset in the velocities between the two datasets is evident, both north and south of the uplift area. In combination with the rather smooth velocity field, these offsets cause a smaller overlap of the ADAs compared to the ascending orbit 88 comparison. However, it should be noted that the comparison of absolute values in this case is not meaningful due to the use of different GNSS reference systems for the calibrations of the Calibrated/L2b products in the EGMS and the Dutch GMS, respectively. Consequently, such a slight general offset in the velocities has to be expected and considered in the interpretation of the results.

Figure 22 shows a detailed comparison for the largest ADA in the centre of the uplift area. Figures 22(a) and 22(b) show the respective velocity maps with the detected ADAs, which match very well in extent. The velocity difference map in Figure 22(d) shows that there is no notable difference in velocity across the entire ADA. Figure 22(e) illustrates the time series for both datasets, which show good agreement in both slope and linearity.

The averaged time series in Figure 22(e) suggest that the Dutch GMS dataset is a bit noisier. In Figure 22(f), the spatial correlation of the velocity values is depicted by plotting EGMS velocities on the horizontal axis against Dutch GMS velocities on the vertical axis. Ideally, the distribution of the points should align with the diagonal marked in red, but the distribution of the points is rather compact, indicating a mismatch of up to 5 mm/year for a considerable number of points. This misalignment can also be observed in the differenced map shown in Figure 22(d).

Table 6 summarizes the calculated validation measures averaged for all ADAs derived from Calibrated/L2b products, along with the resulting IoAs.

Table 6: Validation measures and IoAs for Limburg.

Limburg	Validation Measure	IoA
Spatial overlap [%]	54.97	0.50
Relative Velocity Difference [%]	28.68	1.00
Velocity Correlation	0.42	0.37
Displacement Time Series Correlation	0.89	1.00
Total		0.72

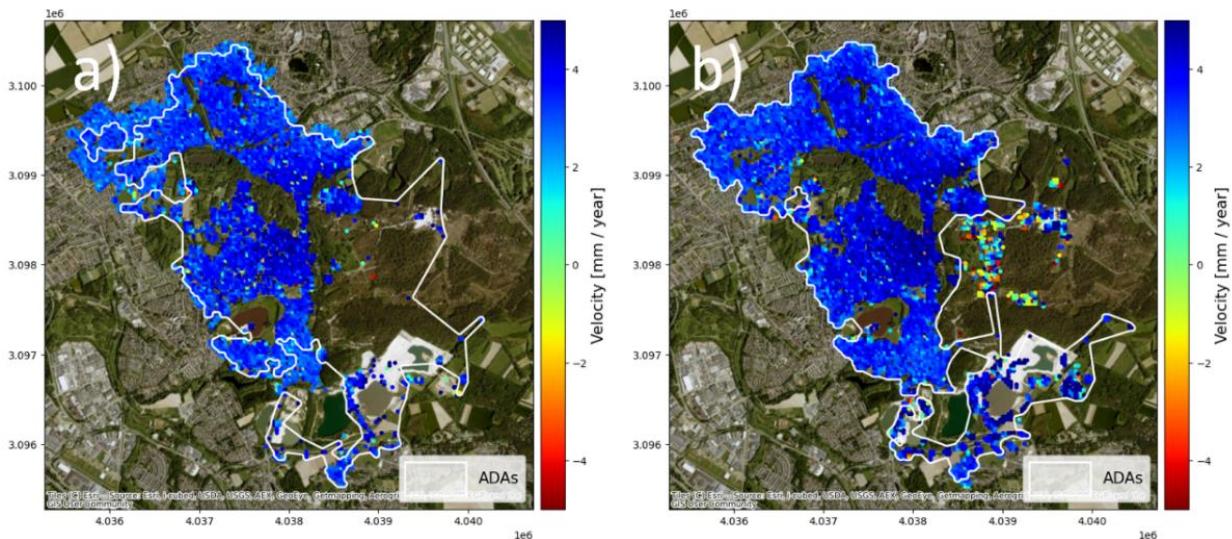


Figure 22: (a) Dutch GMS derived ADAs (b) ADAs derived from EGMS Calibrated/L2a product (Continues on next page)

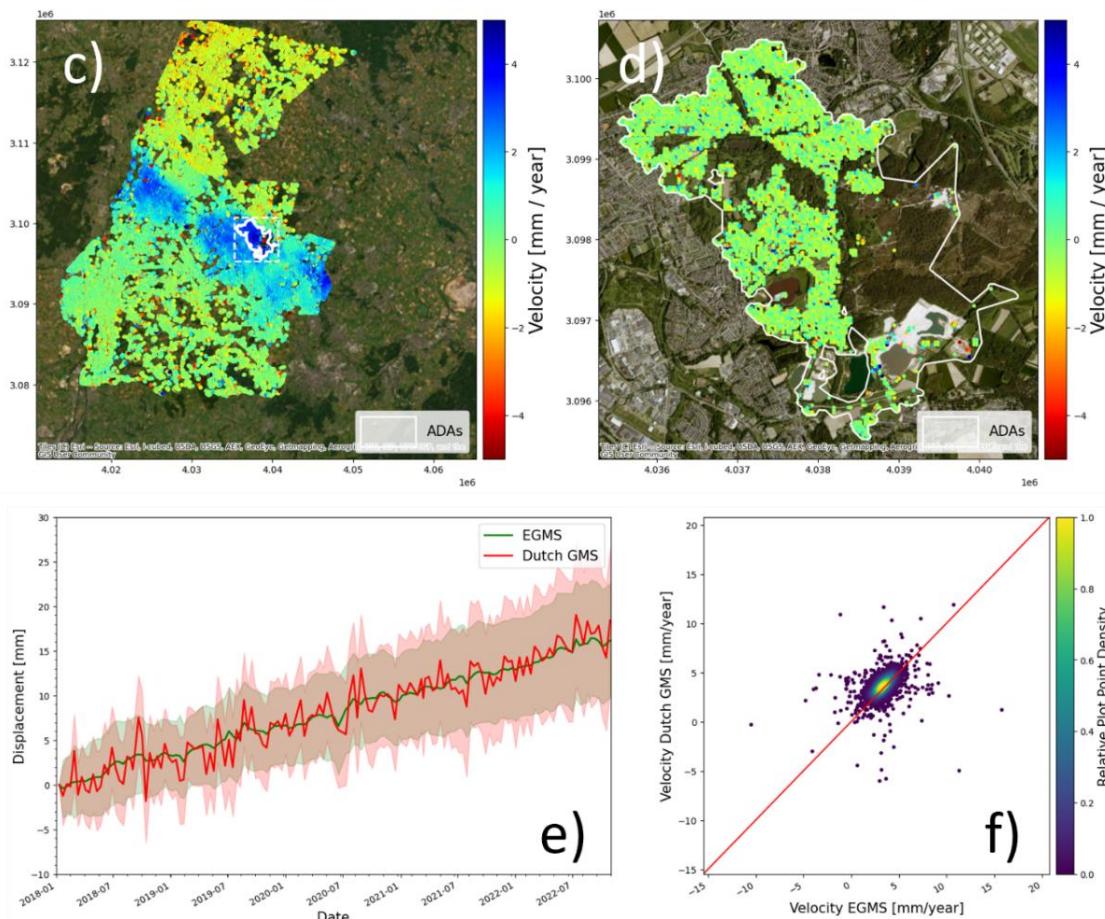


Figure 22: Focus on the largest Active Deformation Area (ADA) in the centre of the uplift area: (c) overview of the ADA location; (d) velocity difference ($dvel = vel_{EGMS} - vel_{Dutch\ GMS}$) between the EGMS and the Dutch GMS; e) average and standard deviation of all the ADA time series; (f) velocity correlation.

The achieved spatial overlap between the two interferometric sources is relatively low, primarily due to slight velocity offsets, especially in the descending orbit 37 data, combined with the rather smooth and wide uplift patterns. The smoothness of the velocity fields means that the size of the detected ADAs is very sensitive to even the smallest variations in the velocities, resulting in a 50% overlap despite a relative velocity difference for the ADAs below 30%. The spatial velocity correlation, 0.37, is also relatively low, as observed in Figure 22(f). The time series correlation yielded a value of 0.89, indicating that both time series exhibit similar linear behaviour with some variation in trend, as reflected in the velocity differences.

Conclusion for the Limburg validation site:

The comparison between EGMS and the Dutch GMS results in an IoA of 0.72, which indicates a good match although some differences are observed. These can mainly be attributed to differences in the calibration process. The lower IoA for spatial overlap is due to the regional character of the phenomenon displaying low velocity, which make the ADA detection sensitive to small differences.

In terms of usability, this does not pose a limiting factor to the ability of the EGMS to detect such large scale, mining-induced ground motion and both datasets show the same large-scale displacement areas.

French national landslide inventory (Lorraine region)

The Lorraine region includes municipalities of Forbach and Freyming-Merlebach, featuring an abandoned coalmine complex (active until 2004). It extends for over 50 km²; the EGMS coverage is shown in Figure 23. ADA derived polygons were processed based on a 2 mm/year velocity threshold, due to the characteristics of the phenomenon (very slow uplift, with about 10 km width). A subsidence phenomenon is also observed on the German side of the area but not included in the inventoried data (limited to France). No significant regional motion is observed and therefore the Calibrated/L2b EGMS product is used for the analysis (Figure 23).

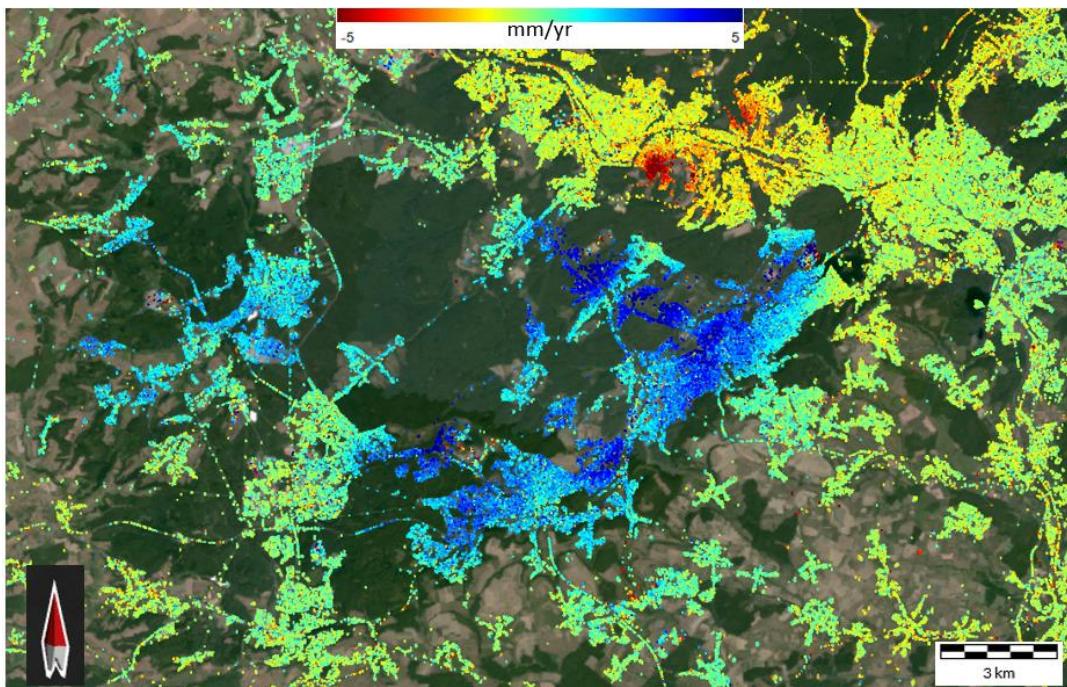


Figure 23: EGMS Calibrated/L2b ascending product for the Lorraine region.

Figure 24 shows the comparison between the local inventory (polygons derived/interpreted from in situ levelling measurements) and EGMS derived ADA polygons for Calibrated/L2b. The similarity between polygons is very relevant more than 50% of overlap, 70% when only the ADA polygons in France are considered. Note that the ADA polygons estimated on the German side of the border cannot be compared with any inventory. A slight difference between ascending and descending polygons is observed.

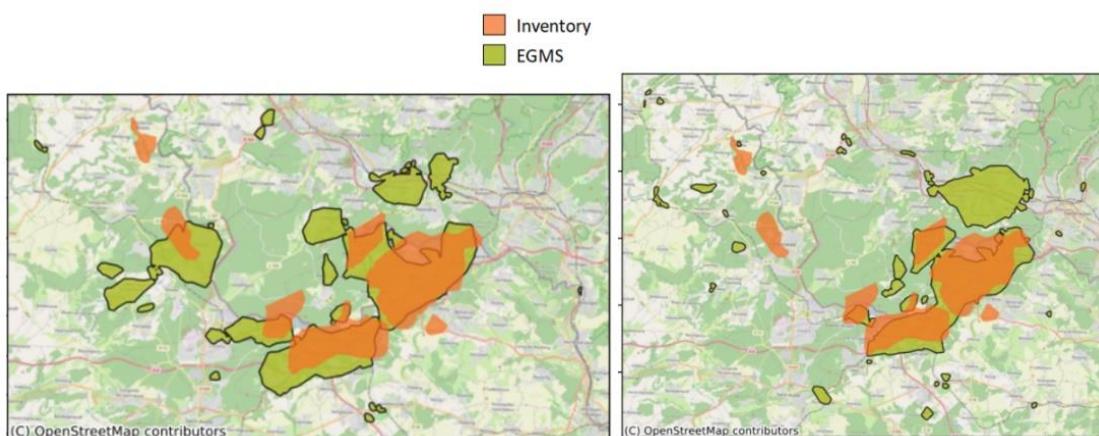


Figure 24: Inventory versus EGMS Calibrated/L2b (left: descending, right: ascending)

Figure 25 shows the contributions of the ascending/descending/vertical versus de ADAs obtained from both Calibrated/L2b orbits (LOS) and Ortho/L3 (vertical). Calibrated/L2 descending polygons seem to be shifted towards the west and ascending polygons towards the east direction of movement. Those slight differences suggest the presence of a horizontal components of the motion at the border of the uplifting area. This results in better consistency between Ortho/L3 vertical and levelling derived polygons.

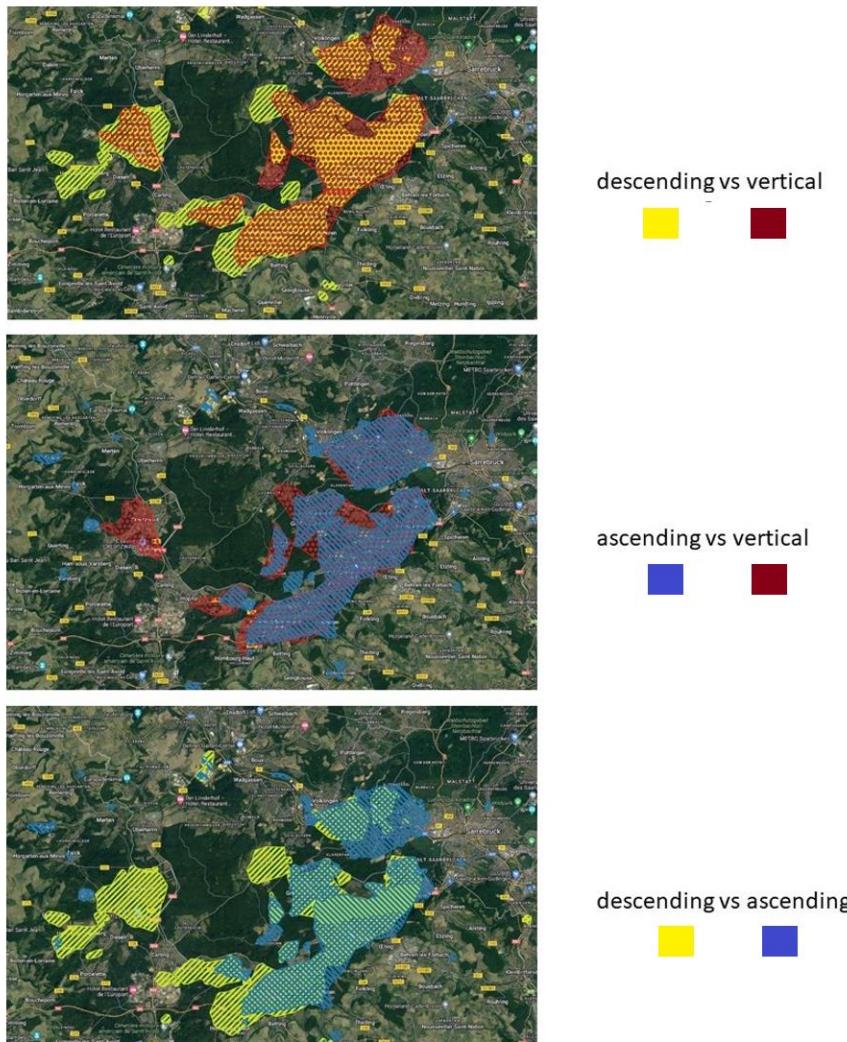


Figure 25. Comparison of Calibrated/L2b ascending and descending versus Ortho/L3 vertical derived polygons.

EGMS derived ADAs are very consistent with vertical movements from the inventory for ascending and descending orbits. Table 7 summarizes the IoAs resulting from the overlap between inventories and EGMS derived ADAs.

Table 7: Validation measures and IoAs for the Lorraine region.

EGMS product	Overlap area between inventory polygons and EGMS derived ADAs. In % of the polygons area.	Difference area between inventory polygons and EGMS derived ADAs. In % of the polygons area.
Calibrated/L2b/ASC	54% (<i>66% excluding ADA outside the French border</i>)	60%
Calibrated/L2b/DESC	53% (<i>60% excluding ADA outside the French border</i>)	68%
Ortho/L3/Vertical	59% (<i>70% excluding ADA outside the French border</i>)	61%

Are EGMS-derived ADAs similar to the polygons from national inventories?

The amount of EGMS moving areas that are considered consistent with the available inventory represent up to 59% (up to 70% when excluding EGMS ADA polygons located in Germany) of the affected areas. EGMS is reliable for identifying areas affected by post-mining phenomena, including on sectors where the inventory is incomplete. These observations also highlight the benefits of a trans-border service.

La Unión (Spain)

The validation site in La Unión, Spain, was specifically selected for its mining activities, encompassing both underground and surface mining, containing tailings dams and waste dump sites. Located on the south-eastern coast of Spain along the Mediterranean, this site was exploited for lead and zinc deposits until 1992. The mining activities were mainly underground until 1960, after which open-pit exploitation started. Over the past fifty years, the landscape of La Union underwent significant transformations, with surrounding valleys and hills completely covered by mine waste material. To assess the consistency of EGMS measurements in this complex mining terrain, the EGMS data over La Unión were compared to ancillary geoinformation. As part of this comparison, automated detection of ADAs in the EGMS was crucial. Using the same configuration from the previous validation cycle (2015-2021), the ADA detection resulted in a notably increased number of smaller ADAs, which might be attributed to a slightly higher noise level in the second update of the EGMS products due to the shorter time series reference period. Therefore, the ADA parameters were slightly adjusted, i.e., the point-wise velocity threshold was increased from 3 to 4 mm/year, and the cluster velocity threshold from 4 to 5 mm/year. Figures 26 and 27 show the EGMS velocity maps with detected ADAs for La Unión, featuring Basic/L2a data for both ascending (orbit 103) and descending (orbits 8 and 110) orbits.

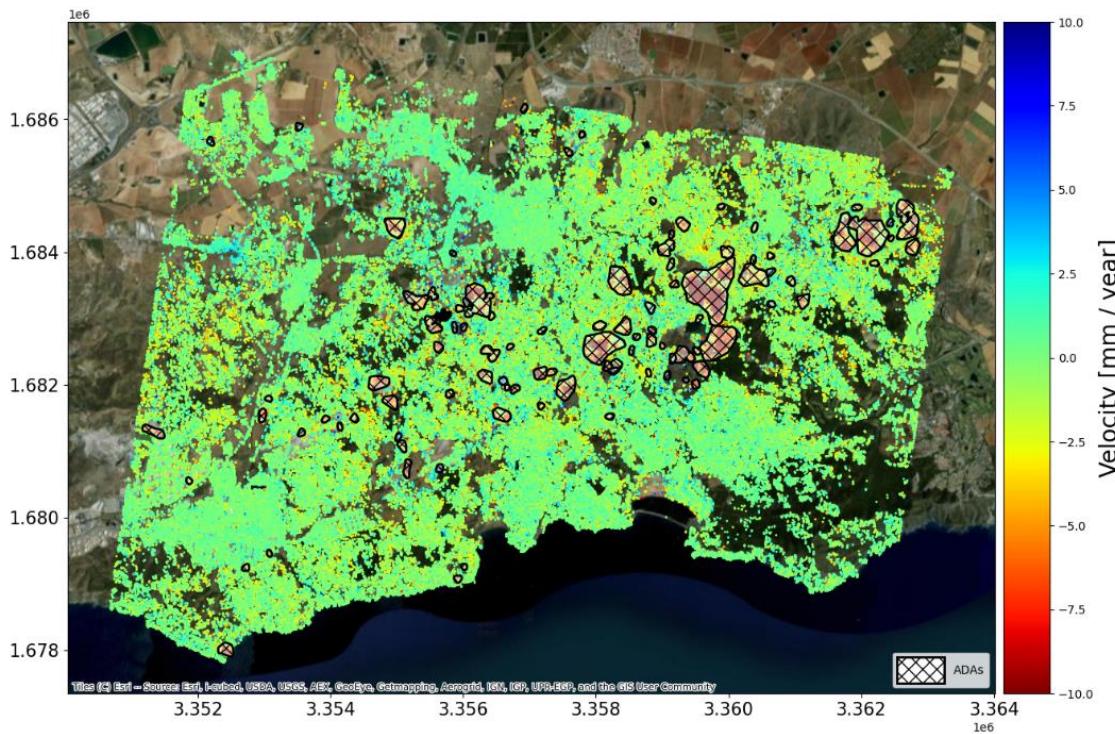


Figure 26: EGMS Basic/L2a velocity maps for ascending orbit 103 for La Unión, with detected ADAs marked as black polygons.

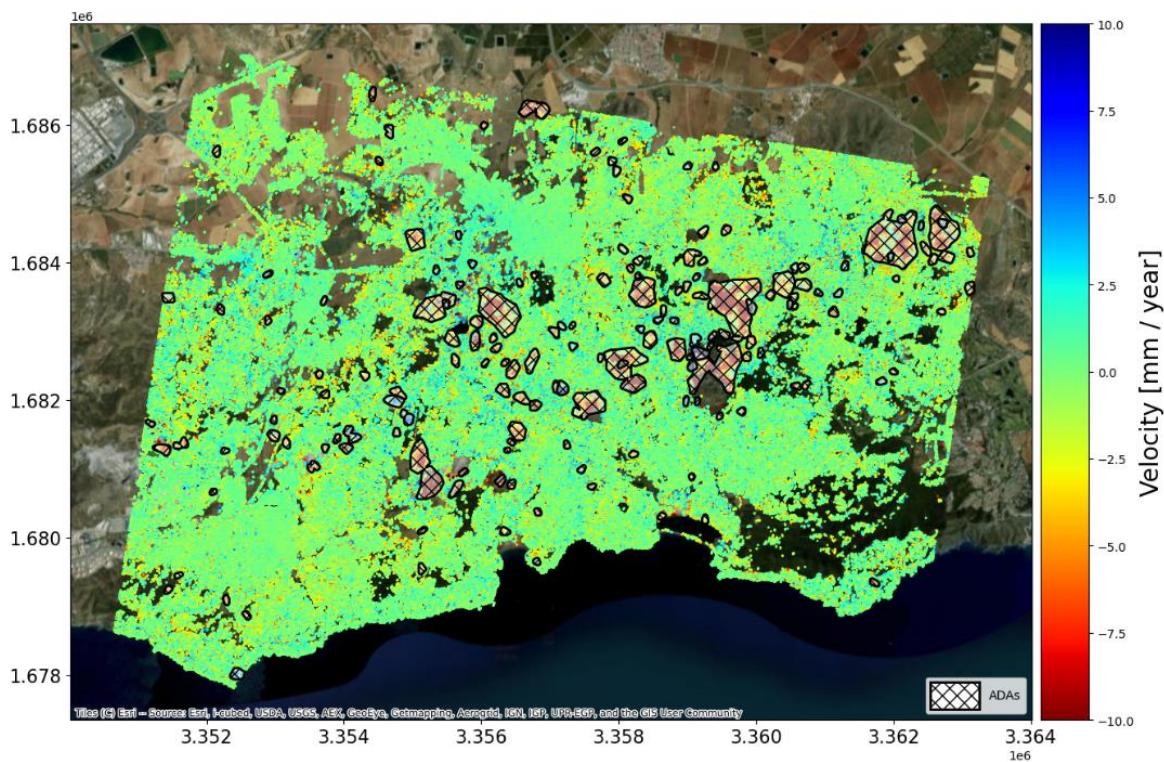


Figure 27: EGMS Basic/L2a velocity maps for descending orbits 8 and 110 combined for La Unión, with detected ADAs marked as black polygons.

Comparison with Corine Land Cover Map:

The comparison with Corine Land Cover (CLC) aims to assess the consistency of land cover related factors causing ground displacement. Figures 28 and 29 show the detected ADAs overlaid on the CLC categories for both ascending and descending orbits. An obvious overlap with the mineral extraction class is observed.

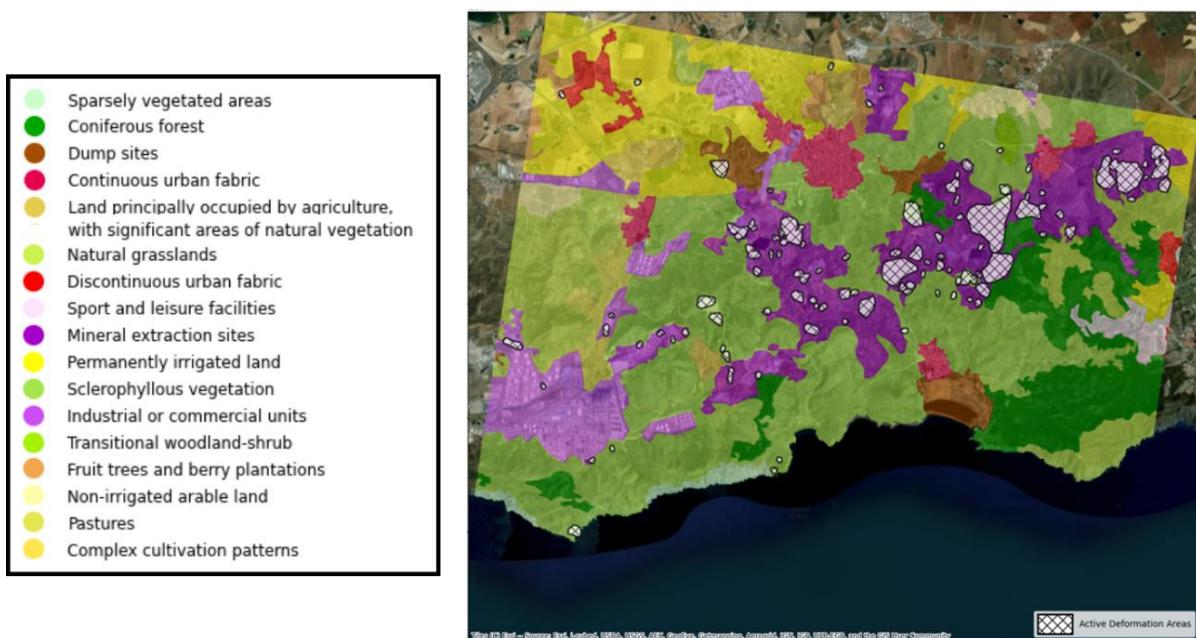


Figure 28: Active deformation areas (ADAs) superimposed on the Corine Land Cover (CLC) map for Basic/L2a products in ascending orbit.

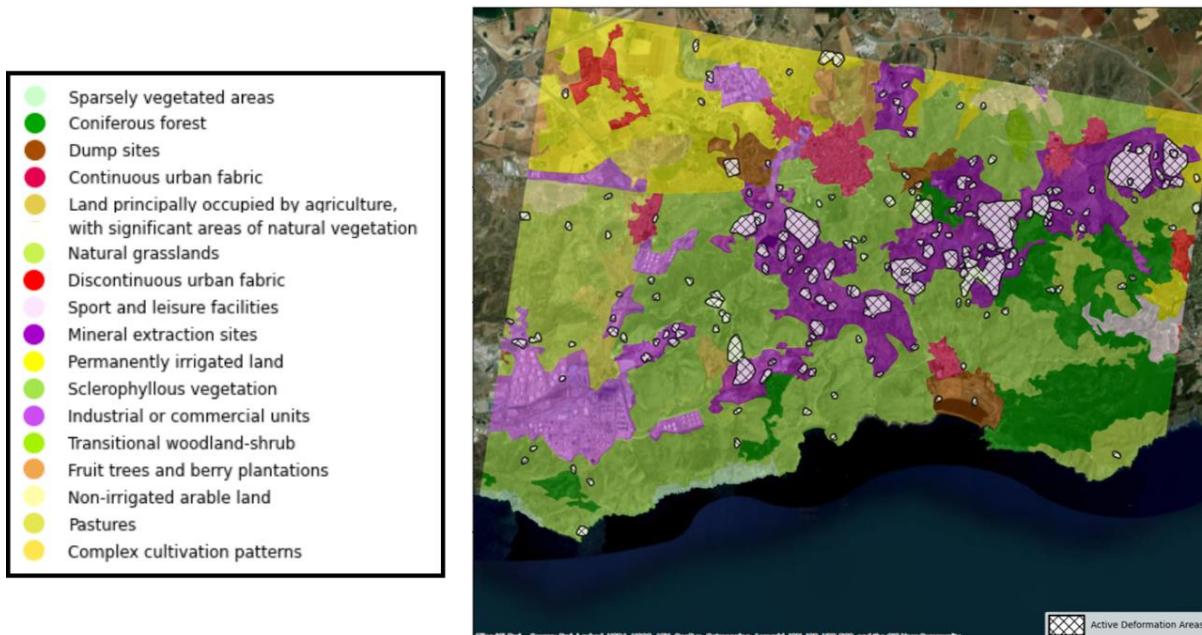


Figure 29: Active deformation areas (ADAs) superimposed on the Corine Land Cover (CLC) map for Basic/L2a products in descending orbit.

In addition, Figure 30 provides an overview of the measured areal coverage of thematic units by ADAs (in percentage) for all EGMS products. As expected for this validation site, there is a clear correlation between the presence of ADAs and the “Mineral Extraction site” class, i.e., areas impacted by mining activities.

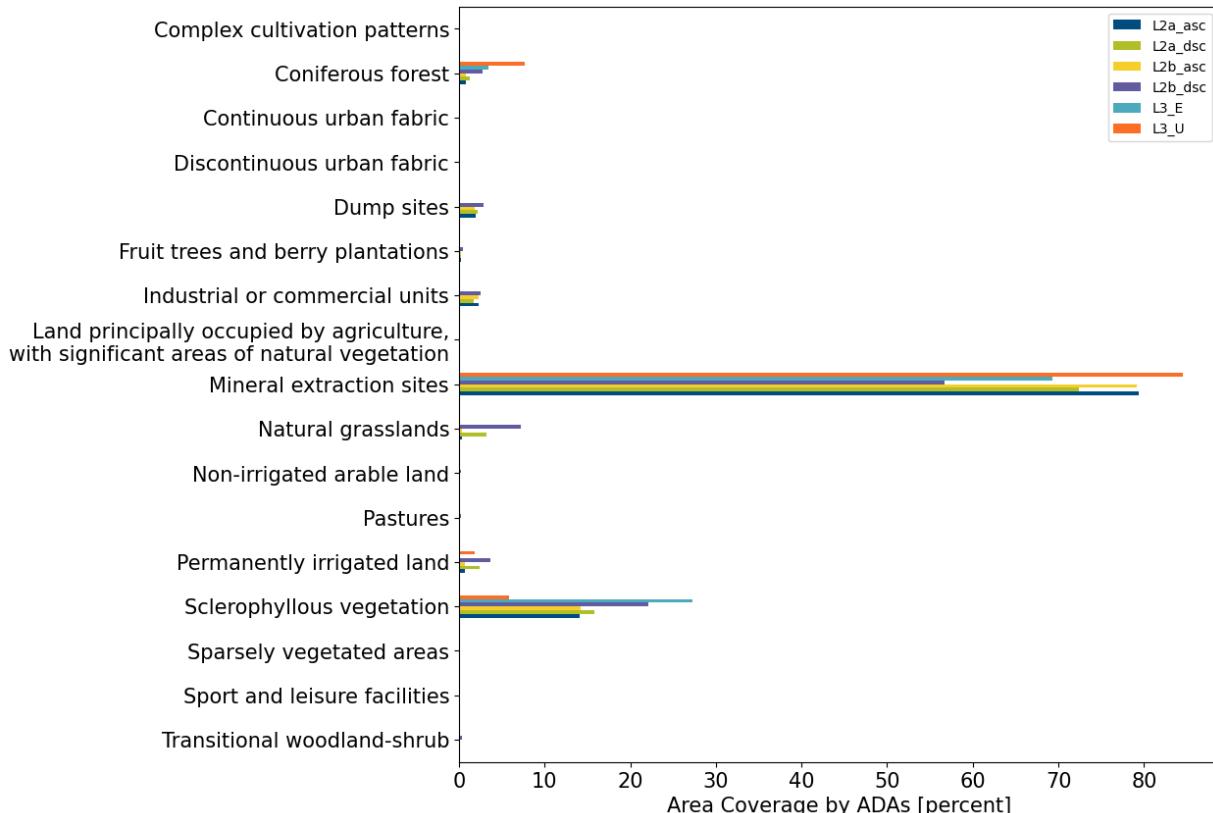


Figure 30: Measured overlap of Active Deformation Areas (ADAs) derived from Basic/L2a data with Corine Land Cover (CLC) categories in La Union. Different colour bars represent different EGMS product levels. The measured values represent the overlap of ADAs with the respective CLC category in percentage of the ADA's total area.

Do the detected ADAs correlate with expected mostly mining-related areas categories in the Corine Land Cover map?

The EGMS products are considered consistent with the Corine Land Cover map, as the detected ADAs predominantly overlap with areas classified as mining-related land cover. This demonstrates the capability of the EGMS to map active motion (if any) in such areas, within the technical boundaries of the interferometric technique.

Comparison with a mine waste inventory:

The EGMS products were also compared with an inventory of “Mine waste” and “Tailings”, where mine waste covers various types of predominantly solid waste materials, and tailings are usually deposited as slurry, mixed with substantial amounts of water. Figure 31 shows the overlap of ADAs detected for Basic/L2a ascending (a) and descending (b) datasets. In addition, Figure 32 provides an overview of the measured areal coverage of both mine waste and tailings by ADAs (expressed in percentage) for all EGMS products.

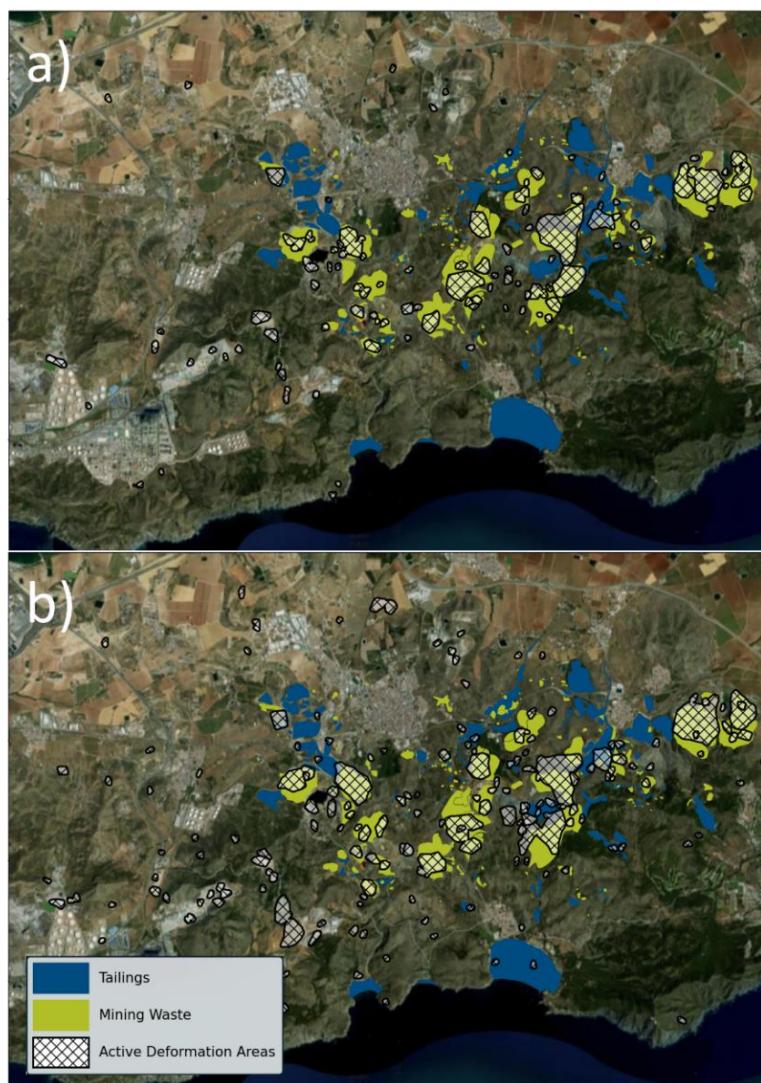


Figure 31: Ascending (a) and Descending (b) EGMS Active Deformation Areas versus mine waste land cover classes.

Visual inspection of Figures 31 and 32 reveal that many ADAs overlap with mine waste areas. However, there is only a very small overlap with tailings zones. The expected overlap with tailing areas, which typically exhibit significant subsidence due to the compaction, is not observed. It is plausible that, given that mining activities in this area ceased approximately two decades before the start of the EGMS dataset, the tailings have consolidated over time resulting in the absence of significant motion.

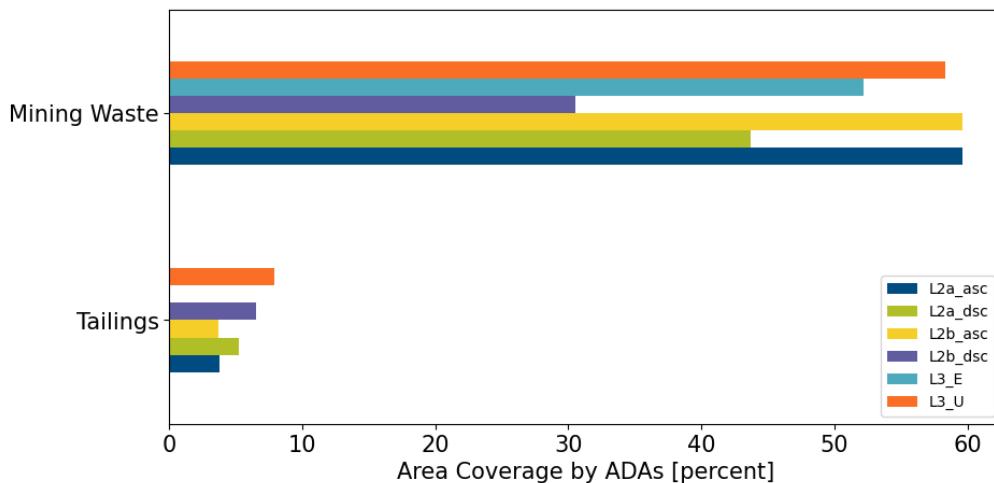


Figure 32: Measured overlap of Active Deformation Areas (ADA) with mine waste and tailings storage facilities. Coloured bars represent different EGMS product levels. The measured values represent the overlap of ADAs with the respective category in percent of the ADA's total area.

Do ADAs significantly overlap with mine waste categories?

The polygons categorised as "Mining Waste" show a significant overlap with ADAs detected in the EGMS products, unlike the "Tailings" polygons, which do not exhibit such correspondence.

Despite this, the EGMS products are still considered consistent with the mapped mine waste categories. It is plausible to assume that the tailings have been inactive long enough to have consolidated, resulting in the absence of significant ground motion.

Three additional datasets have been compared to the EGMS products: lithology, fault lines and topography. Since the motion in this region is mainly associated with post-mining phenomena, no significant correlations were found, as expected.

Conclusion for La Unión area:

The comparison with Corine Land Cover Map and mine waste categories shows that the EGMS is capable of mapping the motion of mining waste deposits and of distinguishing their state of activity.

Silesia (Czech Republic)

The validation site in Silesia, a region shared between Czech Republic and Poland, was selected due to its ongoing and active underground mining. It is one of the largest hard coal mining areas in Europe, with mining activity starting in the 19th century. The development of the mining industry was accompanied by urban growth, and currently, 37 cities collectively host almost three million inhabitants. Figures 33 and 34 show the Basic/L2a velocity maps for both ascending and descending orbits, for which all available orbits have been combined into a single dataset for ascending (orbits 73, 102, 175) and descending (orbits 51, 124).

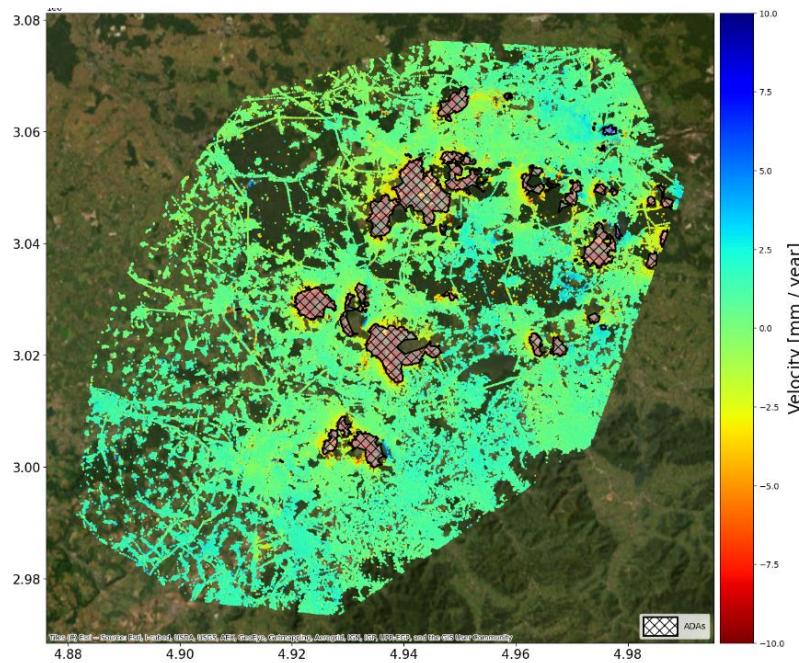


Figure 33: EGMS Basic/L2a velocity maps for the ascending orbits 73, 102, and 175 for the Silesia area with detected Active Deformation Area polygons.

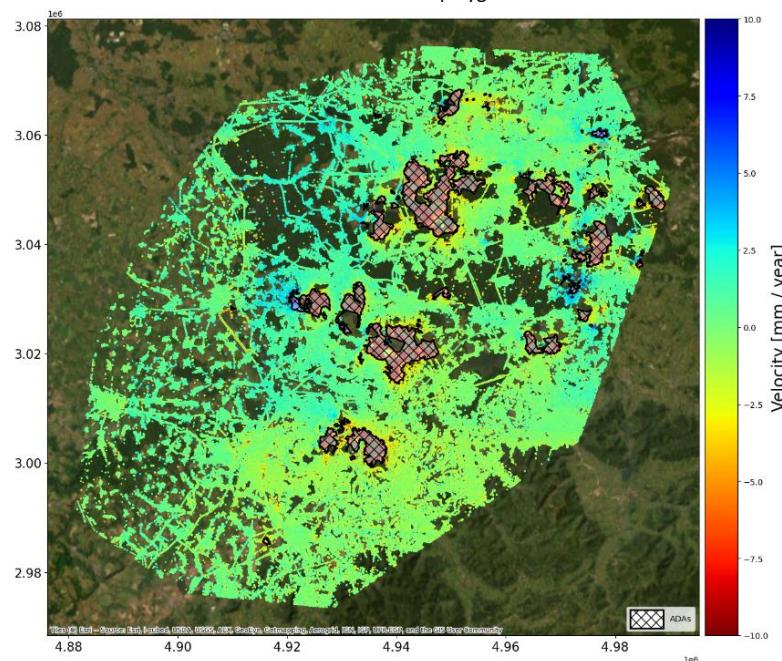


Figure 34: EGMS Basic/L2a velocity maps for the descending orbits 51 and 124 for the Silesia area with detected Active Deformation Area polygons.

Comparison with Corine land Cover:

As for the La Unión site, a comparison with CLC was conducted at the Silesia site to assess the consistency of ground displacements measured by the EGMS with land cover categories. Figure 35 show the detected ADAs alongside the corresponding land cover categories.

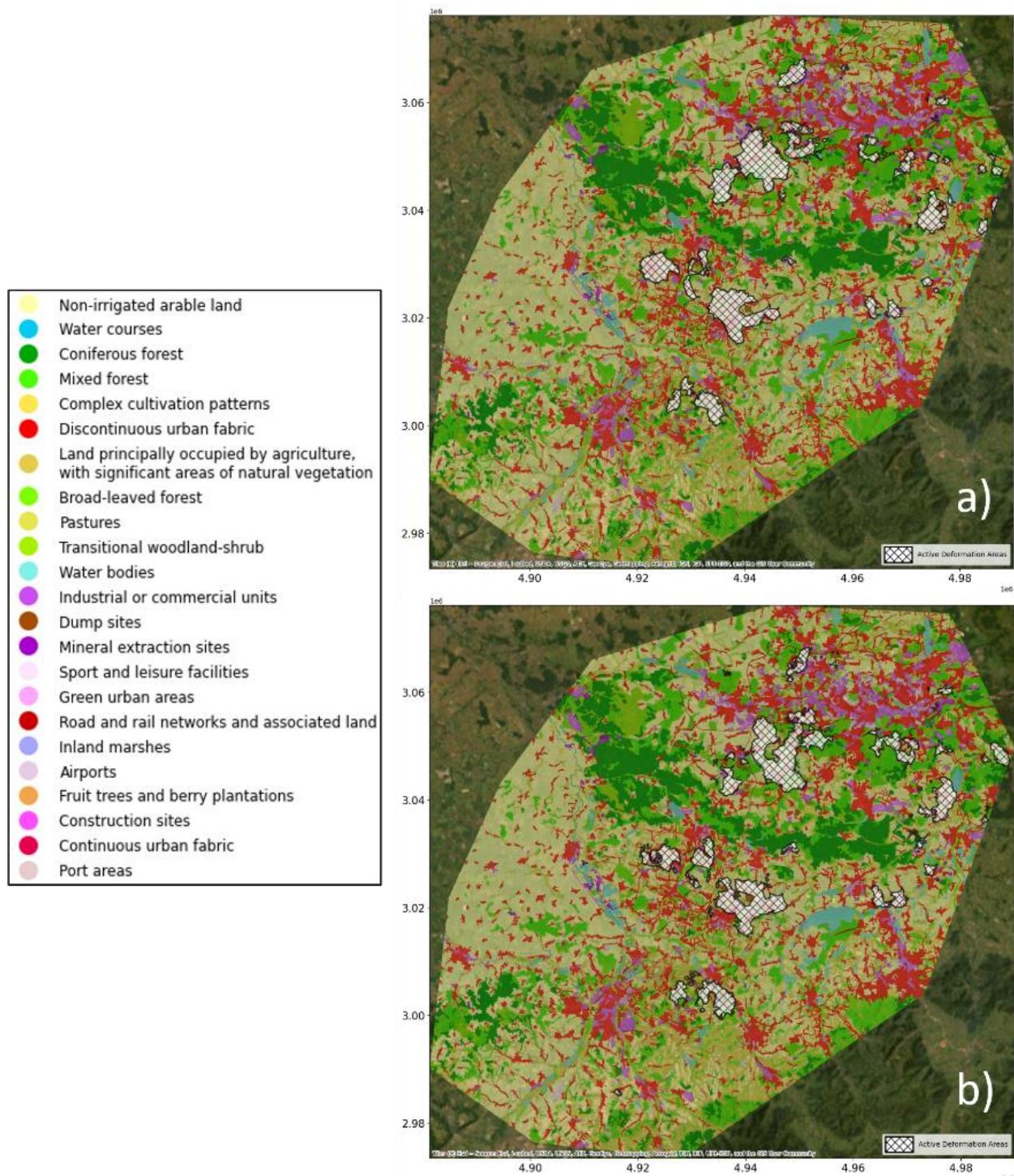


Figure 35: Active deformation areas (ADAs) superimposed on the Corine Land Cover map for Basic/L2a products in ascending (a) and descending (b) orbits for the Silesia region.

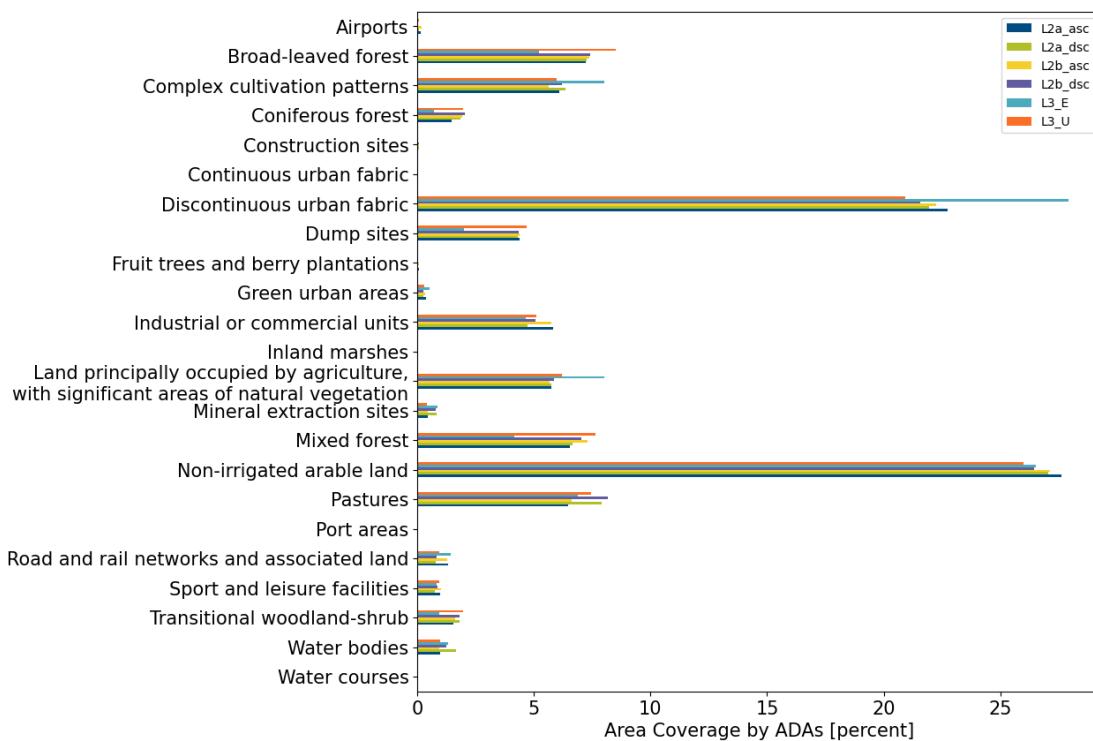


Figure 36: Measured overlap of Active Deformation Areas (ADA) with Corine Land Cover (CLC) categories for the Silesia area. Coloured bars represent different EGMS product levels. The measured values represent the overlap of ADAs with the respective CLC category in percent of the ADA's total area.

In addition, Figure 36 provides an overview of measured areal coverage of thematic units by ADAs (in percentage) for all EGMS products. Visual examination of the maps in Figure 35 reveals no clear correlation between the ADAs and any CLC category. This lack of correlation is consistent with subsidence in this area primarily being caused by underground mining activities, resulting in surface deformation unrelated to the land cover above the mined area. Nevertheless, the observed overlap between ADAs and CLC classes in Figure 36 indicates a higher overlap with two CLC categories, namely “Discontinuous urban fabric” and “non-irrigated arable land”. This can be attributed to these categories being dominant in the area, making an overlap with these categories more likely.

Do the detected ADAs show any unexpected correlation with the Corine Land Cover Map?

The number of detected ADAs only reflects the relative coverage by the different Corine Land Cover categories and there are no unexpected correlations.

Comparison with mining-related areas:

Another dataset that has been compared is an inventory of mining-related areas in the Czech Republic. As mentioned earlier, the mining activities in this region are predominantly underground. The inventory does not distinguish between different categories; thus, a single category, “Mining Areas”, is compared to the ADA locations. Figure 37 illustrates the overlap of ADAs detected in the Basic/L2a datasets for ascending orbits 73, 102 & 175 and descending orbits 51 & 124 with the mining areas.

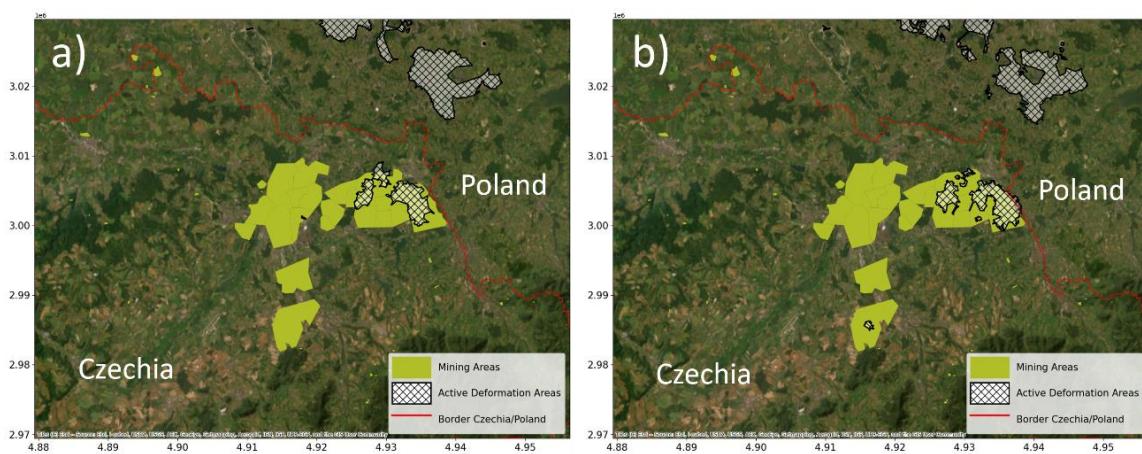


Figure 37: Locations of mining-related areas (green) plotted together with Basic/L2a Active Deformation Area locations for (a) ascending orbits 73, 102, and 175 (b) descending orbits 51 and 124 (white). The mining-related areas dataset only contains areas within the Czech territory, but not in Poland.

Both maps show a good overlap between the detected moving areas and the mining-related areas. In particular, on the eastern side, the boundaries of the ADA and the mining area exhibit a very good correlation. Additionally, the small ADA located further to the south correlates with a mining area, although it is only detected in the descending dataset in this validation. The absence of ADA over certain mining areas can likely be attributed to various factors, such as different types of mining activities and/or activities that have ceased in the past with no associated ongoing ground motion. However, detailed information on the status or type of mining activities is not available. Another possible explanation could be a lack of EGMS MPs due to fast and non-linear displacements. However, a comparison with the MP distribution in the velocity maps shown in Figures 33 and 34 suggests that this hypothesis is unlikely in the area covered by the mining-related areas map.

Do the detected ADAs correlate with mapped mining related areas?

All major detected ADAs overlap a mining related area. Absence of moving MPs over some mining related areas is most likely related to mining activities that do not or do no longer cause displacements.

Three additional datasets have been compared to the EGMS products: fault lines (Czechia only), a geologic map (Czechia only) and topography. These datasets have mostly been investigated for any unexpected correlations in this area. Since the motion in this region is mainly associated with mining activity, no significant correlations were found, including for the fault lines, which are almost exclusively outside the mining affected areas.

Conclusion for the Silesia area:

EGMS is capable of mapping ground motion related to subsurface mining, within the technical boundaries of the product. The ability to detect areas with ground displacements is not significantly affected by land cover. Non-linear deformation patterns may affect MP density and the usability of the EGMS in presence of fast motion rates.

Urban

Thyborøn (Denmark)

Thyborøn, located on a sandy barrier facing the North Sea, is vulnerable to flooding, particularly during storm surges from the adjacent Linford, due to its low elevation (1.0–2.5 m). Subsidence in this region is attributed to the overall sedimentary structure of the sand barriers, with a significant part of the hamlet constructed on highly compressible landfill layers. For validation in Thyborøn, Basic/L2a data produced by DTU were used. The focus area is the harbour, which is dominated by a single ADA. In general, a slight velocity offset between the two datasets is evident, as observed in the displacement maps in Figure 38 (a) and (b), as well as in the difference map in (c). This offset could be a result of different reference point selections. It is also worth noting that the EGMS reveals a very slight heave pattern north of the fjord, which is unexpected given the results of the previous validation exercise (see Figure 33 in validation exercise [2015-2021](#)), where the DTU product does not show the same pattern.

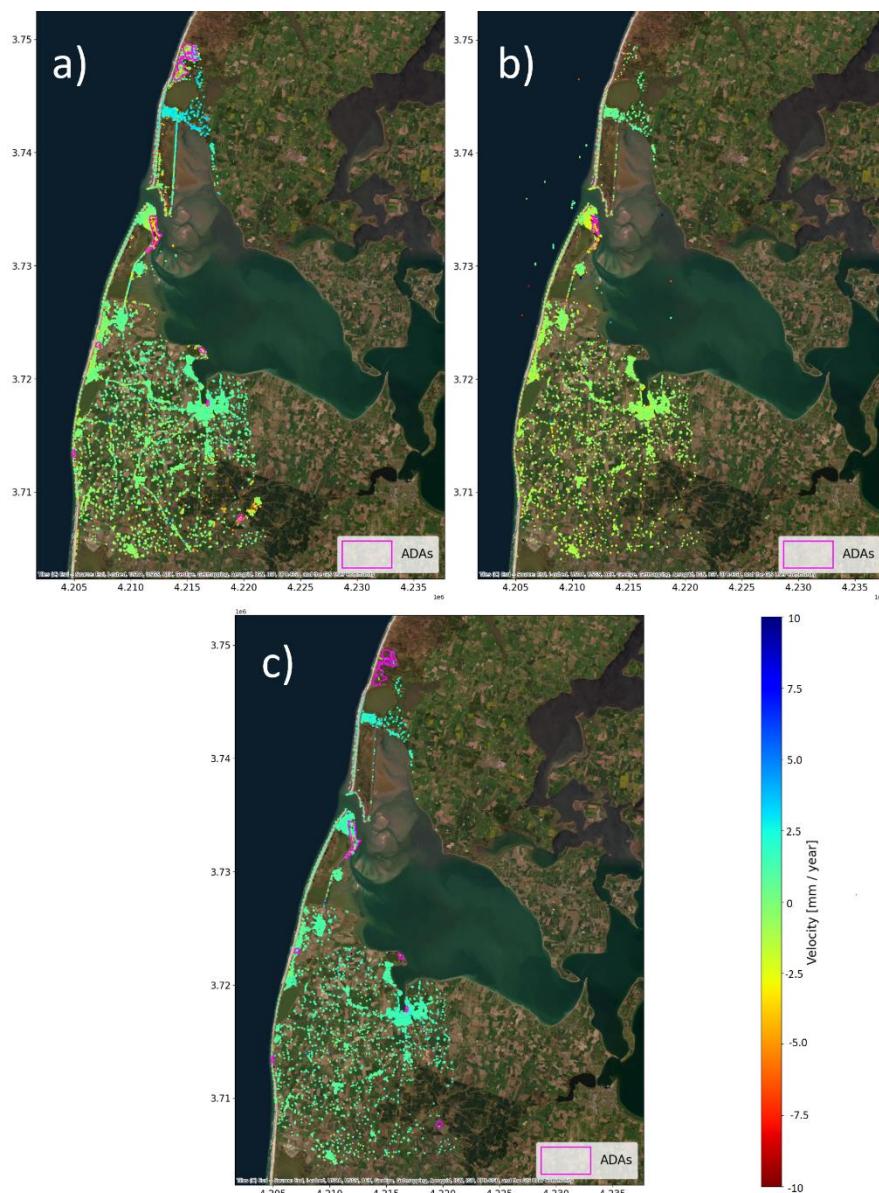


Figure 38: Comparison of Basic/L2a velocities from ascending orbit 15 for (a) the EGMS and (b) DTU-derived InSAR map; (c) velocity difference ($dvel = vel_{EGMS} - vel_{DTU}$). Active Deformation Areas are marked by magenta polygons.

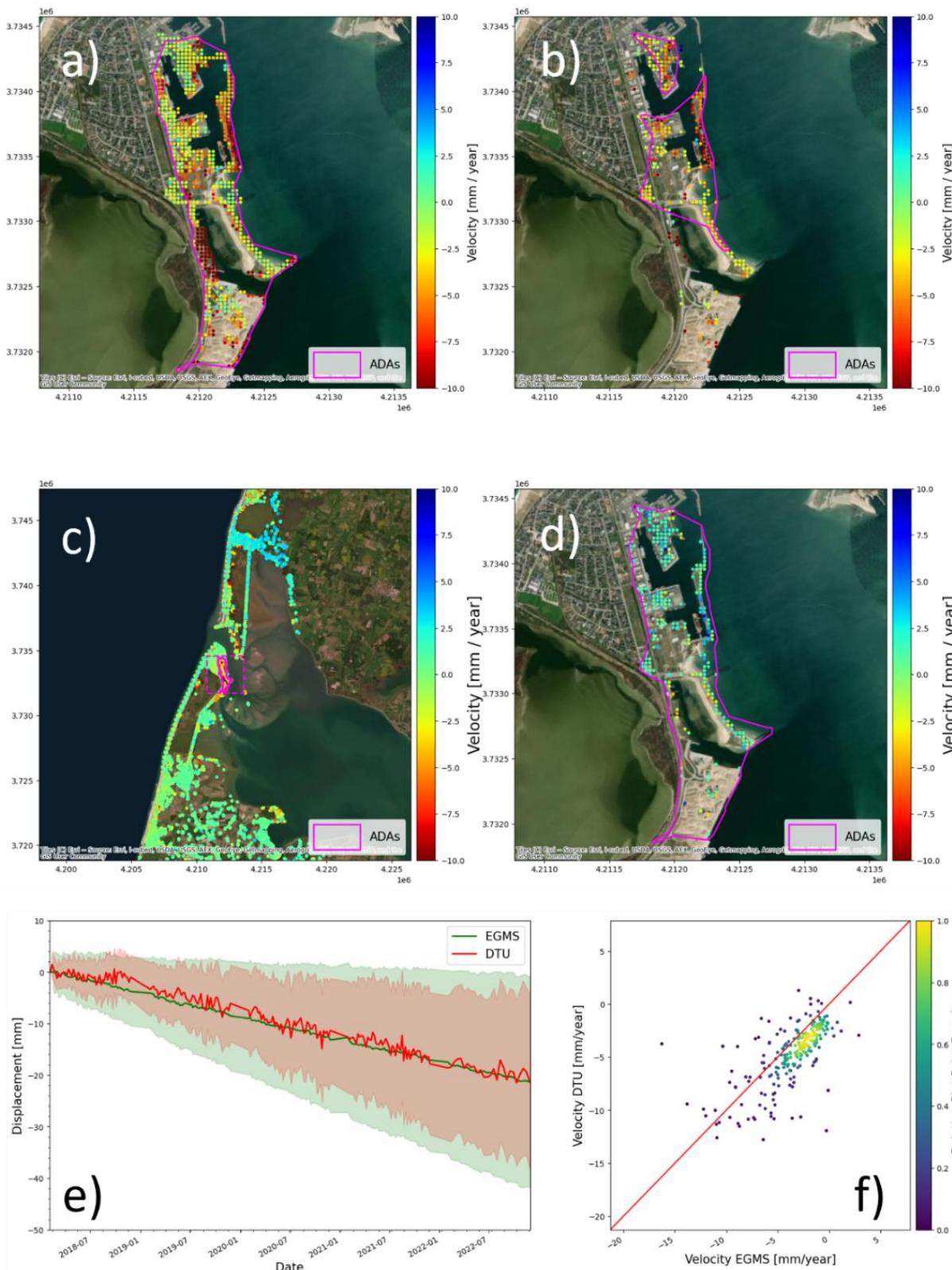


Figure 39: Zoom-in of the Basic/L2a product visualised in Figure 38, with focus on the largest Active Deformation Area (ADA) in the centre of the uplift area: (a) EGMS velocities; (b) DTU velocities; (c) overview of the ADA location; (d) velocity difference ($dvel = vel_{EGMS} - vel_{DTU}$), e) average and standard deviation of all the ADA time series; (f) velocity correlation.

Figure 39 focuses on the Thyborøn harbour area, highlighting the most significant ADA with subsidence exceeding 10 mm/year. The comparison reveals that the EGMS subsidence velocities are similar to those from the DTU dataset, although some differences are noticeable, particularly



in the northernmost part of the ADA. The EGMS data provides a higher MP density, resulting in a single large ADA instead of two separated ones. It is worth noting that both datasets have been resampled to the same spatial grid and time period but have not been referenced to the same reference point.

The averaged time series in Figure 39 (e) display nearly linear trends, with only slight variations in slopes. The associated standard deviations appear very similar, suggesting a comparable level of noise in the data. The velocity correlation plot in Figure 39 (f) exhibits a roughly linear pattern, with a shift towards positive velocity values for the EGMS dataset. This trend is consistent with the general slight offset observed between the velocity values of the two datasets in Figure 39 (d).

Table 5: Validation measures and IoAs for Thyborøn, Denmark.

Thyborøn	Validation Measure	IoA
Spatial overlap [%]	39.78	0.20
Relative Velocity Difference [%]	47.72	0.93
Velocity Correlation	0.69	0.81
Displacement Time Series Correlation	0.70	0.83
Total		0.69

For most products, slight velocity offsets that stretch over a significant portion or the entire observed area are noticeable. This mainly influences ADA detection, leading to a low IoA (0.20) for the spatial overlap when averaged across all products. However, the other validation measures produce considerably higher IoA values, indicating an overall good match between velocities and time series for the main ADA in the Thyborøn harbour area.

The overall IoA for this validation site is relatively low, primarily due to differences in ADA detection revealing slight differences in the regional velocity fields. However, as both datasets provide comparable results for the main ADA in the Thyborøn harbour area, it can still be concluded that the EGMS allows the identification of subsidence at the local scale, which aligns with one of its expected fields of application.

Oslo (Norway)

The main validation site for urban subsidence and the impact of engineering/construction works is the Municipal area of Oslo. Over the past 10 to 15 years the area surrounding the central station in Oslo has undergone extensive building and infrastructure development.

The construction activities have resulted in significant settlements in the area, primarily induced by the reduction of pore pressure, mainly attributed to water pumping associated with drilling activities. Figure 40 shows the EGMS Basic/L2a velocity maps for all available orbits in the area combined into a single dataset for both ascending (orbits 44 and 146) (a) and descending (orbits 37, 66, and 139) (b). ADA detection in the area resulted in a significantly higher number of ADAs compared to the previous validation ([2015-2021](#)), with an increase by a factor 3.7 for ascending orbit and a factor 2.7 for descending orbit. This increase is likely caused by a slightly higher level

of noise in the velocity values due to the shorter time series (2018-2022 versus [2015-2021](#) in the previous release). To address this issue, the “eps_m” parameter, which controls if MPs are considered to be “neighbours” (see [D6-Validation Methodologies](#)), of the applied DBscan algorithm was lowered from 150m to 50m. While this adjustment might cause larger ADAs to be split, it reduces the number of ADAs composed only of a number of noisy MPs with stable MPs in between.

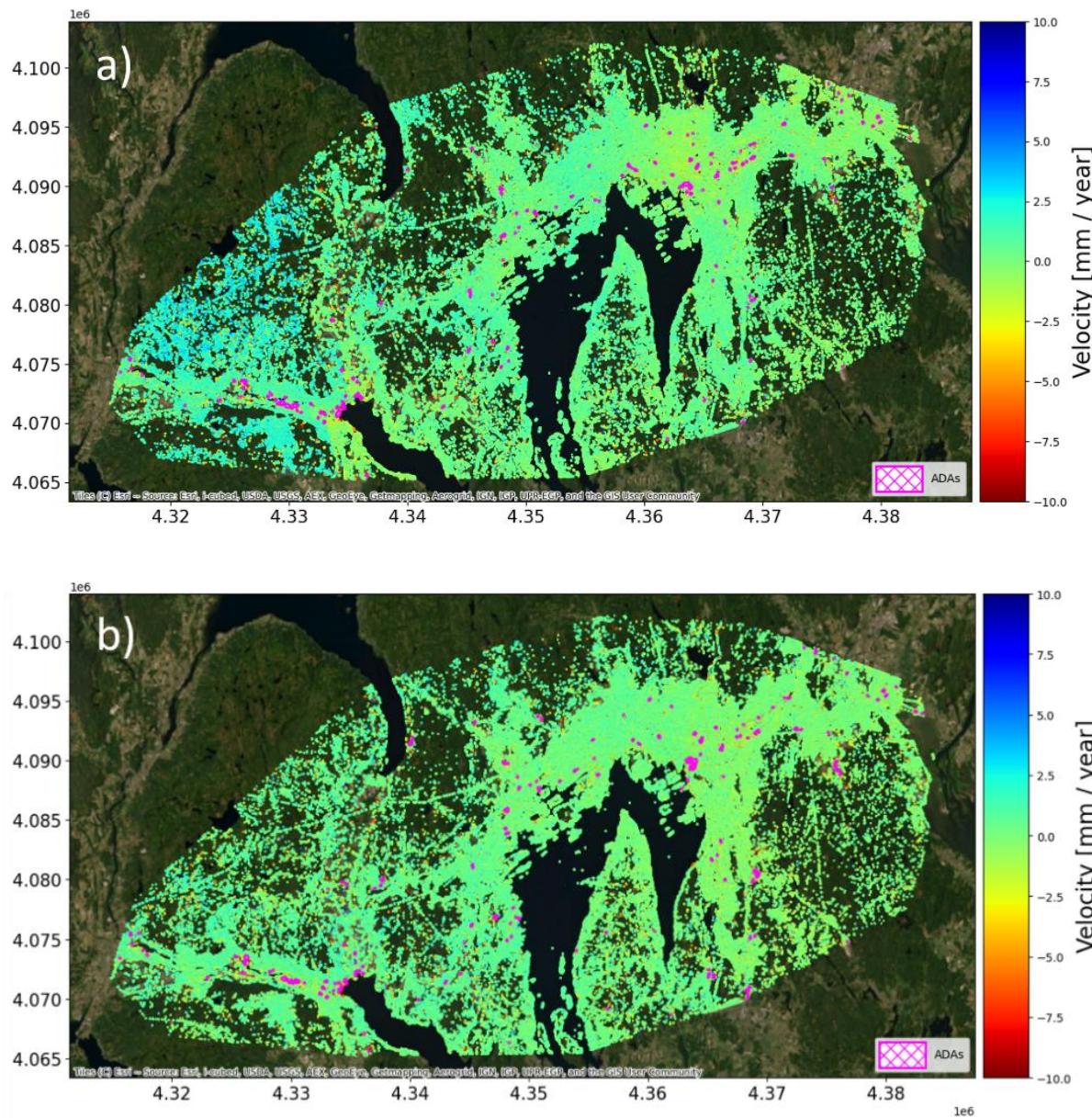


Figure 40: EGMS Basic/L2a velocity maps for ascending orbits 44 and 146 (a) and descending orbits 37, 66, and 139 (b) for the Oslo area with detected Active Deformation Areas marked as pink polygons (Basemap: ESRI)

Comparison with Corine Land Cover:

The comparison of displacement velocity patterns with the CLC map has been conducted to assess the consistency with land cover related factors contributing to ground displacement. Figure 41 (a) provides an overview of the metropolitan area of Oslo, with detailed views of Drammen and Oslo City regions presented in Figure 41 (b) and (c), respectively.

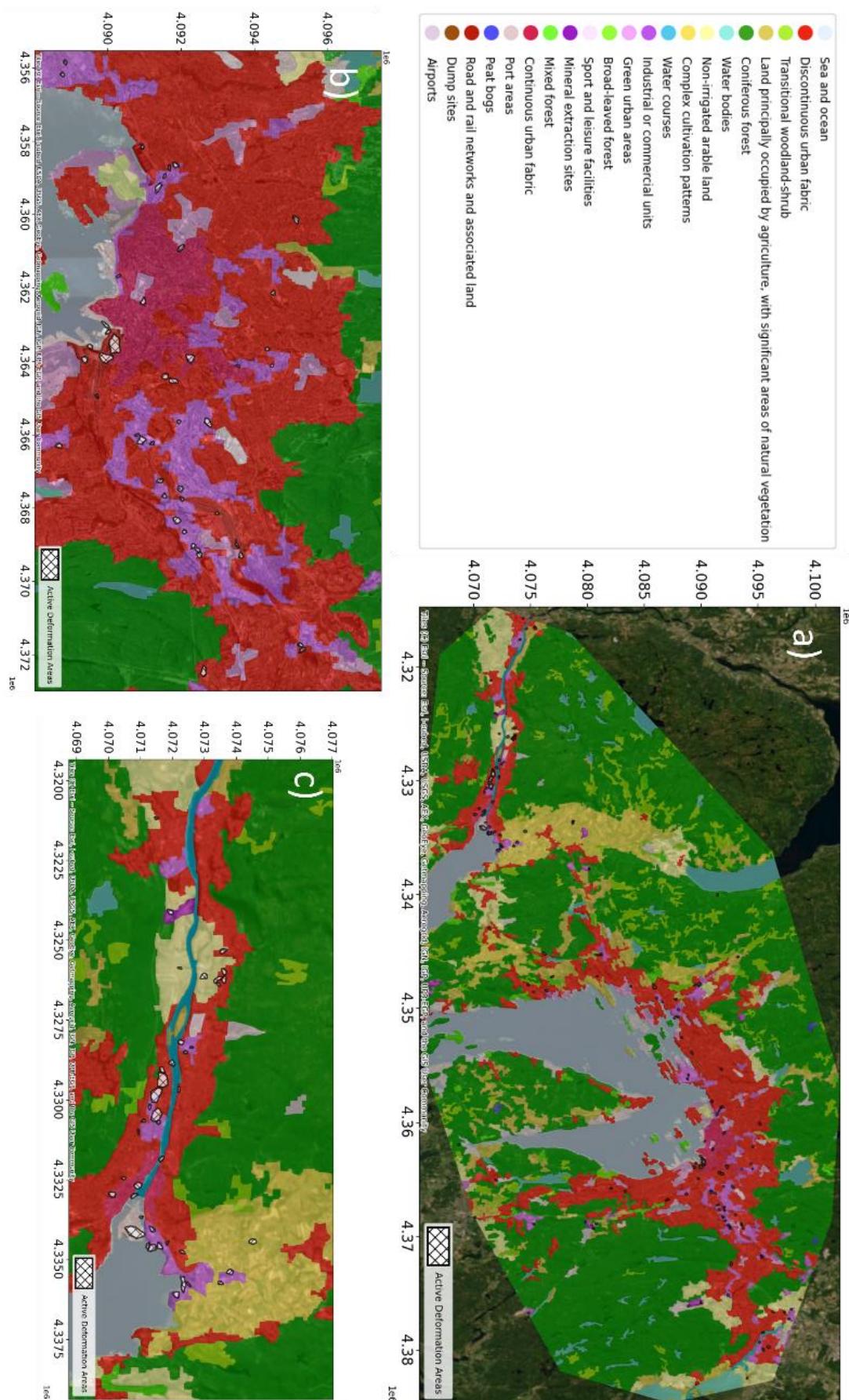


Figure 41: Comparison of Corine Land Cover (CLC) with Basic/L2a ascending Active Deformation Areas (ADA) for the Oslo municipal region. (a) CLC with ADAs overlaid; (b) Zoom-in of Drammen region; (c) Zoom-in of Oslo City region.

Figure 42 provides an overview of the measured areal coverage of thematic units by ADAs (expressed as a percentage) for all EGMS products. A clear correlation is evident, indicating subsidence primarily occurring in anthropogenic areas, especially industrial and urban fabric, as expected for this validation site.

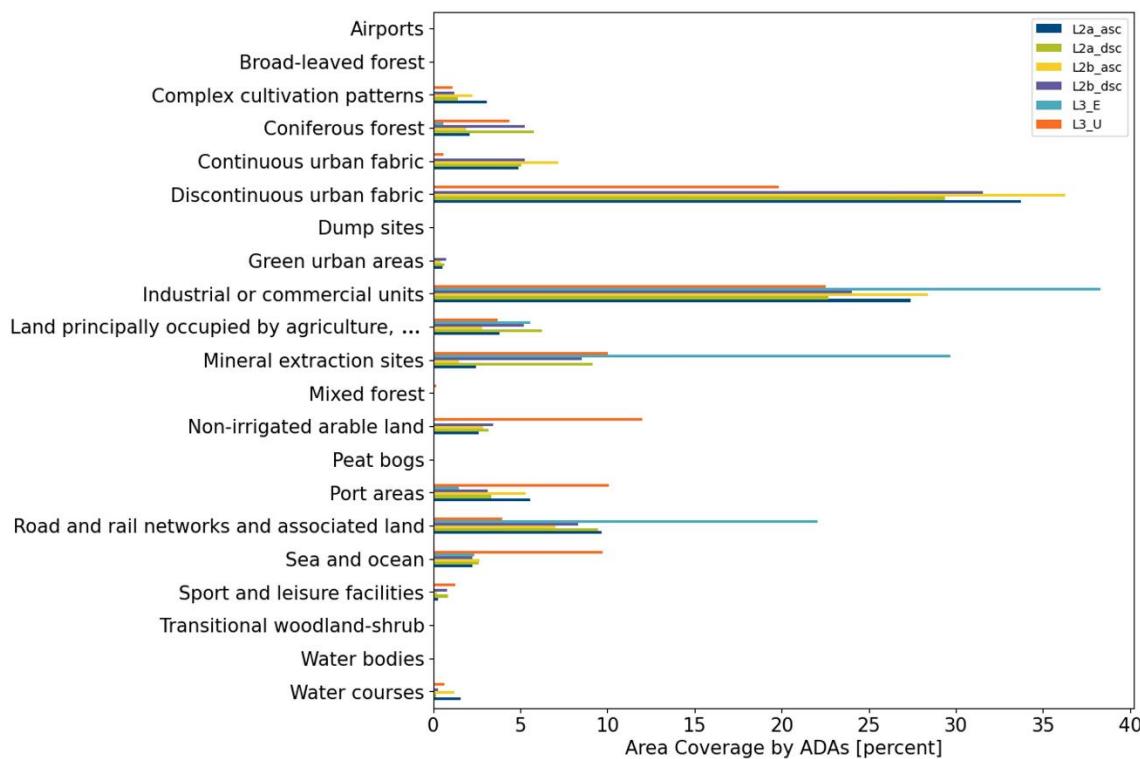


Figure 42: Corine Land Cover area (CLC) coverage with Active Deformation Areas (ADA). Colour bars represent different EGMS product levels. The measured values represent the overlap of ADAs with the respective CLC category in percentage of the ADA's total area.

Do the detected ADAs correlate as expected mostly with anthropogenic areas?

The ADAs detected in the EGMS products mostly overlap with urban and industrial areas as classified by the Corine Land Cover map.

Comparison with Quaternary Geology Map:

The comparison with geological data allows verifying whether the ground motion detected by the EGMS is consistent with the local geological or geomorphological features. Figures 43 and 44 show the comparison of a quaternary geology map with the ADAs detected for the Oslo metropolitan area. Across all products, a clear correlation emerges between the locations of ADAs and the presence of anthropogenic filling, and/or marine and fluvial deposits. These areas typically consist of compressible soils with geotechnical characteristics that make them prone to long-term compaction, thereby leading to subsidence recorded by the EGMS. Subsidence in the area is related to soft overburden, often in combination with construction activities that reduce pore pressure in these materials.

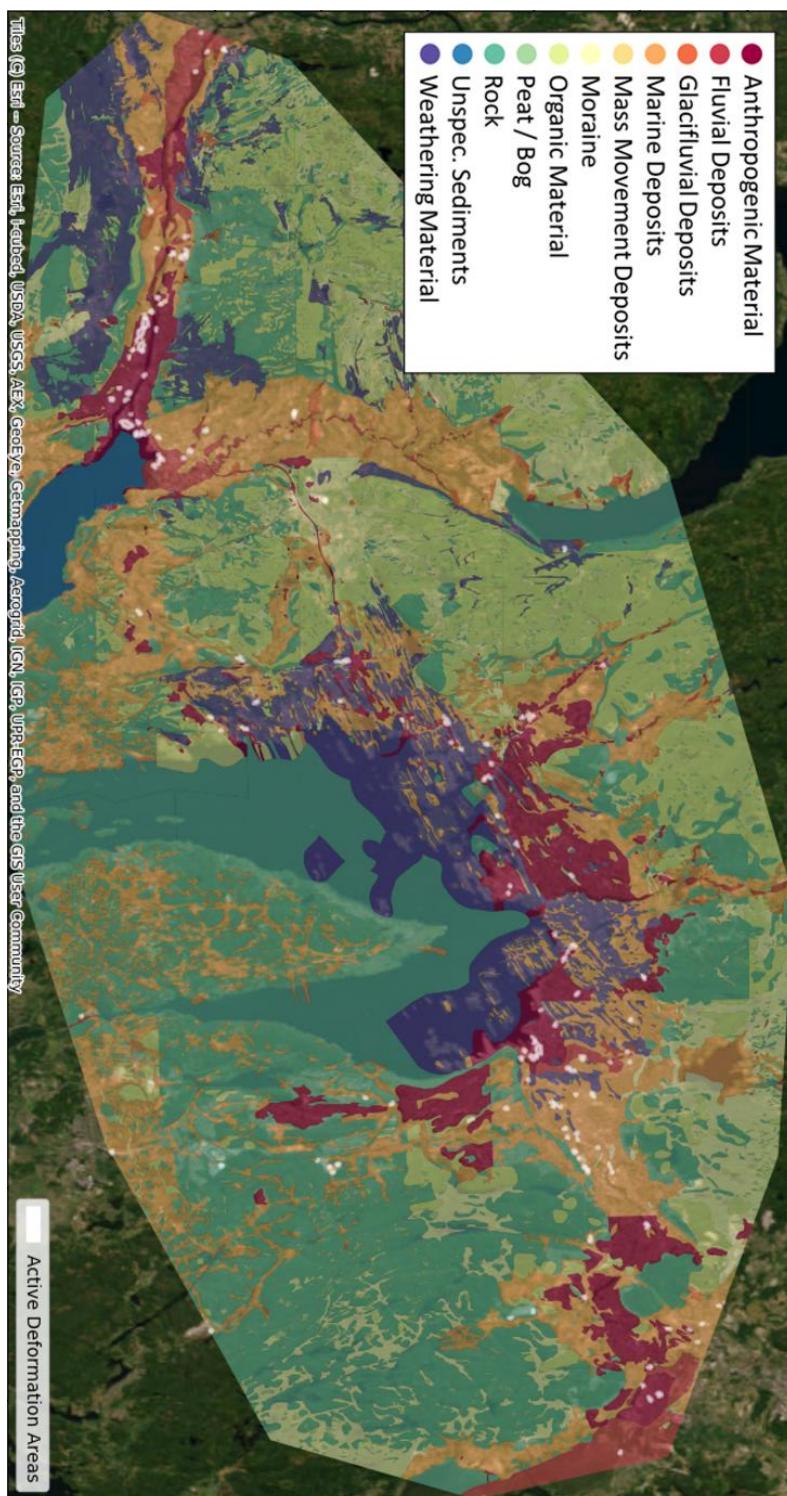


Figure 43: Comparison of detected ADA with the quaternary geology for the Oslo metropolitan area. The map shows the ADAs from the Basic/L2a ascending orbits in yellow overlain onto the quaternary geology (Basemap: ESRI)

Do the detected ADAs correlate with soft layers?

The ADAs detected in the EGMS products mostly overlap with sedimentary layers (marine and fluvial deposits) and anthropogenic material. This is coherent with the initial hypothesis.

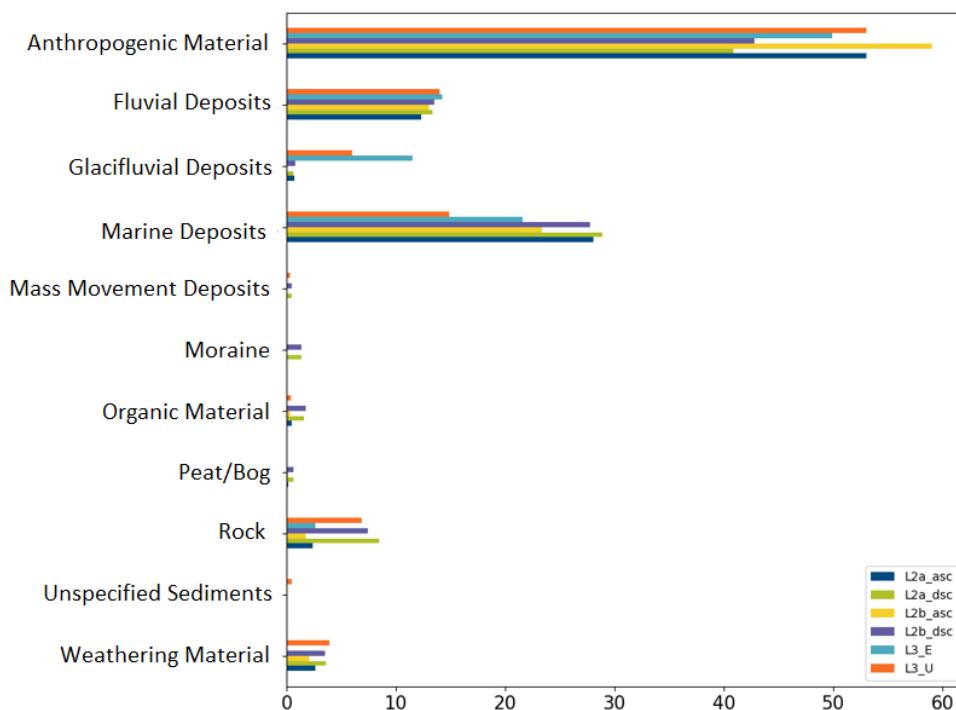


Figure 44: Bar plot showing the overlap of the different geological units by Active Deformation Areas (ADA). Coloured bars represent different EGMS product levels. The measured values represent the overlap of ADAs with the geological unit in percent of the ADA's total area.

Comparison with Depth to Bedrock Map:

Figure 45 depicts the thickness of the overburden layer “depth to bedrock” for Oslo compared with the ADAs detected for the Basic/L2a ascending orbits 44 and 146. In areas with soft overburden layers, the thickness of these layers is expected to have an impact on the magnitude of subsidence. Assuming the same urban setting, an area with the maximum thickness of compressible soil will experience the highest subsidence rates. However, the presence of new buildings may accelerate this process. While the depth to bedrock map does not cover all identified ADAs, there is a clear correlation in several locations between the thickness of the overburden and the location and extent of the ADAs. This correlation is particularly evident for the two larger ADAs near Oslo Central station in the lower centre of the map.

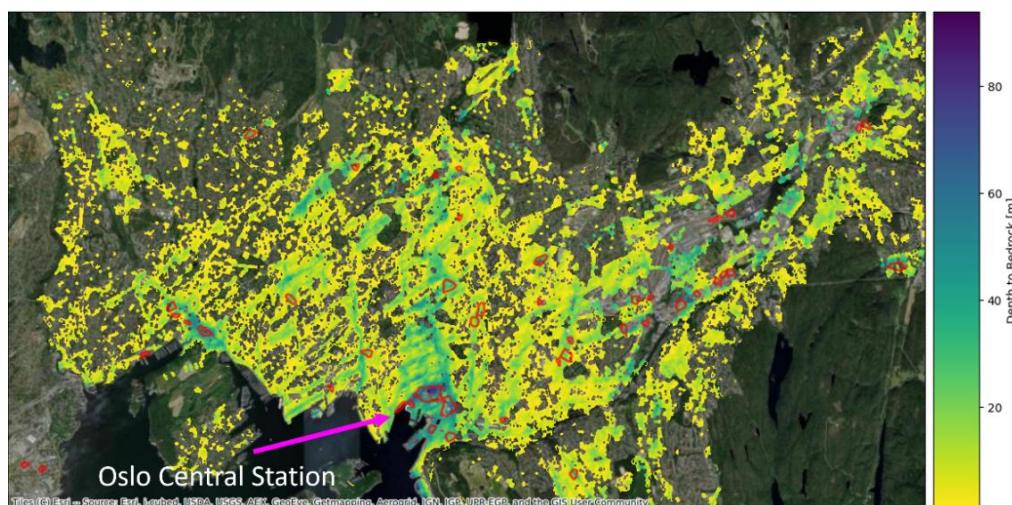


Figure 45: Active Deformation Areas (ADA, red polygons) detected in the EGMS Basic/L2a ascending (all orbits combined) plotted with soft soil thickness.

Do the detected ADAs show a correlation with areas of higher depth to bedrock?

There is a clear correlation between the presence of moving points and areas of increased depth to bedrock. In the case of the Oslo Central station, the ADAs correlate well with the shape of the areas with deeper bedrock.

Two additional datasets, a bedrock map and topography, have been compared to the EGMS products. The findings from both datasets confirm that ADAs are mostly located in areas hosting thick sedimentary sequences. The topography analysis reveals that ADAs are almost exclusively situated in flat areas.

The high degree of consistency demonstrated across all the EGMS datasets underlines the EGMS's capability to reliably map anthropogenic ground deformation phenomena within an urban environment.

Po delta (Italy)

The Po River delta, covering an approximate area of 400 km², is a complex ecosystem shaped by sedimentary processes and influenced by human activities such as ground water pumping. Figure 46 shows a comparison of displacement velocities for the Po River delta between EGMS Basic/L2a ascending orbit 117 and the regional GMS provided by the Regione del Veneto (RDV, Veneto Region). The comparison reveals discrepancies across a broad area in the Po River delta, with the EGMS data indicating stronger subsidence rates than the RDV data. This difference has already been observed in the validation of the previous EGMS release (see Figure 41 in the validation exercise [2015-2021](#)), where the difference was even larger .

Figure 47 shows the same comparison for Basic/L2a descending orbit 95, which confirms that the EGMS observes subsidence in the delta area, while the RDV data does not. As already argued in the report for the [2015-2021](#) update, existing literature has consistently reported subsidence in the Po River Delta [Faris et a, 2014; Faris et a, 2022; Cenni et al, 2021], and therefore, it is reasonable to infer that, for this area, the EGMS provides a more accurate reflection of large-scale deformation patterns compared to the regional GMS, whose data processing is focused on detecting local phenomena.

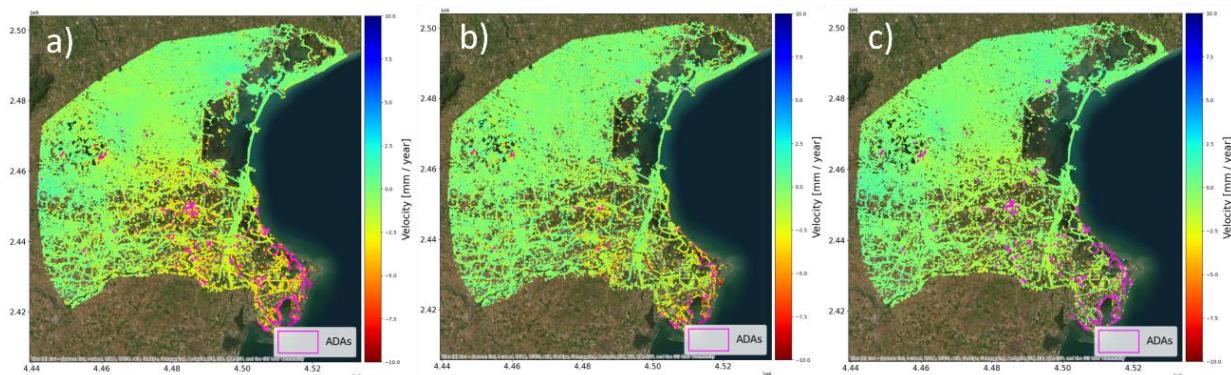


Figure 46: Comparison of displacement velocities for the Veneto validation site: (a) EGMS Basic/L2a ascending orbit 117; (b) Regione del Veneto GMS; (c) Velocity difference between (a) and (b).

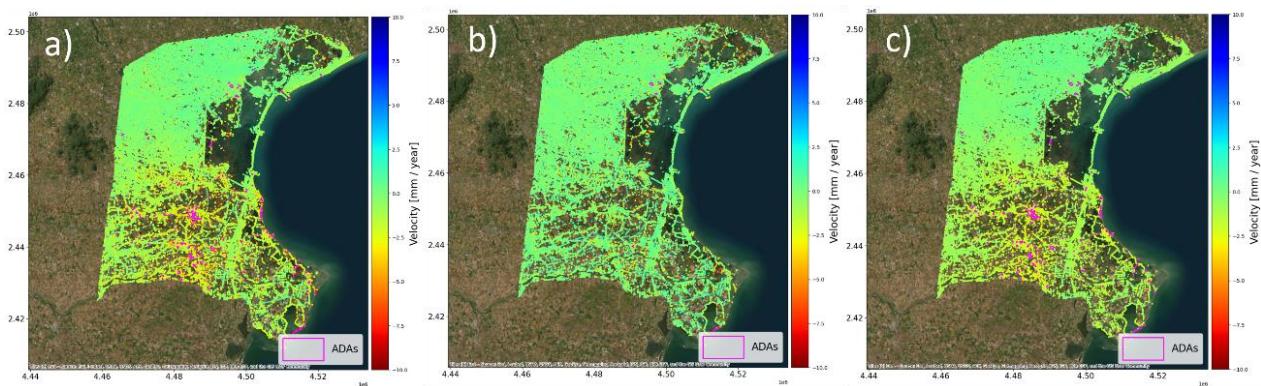


Figure 47: Comparison of displacement velocities for the Veneto validation site: (a) EGMS Basic/L2a descending orbit 95; (b) Regione del Veneto GMS; (c) Velocity difference between (a) and (b).

The relative velocity difference for the identified ADAs is approximately 40%. However, because of the rather smooth and large-scale, but low amplitude nature of the velocity difference, the majority of ADAs detected in the EGMS is not detected in the Regione del Veneto dataset, which results in a very low IoA of 0.08 for the spatial overlap. The velocity and time series correlation again indicate relatively good agreement, which also can be attributed to the rather smooth and large-scale, but low amplitude nature of the velocity difference and the strong linearity of the time series in both datasets. The resulting IoA for the comparison with the data provided by the Regione del Veneto is 0.72.

Table 6: Validation measures and IoAs for Po River Delta

Veneto	Validation Measure	IoA
Spatial overlap [%]	34.13	0.08
Relative Velocity Difference [%]	40.99	0.96
Velocity Correlation	0.72	0.86
Displacement Time Series Correlation	0.78	0.96
Total		0.72

Conclusion for the Po delta area:

The comparison for the Veneto area results in an IoA of 0.72, which means that differences between EGMS and RDV products were found.

However, these differences are confined to the area of the Po River delta, and based on literature, it can be concluded that the EGMS products are able to capture the large-scale deformation of the Po Plain which cannot be captured by the regional dataset because of the smaller size of the processed area and the processing strategy being focused on local phenomena.

The ability of the EGMS to detect both large and detailed scale ground motion patterns is confirmed.

Tagus Valley (Portugal)

The Lower Tagus Valley in Portugal (Figure 48) is historically associated with damaging earthquakes impacting the Greater Lisbon Area, the region presents seismic hazard (see e.g., Carvalho et al, 2017). Additionally, potential effects on various projects, such as CO₂ storage, geothermal endeavours, and underground energy storage, need consideration (Pereira et al, 2013). Beyond earthquake activity, subsidence is suspected to result from the compaction of a clay-rich aquitard, led by the over-exploitation of adjacent aquifers.

The comparative analysis of EGMS products focused on fault lines, considering previous studies that reported ground displacements either related to or correlated with the presence of fault lines due, for example, to their influence on local geology and acting as hydrogeological barriers (Heleno et al, 2011). However, it has to be noted that the fault lines have been mapped through geological interpretation and they are not classified as seismogenetic sources. Therefore, ground motion may be caused by other factors, such as anthropogenic activities.

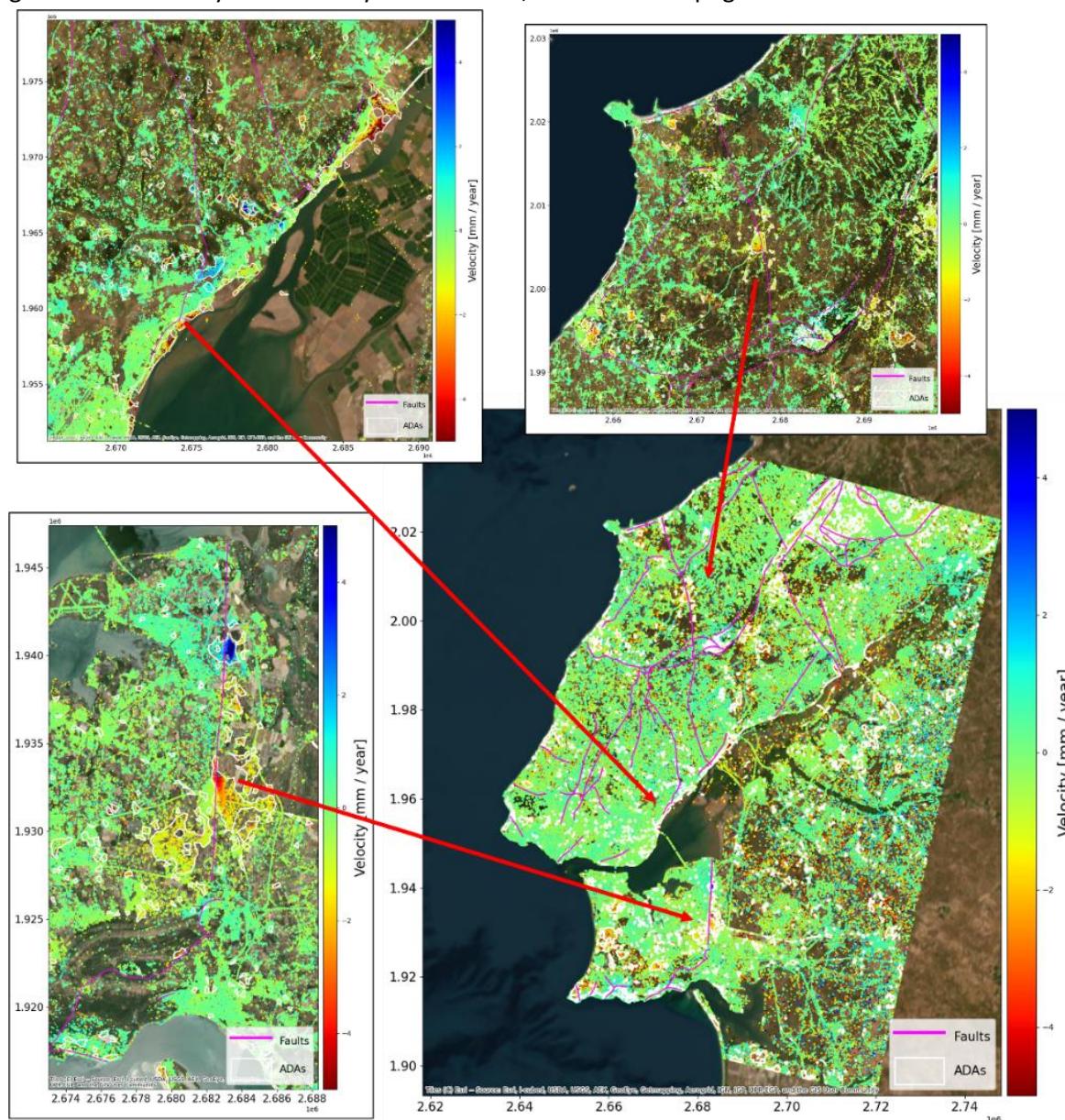


Figure 48: EGMS Basic/L2a velocity maps (ascending orbits 45 and 147) for the Tagus Valley highlighting fault lines (magenta) alongside detected Active Deformation Areas (white polygons). Zoom-in views show the locations indicated by the red arrows.



As already mentioned above, it should be emphasized that a correlation of ground deformation with a fault line does not necessarily mean that the fault is the direct cause of the observed deformation. A fault may also act as a geological “barrier” for e.g. groundwater flow, either facilitating or hindering the extraction of water and thus potentially acting as a predisposing factor for subsidence.

Do you see the expected effect of fault lines on displacement patterns?

Several ADAs show a correlation between their location and the position of a fault line. However, this does not indicate that the faults are generating the motion.

Three additional datasets have been compared to the EGMS products: CLC, a geological map and topography. These datasets have been investigated for any unexpected correlations; however, none were observed.

Conclusion for Tagus Valley:

Co-occurrence of a fault and displacements may be due to an active fault or due to a fault acting as geological barrier for displacements caused by other factors (e.g. groundwater exploitation). As faults may also be inactive and unrelated to external displacements sources, a direct correlation is not expected.

However, several co-occurrences between ADA location and the presence of fault lines have been observed. Note that there might not be correlation between motion detected and seismicity.

Groundwater exploitation

Lorca (Spain)

The Alto Guadalentín valley in Spain has been selected as a validation site due to the extensive subsidence resulting from prolonged ground water extraction, marking the largest subsidence area of its kind in Europe. The basin contains a multi-layer aquifer system spanning approximately 277 km², which has been subjected to water extraction over the past 50 years. This extraction has led to a decline in pore water pressure, triggering a gradual compaction of the sediments and subsequent lowering of the ground surface.

Figure 49 depicts the soft soil thickness dataset available for the Alto Guadalentín valley, clipped at the 5m thickness contour, and compares this data with the EGMS Ortho/L3 vertical displacement velocities and the ADAs derived from this EGMS product. The ADA almost exactly aligns with the 5m thickness contour, demonstrating a very strong correlation between the soft soils thickness and measured subsidence velocity. This correlation is particularly evident in the central region of the ADA, where thickness and subsidence rates peak, and near the southwest end of the ADA, where a slight thickness increase coincides with an increase in subsidence rates.

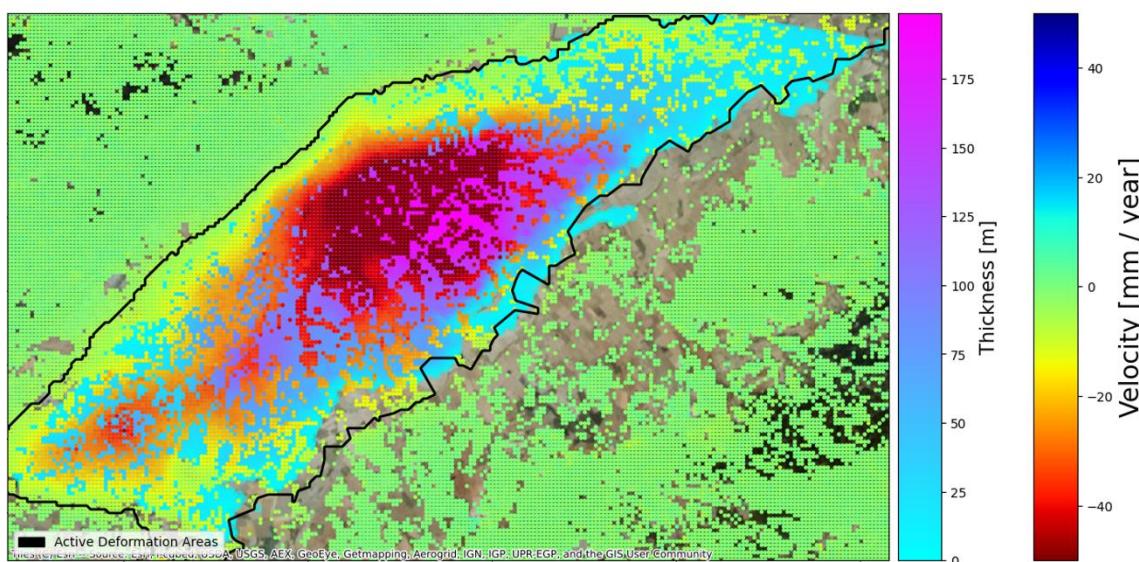


Figure 49: EGMS Ortho/L3 vertical and detected Active Deformation Areas (black line) co-plotted with soft soil thickness.

Do the mean velocity values of the EGMS correlate spatially with soft soil thickness?

The major ADA shows a clear correlation with the outline of the area with soft soil thickness higher than 5 m. Also, local maxima in the soft soil thickness map correlate well with local maxima in the subsidence rates mapped by the EGMS.

Figure 50 illustrates a comparison between the detected ADAs and the EGMS displacement velocities (Ortho/L3 vertical dataset) with a ground water model derived from piezometric levels (this will be assessed in the accuracy section 3.2.2).

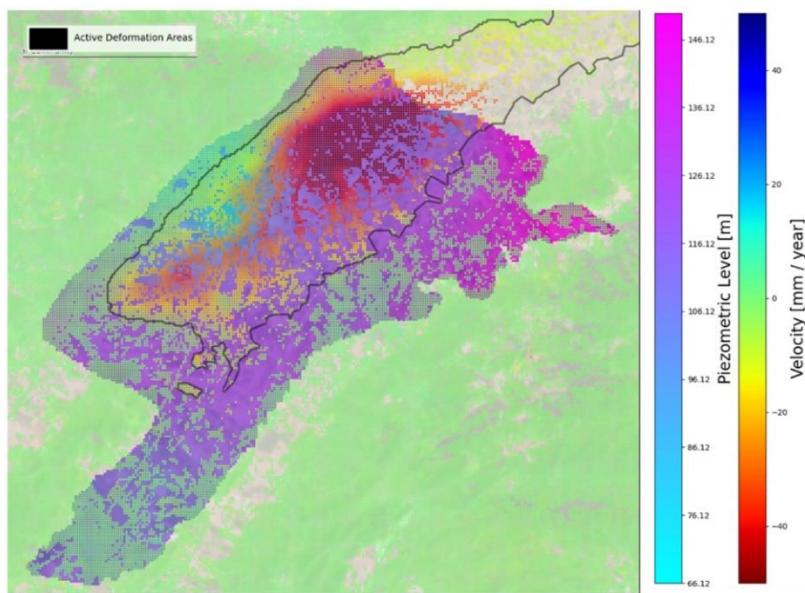


Figure 50: EGMS velocity maps in for Ortho/L3 vertical compared with a ground water model given as piezometric levels for the Lorca area.

It is worth noting that this ground water model is referred to 2012, six years before the start of the EGMS time series. Still, the expectation is that patterns in the subsidence field should correlate with those in the piezometric levels, as they reflect the degree of ground water exploitation. While a correlation can be observed, the locations of highest piezometric level and highest subsidence rate are spatially shifted.

Do the piezometric levels from the ground water model show a correlation with areas of higher velocities in the EGMS datasets?

Although some correlation can be observed between piezometric levels and subsidence, the peaks in both datasets are not perfectly collocated, i.e., the area with the lowest piezometric level is located slightly west of the area of maximum observed subsidence in the EGMS.

Three additional datasets were compared to the EGMS products: CLC, well locations and topography. These datasets were investigated for any unexpected correlations; however, none were observed.

Conclusion for Lorca (Spain):

The comparison of the EGMS products with ancillary geoinformation for Lorca area shows correlations as expected. The highest correlation was found with the soft soil thickness, suggesting that this is the most important factor explaining the amplitude of the subsidence. The ground water model also shows a correlation, although the peaks in both datasets are not perfectly spatially aligned. Nevertheless, the comparison for Lorca clearly demonstrates the ability of the EGMS to map ground displacements caused by ground water extraction in very high detail.

Volcanism

Etna Volcano (Italy)

The validation site at **Mount Etna** was selected due to its active volcanism, being the largest active volcano in Europe. The area is particularly interesting for its abrupt surface deformation phenomena, such as those resulting from the earthquake connected to the onset of the eruption that took place from 24–27 December 2018. Mount Etna is a highly dynamic volcanic system characterized by summit eruptions from five craters and fissure eruptions mainly clustered along three rift zones extending from the summit toward the northeast, south, and west (Cappello et al., 2013). Given the specific purpose of this analysis, a separate ad-hoc InSAR processing was conducted by IREA, resulting in the availability of all products levels for comparison with EGMS products.

Figure 51 shows the comparison of Basic/L2a displacement velocities, revealing an overall good spatial agreement between the datasets. Consequently, the detected ADAs exhibit notable similarities in size and form. Despite some differences in coverage, particularly in the crater region due to the different definition of MPs in the processing algorithms, the overall spatial agreement is very good. A detailed examination of the velocity maps for the ADA on the eastern flank shows that also the velocity values are in good agreement, while for most areas the IREA dataset shows only slightly higher velocity values (Figure 51).

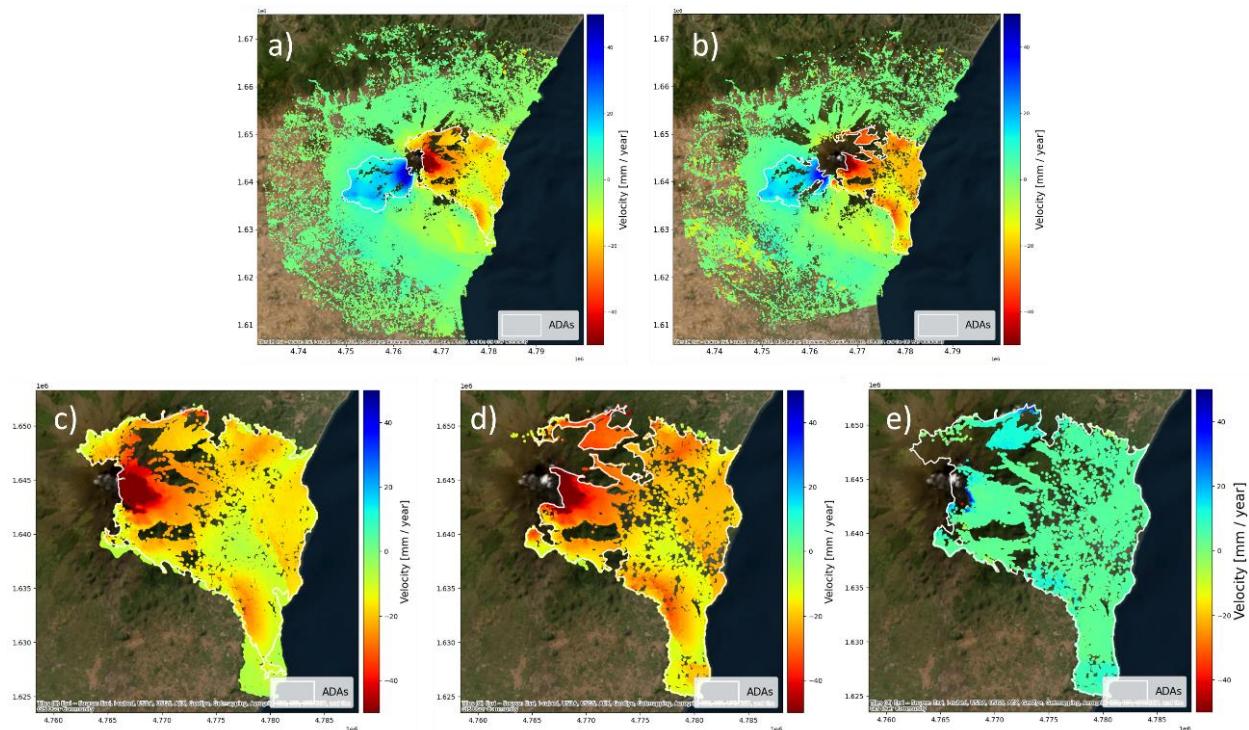


Figure 51: Comparison of EGMS velocities with those provided by IREA for the Basic/L2a ascending orbit 44: (a) EGMS velocities; (b) IREA velocities; (c) EGMS velocities for the eastern ADA; (d) IREA velocities for the eastern ADA; e) velocity difference for the eastern ADA ($dvel = vel_{EGMS} - vel_{IREA}$). ADAs are marked by white polygons.

The displacement time series for the same ADA, illustrated in Figure 52 (a), also show a moderate level of agreement between the two datasets. This includes the sharp drop in the time series corresponding to the earthquake associated with the eruption onset in December 2018. The velocity correlation plot in Figure 52 b) further confirms this agreement, showing an almost

linear relationship with only an offset from the diagonal (red line), indicating the generally slightly higher velocities observed in the ADA in Figure 51. It is important to note that a large-scale continental processing strategy (EGMS) is being compared to an ad-hoc InSAR processing tailored to the phenomena of interest in the area.

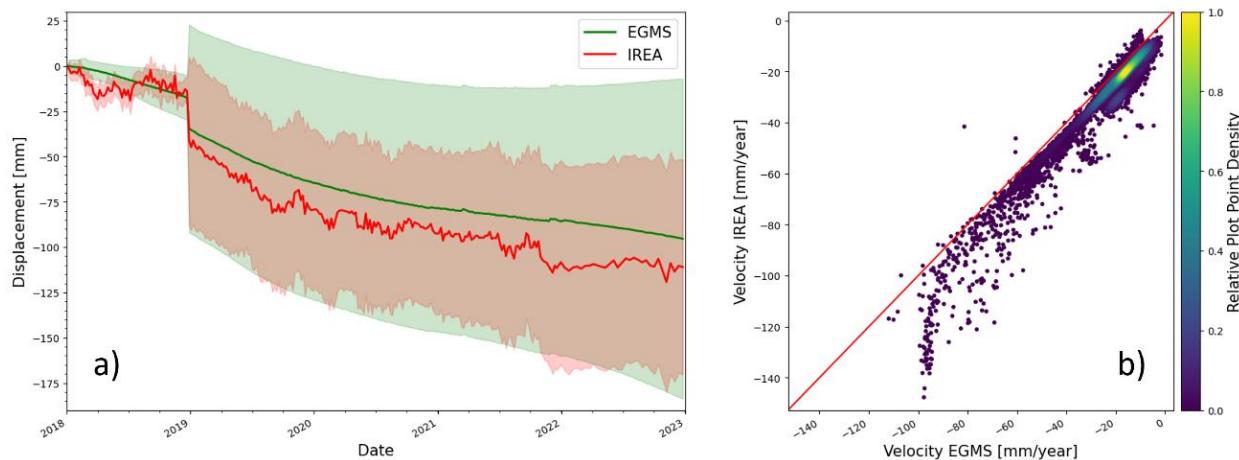


Figure 52: Time series and velocity correlation for measurement points within the Active Deformation Area shown in Figure 51. (a) average and standard deviation of displacement time series; (b) velocity correlation.

Table 7 provides a summary of all validation measures averaged across all products, along with the resulting IoAs. The table demonstrates that a very good match is observed for all validation measures. Compared to the previous validation of the [2015-2021](#) datasets, the match for the relative velocity difference and the velocity correlation have improved.

Table 7: Validation measures and IoAs for Etna.

Etna	Validation Measure	IoA
Spatial overlap [%]	94.44	1.00
Relative Velocity Difference [%]	37.36	0.97
Velocity Correlation	0.91	1.00
Displacement Time Series Correlation	0.94	1.00
Total	0.99	

Conclusion for Etna Volcano:

The comparison of the EGMS and IREA products results in an IoA of 0.99, reflecting an excellent match between the datasets despite the dynamic character of the volcanic system and the highly non-linear time series. This demonstrates the EGMS's capability to reliably map displacements under challenging conditions.

3.2 Consistency/Accuracy

This section aims to evaluate the accuracy of the EGMS portfolio in estimating ground motion across certain thematic areas. Specifically, the goal is to evaluate the EGMS's accuracy within the context of several applications, determining how effectively the data can quantitatively describe specific ground motion phenomena. Figure 53 provides an overview of the validation sites. Detailed descriptions of the data and sites can be found in [D3-Validation Data Collection](#) and [D5-Validation Areas](#).

Table 8: Overview of validation sites (Consistency/Accuracy).

	Validation with GNSS data	Validation with in situ data	Position and displacement validation with CR
Landslides	<i>Not evaluated</i>	Tyrol (AT)	Indre Nordnes, Jettan and Gamanjuni (NO)
Mining and post-mining	<i>Not evaluated</i>	Turow (PL) Lorraine (FR)	<i>Not evaluated</i>
Urban / Anthropogenic	Jutland (DK) Gran Canaria (ES)	<i>Not evaluated</i>	Thyborøn (DK)
Groundwater exploitation	Lorca (ES)	Lorca (ES)	<i>Not evaluated</i>
Seasonality (Basic/L2a products only)	Lorca (ES) Gran Canaria (ES) Jutland (DK)	<i>Not evaluated</i>	<i>Not evaluated</i>
Extra (Volcanism)	La Palma (ES)	<i>Not evaluated</i>	<i>Not evaluated</i>

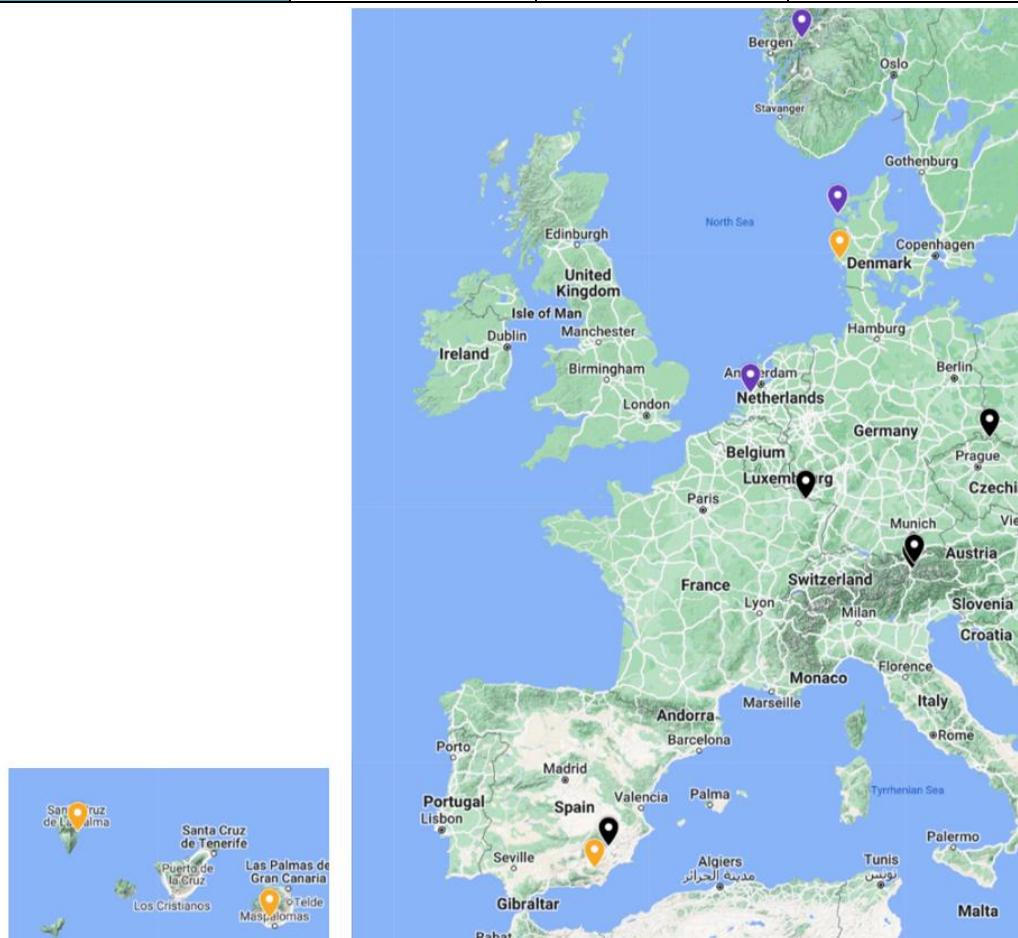


Figure 53: Validation objectives and thematic areas versus sites (Consistency/Accuracy). The colours refer to the different activities reported in the Table 8 (Basemap: Google)



At these sites, the EGMS portfolio is compared to other high resolution and in situ data sources including:

- GNSS observations (velocity components and time series).
- Geodetic data acquired by in situ landslide monitoring stations.
- Levelling data acquired by in situ campaigns over abandoned mining.
- Piezometric data (groundwater level measurements).
- Artificial Corner Reflectors (CRs) deployed to optimally reflect the radar signal back to the satellite, along with precise measurements of CRs location.

3.2.1 Methodology overview

Three validation activities were conducted at various validation sites (Figure 53). A detailed description of each methodology can be found in [D6-Validation Methodologies](#). A summary with the main aspects follows:

- **Comparison with GNSS data:** The goal of this activity is to validate the geocoding and ground motion time series of EGMS products using GNSS measurements. Test statistics are applied to compare EGMS time series and velocities against GNSS data to determine the significance of any differences found. Some of these test statistics are adapted into the IoAs. The following steps were followed to validate EGMS products with GNSS data:
 - **Temporal interpolation:** GNSS time series are interpolated to match EGMS acquisition dates, ensuring the same time interval is covered. A 12-day interpolation window is used, which weights the inverse of the time difference.
 - **Time reference:** GNSS and EGMS time series are aligned to the same reference date.
 - **Projection of GNSS time series to LOS:** Given the observation geometry, GNSS displacement is transformed to radar LOS for EGMS Basic/L2a and Calibrated/L2b products.
 - **GNSS spatial referencing:** For Basic/L2a data, a GNSS station is selected as the reference station per validation site. The time series difference between the reference and the rest of stations is then calculated. For Calibrated/L2b and Ortho/L3 products, velocity differences are calculated between the GNSS reference frame and the A-EPND velocity model used in Calibrated/L2b and Ortho/L3 products, which are then subtracted from the GNSS time series.
 - **EGMS MP selection:** MPs are selected based on distance (within a 100m radius from the GNSS station) and height criteria.
 - **Spatial interpolation:** Using only the selected EGMS MPs, spatial interpolation is performed to the GNSS location. The interpolation error is estimated, considering the provided MP accuracy. Double differences are used for Basic/L2a products only because they are referred to a virtual reference point. This step is unnecessary for Calibrated/L2b and Ortho/L3 products, as they are relative to the same reference system, i.e., ETRF 2000.
 - **GNSS-EGMS comparison:** The correlation between GNSS and EGMS time series is calculated together with the standard deviation of the differences in the time series. Only overlapping parts of the EGMS and GNSS time series are selected, and the BLUE model (Best Linear Unbiased Estimation) [Teunissen, 2000a, Teunissen, 2000b] is applied, providing the variance of the estimated parameters.



- **Comparison with in situ data:** The objective of this activity is to evaluate in situ measurements such as levelling data, piezometers, and geodetic monitoring against the EGMS ground motion data. Two workflows have been designed to evaluate EGMS time series and their associated velocity:
 - o **In situ vs EGMS velocity comparison:** To compare velocities, in situ XY measurements are converted to LOS. EGMS MPs within 50 or 100 m buffers surrounding the in situ measurement locations are collected. The averaged velocity values of these EGMS MPs are used to evaluate the accuracy and precision of the EGMS in comparison to the in situ measurements.
 - o **In situ vs EGMS time-series comparison:** The same pre-processing steps employed for the velocity analysis is applied to the time series data. Aggregation of both EGMS and in situ time series data is performed at different intervals (6 days, monthly, yearly). Outlier and seasonality extraction are conducted to evaluate how trends, accelerations, decelerations, and seasonal variations impact the TS inter-comparison. Smoothing is applied to both time series to focus on the general agreement between the two measurement techniques, rather than their individual accuracies, to characterize the deformation phenomena.
- **Evaluation of XYZ and time series with CRs:** The purpose of this activity is to evaluate the precision of the EGMS time series concerning location, height, and measured motion, focusing on three main aspects:
 - o **Height estimation (Z):** For this task, CRs with known heights derived from levelling campaigns are used. If these data are not available, GNSS measurements in correspondence with the CRs are considered. Differences between orthometric and geometric heights are considered negligible, given the small distances between CRs. A 100m buffer is taken to collect all EGMS MPs surrounding each CR. Then, the relative heights of the CRs are compared with the closest EGMS MPs, using statistical testing to determine if the differences are significant, considering their corresponding standard deviations.
 - o **Geo-positioning accuracy (XY):** The product specifications require the geo-positioning accuracy to be below 10 m. To verify this, GNSS local observations are used due to their high accuracy in horizontal positioning. The accurate positions of the CRs are known, and a 25-meter buffer is created around each CR to isolate all proximate EGMS MPs, followed by a meticulous selection of EGMS MPs with similar time series behaviour. Finally, the distance (offset) between each CR and its nearest MPs is calculated to verify the geo-positioning accuracy.
 - o **Quality of the EGMS time series:** To evaluate the quality of EGMS time series displacements, GNSS stations located at selected CR sites or levelling measurements are used. The same procedures described in “comparison with GNSS data” are applied.



3.2.2 *Index of Agreement overview*

For each validation activity and methodology summarized above, reproducible IoAs have been derived. Table 9 summarizes each of these normalized indexes together with the EGMS product levels evaluated:

- **IoAs for GNSS:** the indexes of agreement here applied are metrics to compare time series, velocity, and seasonal signals between EGMS and GNSS measurements. Two additional tests have been applied to test the similarity of time series and velocity estimations between EGMS and GNSS. For the seasonal effects, the following four metrics are computed to analyse the seasonal signal component and facilitate a comprehensive interpretation: the standard deviation, mean, and root mean square (RMS) of the detrended signals —post linear trend removal. It is important to note that all IoA metrics are normalized across the entire spectrum of GNSS stations and product datasets to ensure an aggregated evaluation of the EGMS products. This normalization process involves calculating each IoA metric using the extremal (minimum and maximum) values observed across the EGMS data in the area of interest and the station readings. However, this normalization procedure may introduce bias in representing specific locations or products. As will be evident in subsequent time series graphical representations, this normalization can result in certain site stations or products being disproportionately represented, potentially leading to the underrepresentation of some in favour of others or vice versa.
- **IoAs for in situ:** three indexes that evaluate time series correlation, error, and agreement between EGMS and in situ data have been defined. A fourth index is averaged within the base index to establish a general agreement and enable site intercomparison. The use of the Mean Absolute Error (MAE) was adopted as a proxy to find the best EGMS MPs which have the lowest error in comparison to each in situ station. To homogenise the three chosen metrics, the error group was reclassified with a score varying between 0 (for MAE between 50-100 mm) and 1 (0 < MAE < 5mm).
- **IoAs for CRs:** For CRs, similar IoAs to GNSS time series comparisons are used, focusing on time series agreement. An additional IoA evaluates geo-positioning accuracy.



Table 9: Index of Agreement (IoA) for Accuracy/Precision

IoA	Methodology	Short description of how the index is calculated and interpreted	EGMS products
Time series: correlation	Validation with GNSS and CR	Correlation: Time series correlation (after normalization described in the previous sections). Higher IoA (close to 1) indicates higher agreement.	L2a/L2b/L3
Overall model test for time series	Validation with GNSS and CR	Statistical test: The overall model test (OMT) procedure compares the means of explained and unexplained variation (between EGMS and GNSS) in the model in order to determine the explained variation. Higher IoA (close to 1) indicates higher agreement.	L2a/L2b/L3
Velocity differences	Validation with GNSS and CR	Difference between measures: Percentual difference between the EGMS and GNSS velocities. Higher IoA (close to 1) indicates less differences found.	L2a/L2b/L3
Velocity t-test for velocity difference	Validation with GNSS and CR	T-test: Statistical test used to compare means of two groups (EGMS, GNSS). Higher IoA (close to 1) indicates higher agreement.	L2a/L2b/L3
Seasonality: Correlation of detrended signals	Validation with GNSS and CR	Correlation: after detrending described in the previous sections. Higher IoA (close to 1) indicates higher agreement.	L2a
Seasonality: Standard deviation of differences of the detrended signals	Validation with GNSS and CR	Error: Measure indicating how much EGMS and GNSS differ after removal of linear trends (velocity model). Higher IoA values (close to 1) indicate the error is lower.	L2a/L2b/L3
Seasonality: Mean of differences of the detrended signals	Validation with GNSS and CR	Mean of differences: of the detrended signals (GNSS). Higher IoA values (close to 1) indicate the difference is less significant.	L2a/L2b/L3
Seasonality: RMS of differences of the detrended signals	Validation with GNSS and CR	RMS: of differences of the detrended signals (GNSS). Higher IoA values (close to 1) indicate the difference is less significant.	L2a/L2b/L3



Time series/ velocities correlation	Validation with in situ	R²: Comparison between deformation time series (EGMS / In situ). Higher IoA (close to 1) indicates higher agreement.	L2a/L2b/L3
Time series/ velocities Error	Validation with in situ	Mean Absolute Error (MAE): Error or difference between deformation time series (EGMS / In situ). Higher IoA values (close to 1) indicate the error is lower.	L2a/L2b/L3
Time series/ velocities agreement	Validation with in situ	Time series and Velocity agreement (d): Time-series quality assessing how well the EGMS time series agree with the in situ measurements. It is dimensionless and varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all.	L2a/L2b/L3
Normalized mean of (corr, error, agg)	Validation with in situ	Combined index: averaging the 3 indexes defined above with equal weight.	L2a/L2b/L3
Time series quality and velocity of time series with CR	Validation with GNSS at or close to CR	Quality assessment of how well the EGMS time series agree with those at the CR locations. The latter have been performed using GNSS, therefore the IoA are the same as described in the first five rows of the table in the previous page.	L2a
Positioning accuracy estimates	Position/Displacement validation with CR	Position difference: X, Y, Z accuracies or geo-positioning and height accuracies. How close the estimated EGMS heights and locations are to the measured CRs heights and locations.	L2a

EGMS products:

L2a = Basic

L2b = Calibrated

L3 = Ortho

3.2.3 Validation results per thematic area

Landslides

Navis (Austria)

Kerschbaumsiedlung, a residential estate complex located on the western part of the municipality of Navis, lies on the southern slope of the mountainous Misjoch region. Since 2012, GPS surveys have demonstrated that part of this slope is experiencing movement of up to 3 cm/year. Twelve buildings of a total of 84 have been affected by this slope movement. At the end of the 80s, work started to build an urban settlement on a slope above the *Naviser Oberwegs*. After ten years, the first cracks appeared on the streets and buildings of the Kerschbaumsiedlung. In 2001 hydrogeological investigations started. In order to understand the process and the causes of the slope movement and to be able to introduce efficient remediation measures, extensive testing and monitoring activities were carried out in the years 2012 – 2014 (Hofmann & Sausgruber, 2017). On the upper ridge, various mountain deformation phenomena such as normal faults, tension cracks and trenches are occurring, which are unambiguous signs of deep-seated rock slope deformation.

Brewer and Marlow, 1983, introduced a map style which combines slope and aspect in a unique map for enhanced terrain visualization. Figure 54 illustrates this style for two landslides, employing three slope categories distinguished by differences in saturation combined with eight aspect categories rendered with an orderly progression of colours. Navis predominantly faces south, south-east and south-west. Moreover, the kinematics of the deep-seated structure underlying Kerschbaumsiedlung indicates slow movement mostly towards the south.

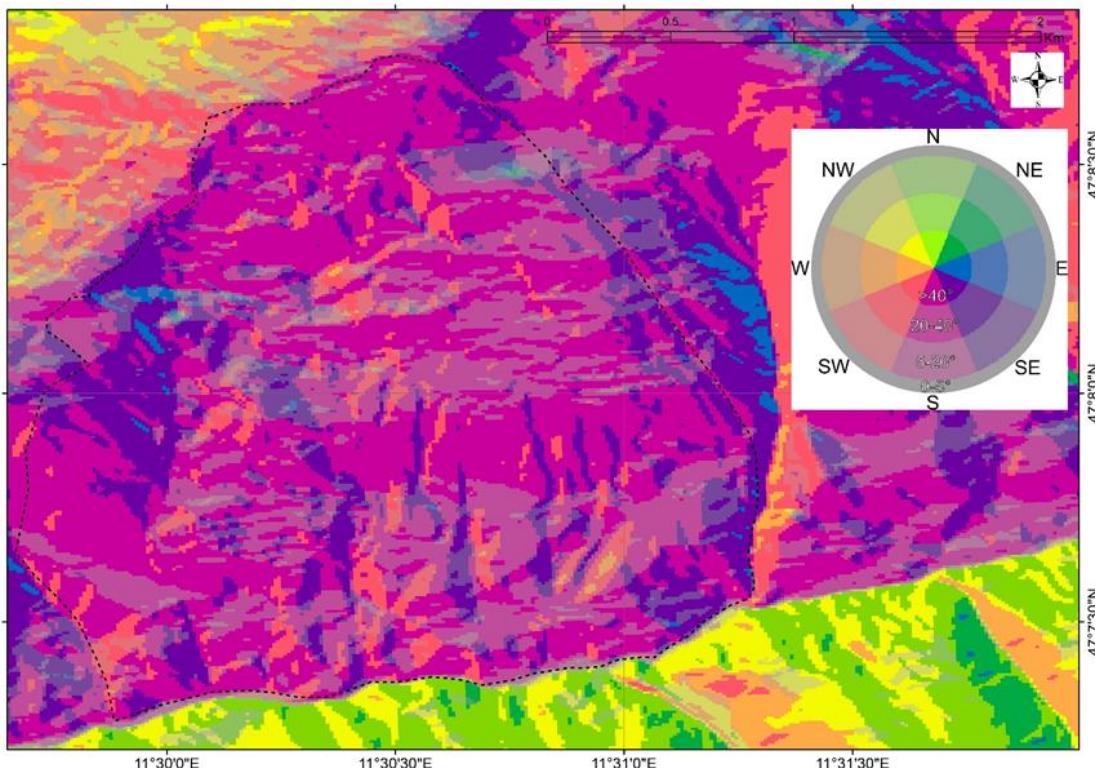


Figure 54: Aspect – slope map for Navis using the brewer scale (colour indicates aspect).

In August 2013, an Automatic Tracking Total Station system (ATTS) was deployed for 80 points throughout the Navis landslide area. For comparison with EGMS products, data from six stations are used. The ATTS system measures X, Y and Z components of deformation, automatically capturing displacement on a daily basis (in mm/day). The device's stated accuracy is about ± 5.4 mm/year. Figure 55 illustrates the density and proximity of EGMS MPs relative to the in situ stations, providing an overview of the Navis area with a 50m buffer drawn around each station.

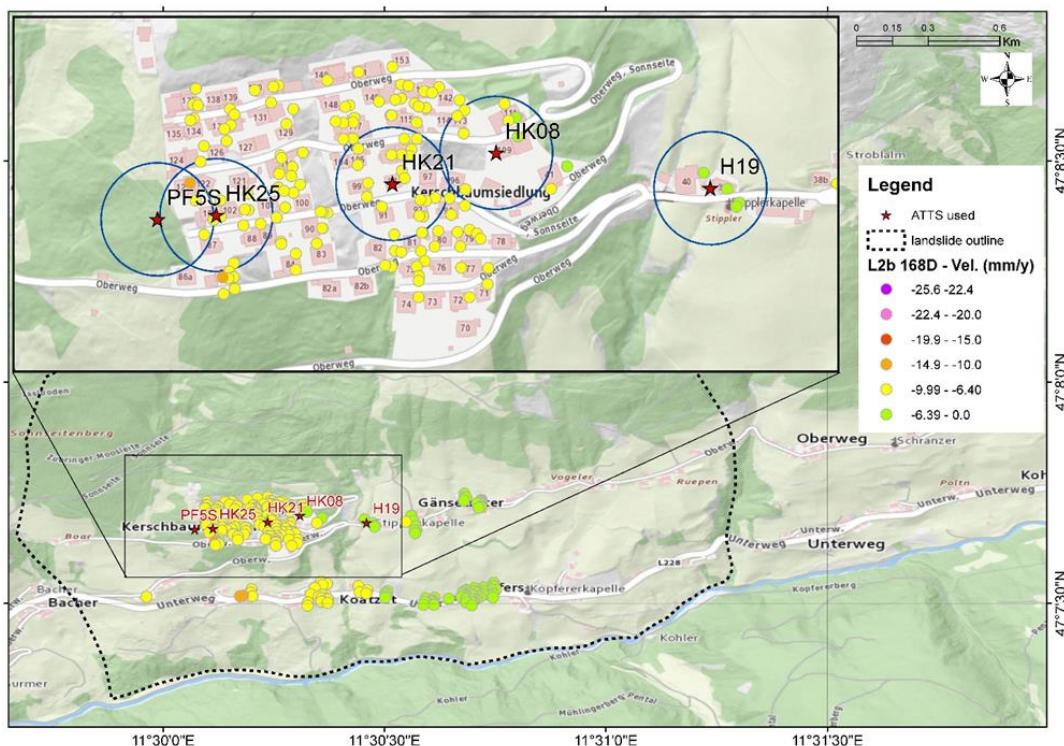


Figure 55: EGMS Descending Calibrated/L2b measurement point distribution in Navis and position of the in situ stations.

Figure 56 displays the daily time series for the three-dimensional components for the Navis case study, focusing on ATTS station TS1 - PF5S used for the validation. The data reveals a predominant motion towards the south with a 40 mm cumulative displacement over 5 years (2018-2022).

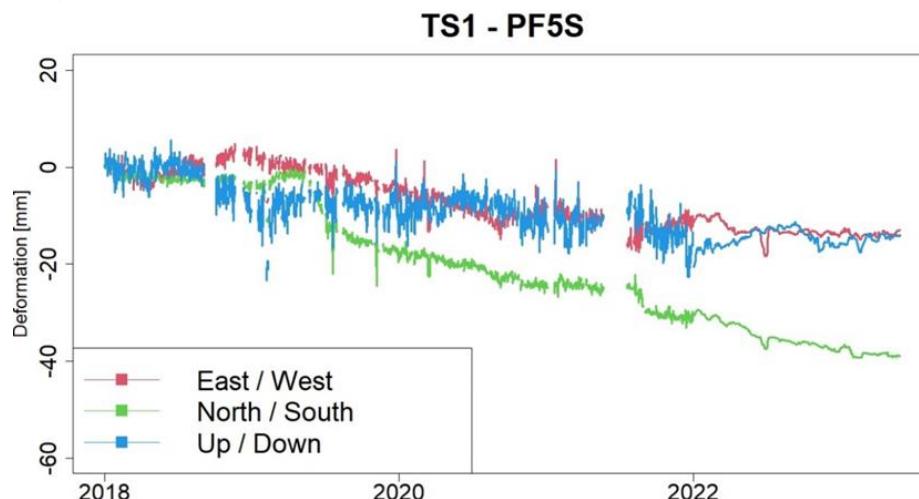


Figure 56: ATTS time series for station TS1 – PF5S (unfiltered data until end of 2021).

Source: <https://geoinformation.tirol.gv.at/client/?projekt=kerschbaumsiedlung>

Figure 57 illustrates the velocity inter-comparison results for the EGMS Basic/L2a and Calibrated/L2b descending orbit 168, as ascending orbits did not cover the area in this EGMS update. In the previous EGMS update (2015-2021), MPs were found over Navis in the ascending orbit (track 117). In this new release, the absence of MPs in the ascending orbit can be attributed to the challenges posed by mountainous terrain and irregular land cover changes, such as a longer snow period. Despite this, both Basic/L2a and Calibrated/L2b descending products exhibited very similar agreement scores (Figure 57), reaching a combined IoA of 0.7. However, due to the lack of ascending data, comparisons for the Ortho/L3 dataset could not be conducted.

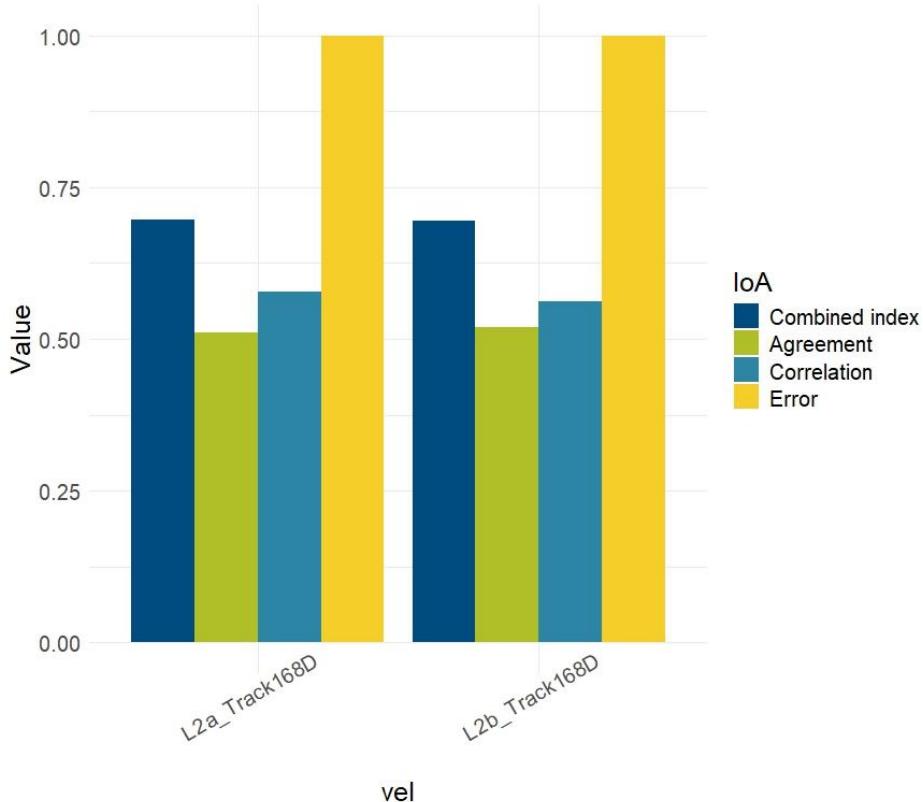


Figure 57: Indexes of Agreement for the velocity results in the Navis case study: Basic/L2a and Calibrated/L2b (descending orbit 168. The ascending orbit did not cover the area of interest).

Figure 58 depicts the IoAs for the time series comparison analysis. Overall, the Basic/L2a data show slightly better results than the Calibrated/L2b data. The poorer performance was found for station HK08 with a combined index of 0.39 for Calibrated/L2b (Figure 59), whereas station PF5S achieved the best performance, also shown as a single time series IoA represented in Figures 59 and 60. The performance of station PF5S can be attributed to the location of the point measured by the ATTS, which is located on the ground (Figure 55). The error IoA scores very high compared to the other metrics (Note: error score of 1 corresponds to low MAE value of less than 5mm).

On the other hand, all other monitoring points are installed on top of the roofs of individual houses. Therefore, while ground deformation measured at PF5S is accurately captured by the EGMS (with a combined index of 0.82), roof tilting due to foundation instabilities and cracks in building walls may lead to an underestimation of vertical deformation which is the predominant motion captured by EGMS.

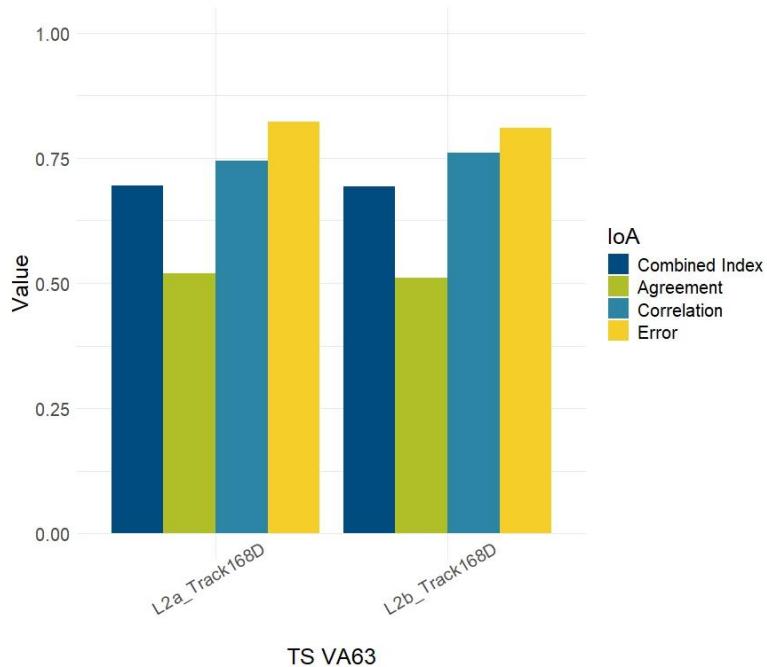


Figure 58: Indexes of Agreement for time series in the Navis case study.: Basic/L2a and Calibrated/L2b descending orbit 168 intercomparison with in situ data.

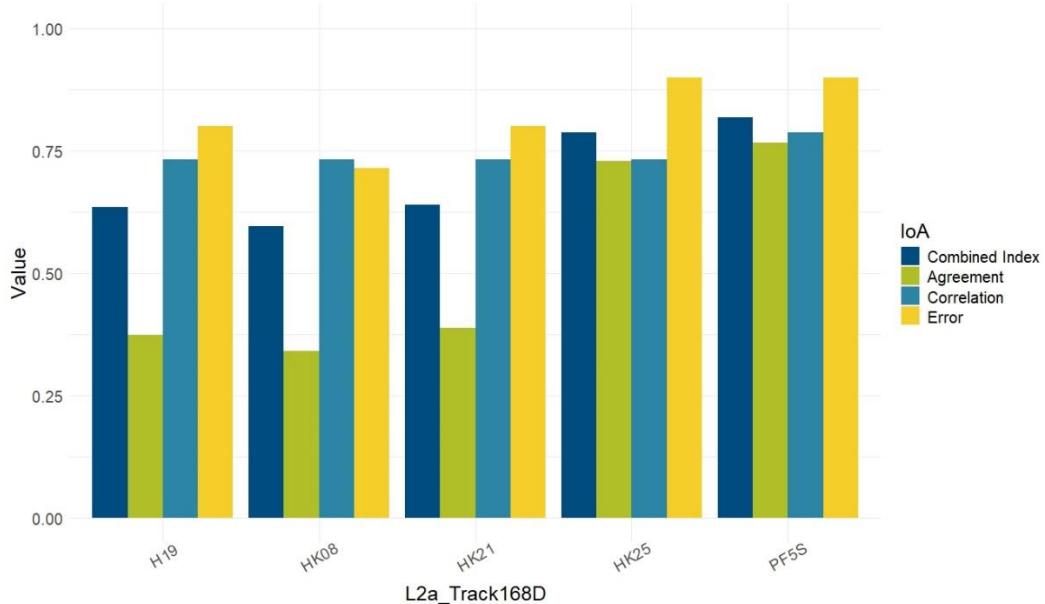


Figure 59: Indexes of Agreement for the time series results in the Navis case study: Basic/L2a (descending orbit 168) compared with 5 total stations (H19, HK08, HK21, HK25, PF5S).

In Navis, the primary sense of motion is southwards (Figure 55). The conversion of the velocity and time series from the three components of the in situ measurements (East-West, North-South, Vertical) to LOS was made under the assumption that, being the south direction of displacement the strongest component, it obliterates the rest of the motion (vertical and east-west). Therefore, the north-south deformation rate was assumed to be zero. That limitation explains why in Figure 61 the EGMS detects an excess of deformation with respect to the in situ data and this could represent the missing southward component of motion. As an example of time series validation for the descending Calibrated/L2b Orbit 168, Figure 61 presents the plot of the TS1-PF5S ATTS station against the EGMS MP. This MP was chosen because of his lowest

MAE when compared to the in situ time series, which falls inside the 50 m buffer drawn around the in situ data.

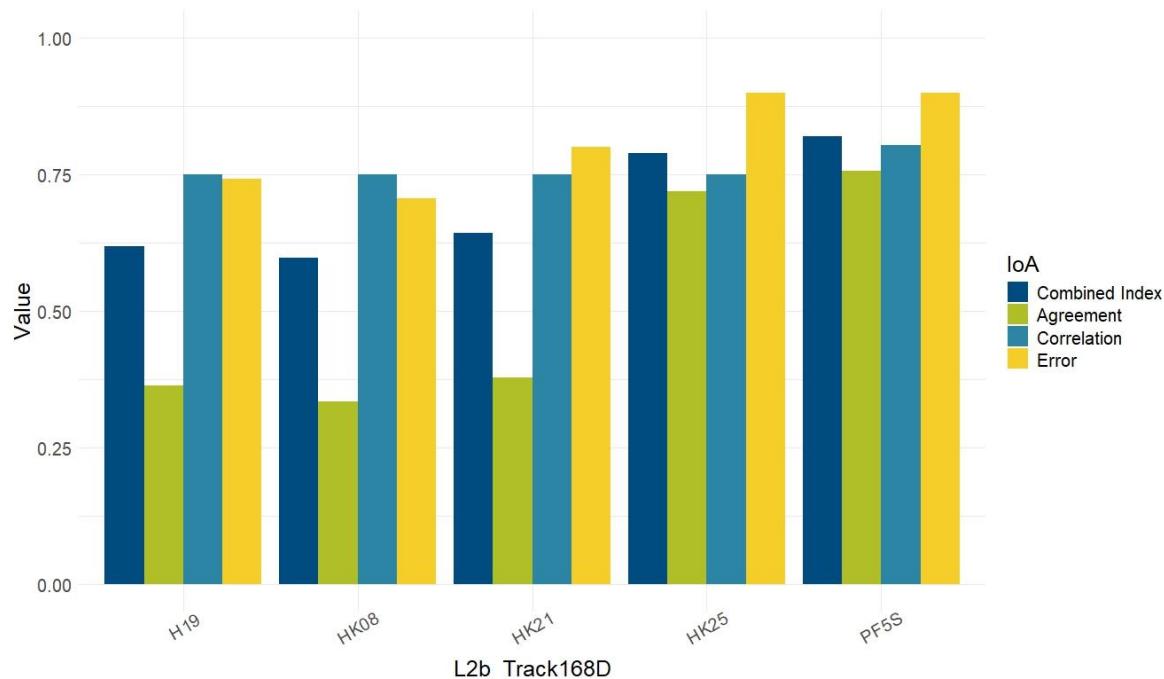


Figure 60: Indexes of Agreement for the me series results in the Navis case study: Calibrated/L2b (descending orbit 168). compared with five total stations (H19, HK08, HK21, HK25, PF5S).

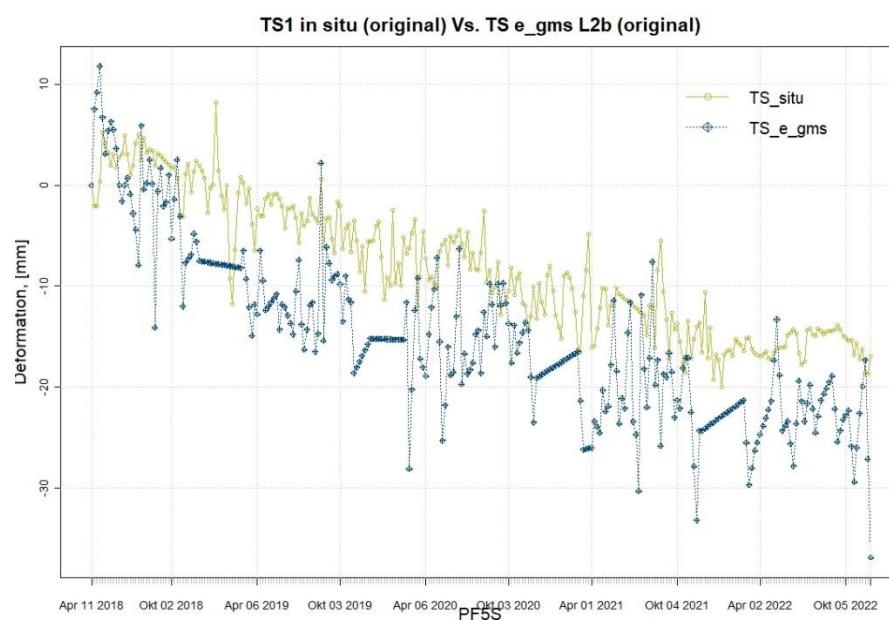


Figure 61: Comparison plot of in situ TS1-PF5S time series against the closest EGMS MP time series that falls within the 50 m buffer around the ATTS TS1-PF5S.

In conclusion, despite the geometrical constraints of Navis (south orientation), this validation site reached a level of agreement of about 0.7 in both velocity and time series when comparing the in situ data with the EGMS products.

Indre Nordnes, Jettan and Gámanjunni (Norway)

The validation sites in Norway are situated within landslide prone mountain areas in Troms and Finnmark County, located in northern Norway (Figure 62). Indre Nordnes and Jettan are two unstable mountain ranges on the eastern side of the Lyngenfjord. Gámanjunni is an unstable mountain section, known as compound slide¹, located on the eastern side of Manndalen. These locations are part of a cluster of deforming rock slopes in the region, which are influenced by the geological history, bedrock structure, fluid flow, permafrost, and weathering processes [Vick et al, 2021, Rouvet et al., 2021].

These rock slopes pose a significant hazard, as they have the potential of triggering rock avalanches that could endanger nearby settlements and infrastructures [Hermanns et al, 2018]. Because of the high risk of landslides, several monitoring systems have been deployed to acquire continuous, real-time, or periodic (with weekly intervals) measurements. At each of the three test sites, a total of five CRs have been installed together with continuous GNSS measurements either at or nearby the CR locations. The GNSS time series data have been analysed and compared with the MPs located near the GNSS locations.

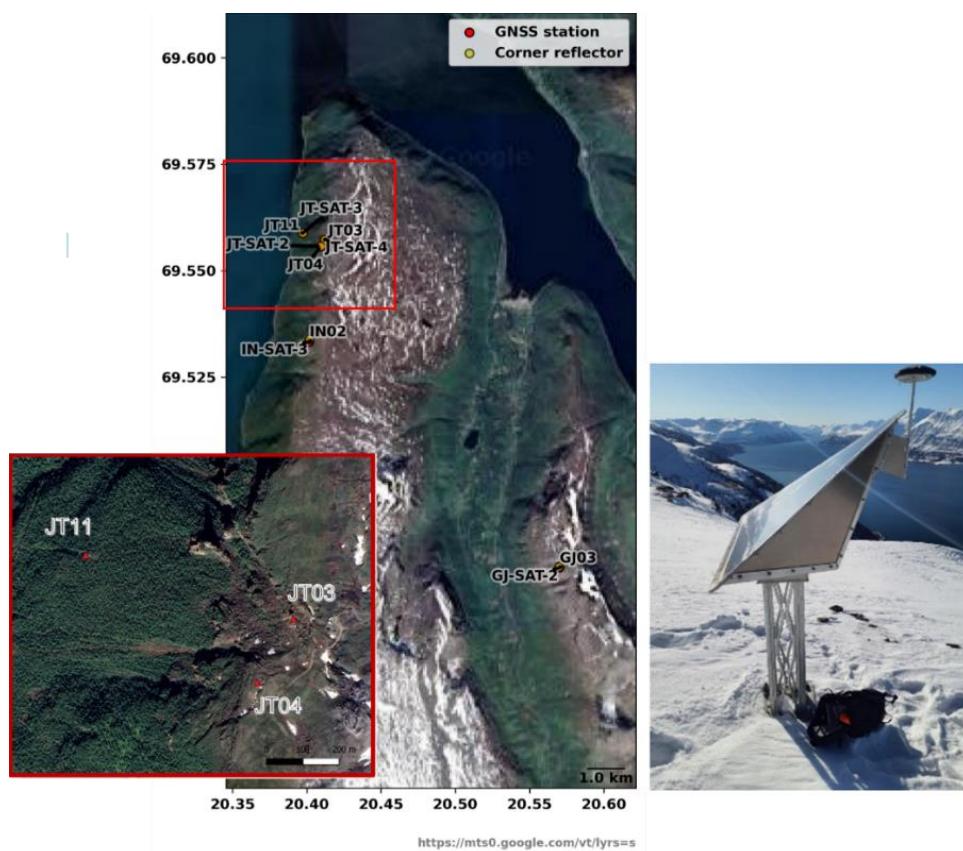


Figure 62: Map of the Norwegian corner reflector (CR) site with Indre Nordnes (one CR with 'IN' initials), Jettan (three CRs with JT initials) and Gámanjunni (one CR with GT initials) mountains with satellite background. The Google Maps satellite inset figure shows the Jettan mountain survey with CR stations JT-SAT-4, JT-SAT-3 and JT-SAT-2, of which, at the westernmost the CR (JT-SAT-4) is located within a highly vegetated area. The ID numbers were kept as used by NVE, and the corresponding GNSS stations do not have 'SAT' in the name. On the right bottom corner an image of one of the CRs is shown.

¹ Complex or compound slide is a category within the types of landslide movements. According to the Varnes classification [Varnes, 1978] of landslide types Hungr et al., [2014] defined a rock compound slide as the “sliding of a mass of rock on a rupture surface consisting of several planes, or a surface of uneven curvature, so that motion is kinematically possible only if accompanied by significant internal distortion of the moving mass.”

Decisions regarding the comparison between the five existing stations and the three EGMS products were made considering the following constraints: the comparison was limited to the Basic/L2a product due to the unavailability of original GNSS data converted into a compatible coordinate system required for evaluating the Calibrated/L2b product.

The locations of the CRs in Norway are depicted in Figure 62. The GNSS station JT11 was selected as the reference station to evaluate the performance of the Basic/L2a products (descending orbit, track 168). It should be noted that the GNSS stations' locations are different from the locations of the CRs, with distances ranging from 2 to 60 m apart. Therefore, the GNSS measurements may or may not mirror CR measurements, especially for GNSS stations beyond the resolution of the EGMS LOS products (i.e. 20x5 m) or those further away from the CRs. While there might be better procedures to validate the time series at a CR location, given that the GNSS stations are meters apart from the CR, the 100m radius allows for comparability and makes possible the estimation of the standard deviations of the EGMS MPs.

Figure 63 shows the double differences between EGMS MPs within the 100m search radius (see [D6-Validation Methodologies](#)) and the GNSS stations, using station JT11 as a reference. The EGMS does not include winter acquisitions in this region to maintain coherence, resulting in observation gaps during the winter months. Nonetheless, the time series show a good fit with the GNSS observations falling within the error bars of the EGMS MPs. An exception is station GJ03 (Figure 61 (d)), where the GNSS data does not align with the EGMS measurements at the beginning of the time series. Despite this poor initial fit, it's important to note that the displacements at this station are around 200 mm for the analysed time period. Even with such a significant displacement, the overall trend and magnitude are well estimated.

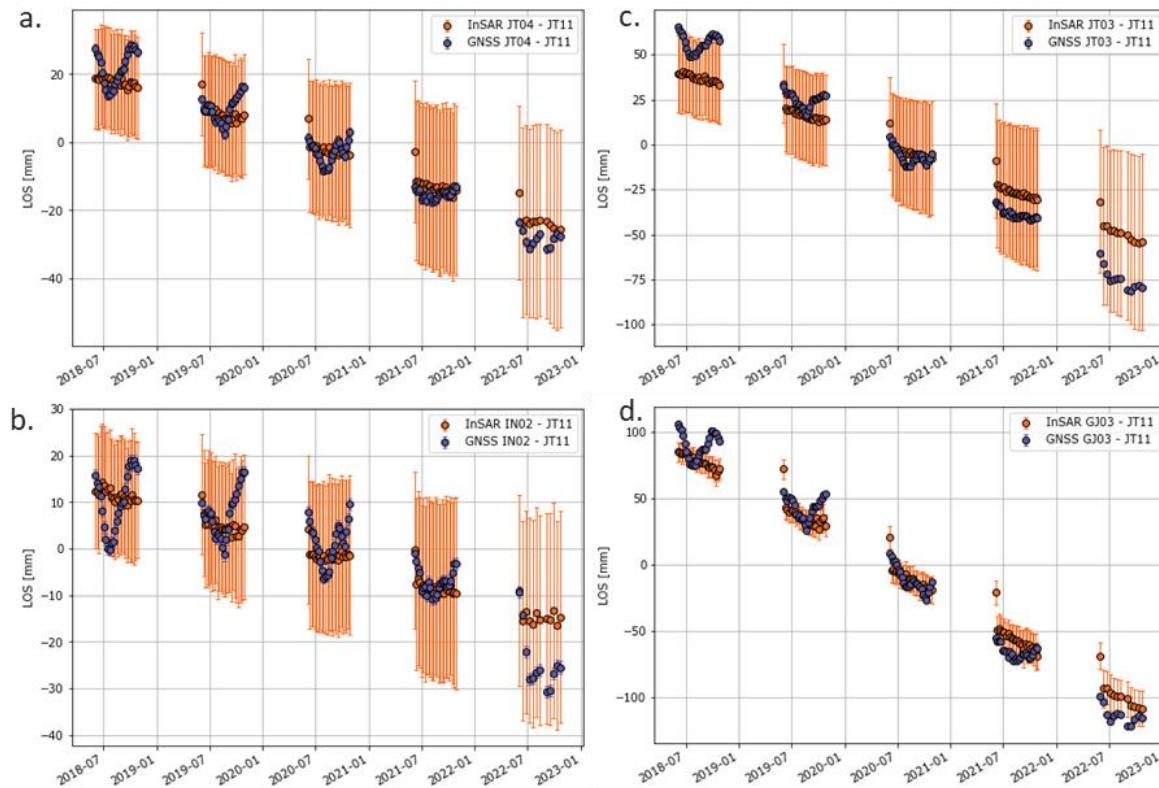


Figure 63: Examples of time series double differences between three of the stations for Basic/L2a descending orbit 168. Station IN02 is the reference station. Acquisitions during wintertime were not processed to avoid loss of coherence due to snow cover. The error bars of the EGMS measurement points were derived using all the datapoints falling within the search radius. Stations a) JT03 b) GJ03 c) JT04 d) IN02. The orange error bars of the EGMS MPs were derived using all the data points falling within the search radius.

Another way to visualise the fit between the double differences is to subtract the double differences time series of the GNSS from the ones of the EGMS as illustrated in Figure 64. Ideally, the subtraction between the double difference time series should be around zero. Figure 64 shows that the linear displacement rate (or velocity) is either under or over-estimated whenever these differences are not around zero. Stations JT04 and IN02 have time series differences around zero, indicating an excellent agreement. Station JT03 shows an underestimation of the EGMS with respect to the GNSS of approximately 30 mm in 5 years of observations (c.a. 5 mm/year).

The results of the differences between EGMS and GNSS time series generally fall within a one-sigma deviation or one standard deviation from the mean.

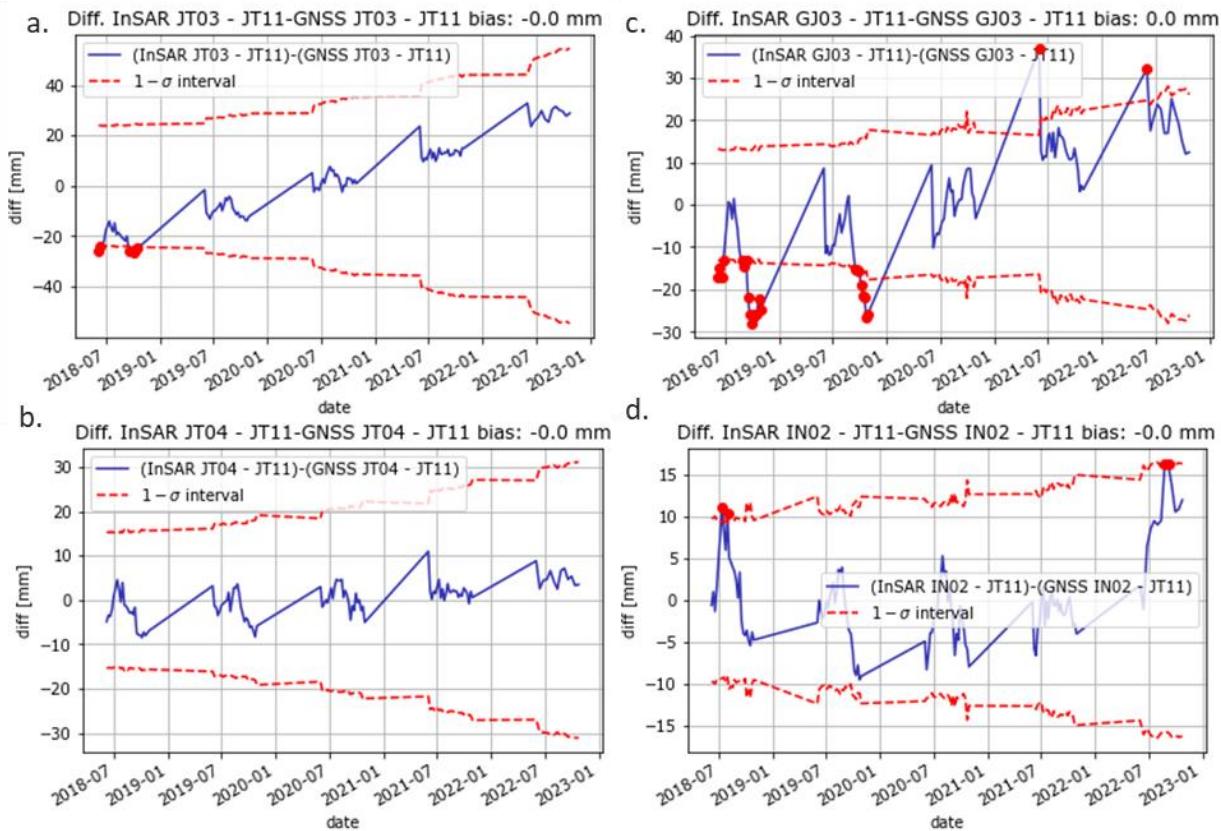


Figure 64: Subtraction between the EGMS and the GNSS double differences time series for the four stations using JT11 as a reference (blue line). Red lines indicate a one-sigma deviation interval or one standard deviation from the mean.

Figure 65 demonstrates the correlation of double difference velocities between EGMS and GNSS for all stations for the four descending orbits covering the area. This graph corroborates the results shown in previous figures. The velocity estimation at station GT03 and JT03 slightly deviates from the ideal correlation (black filled line), indicating that the EGMS velocities are lower than those measured by GNSS. For station JT03, the average difference of the velocity between EGMS and GNSS for all the four orbits is about 12 mm/year while for GT03 is lower, about 8mm/year. The EGMS velocity at stations JT04, JT11 and IN02 almost matches the GNSS estimation.

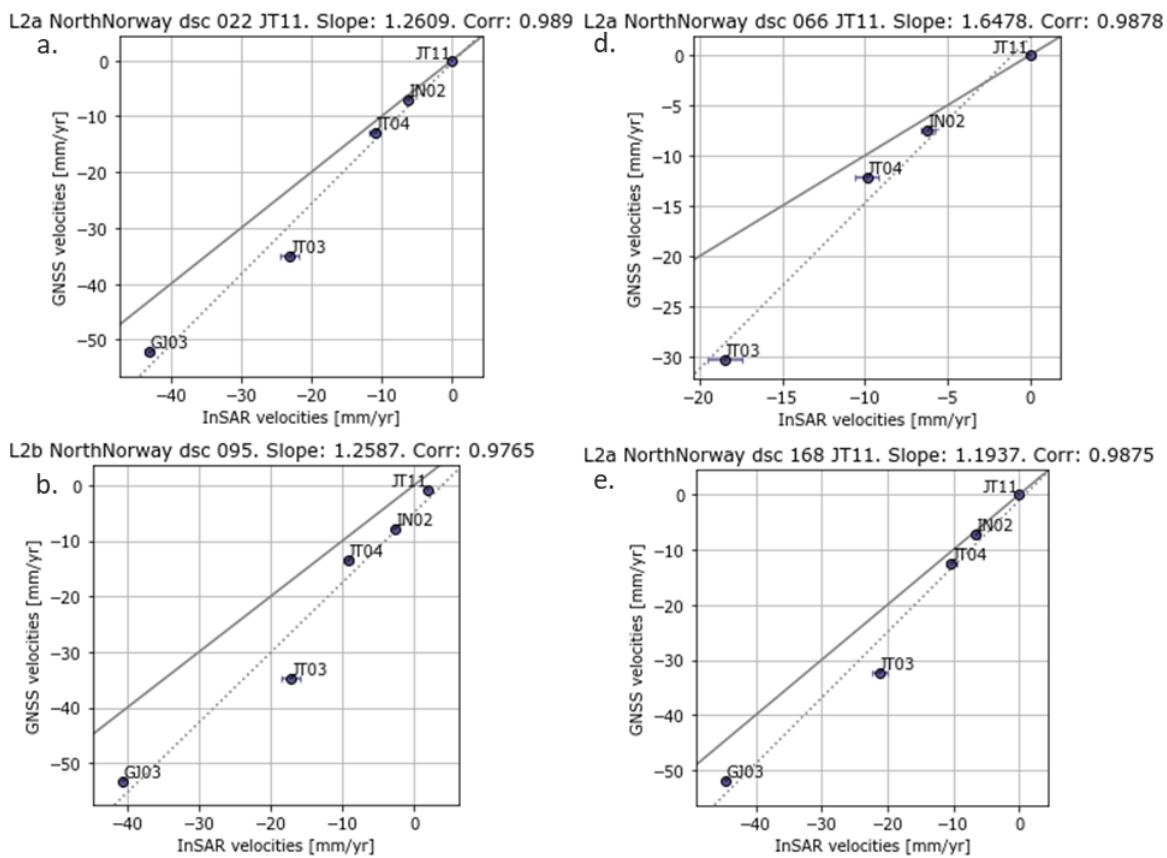


Figure 65: Correlation between EGMS/GNSS velocities. Station location falling within the black full line indicates perfect agreement between the estimated double difference velocity of the EGMS vs GNSS. Dashed line indicates the best fit line between all stations.

Overall, the velocity correlation for all studied stations is 0.98, indicating that the Basic/L2a product velocities generally align well with the GNSS estimated velocities. Basic/L2a products are recommended for landslide applications, and double differences should be performed to avoid problems with referencing. If there are not enough GNSS stations or no stations at all, double differences between EGMS observations can be performed between MPs outside and inside the location of a potential landslide. An advantage of high-latitude locations is the orbit overlapping, as in the case of North Norway where three orbits might be available for the same area. The optimal orbit pair (ascending or descending) should be used depending on the direction of the mountain slope.

For this validation site, the correlation of velocity estimation between EGMS and the GNSS measurements close to the CR (Figure 65), indicate a very good correlation.

The most significant discrepancy in velocity occurs at station JT03 (Fig 62), with an estimated difference in velocity between EGMS and GNSS of approximately 12mm/year, although this difference remains within the one-sigma standard deviations of the EGMS (Figure 64-c). These findings underscore the applicability of the EGMS for landslide monitoring, especially at high latitude environments benefiting from multiple overlapping orbits.

Mining and post-mining

Turow (Poland)

Turow, located at the Czech Republic and Polish border, stands as the second largest active coal mine in Poland. The mining activity is depleting water supplies and damaging nearby houses due to induced subsidence. The extensive network of water boreholes established to monitor the impact of the open-pit coal mine on its surroundings (36 boreholes 1997-2023) will be used for the validation, although only 15 stations from this network align with the monitoring period 2018-2022 (shown in Figure 66).

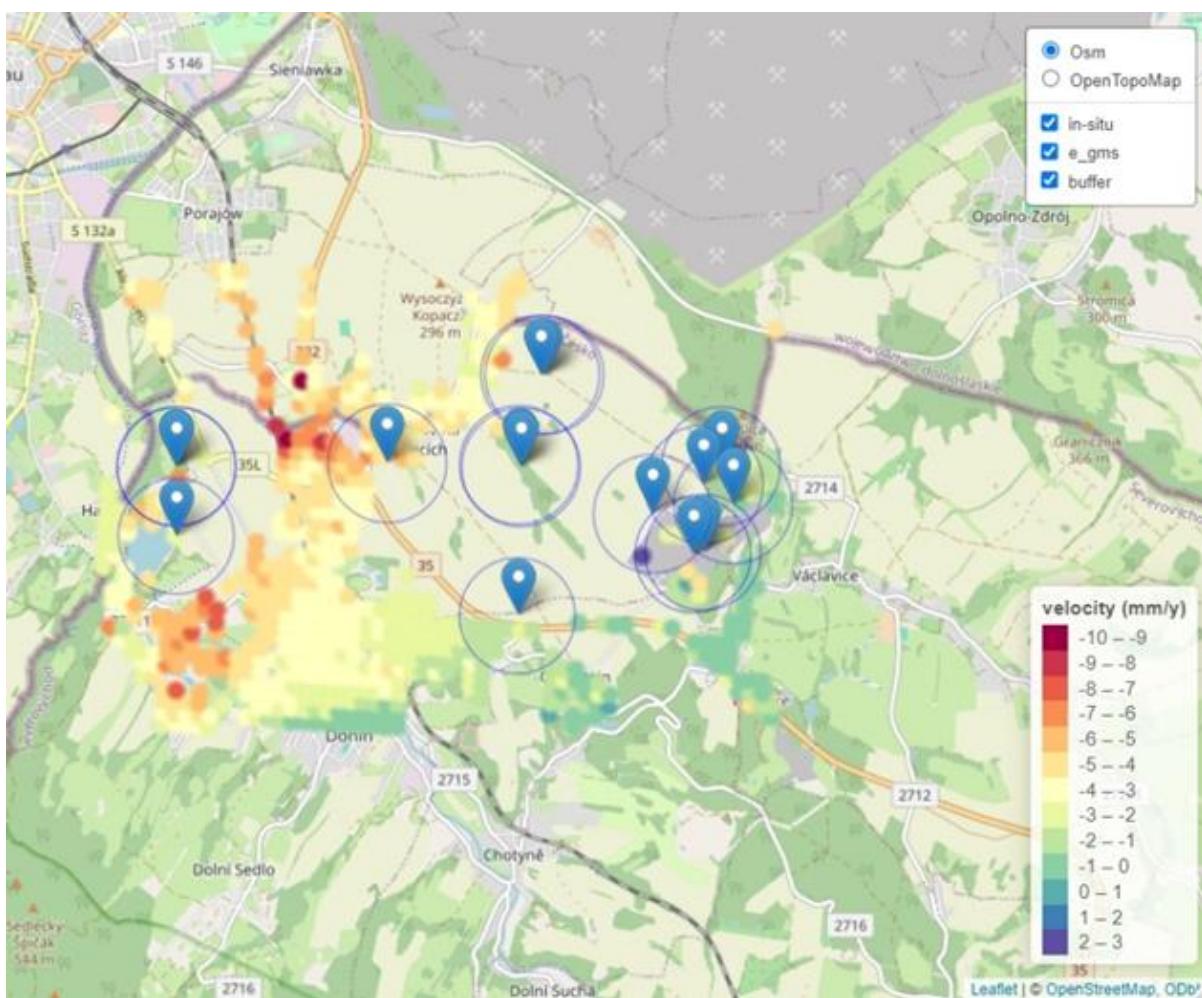


Figure 66: Turow validation site showing the Ortho/L3 Vertical EGMS product, the piezometer position, and the drawn buffer.

The comparison between piezometers and EGMS was performed by adopting the same methodology described in the previous validation report ([2015-2021](#)). The same algorithm and parameters were used, with adjustments made to the script to accommodate the shorter time series. In the current analysis period (2018-2022) two piezometers (H2a and H8a) were excluded due to malfunctions, while an additional piezometer (U-1a) was added. In Figure 67, an example of the adjusted piezometer TS15 – U-1a (in mm/year) is plotted against the best matching (i.e. the one with the lowest MAE) EGMS MP within the 500 m buffer.

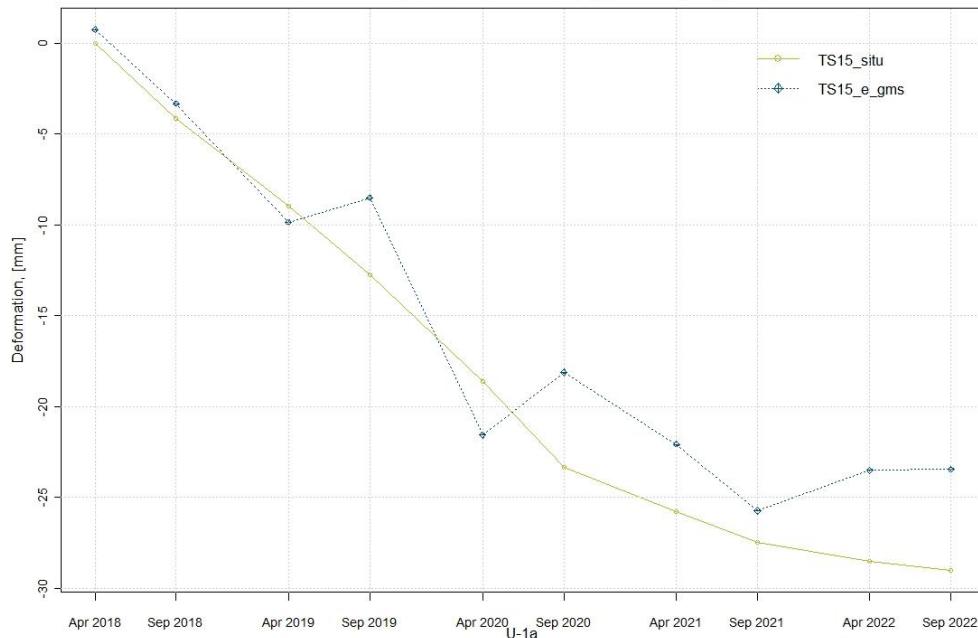
TS15 in situ (original) Vs. TS e_gms L2b (original)


Figure 67: Comparison plot of in situ piezometers time series U-1a against the best EGMS Calibrated/L2b measurement point that falls within the 500m buffer draw around the recently added piezometer U-1a.

Overall, the combined index indicated high consistency for all the time series evaluated (Figure 67) with the only exception of the piezometer H-3 (Figure 68), where the original curve did not exhibit a linear trend as the rest of the data. It is commonly known that InSAR datasets struggle to adapt to non-linear deformation trends.

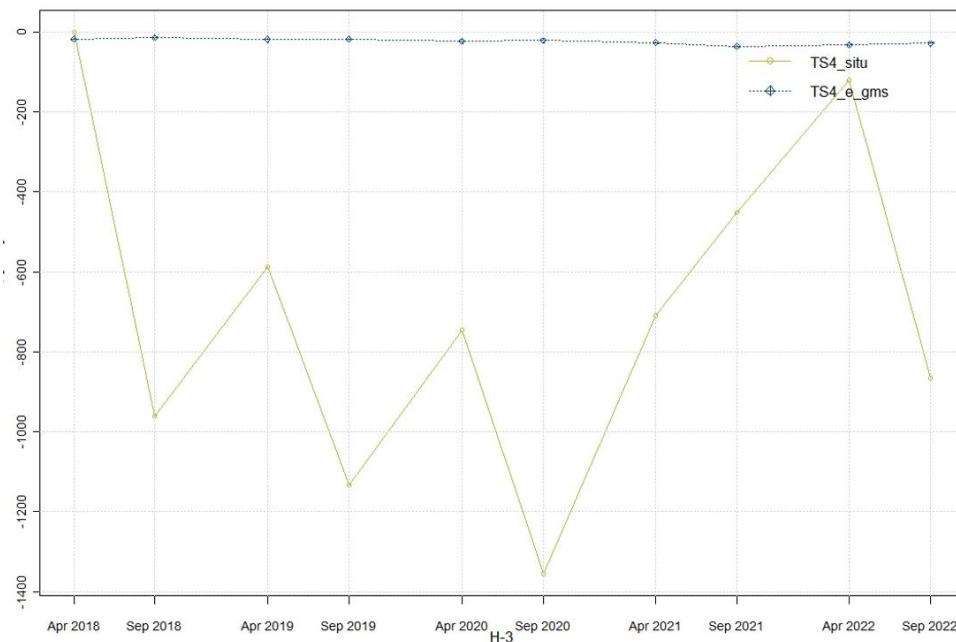
Time series of piezometer H3 and EGMS Calibrated/L2a


Figure 68: Comparison plot of in situ piezometer time series against the best EGMS Calibrated/L2b measurement points that fall within the 500m buffer draw around the piezometer H-3.

For the Turow area, the piezometric time series were compared against the EGMS products. For this study case, two sets of ascending orbit data (tracks 073 and 146) and the 095 descending orbit were available.

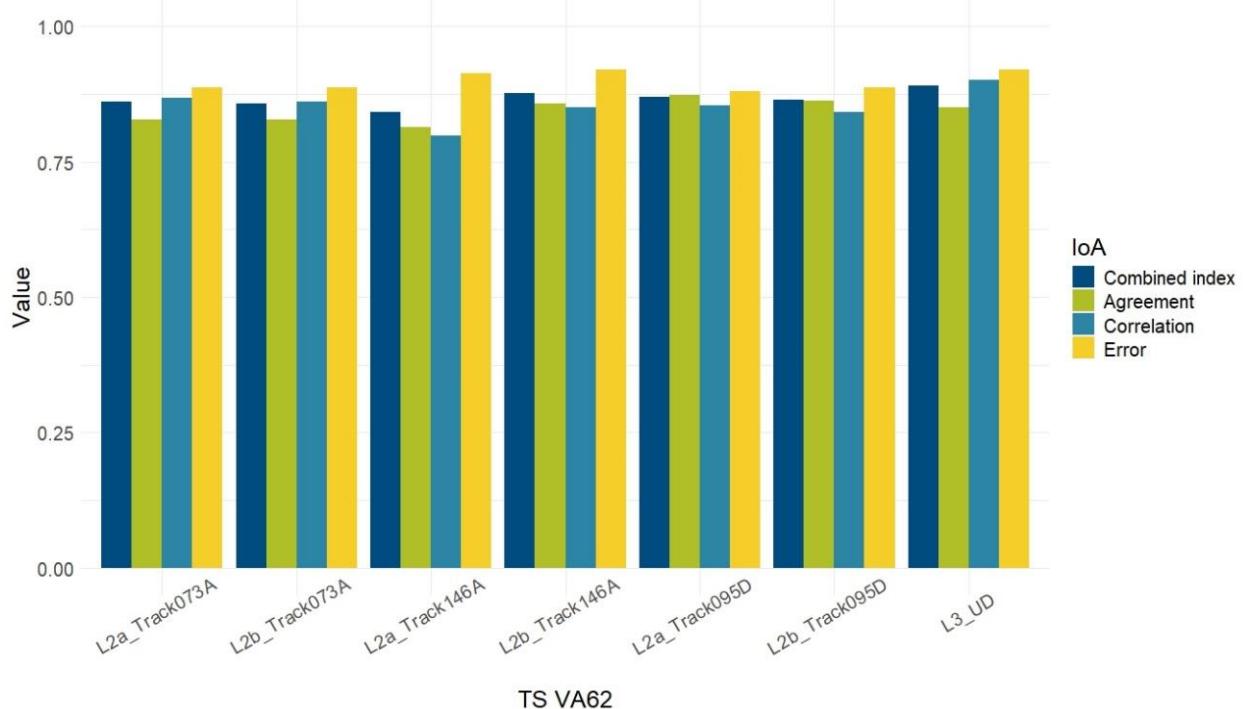


Figure 69: Indexes of Agreement for the time series results for Turow: Basic/L2a (ascending orbits 73/146) and Calibrated/L2b (ascending orbit 146 and descending orbit 95) compared to the in situ piezometer dataset.

The performance of the Calibrated data is good in general, with orbit 146 scoring the highest IoA values among all (Figure 69). Error scores consistently showed the higher values (i.e. low MA) compared to the other metrics.

A strong agreement between Basic/L2a and Calibrated/L2b products was found for most of the orbits. The only exception is visible for ascending orbit 146 where a performance gap between the Calibrated/L2b and Basic/L2a could be spotted. This gap in the final combined index is driven by the lower score obtained by the Basic/L2a in the correlation and agreement IoAs.

A general conclusion can be drawn by considering that the datasets with the lowest viewing angle (near beam) geometry of acquisition are the most suitable for monitoring subsidence in Turow.

Lorraine (France)

The municipality of Freyming-Merlebach, located in the Lorraine region (France) near the German border, faced concerns over the appearance of uplifts attributed to natural water filling in formerly exploited underground coal mines.

To validate the EGMS velocity, a large dataset of over 850 annual levelling measurements was used for comparison with the EGMS product levels (figure 70). However, only ten levelling stations exhibiting the highest uplift rate were considered for time series validation. In this validation site, the levelling measurements' accuracy is around ± 20 mm/year, and the motion is measured along the vertical.

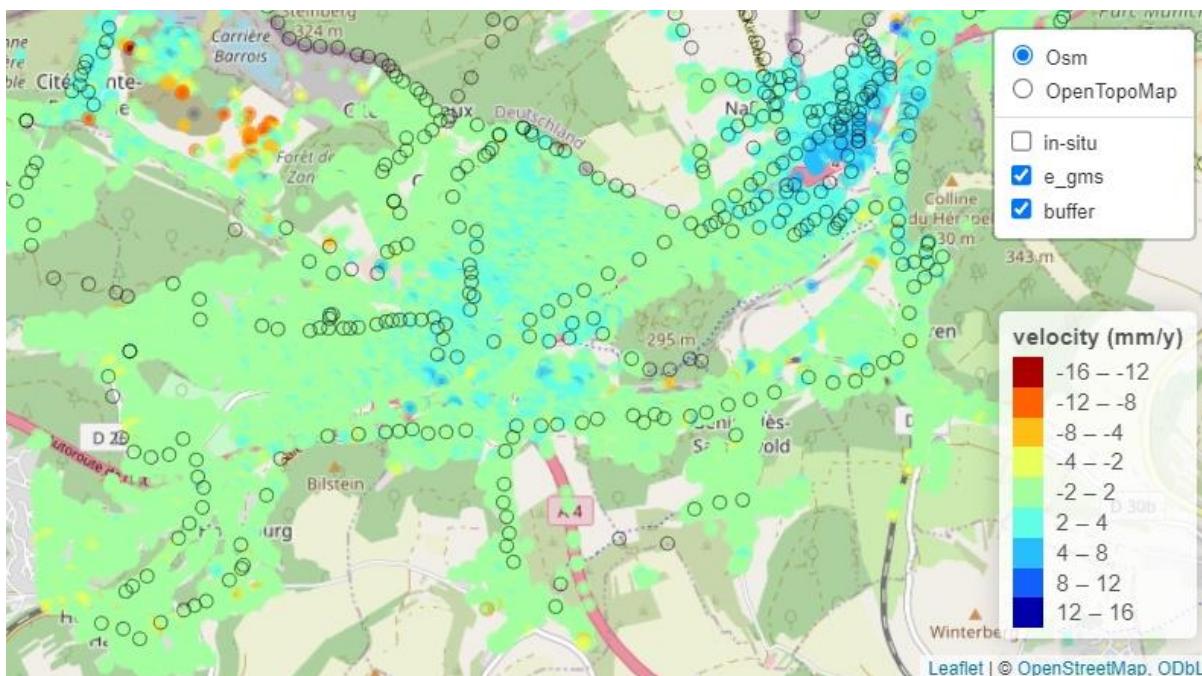


Figure 70: Map showing the EGMS Basic/L2a descending orbit (track 37) over Lorraine overlaid to the in situ levelling stations available for the validation in blue circles. (Basemap: OpenStreetMap)

Consequently, comparisons focused solely on vertical displacement, and the east-west or horizontal displacement (Ortho East-West) were not considered in the comparisons. The density of the first EGMS release (2015-2021) and the EGMS recent update (2018-2022) is notably different.

A comparison between the plots in Figure 71 (EGMS 2021-2025) and Figure 72 (EGMS 2018-2022) reveals a difference in the number of observations. Moreover, while both EGMS updates underestimate the uplift, this underestimation was notably higher in the 2018-2022 update (Figure 72). The observed discrepancy, particularly evident in the first 200 stations, can be spatially associated to an area called "le Porcelette" in the western part of the study site. Specifically, for these stations, this underestimation almost doubles, from 3 mm to 8 mm.

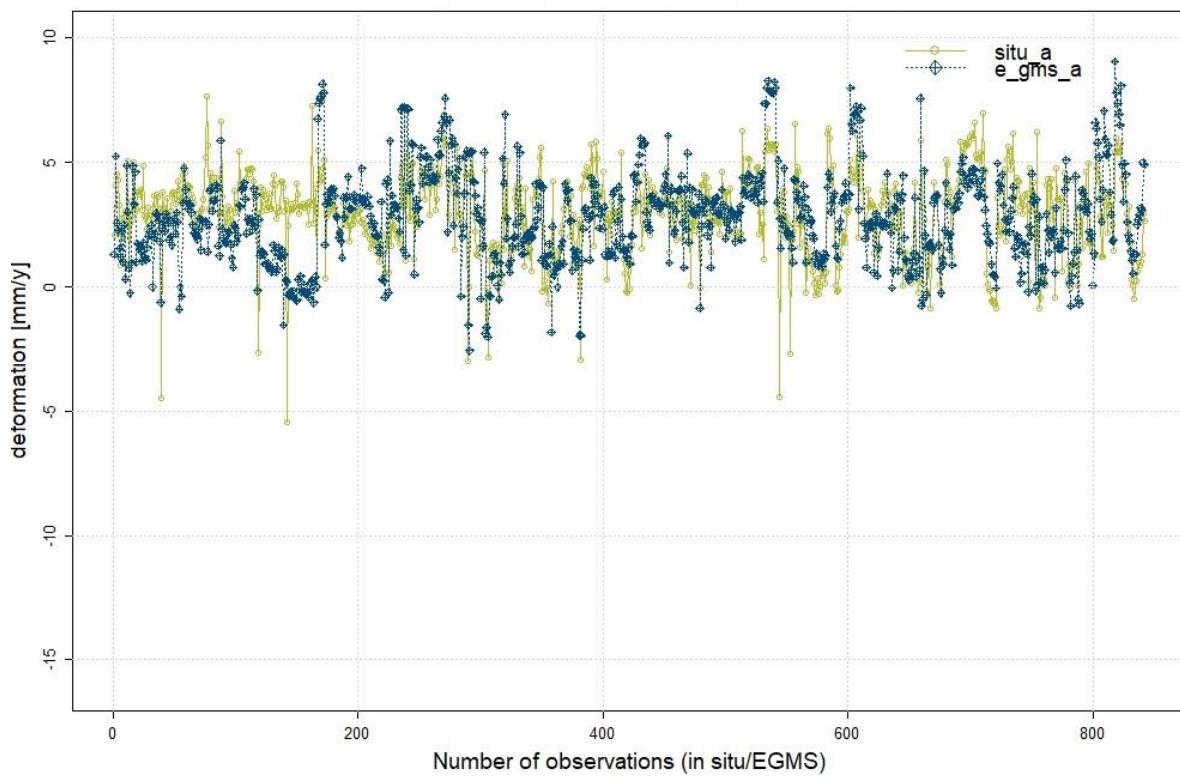
velocity EGMS vs. velocity in situ (2015-2021)


Figure 71: Plot showing the mean velocity of the entire population of levelling points against the mean value of 2015-2021 EGMS measurement points that fall within 50m of the in situ data.

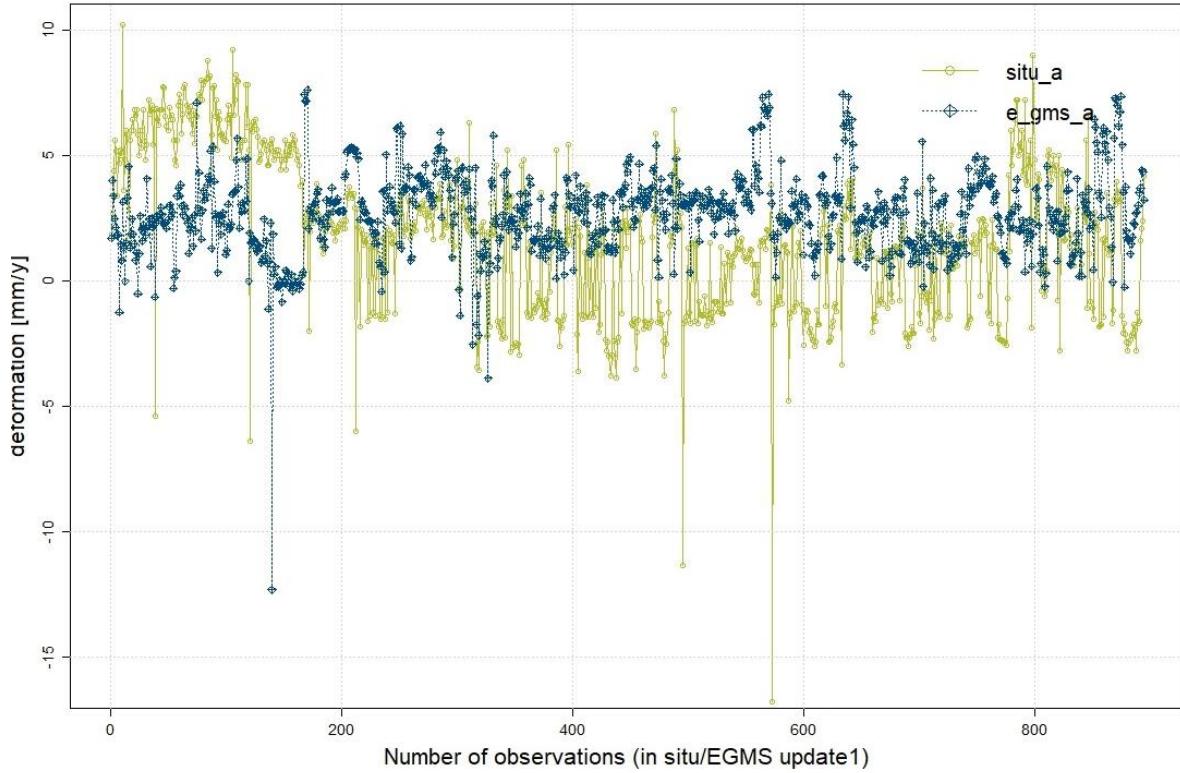
velocity in situ vs. velocity EGMS (2018-2022)


Figure 72: Plot showing the mean velocity of the whole population of levelling points against the mean value of EGMS update 2018-2022 MPs that fall within 50m of the in situ data.

The observed discrepancy, particularly evident in the first 200 stations, can be spatially associated to an area called “*le Porcelette*” in the western part of the study site. In Figure 73, a collection of levelling time series is presented; the two lower ones (black and grey time series), levelling numbers 10723 and 10725, pertain to that area. These time series exhibit a different trend compared to the other linear levelling graphs. This discrepancy is attributed to the presence of clayey soils in the “*le Porcelette*” area, which strongly react to water content variations, thus creating the observed seasonality variations in the time series.

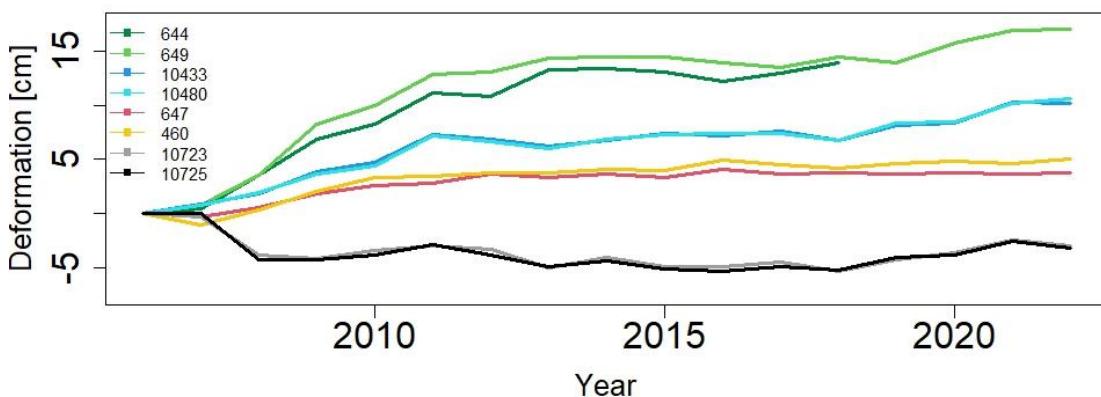


Figure 73: Plot showing the levelling measurements (in cm/year) for eight different levelling stations. Our focus for the discussion is “*le Porcelette*” station n.10723 and n. 10725.

In Figure 74, we can observe that the correlation IoA shows the lowest values. The reason behind this mismatch is explained by the seasonal patterns introduced by “*le Porcelette*” area (Figure 73). Error IoAs score very high since the MAE is below 5mm for all orbits. The Agreement IoA shows the best performance for Basic/L2a orbit 088 ascending. The best combined index among all is associated to Basic/L2a orbit 088 ascending with a score of 0.44.

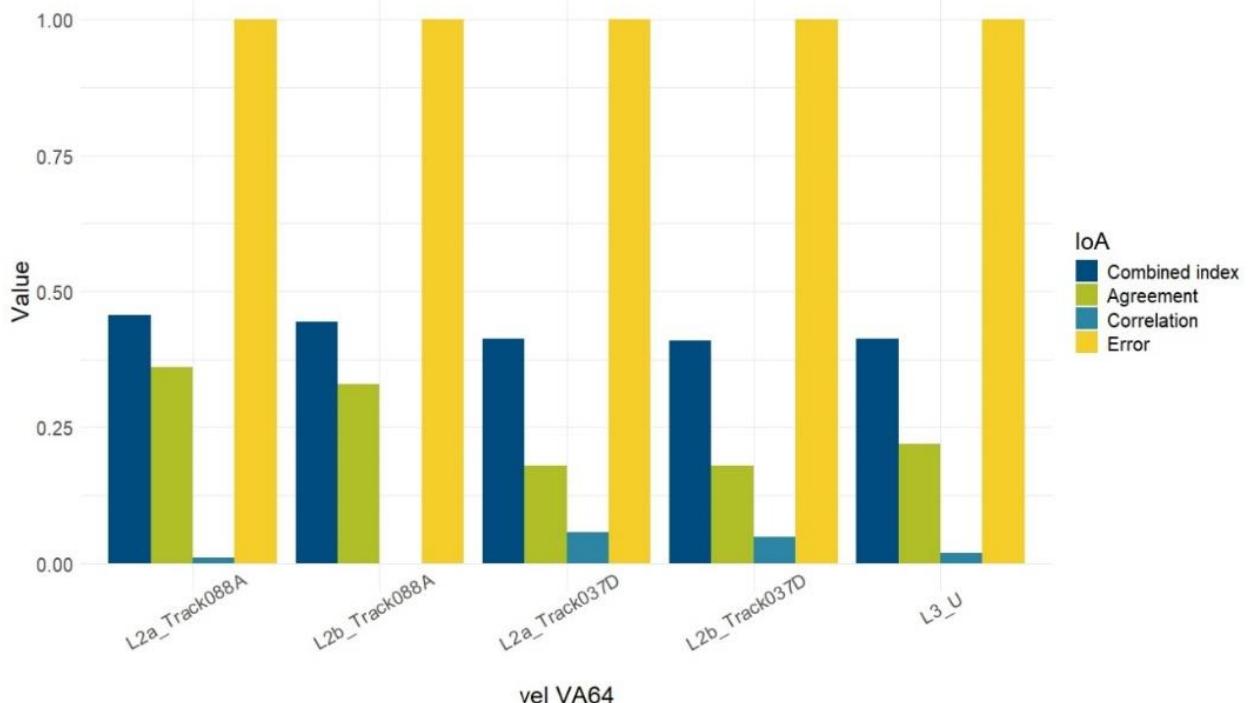


Figure 74: Plot showing the IoAs for mean velocity of the whole population of levelling points against the mean value of the measurement points that fall inside the 50 m buffer of the EGMS second release 2018-2021.

Figure 75 illustrates the time series results for the 10MPs displaying the highest velocities that fall within the levelling buffer. The descending data (orbit 037) and the Ortho/L3 Vertical products exhibit the highest IoAs. Most likely, the fact that the descending data (orbit 037) were acquired at a lower incidence angle than the ascending data (orbit 088) eased the comparison with the levelling data, especially in case of the vertical component of displacement. The product with the best performance is the Ortho/L3 data which scored a combined index of 0.7.

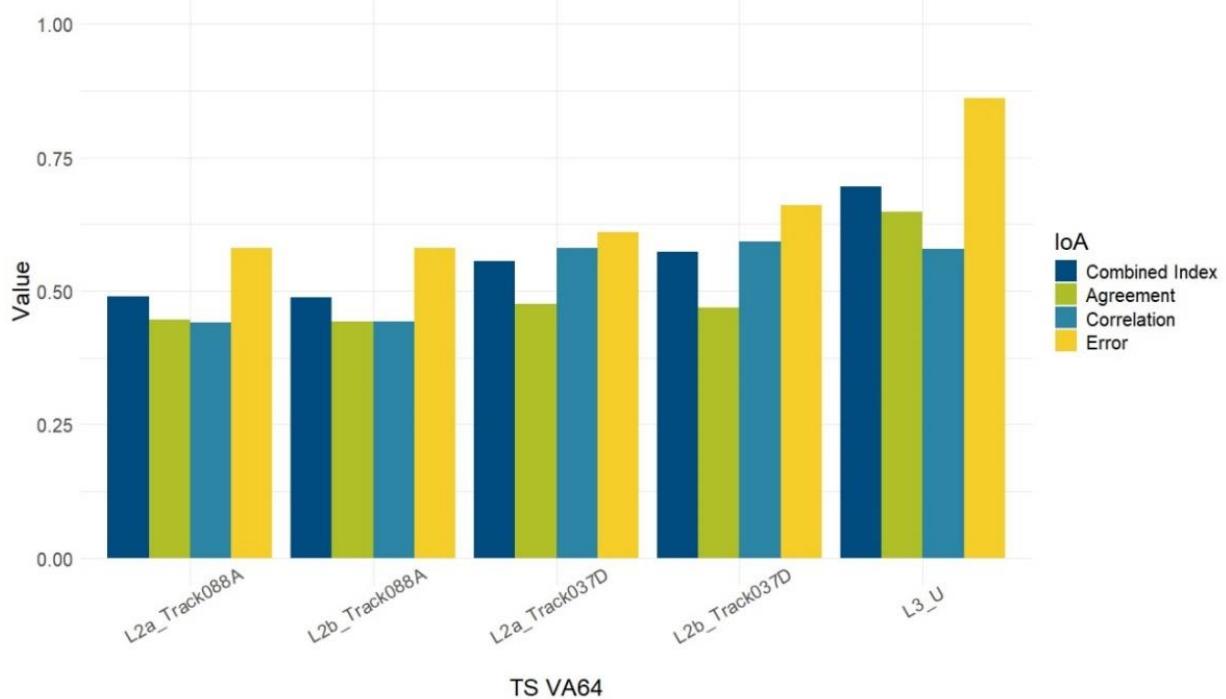


Figure 75: IoAs for the time series results for the Lorraine case study
(In situ levelling versus EGMS Basic/L2a, Calibrated/L2b and Ortho/L3 products).

In conclusion, the evaluation of the velocities did not deliver the expected IoA which were lower in comparison to the previous release EGMS (2015-2021). The main factor influencing the 2018-2022 update was the time series shortening of two years.

As shown in figures 71, 72 and 73 the presence of soil clay in a portion of the western sector of Lorraine ("le Porcelotte") introduced a seasonality trend which translated into an underestimation of the uplift rate in the EGMS (2018-2022) velocity and time series.

On the other hand, the ten highest uplift rates detected by the EGMS (2018-2022) time series, corresponded well to the in situ levelling stations time series. The Ortho/L3 vertical component obtained the best IoA score. Calibrated/L2b (orbit 037) obtained the second best result (and first within the LOS products). It is important to note that orbit 037 was acquired at a lower incidence angle than orbit 088. Overall, we can observe the consistency of the EGMS with yearly levelling measurement of ground uplift in post-mining areas.

Urban

Jutland peninsula (Denmark)

Jutland is a large peninsula that contains the mainland regions of Denmark, separating the North and Baltic seas and bordering Germany to the south. Along the west coast, the sedimentary sequence is mostly composed of sand and clay. The terrain of Jutland is predominantly flat, with a slightly elevated ridge running through the central parts. The highest hills (~150 m a.s.l.) are located in the east. The west has very low topography, with some areas below the average sea level. This area has been monitored with continuous GNSS stations since around the year 2010 (Figure 76), targeting coastal subsidence.

Although Denmark is uplifting by around 1 mm/year due to post-glacial rebound, large parts of the coastal regions are subsiding due to local phenomena. For example, the harbour in Esbjerg (Jutland region) registers active subsidence. Other subsidence phenomena have also been reported in the town of Thyborøn, as discussed in a previous chapter.

In Jutland, at some station locations in rural areas, few MPs were observed within the applied 100 m radius around the GNSS stations. Because at least three MPs are needed to calculate the EGMS time series standard deviations, stations with less than three MPs are excluded. Consequently, station TEJH was excluded from the analysis. Additionally, station SMID was discontinued at the end of 2021, so the time series for this station only cover until the end of that year.

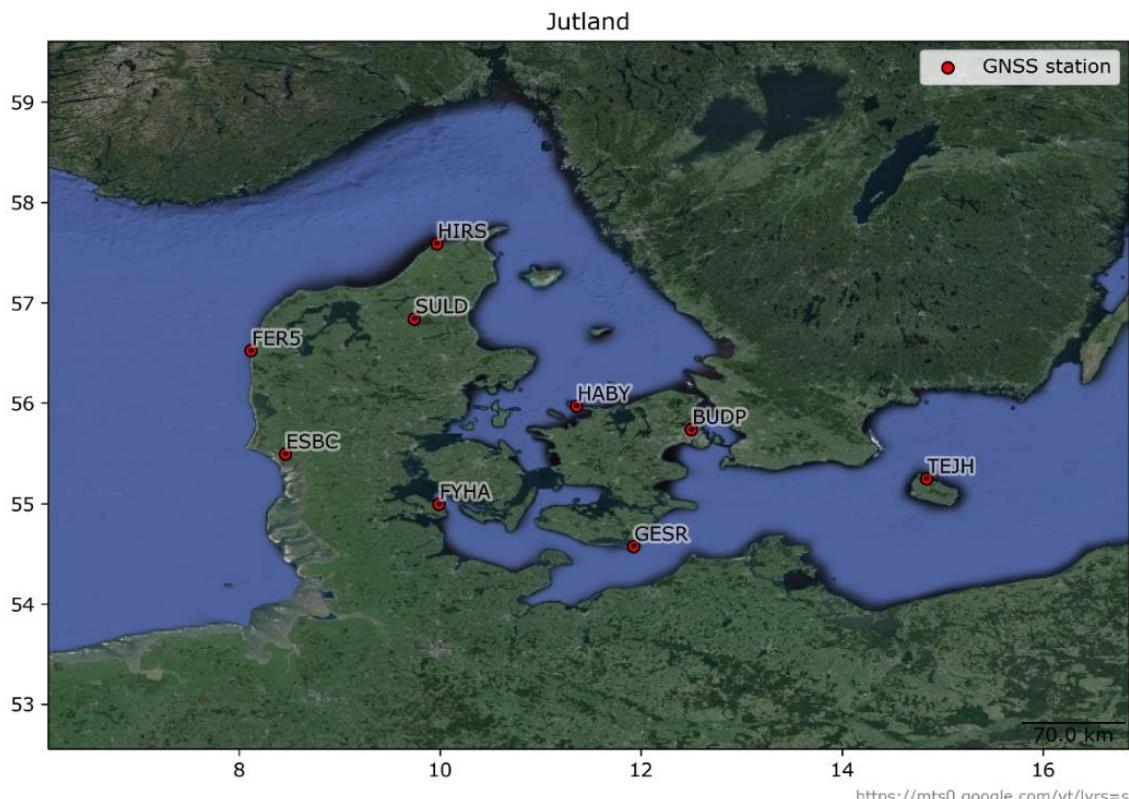


Figure 76: Jutland peninsula in Denmark and the GNSS stations used at this test site for this validation activity.

Given that these GNSS stations velocities are used by the production team to calibrate the Calibrated/L2b products, this report focuses on the Basic/L2a products results.

Figure 77 displays the worse fits (a to d) and best fits (e to h) in the time series examples of EGMS Basic/L2a MPs comparisons around each GNSS station. The same figure shows the double differences with reference to FYHA station for Basic/L2a products for ascending orbits 117.

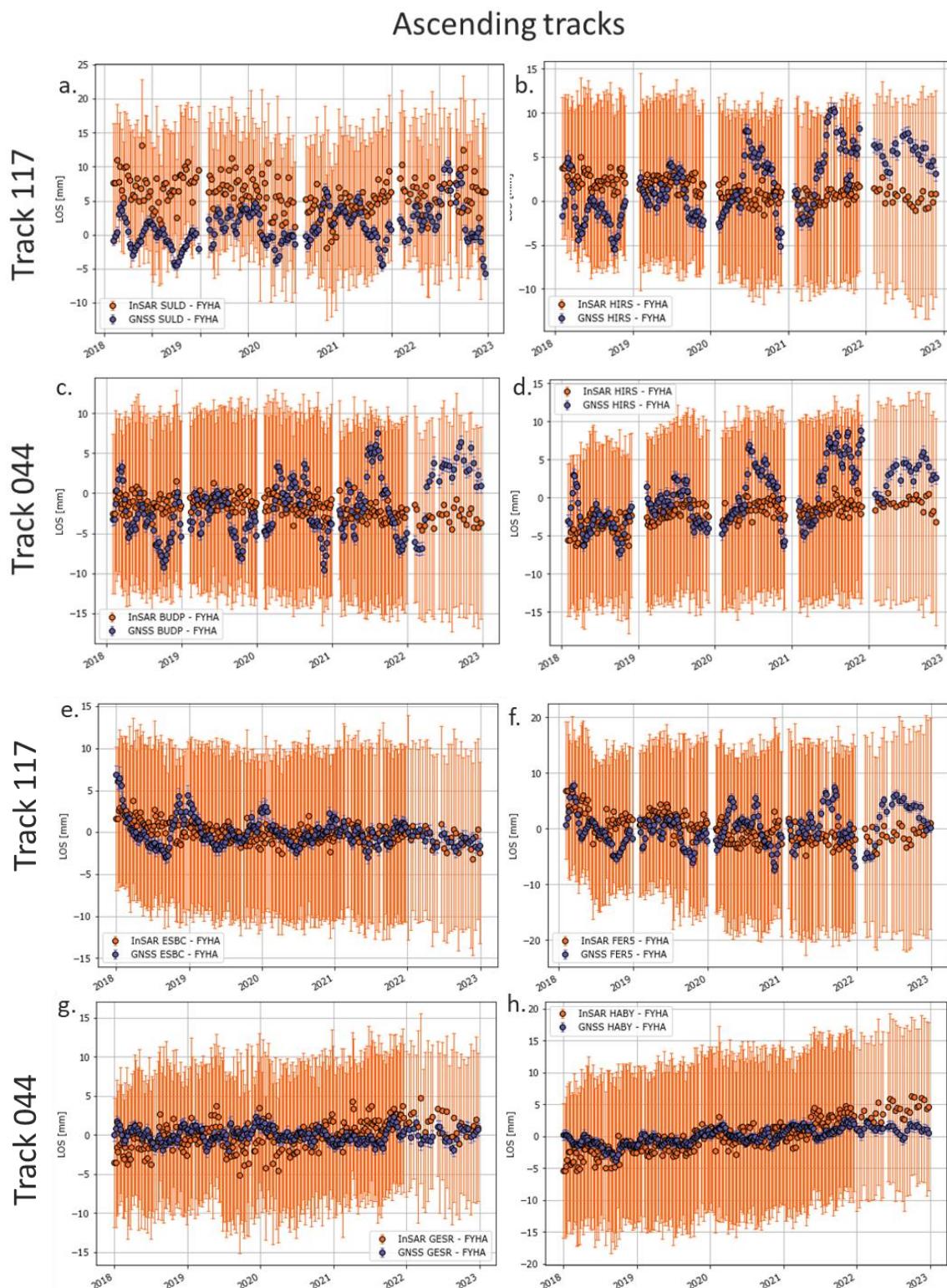


Figure 77: a), b), c) and d) - Examples of double differences between pairs of GNSS stations (those selected that did not pass the velocity test) and Basic/L2a products for ascending orbits. e), f), g) and h) – Examples of stations with a better fit. FYHA station is the reference GNSS station, and the examples shown are for the stations with the worse performance with respect to the velocity estimation. The orange error bars of the EGMS MPs were derived using all the datapoints falling within the search radius.

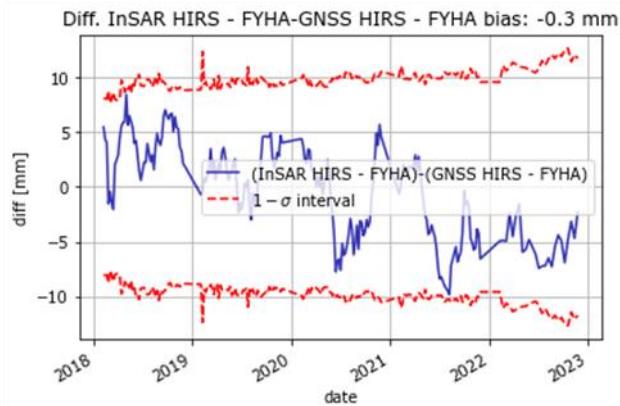
The time series and velocities in Denmark show a good fit between the GNSS and the EGMS MPs around the GNSS stations.

One aspect that makes the EGMS MPs diverge from the GNSS stations is the magnitude of the seasonal effects. The GNSS stations show significant amplitude seasonal signals that the average of the EGMS MPs within the selected radius around each GNSS station does not capture. However, the GNSS time series falls within the estimated standard deviation of the EGMS time series (orange lines in Figure 77). This may mean that the amplitude variations observed in some GNSS stations might just be averaged out while estimating the mean of the EGMS MPs' time series within the selected radius.

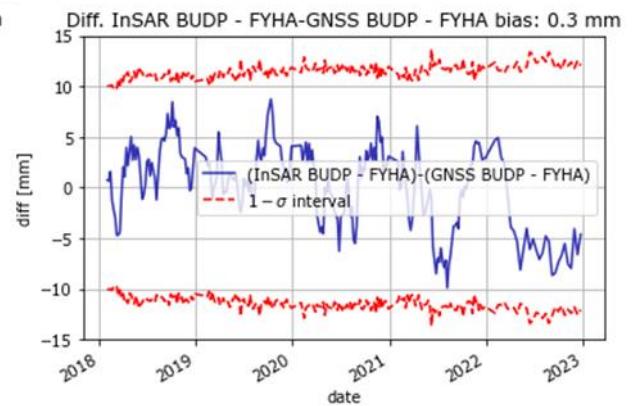
The standard deviation, for the displayed examples (Figure 78), oscillates between -10 and 10 mm. All stations pass the statistical time series test for all four orbits. For some stations, the velocity differences between the GNSS and the EGMS estimations can in some cases be around 2 mm/year.

Figure 78 shows the differences between GNSS and EGMS within a 1-sigma interval (standard deviation) of four out of the six stations that did not pass the velocity test from all stations and analysed products, 21 stations in four orbits. Still, the estimated average velocity differences between GNSS and EGMS is minimal and in the order of 0.5-0.7 mm/year.

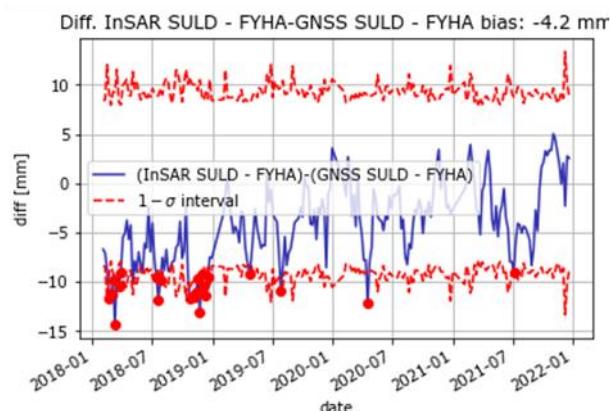
a. Basic/ L2a, ascending, T117



b. Basic/L2a, ascending T044



c. Basic/ L2a, descending, T066



d. Basic/ L2a, descending, T139

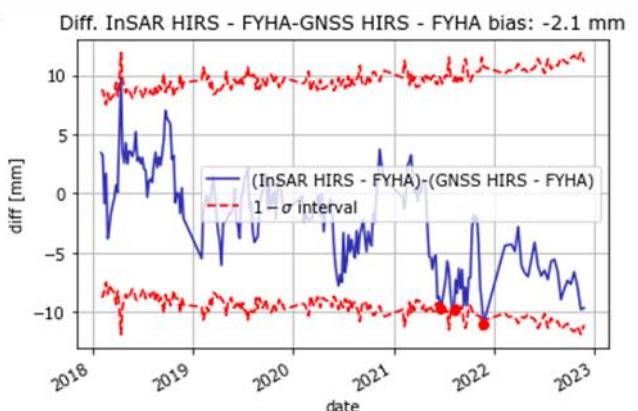


Figure 78: Examples of double differences for Basic/L2a products, highlighting comparisons for ascending and descending for the stations that did not pass the velocity statistical test.

Figure 79 shows the bar charts of the IoAs of all the available ascending and descending orbits for the Basic/L2a. All stations passed the time series test for all orbits of the Basic/L2a products.

For the velocity test, almost all stations and orbit combinations pass the t-test or the statistical test for velocity. The highest velocity differences observed between EGMS and GNSS for Basic/L2a products are around 2 mm/year.

The overall model test for the time series and t-test for velocity differences give a positive outcome for most stations, suggesting a great similarity between the EGMS Basic/L2a products and the GNSS time series.

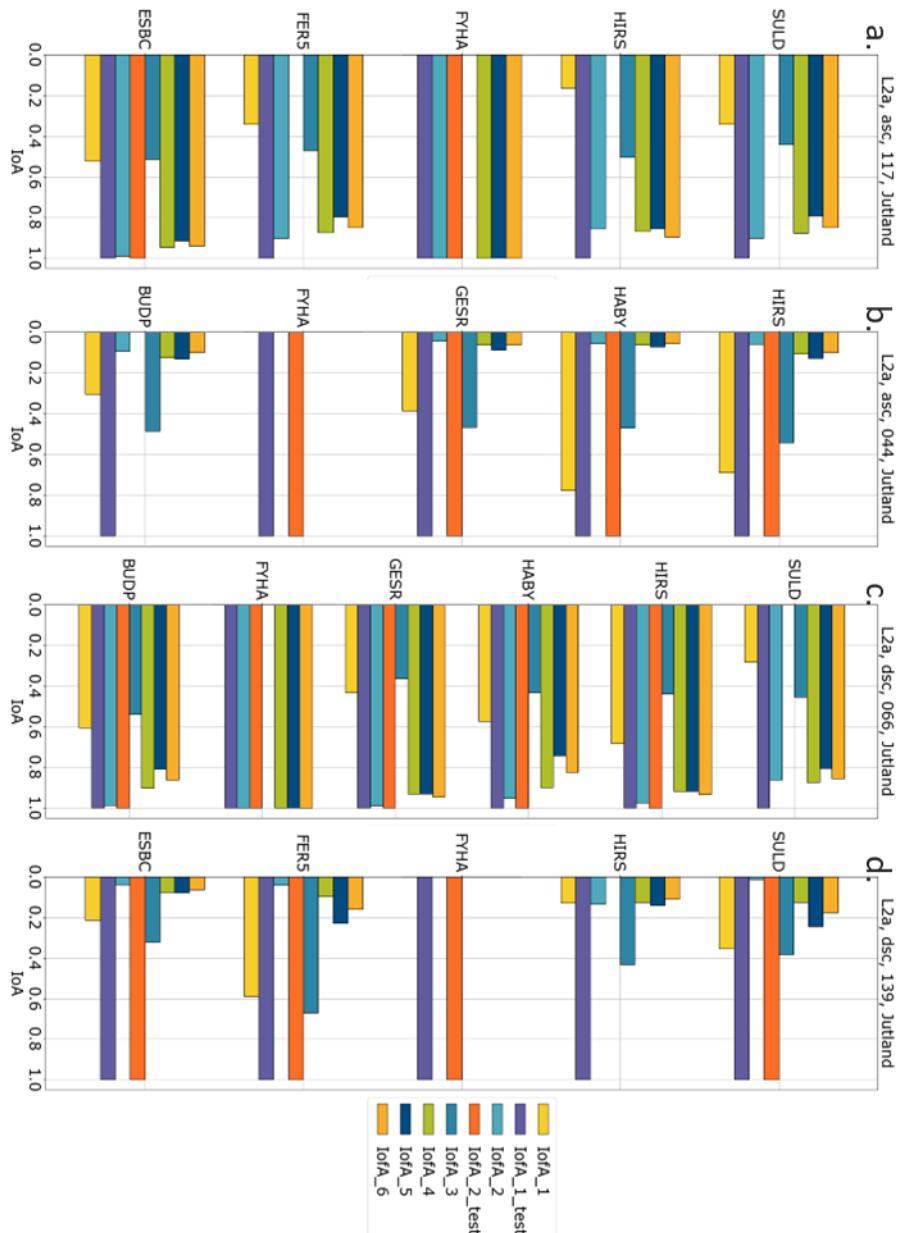


Figure 79: Index of Agreement for two ascending and two descending orbits for Basic/L2a EGMS products. Each of the subplot title indicates the product followed by the type and number of orbits. From table 9: IoFA_1 (time series correlation); IoFA_1_test (overall model test); IoFA_2 (velocity differences); IoFA_2_test (t-test for velocity); IoFA_3 (Seasonality/correlation); IoFA_4 (Seasonality/Standard deviation); IoFA_5 (Seasonality/Mean differences); IoFA_6 (Seasonality/RMS)

Overall, the seasonality index or the correlation of detrended signals indicates an acceptable but not excellent correlation of seasonal effects between EGMS and GNSS for all orbits. In general, the seasonal effects should be carefully interpreted because of the nature of the double-difference estimations.

Figure 80 showcases examples of the correlation of estimated velocities between EGMS and GNSS using all stations per Basic/L2a product. This figure reinforces previous observations of the velocity differences: the correlation coefficients indicate a good agreement between GNSS and EGMS estimated velocities for most of the EGMS products and orbits.

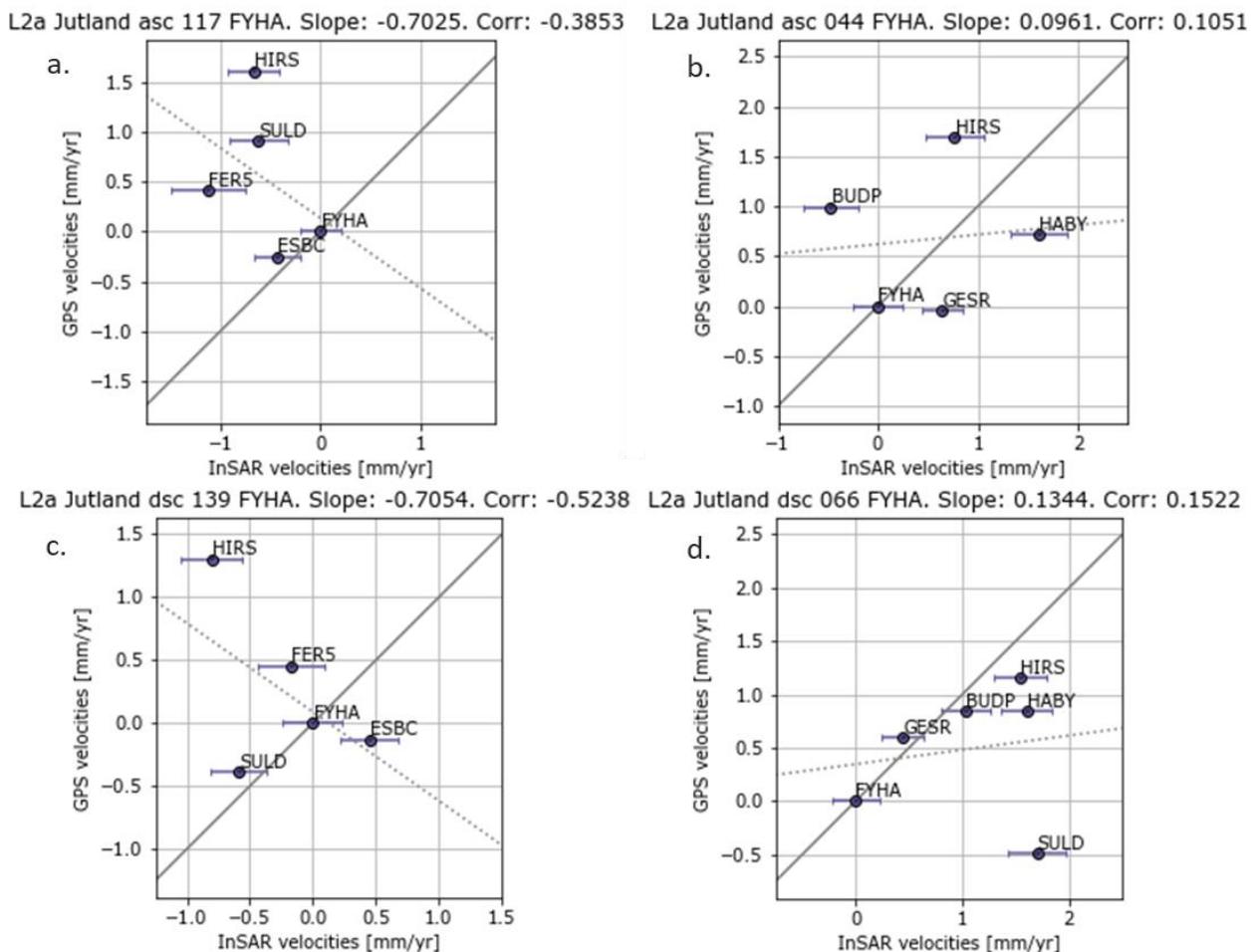


Figure 80: Correlation between EGMS/GNSS velocities for the Basic/L2a EGMS products. Station location falling within the black full line indicates perfect agreement between the estimated double difference velocity of the EGMS with the GNSS. Dashed line indicates the best fit line between all stations.

Figure 81 shows the bar charts of the IoAs of the available ascending and descending orbits for both the Calibrated/L2b products and the Ortho/L3 East-West and Vertical products.

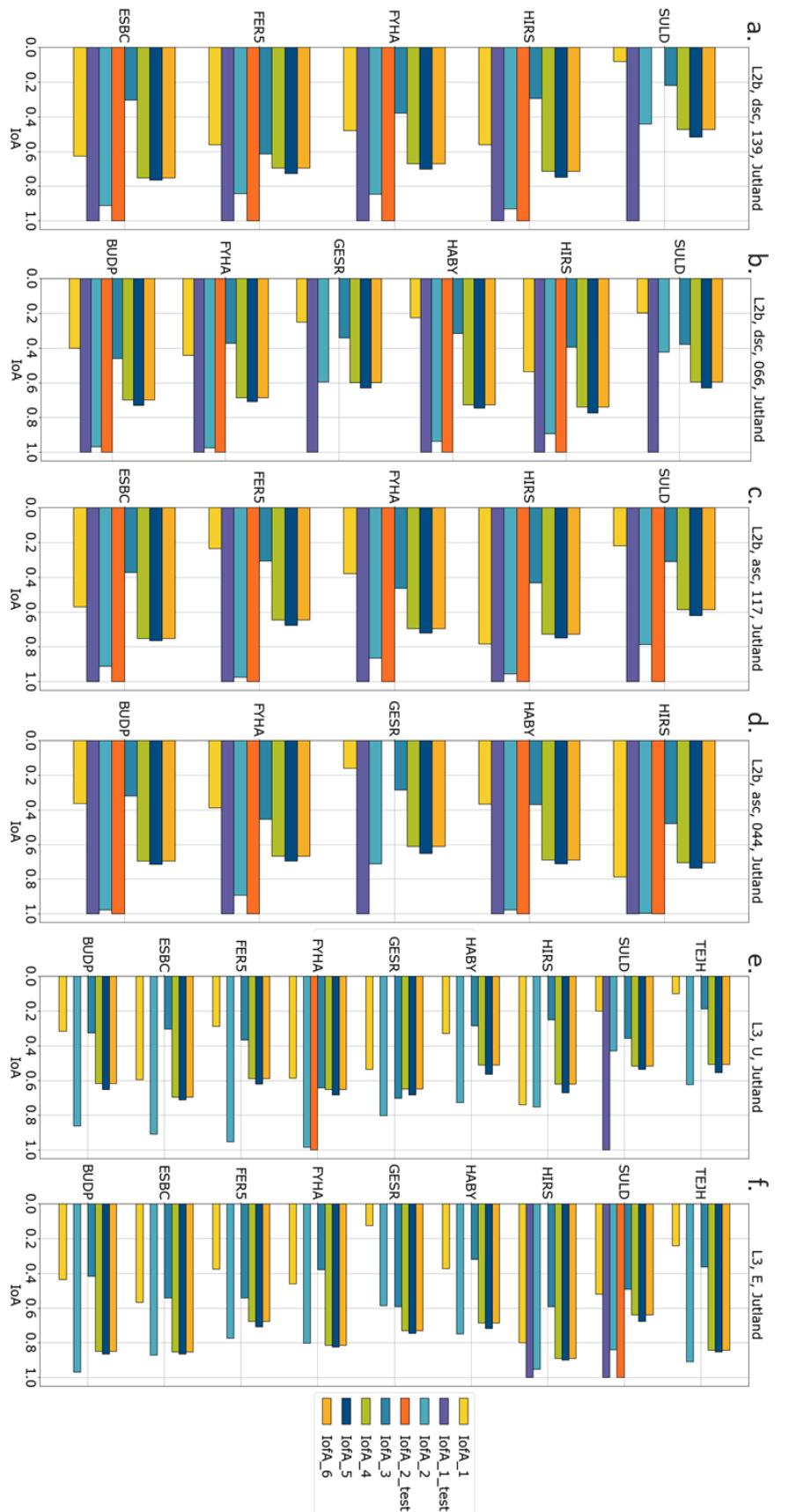


Figure 81: Index of Agreement for the ascending and descending orbits for Calibrated/L2b, and Ortho/L3 Vertical and East-West EGMS products. Each subplot title indicates the product followed by the type and number of orbits. From table 9: IofA_1 (time series correlation); IofA_1_test (overall model test); IofA_2 (velocity differences); IofA_2_test (t-test for velocity); IofA_3 (Seasonality/correlation); IofA_4 (Seasonality/Standard deviation); IofA_5 (Seasonality/Mean differences); IofA_6 (Seasonality/RMS)

The overall model test for the time series and the t-test for velocity differences yield significant positive outcomes for nearly all stations, indicating a strong similarity between the EGMS and GNSS time series. All stations have successfully passed the velocity statistical test for all orbits of the Calibrated/L2b products reassuring this similarity, and only few stations did not pass the time series statistical.

Figure 82 shows the time series of the only two stations not passing the time series statistical test from all stations and analysed products. Figure 82 a) and b) show station GESR ascending orbit 044 results. In Fig 82 a), the EGMS and the GNSS time series are shown, while Fig 82 b) displays differences between GNSS and EGMS within a 1-sigma interval. Figure 82 c) and d) shows the results for station GESR and SULD ascending orbit 044.

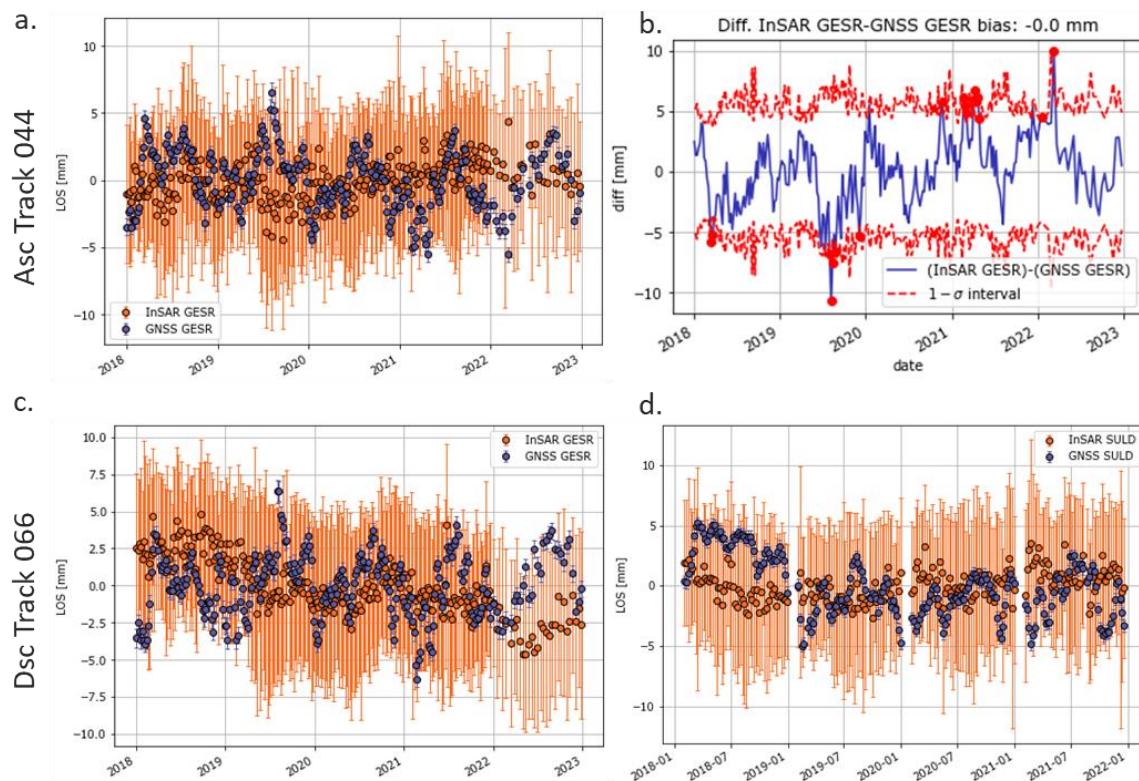
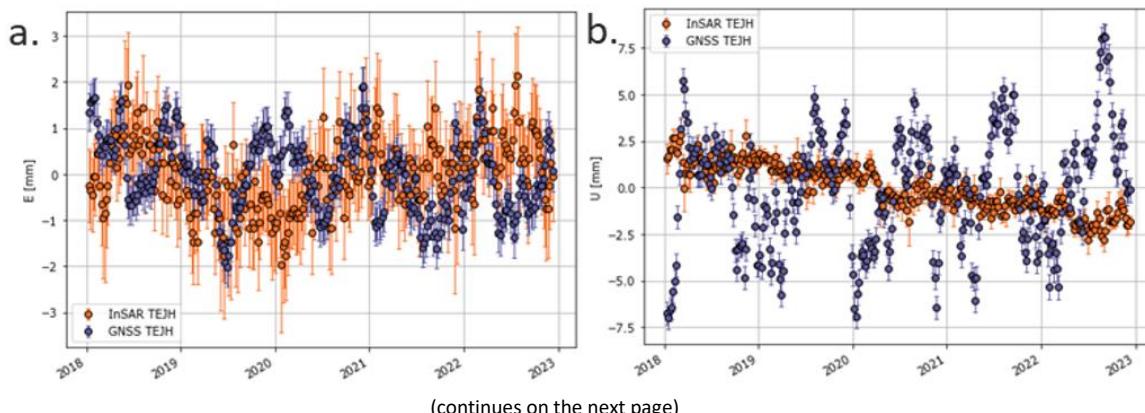


Figure 82: (a), (c) and (d) show examples of single differences between Calibrated/L2b products and GNSS, highlighting comparisons for ascending (044) and descending (066) for the stations that did not pass the time series statistical test (see Figure 81). (b) shows an example of the differences between the EGMS and the GNSS time series for station GESR. The orange error bars of the EGMS MPs were derived using all the datapoints falling within the search radius. Please note that station SULD GNSS only covers the EGMS period until the end of 2021.



(continues on the next page)

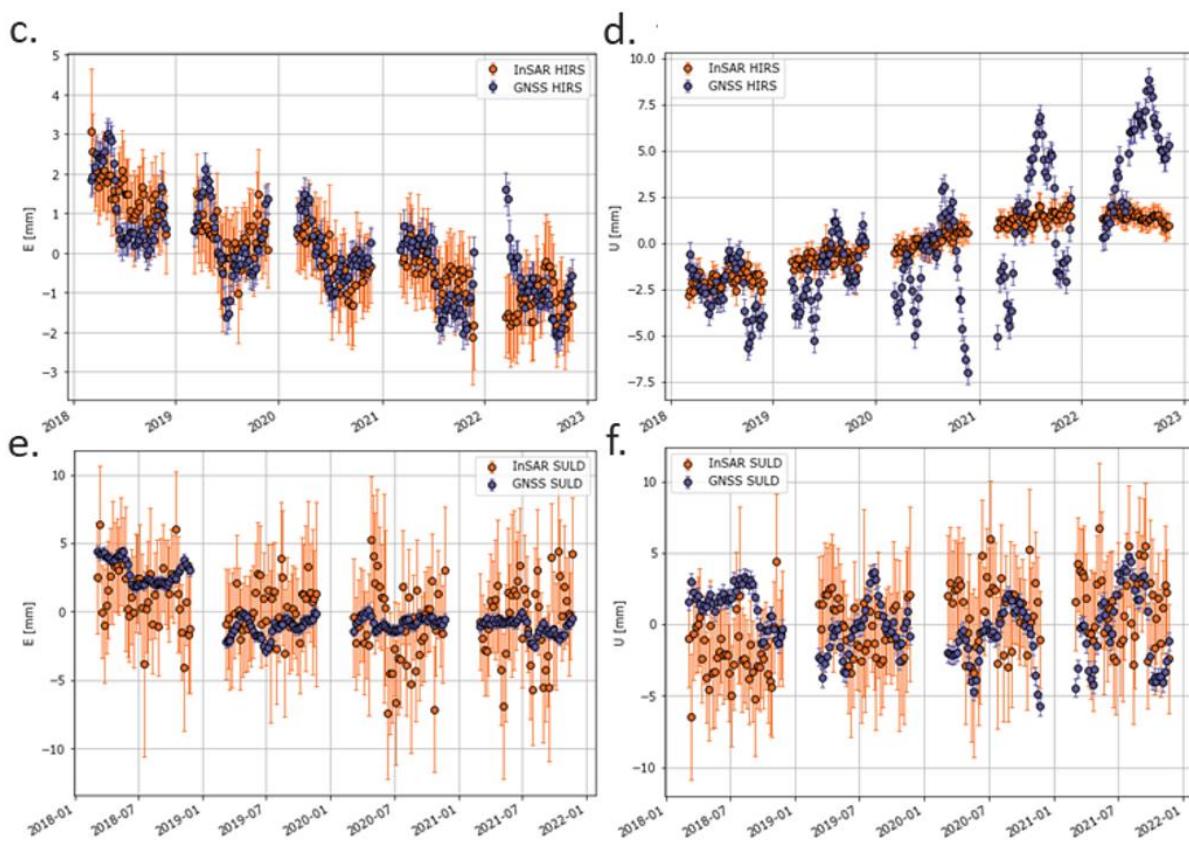


Figure 83: Examples of single differences between Ortho/L3 East-West (E) and Vertical (U) products and GNSS corresponding components (stations TEJH, HIRS and GERS). Please note that station SULD GNSS only covers the EGMS period until the end of 2021.

Figure 83 depicts the displacement of Ortho/L3 products in the east and vertical directions. As seen in Figure 81, the performance of the Ortho/L3 East-West (E) products exceeds that of the Ortho/L3 Vertical (U) products with higher Indexes of Agreement. 11% of the stations pass the time series and velocity statistical tests for the vertical component. For the East component, 22% of the stations pass the time series statistical test and 11% the velocity statistical test.

The time series of the EGMS MPs at each GNSS station follow the trends of the corresponding GNSS

The correlation plots for the Basic/L2a EGMS products reveal that the highest velocity differences are up to 2 mm/year at specific stations, namely SULD, BULPD, and HIRS. For Calibrated/L2b products, these differences decrease, being only up to 1.6 mm/year at station SULD.

For the Ortho/L3 East-West (E), the highest velocity difference is 1 mm/year at station GERS and for the Ortho/L3 Vertical (V) is up to 1.6 mm/year at station SULD.

Thyborøn (Denmark)

In the west coast region of Denmark, Thyborøn holds significant interest due to its unique geographical features. This area is a focal point of a thematic investigation centred on subsidence, primarily resulting from consolidation phenomena. The location, mainly constructed on landfill and soft sediments, exhibits notable subsidence rates exceeding 7 mm/year, particularly in its south-eastern parts. Recent measurements in Thyborøn include CRs linked to a levelling network (Figure 84). This network serves to calibrate satellite-based deformation measurements, offering crucial data for this study.



Figure 84: Map of the Thyborøn Peninsula showing the three corner reflectors (CRs) observable in the EGMS time series. The image in the bottom right corner shows an example of the type of CR deployed in Thyborøn.

Three out of eight CRs are visible in the EGMS products being validated (2018-2022). The three CRs are made from 60x60x120 cm square aluminium/iron plates with double geometry, suitable for both ascending and descending satellite paths. Moreover, there have been two levelling campaigns relevant to this release of the EGMS (2018-2022). Consequently, for the current EGMS comparison, Thyborøn has been primarily utilized for assessing the geo-positioning accuracy.

Table 10: Probability estimation of each MP being the CR

MP (internal id)	MSE	Probability of CR (normalised)
24	0.78	0.06
19	5.73	0.16
25	4.36	0.63
23	9.82	0.0
28	5.82	0.15

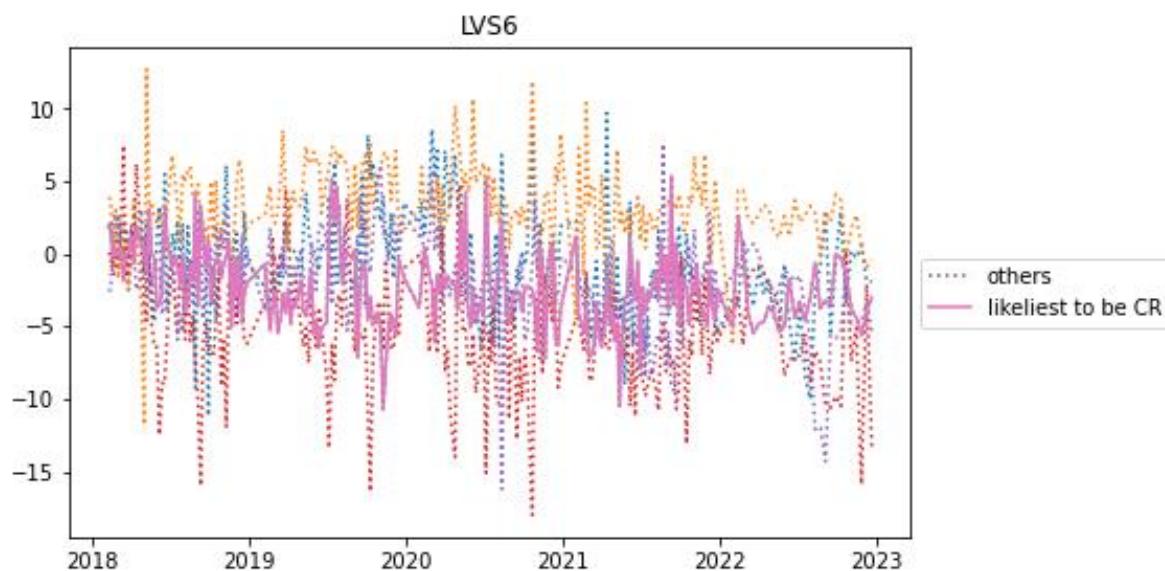
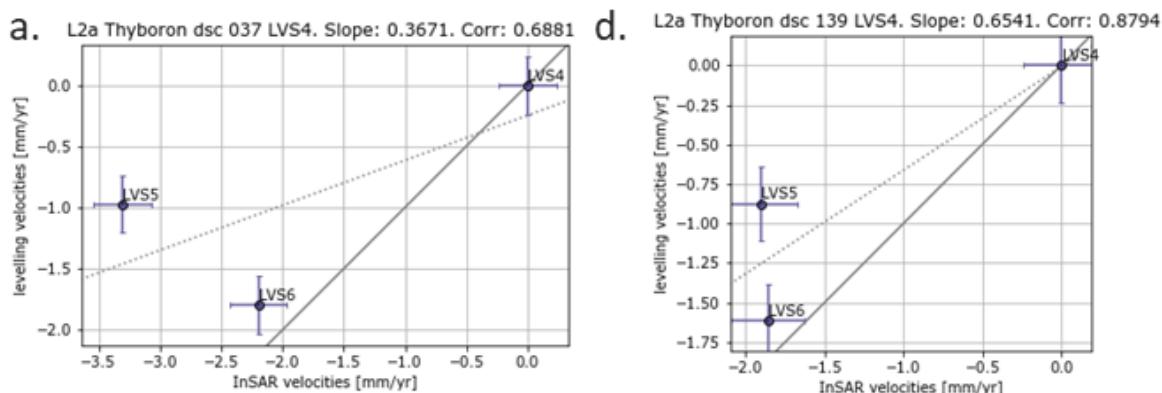


Figure 85: Example of time series of EGMS MPs around the 'LVS6' corner reflector (CR).

Figure 85 shows an example of selecting the EGMS MP time series corresponding to the CR. Table 10 provides the metrics (mean square error) and probability of an MP around the CR location corresponding to the CR. The horizontal distance between the CR and the EGMS MP most likely attributed to the CR determines the geolocation accuracy. A similar operation is performed for height, where the orthometric height measured at the CR is compared with the height of the corresponding EGMS MP.

The geolocation accuracy of the Basic/L2a and the Calibrated/L2b products was evaluated in the Thyborøn site. For both products, the estimated accuracy is below the geolocation accuracy requirement of 10 m defined by the EGMS production tender specifications.

Only Basic/L2a products are analysed and compared to levelling, totalling four orbits, two descending and two ascending. An assumption is made to perform this comparison: the EGMS LOS displacements of the Basic/L2a products at the Thyborøn Peninsula are purely vertical. Figures 86 and 87 show the results of this analysis for the Basic/L2a descending and ascending orbits, respectively.



(continues on the next page)

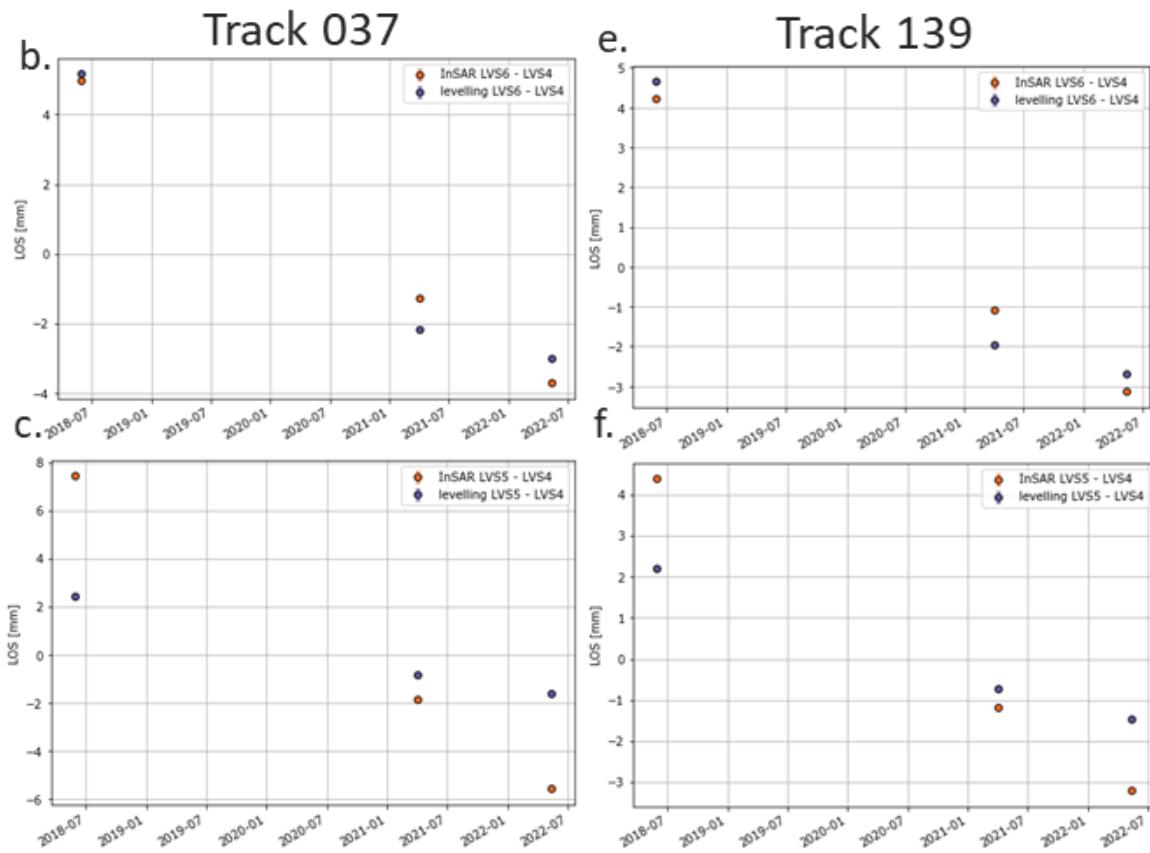
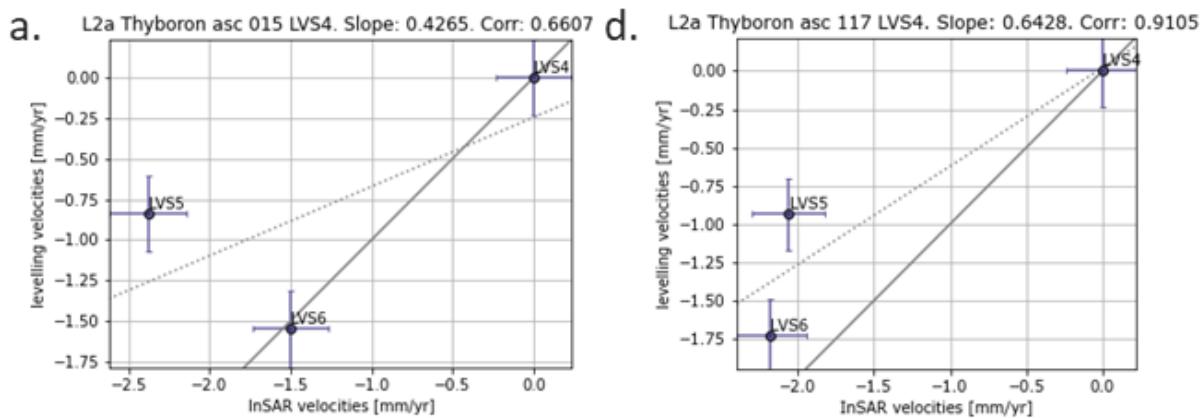


Figure 86: (a) and (d) show the correlation between EGMS/levelling velocities for the descending orbits (037 and 139) of the Basic/L2a EGMS products. Station location falling within the black full line indicates perfect agreement between the estimated double difference velocity of the EGMS with the GNSS. Dashed line indicates the best fit line between all stations.

(b), (c), (e) and (f) show the results of double differences time-series comparison between EGMS and levelling, b) and c) for orbit 037 and e) and f) for orbit 139.



(continues on the next page)

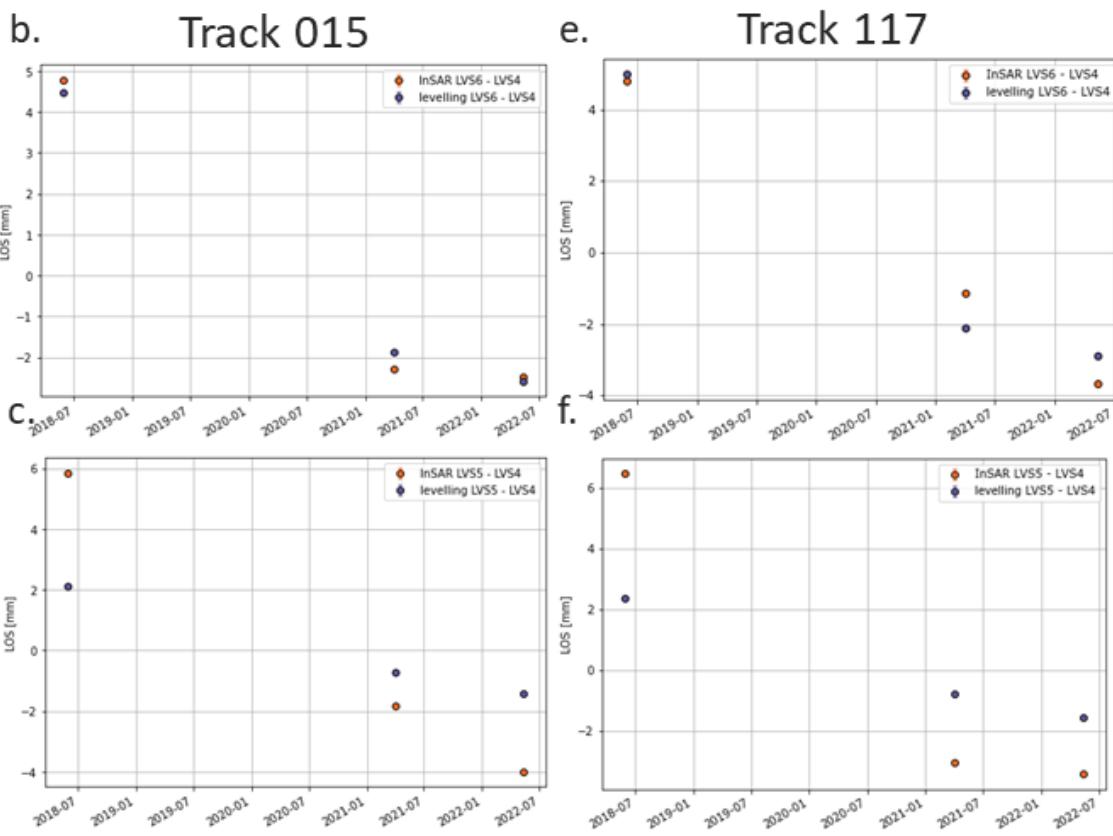


Figure 87: (a) and (d) show the correlation between EGMS/levelling velocities for the ascending orbits (015 and 117) of the Basic/L2a EGMS products. Station location falling within the black full line indicates perfect agreement between the estimated double difference velocity of the EGMS with the GNSS. Dashed line indicates the best fit line between all stations. (b), (c), (e) and (f) show the results of double differences time-series comparison between EGMS and levelling, b) and c) for orbit 015 and e) and f) for orbit 117.

The analysis focuses on the precision of Basic/L2a products, comparing EGMS and levelling. This approach covers four orbits at the site, two descending and two ascending, ensuring comprehensive data coverage. Across all orbits, the levelling benchmark at the CR LVS5 consistently exhibits higher velocity differences between EGMS and levelling (Figure 86 and 87 a) and d), with the most pronounced difference recorded at 2.3 mm/year for orbit 037 descending orbit.

The time series in Figures 86 and 87 show a consistent downward linear trend between EGMS and levelling. The maximum estimated displacement difference between EGMS and levelling is 6 mm at CR LVS5.

The analysis indicates consistency in the time series of the levelling measurements and the EGMS estimation. This comparison is key because it allows for evaluating EGMS time series at CR locations.

Gran Canaria (Spain)

Gran Canaria island, a densely populated outermost Spanish region, is one of Europe's most popular touristic destinations. The Canary Islands is home to over two million people and have an average population density three times higher than the rest of Spain. This archipelago is one of the major volcanic oceanic island groups of the world and has a long magmatic history, which began at the bottom of the ocean more than 40 million years ago. Constructed on the passive continental margin of the African Plate on Jurassic oceanic lithosphere, the Canary Islands comprises seven main volcanic islands forming a chain extending for approximately 500 km across the East Atlantic Ocean.



Figure 88: Grand Canaria and GNSS stations distribution

The aim is to validate data acquired in volcanic regions. Most of the historical eruptions in the Canary Islands have been short lived, ranging from a few weeks to a few months, and have typically been basaltic, strombolian to violent strombolian eruptions. These eruptions have generated scoria cones of different sizes and lava flows of different extent. Sixteen historical eruptions have been documented in the Canarian Archipelago to date. The most recent event occurred in September 2021 in La Palma, lasting 85 days, covering more than 1228 Ha with lava flows, and destroying around 1700 buildings. Due to the availability of GNSS stations, the validation efforts have been focused Gran Canaria Island.

In the analysis of Basic/L2a and Calibrated/L2b products (ascending orbit 162), all stations pass the OMT for the time series except for the AGUI station for the Basic/L2b descending orbit 096. There is a good agreement between the EGMS and GNSS stations, with AGUI being the station where the fit is poorer with velocity differences in the order of 1 mm/year for the Basic/L2a

products and 1.9 mm/year for the Calibrated/L2b products. Figure 89 illustrates the worst and the best performance for the time series comparison for the Basic/L2a and Calibrated/L2b products.

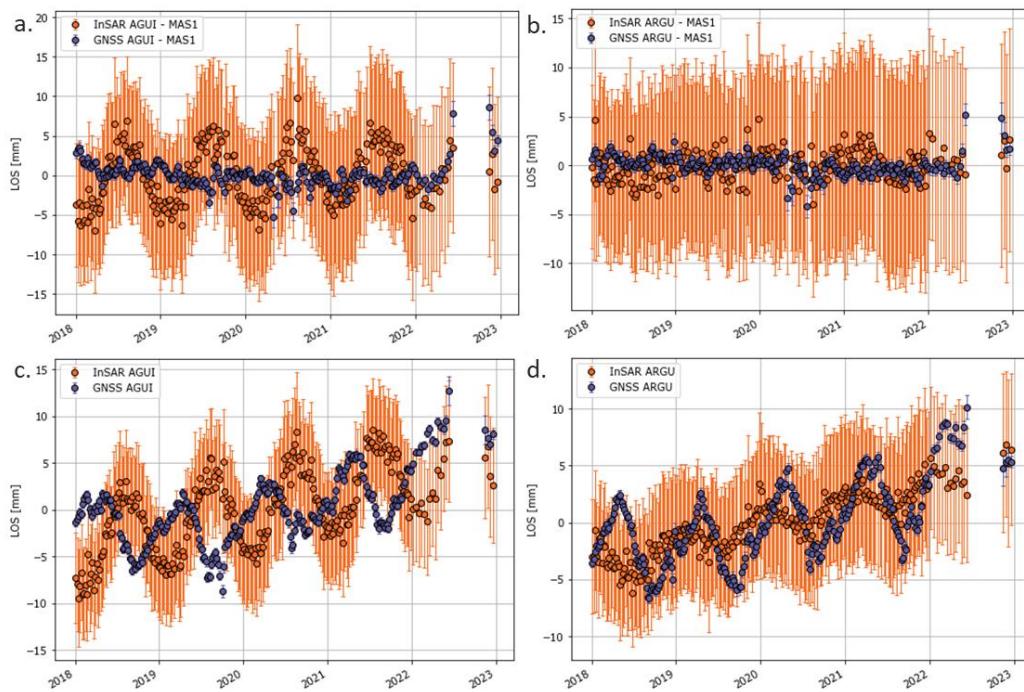


Figure 89: (a) and (b) Examples of double differences between pairs of GNSS stations and Basic/L2a ascending orbit 162. (c) d) Example of single differences between EGMS and GNSS of Calibrated/L2b products. Subplot a) and b) are examples of the worse fits (station AGUI) and (c) and (d) are examples of the best fits (station ALDE). Reference station: 'MAS1'. The orange error bars of the EGMS MPs were derived using all the datapoints falling within the search radius.

In Figures 89 (a) and 89 (c), the AGUI time series double-differences accurately capture the linear trend, the velocity and the IoA on time-series correlation. However, station AGUI has one of the lowest IoA values, the IoA for the correlation of detrended signals, due to the anticorrelated signal between the GNSS and EGMS shown in Figure 89 (c). Station ARGU on Figure 89 (b) and 89 (d) exhibits the lowest velocity differences on ascending and descending orbits for Calibrated/L2b products. This is visible as GNSS captures the seasonal deformation pattern, whereas EGMS displays a clear linear rate of displacement. Please note that the gaps in the GNSS stations TERR, AGUI, ALDE, and ARGU in the last half of 2022 occurred because the data did not pass the quality tests of the GNSS processing. Because we could not assess the reason for this before this report's completion, we decided to exclude this period of data from the comparison. This has been fixed for the end of 2022 and 2023.

Overall, the agreement between EGMS and GNSS stations is better for Basic/L2a than for Calibrated/L2b products. In the case of Calibrated/L2b products, four out of seven stations for the ascending orbit and three out of seven for the descending orbit do not pass the velocity test. However, note that the stations that do not pass the velocity test have velocity differences with the EGMS time series in the order of 0.6 to 1.9 mm/year. The station MASP has the worst performance for the descending orbit with a 1.9 mm/year difference between GNSS and EGMS.

Figure 90 depicts the Ortho/L3 products comparison in the east-west (top row) and vertical direction (bottom row). The Ortho East-West product consistently exhibits higher IoA than the Ortho/L3 Vertical product across all stations. This can be observed from the best (MAS1, ALDE) and worse results (AGUI):

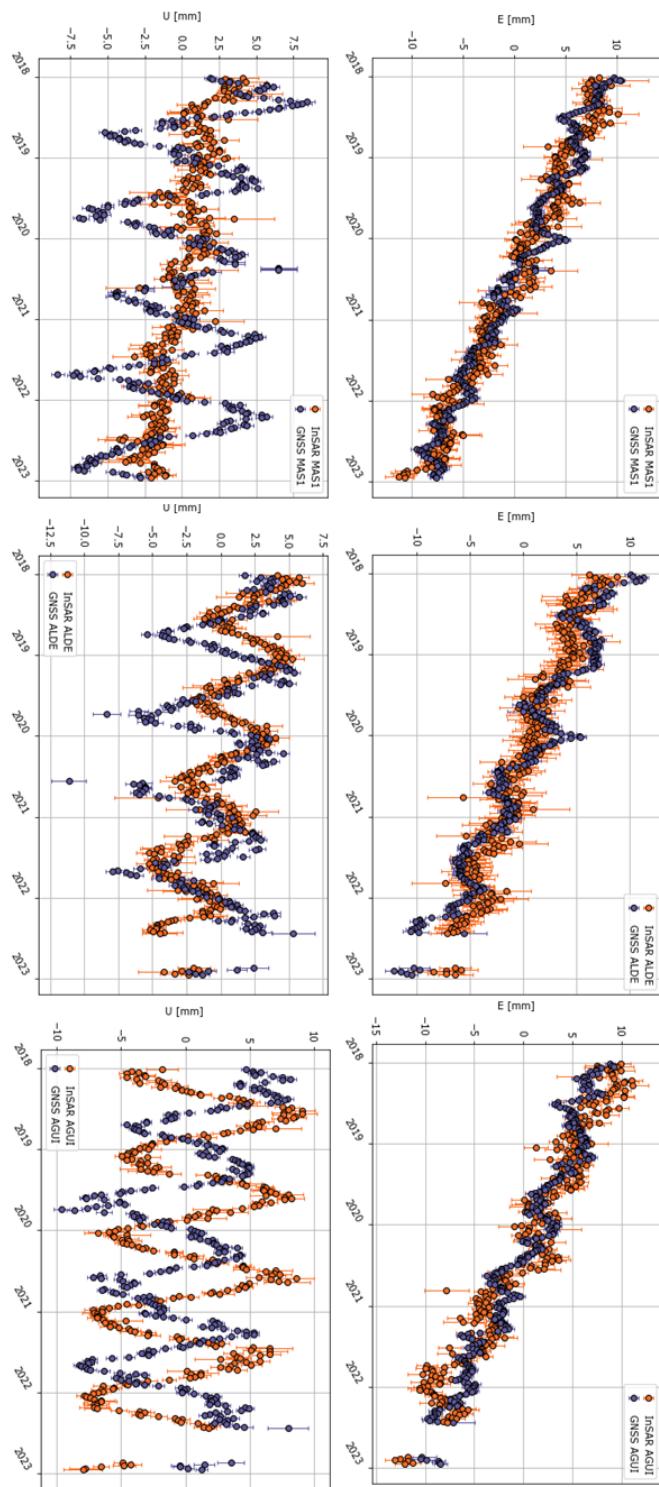


Figure 90: Ortho/L3 products comparison in the East-West (top row) and vertical direction (bottom row).

Figure 90 shows (next page) that the worst fit can be found for AGUI station and the Ortho/L3 Vertical product. Despite that, velocity estimations exhibit a good fit between the GNSS and the EGMS product. Bigger differences are seen in the time series seasonality. The highest velocity differences in East-West Ortho/L3 products are 1 mm/year at ALDE, followed by ARGUI, with a 0.5 mm/year difference between EGMS and GNSS.

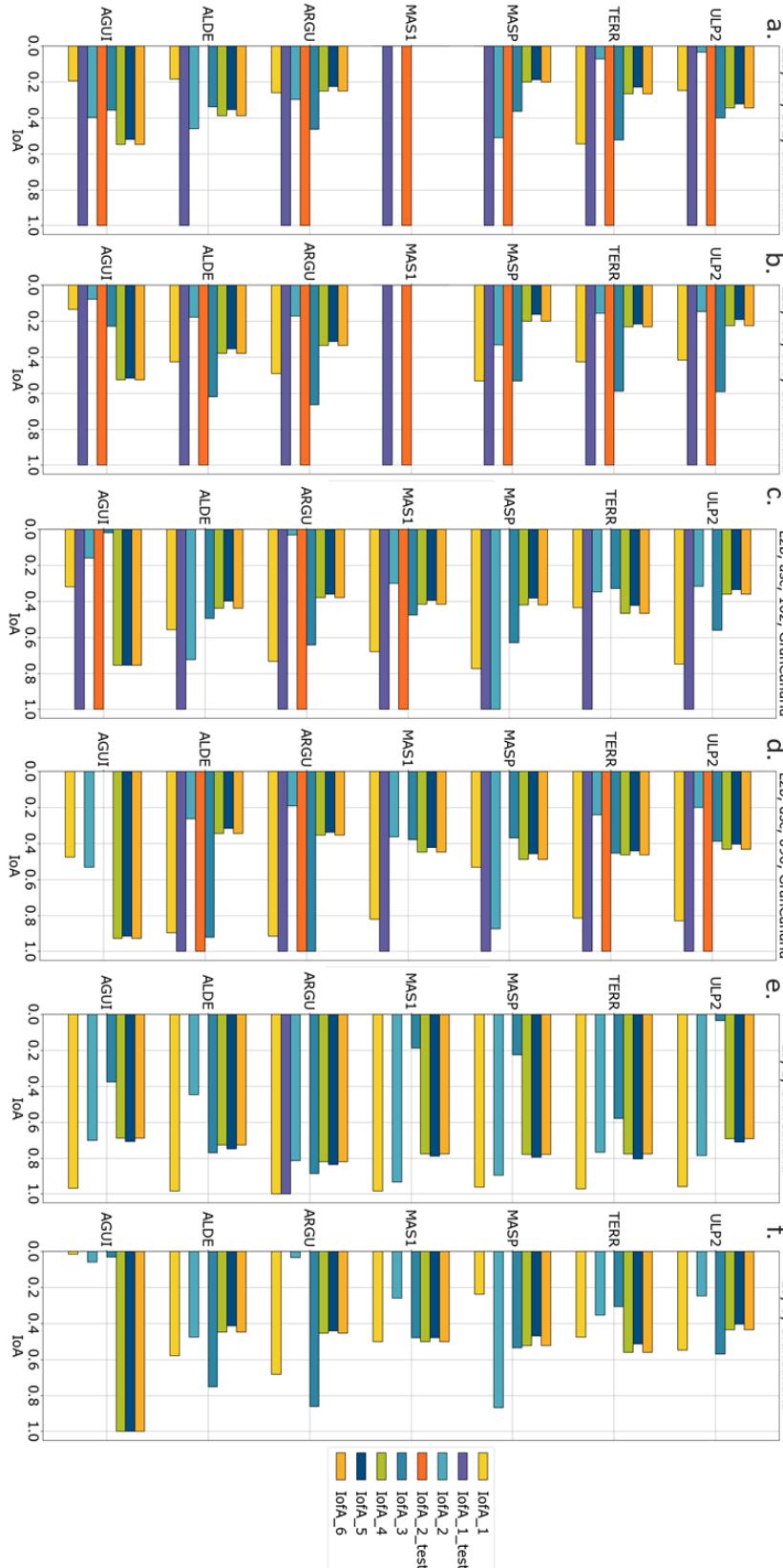


Figure 91: Index of Agreement for Basic/L2a, Calibrated/L2b and Ortho/L3 EGMS products for one of the available ascending and descending orbits. Each of the subplot titles indicates the product followed by the type and number of orbits. From table 9: IoFA_1 (time series correlation); IoFA_1_test (overall model test); IoFA_2 (velocity differences); IoFA_2_test (t-test for velocity); IoFA_3 (Seasonality/correlation); IoFA_4 (Seasonality/Standard deviation); IoFA_5 (Seasonality/Mean differences); IoFA_6 (Seasonality/RMS)



For the Ortho/L3 products in the Vertical direction of displacement, the most significant velocity difference is approximately 1.7 mm/year at station MASP. ALDE follows with velocity differences of around 0.9 mm/year. Generally, the EGMS Ortho vertical time series shows more pronounced anti-correlation than the east-west component. This is expected given the spatial and temporal averaging (resampling to a coarser grid and to a common 6-day temporal sampling) performed to derive these products. GNSS data show seasonal effects at all stations with an amplitude signal up to 15 mm, which the EGMS captures at the stations AGUI and ALDE.

The seasonality index (Figure 91) or the correlation of detrended signals indicates an acceptable but not excellent correlation of seasonal effects between EGMS and GNSS. However, as seen for the GNSS stations in Jutland, seasonal effects should only be interpreted carefully for Basic/L2a products.

The general assessment for the Gran Canaria test site is positive, with a good fit between most GNSS stations and the EGMS time series around those stations. The time series of the EGMS sometimes mimics the GNSS. The most considerable velocity difference has been estimated at the MASP GNSS station. It corresponds to 1 mm/year for Basic/L2a products, 1.7 mm/year for Calibrated/L2b products, and 1.7 mm/year for Ortho/L3 Vertical. Because of the nature of the InSAR and GNSS processing (choice of the spatial reference, resampling in time, average in space, atmospheric corrections, and how the GNSS was processed), seasonal effects should not be interpreted for Calibrated/L2b and for Ortho/L3 products. They should additionally be carefully interpreted for Basic/L2a products.

Overall, the agreement between EGMS and GNSS stations is slightly better for Basic/L2a than for Calibrated/L2b products, but the differences are negligible.

In the case of Calibrated/L2b products, four out of seven stations for the ascending orbit and three out of seven for the descending orbit do not pass the velocity test.

However, note that the stations that do not pass the velocity test have velocity differences in the order of 0.7 to 1.9 mm/year, and MASP has the worst performance for the descending orbit with 1.9 mm/year.

This means that the EGMS can accurately measure moderate ground motion; however, the data should be carefully interpreted when it concerns seasonal variations.

Groundwater exploitation

Guadalentín basin, Lorca Region (Spain) – GNSS comparison

The Guadalentín basin in southeastern Spain (Figure 92) is one of the driest regions of Europe. This basin is a tectonic depression located in the eastern part of the Betic Cordillera, an alpine orogenic belt resulting from the collision of the African and Iberian plates. The Alto Guadalentín aquifer is located between the cities of Lorca and Puerto Lumbreras. Continuous groundwater pumping, mainly for agricultural use, led to a decrease in the piezometric levels of more than 200m since 1975. This overexploitation of the aquifer has led to considerable land subsidence in the area. Lorca, affected by subsidence triggered by groundwater overexploitation, has been extensively studied using different techniques such as GNSS and InSAR. The accumulated vertical deformation close to Lorca is around 24 cm, with even greater subsidence in the centre of the basin, reaching up to 12 cm/year. Of all the validation sites, Lorca shows the highest displacements rates for which GNSS comparison is valuable due to the challenging performance for the EGMS. This strong subsidence area is represented by stations LRCA, ORCA and LORC.



Figure 92: The GNSS station locations used for Lorca test site. (basemap: Google)

Given that most significant deformation has been detected at stations LRCA, ORCA and LORC, the GNSS comparison with the EGMS products will focus on these three stations. All stations are used for the loA calculations. For the Basic/L2a products on the ascending orbit 103, shown in Figure 93 (next page), results vary slightly from station to station. This figure illustrates the stations with the highest displacements for one ascending (a, b, and c) and one descending (d, e, and f) orbit. The figure clearly illustrates that EGMS effectively captures the most substantial deformations in the area of interest.

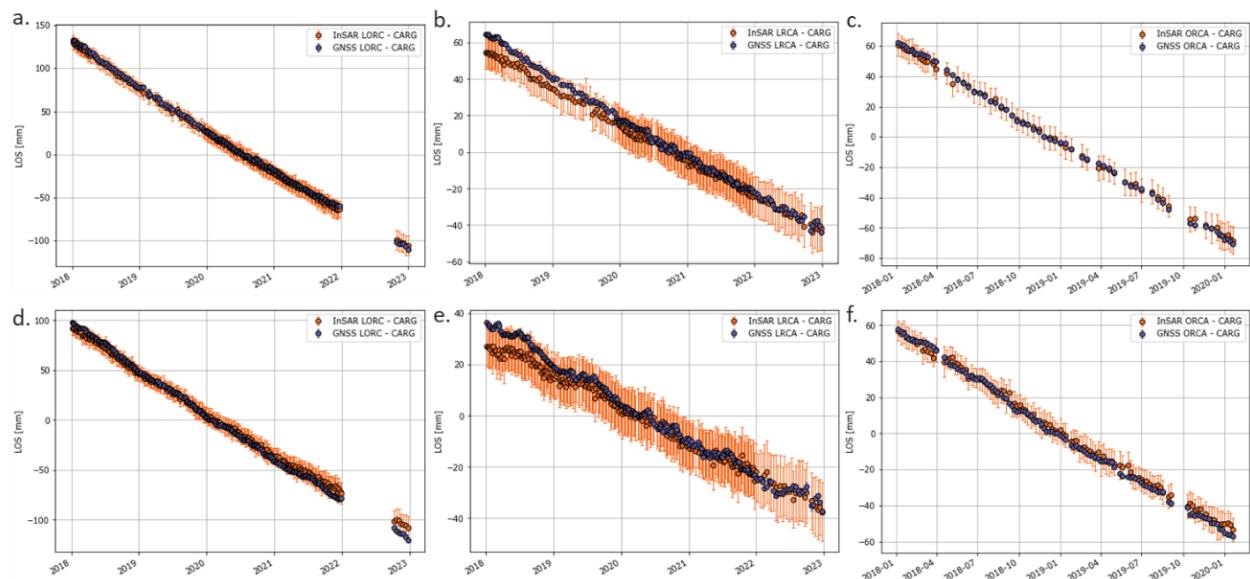


Figure 93: Example of double differences between pairs of stations of Basic/L2a ascending orbit 103 (a), (b) and (c) and for descending orbit 008 (d), (e) and (f). Reference station CARG.

All 36 stations (including all EGMS orbits) pass the time series test for the Basic/L2a products demonstrating that EGMS is able to reasonably capture the subsidence induced by groundwater exploitation.

The average velocity difference between EGMS and GNSS is about 0.8 mm/year (including all orbits and all stations).

Figure 93 illustrates how EGMS is able to capture the strongest deformation in the area of highest groundwater extraction rates with very high accuracy.

Figure 94 (next page) presents single differences between EGMS and GNSS for Calibrated/L2b products on the ascending orbit 103, again for the stations with higher subsidence rates. Stations such as CRVC, MUL1, AIRM, MAZA, ACAL, and MCIA show consistent velocity differences below 0.5 mm/year across most EGMS products, indicating a near-perfect fit between GNSS and EGMS. These stations are outside the boundaries of Lorca's subsidence area.

The Calibrated/L2b products exhibit similar patterns to Basic/L2a regarding the fit between EGMS and GNSS products. For Calibrated/L2b, ORCA, the station with the higher subsidence rate, records a velocity difference of 1.6 mm/year for the descending orbit 008, 2.7 mm/year for the ascending orbit 001 and 1mm/year for ascending orbit 103. The fit between the EGMS and GNSS time series at the stations of the largest displacements (such as LRCA, LORCA and ORCA) is remarkable.

All stations (including all EGMS orbits) pass the time series test for Calibrated/L2b products and the average velocity difference between EGMS and GNSS is significantly low, c.a. 1 mm/year (including all orbits and all stations). This includes all the stations within the subsidence area of Lorca.

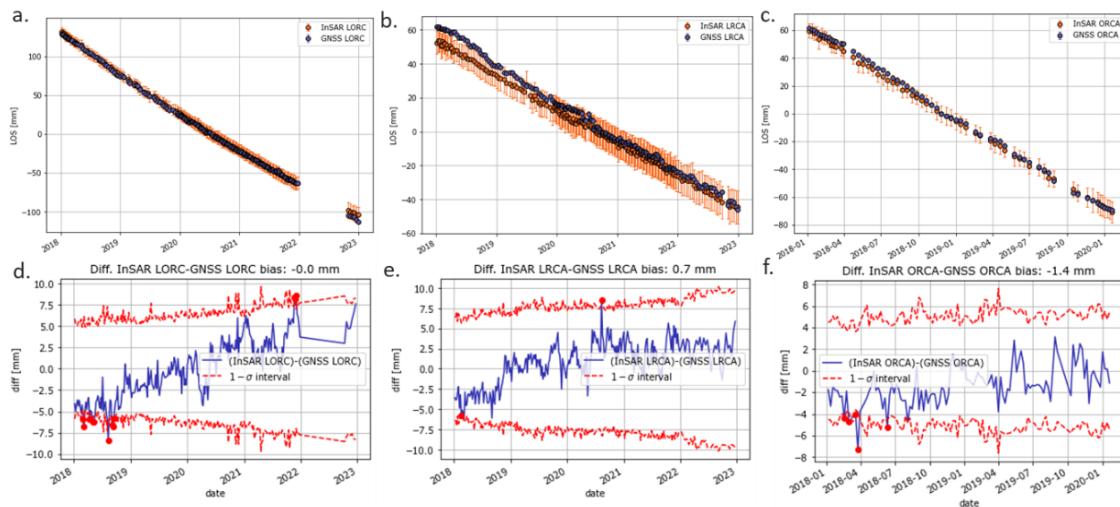


Figure 94: (a) (b) (c) Single station time series comparison between EGMS and GNSS for Calibrated/L2b ascending orbit 103.
 (d) (e) (f) corresponding double differences between the EGMS and the GNSS time series.

With respect to Ortho/L3 products, the fit in the vertical direction consistently outperforms that in the east-west. Notably, stations like MUL1, MRAT, and MAZA exhibit the best time series fit in the vertical direction. In Figure 95, the velocity correlation plots between EGMS and GNSS provide a reliable indication of which stations have similar and deviating velocities. Most stations align perfectly with the black full line, affirming the high level of agreement between the estimated velocities of the EGMS MPs around each GNSS station and the corresponding GNSS station.

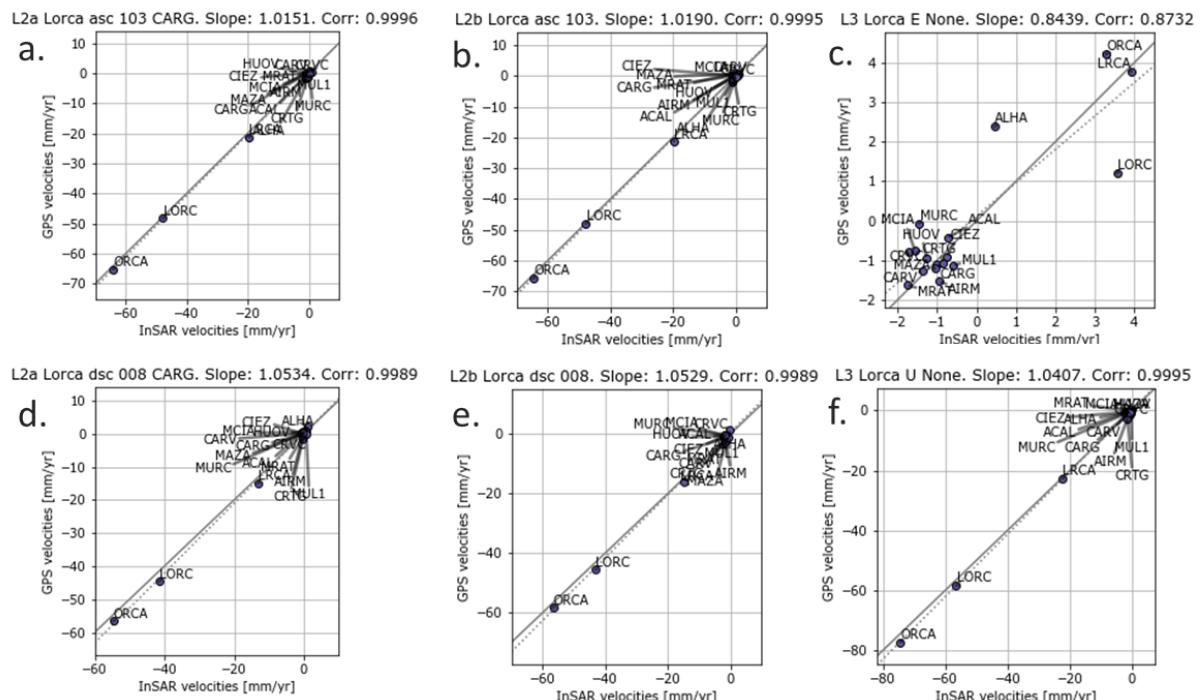


Figure 95: Correlation between EGMS/GNSS velocity estimations for the three EGMS products. The first column (a. and c.) show the results for the L2a-Basic product in ascending and descending orbits, the middle column (b. and d.) show the results for the L2b-Calibrated product in ascending and descending orbits and the third column (d. and e.) show the results for the Ortho/L3 product in east and vertical direction. The station location falling within the black full line indicates perfect agreement between the estimated velocities of the EGMS MPs around each GNSS station and the corresponding GNSS station. Dashed line indicates the best fit line between all stations.

Figure 96, containing bar charts, summarizes the IoA of all products per station. Interpretation can be found on the next page highlights:

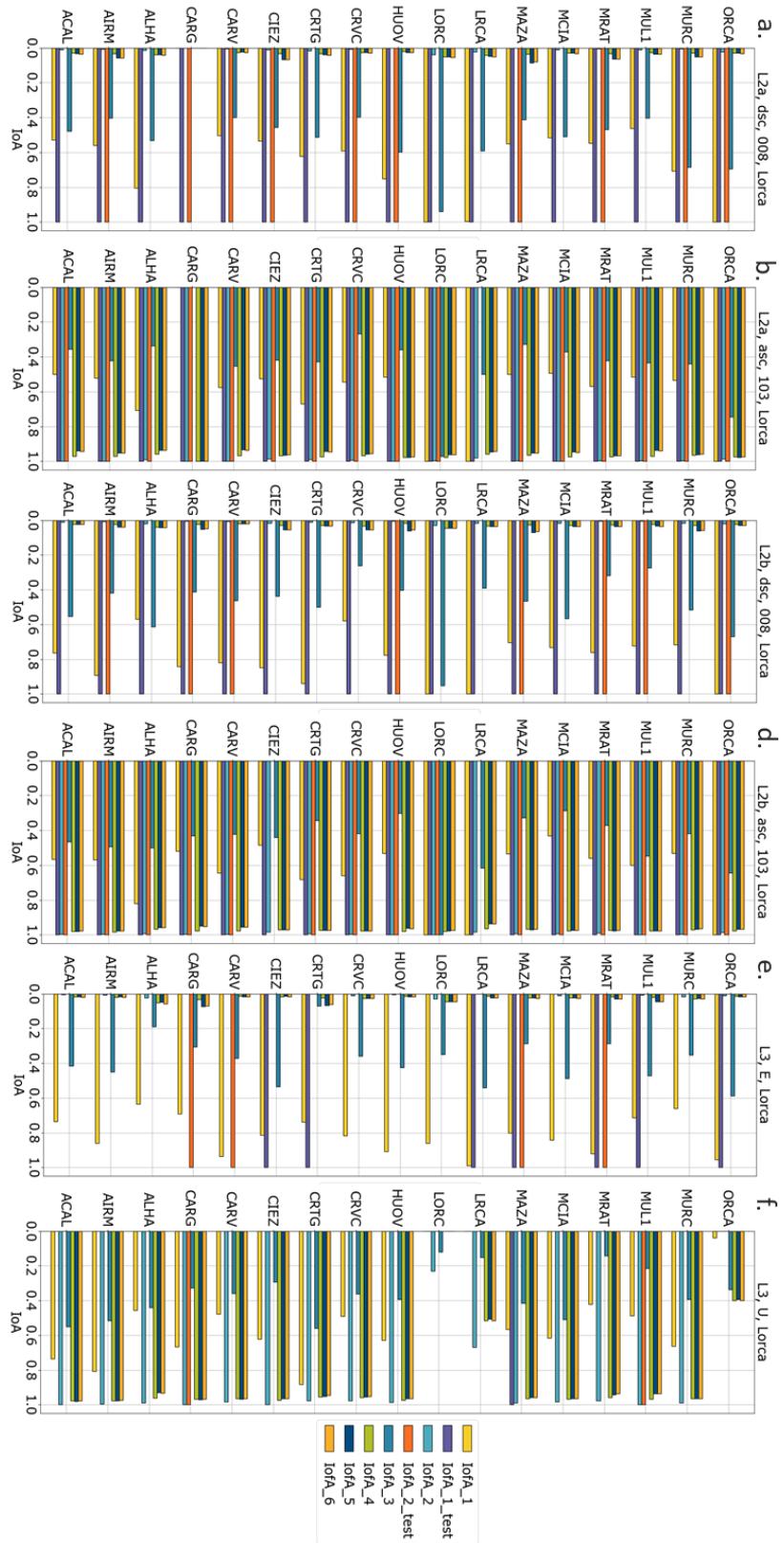


Figure 96: Indices of agreement for Basic/L2a, Calibrated/L2b with the corresponding ascending and descending orbits and Ortho/L3 products. From table 9: IofA_1 (time series correlation); IofA_1-test (overall model test); IofA_2 (velocity differences); IofA_2-test (t-test for velocity); IofA_3 (Seasonality/correlation); IofA_4 (Seasonality/Standard deviation); IofA_5 (Seasonality/Mean differences); IofA_6 (Seasonality/RMS)

Given the significant displacements at Lorca and the inherent challenges of InSAR in highly deforming locations, the alignment between EGMS and GNSS at this test site is noticeable.

The comprehensive performance at this test site clearly demonstrates that ascending products, notably for Basic/L2a and Calibrated/L2b, exhibit a closer alignment with GNSS data than their descending counterparts.

Similarly, for Ortho/L3 products, the vertical product outperforms the east-west products. Considering the estimated velocity differences and time series fit, the EGMS proves its efficacy for not just further assessment, but also for the ongoing monitoring of the Murcia region and Lorca subsidence area.

Guadalentín basin, Lorca (Spain) – In situ comparison

A comparison between the water level change (expressed in meters a.s.l) and the second EGMS update is performed (Figure 97). The same two methods mentioned in the previous validation report ([2015-2021](#)) were applied to this new update. In terms of algorithm used, the same script was adapted to the shorter time series and the same parameters as in the previous validation exercise were applied.

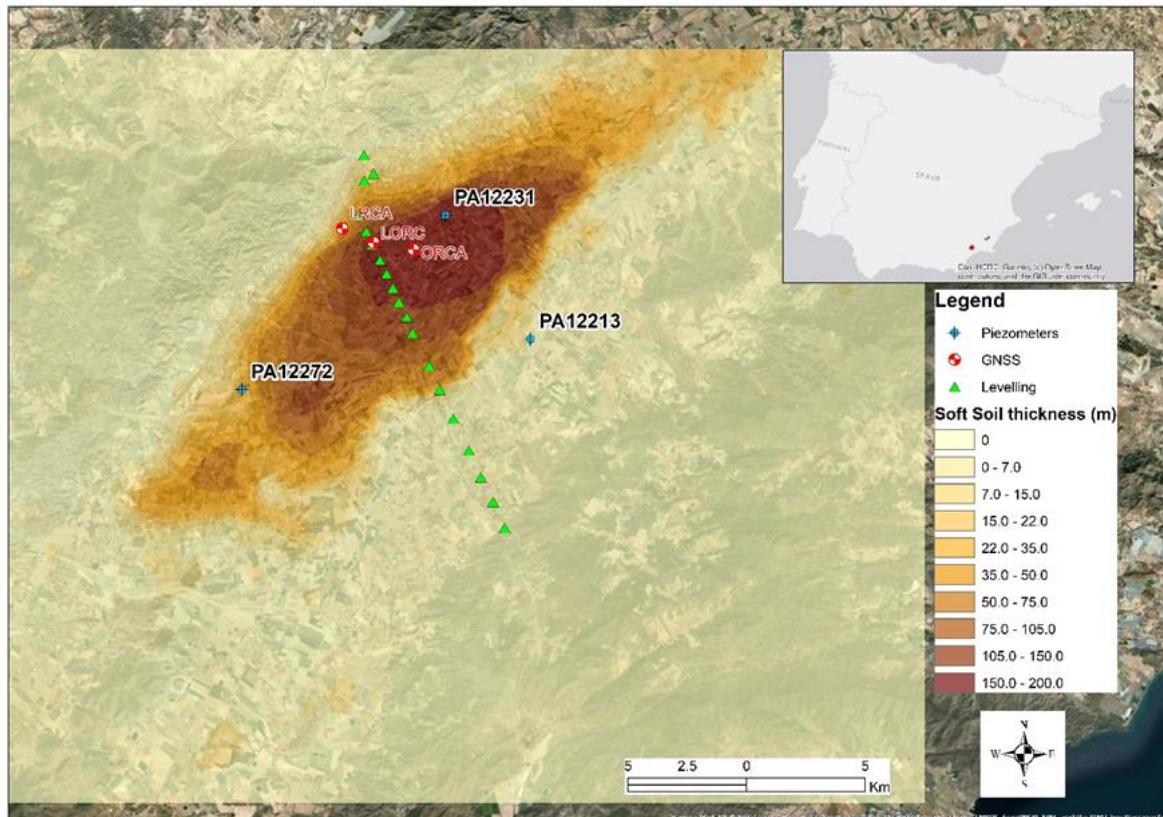


Figure 97: Lorca study case showing levelling, GNSS and piezometer positions.

The piezometer velocity (in mm/year) were derived by linearly interpolating the water level changes observed during the study interval (2018-2022). In Lorca, the time series results exhibit the lowest scores among the evaluated in situ case studies (Figure 98). In fact, in order to avoid the incorporation of partial horizontal deformation from L2 products only the Ortho/L3 Vertical was evaluated. The combined index is 0.41, indicating intermediate consistency, with only the agreement metric scoring slightly better (0.51). One of the reasons for these low scores is that one piezometer, located in the thickest soil area (PA-12231) and registering the highest rate of subsidence (a cumulative of 500 mm in five years), resulted in the lowest score in error possible, thereby lowering the overall averaged scores.

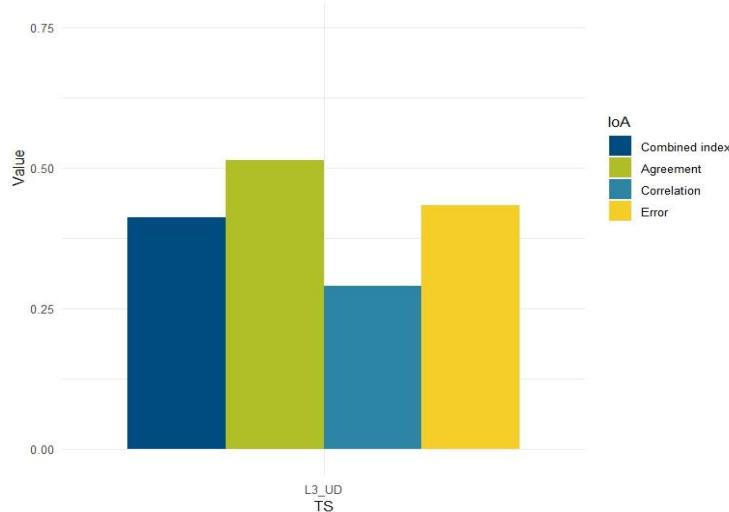


Figure 98: IoA corresponding to the time series results for the Lorca case study (In situ versus EGMS Ortho/L3 products).

Another factor is evident in Figure 99, where the nature of the piezometric time series displays strong non-linearity, contrasting with the almost linear behaviour of the EGMS time series. It is worth noting that a much longer time series and regularly spaced piezometric campaigns could have been beneficial for evaluating the storage coefficient adapted to the soft soil compressible thickness of the Alto Guadalentín aquifer.

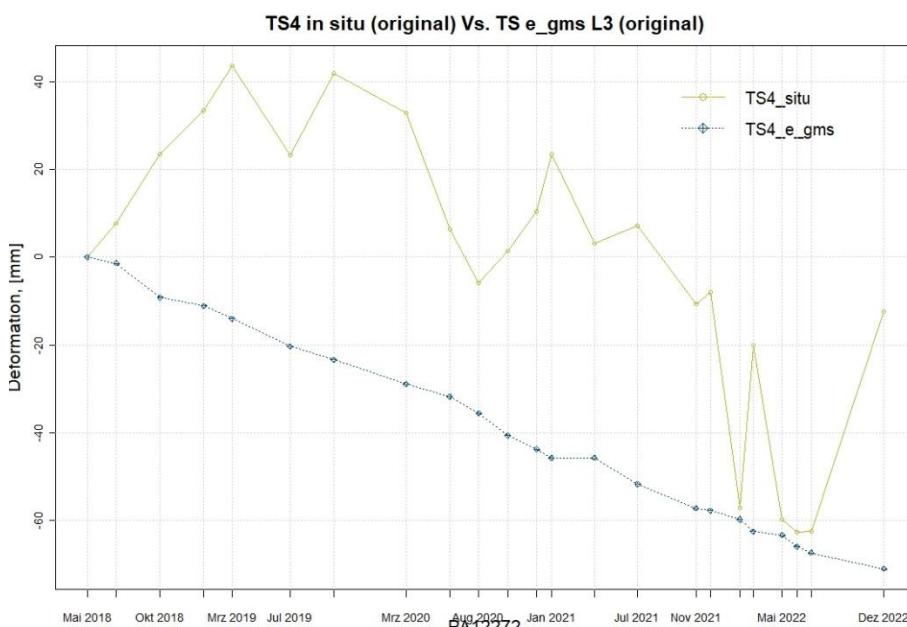


Figure 99: Time series plot of an in situ piezometer data (station number PA12272) against the EGMS Calibrated/L2b MP with the lowest MAE error.

The comparison of EGMS and in situ data in Lorca is challenging due to the presence of strong non-linear deformation patterns, which can be difficult to capture with InSAR, as shown in Figure 99.

Despite these limitations of the technique, EGMS demonstrate its capability to follow the temporal evolution of the displacement resulting from groundwater exploitation with good accuracy.

Volcanism

La Palma (Spain)

La Palma (Figure 100), one of the seven islands of the Canary Islands archipelago, recently witnessed an unprecedented volcanic event, the longest-lasting eruption in the island's recorded history. This geological event started on September 19th and concluded on December 13th, 2021, leaving a lasting impact on the island's physical landscape. The eruption originated from the Cumbre Vieja ridge, a known hotspot of volcanic activity since 1971.



Figure 100: GNSS stations (La Palma)

Characterized by explosive activity, the eruption manifested through the emergence of several fissures, lava fountains, and ash plumes that reached staggering heights. The lava cascaded down the western flanks of the island advancing towards the sea. Over 3,000 buildings were destroyed and more than 7,000 people forced to evacuate their homes. The global community

mobilised to support the affected residents, underscoring the island's vulnerability to volcanic activity and the critical role of continuous monitoring services.

In La Palma, there are eight continuous GNSS stations, four of which were deployed during the eruption. Due to ash cover and the vegetated nature of the surrounding areas of some stations, only some MPs are observed within the applied 100 m radius around the GNSS stations at some station locations. Since a minimum of three MPs is required to calculate EGMS time series standard deviations, stations with less than three MPs were excluded from the analysis.

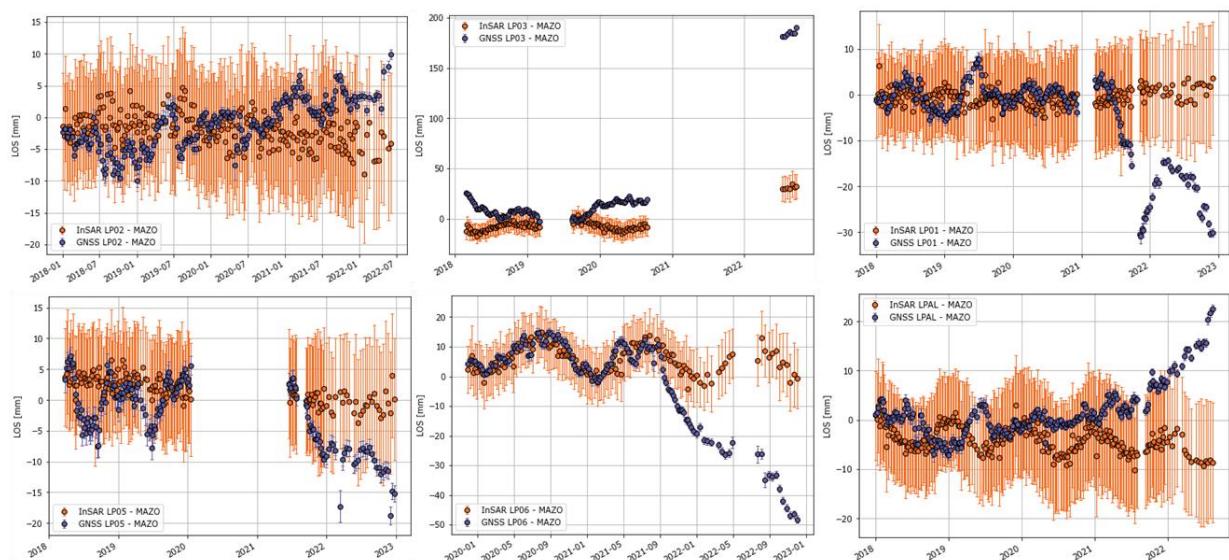


Figure 101: Example of double differences between pairs of stations with EGMS Basic/L2a ascending orbit 060.
Reference station: MAZO.

Figure 101 shows an example of the double differences performed on the Basic/L2a products on ascending orbit 060. The results vary slightly from station to station, but the poor fit between EGMS and GNSS for ascending orbit 060 is clear, especially at station pairs where the displacements are higher, primarily due to the 2021 eruption.

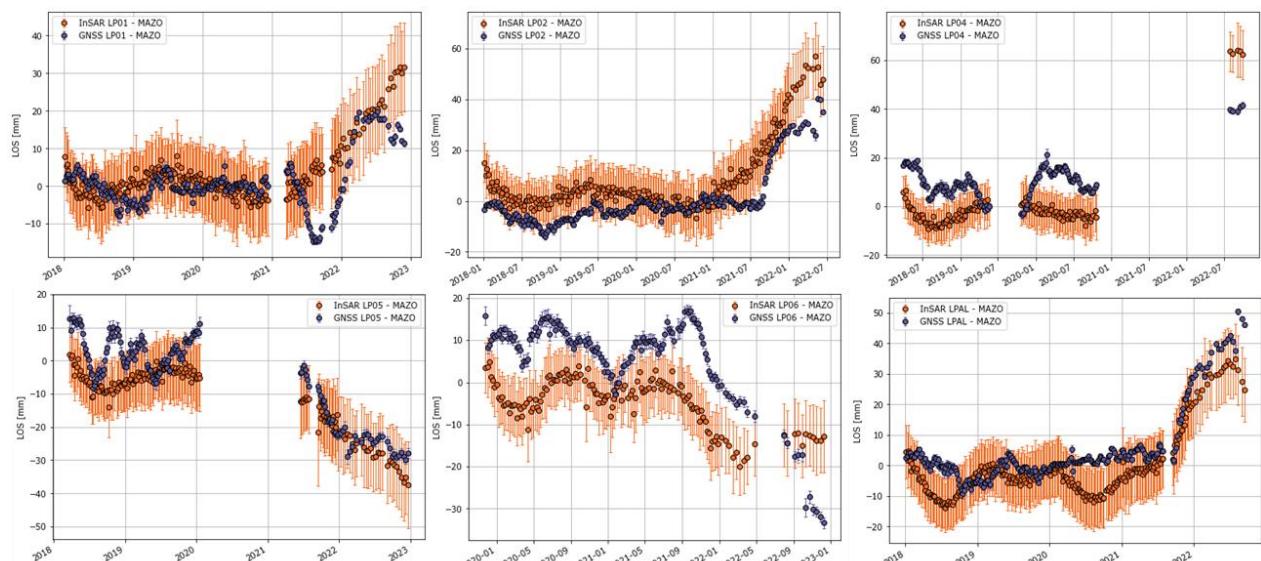


Figure 102: Example of double differences between pairs of stations with EGMS Basic/L2a descending orbit 069.
Reference station: MAZO.

The focus remains on the Basic/L2a products, and it is important to note that the descending orbit 069 (Figure 102) presents a different scenario. Here, the EGMS can mimic the GNSS time series displacement signature, albeit not with a perfect fit. This understanding is crucial for a comprehensive analysis of different processing parameters. Figures 103 and 104 present the same findings for the Calibrated-L2b product, reaffirming the superior performance of the descending orbit. This achievement marks a significant step forward in possibly tuning the EGMS over volcanic events to improve monitoring.

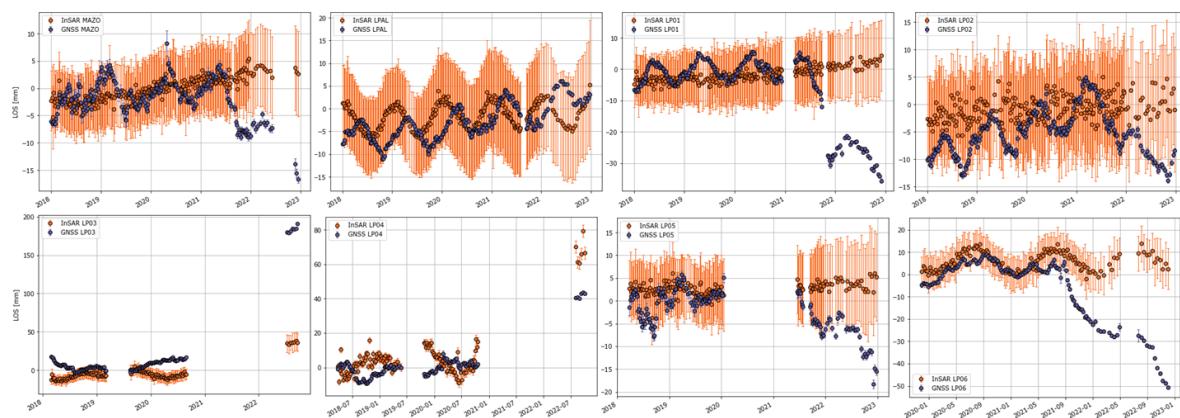


Figure 103: Example of double differences between pairs of stations with EGMS Calibrated/L2b ascending orbit 060.

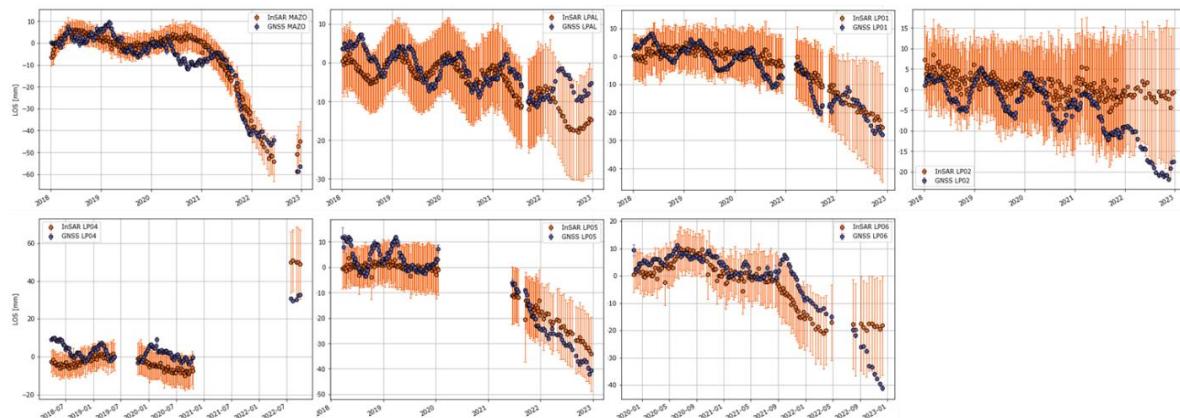


Figure 104: Example of double differences between pairs of stations with EGMS Calibrated/L2b descending orbit 069.

As anticipated, the IoA of Figure 105 (next page) robustly reinforces the higher performance of the descending over the ascending orbit. This expected outcome further solidifies our confidence in the performance of the descending orbit, as all the stations pass the time series test.

The La Palma validation site is challenging because of the volcanic event in 2021. The results have yielded the most compelling results when comparing the performance of GNSS and EGMS (summary Figure 105 on the next page).

Notably, the descending orbit has presented a more promising scenario, with the EGMS demonstrating a good ability to mimic the GNSS time series displacement signature. This performance is a significant step forward in possibly tuning the EGMS over active volcanic areas.

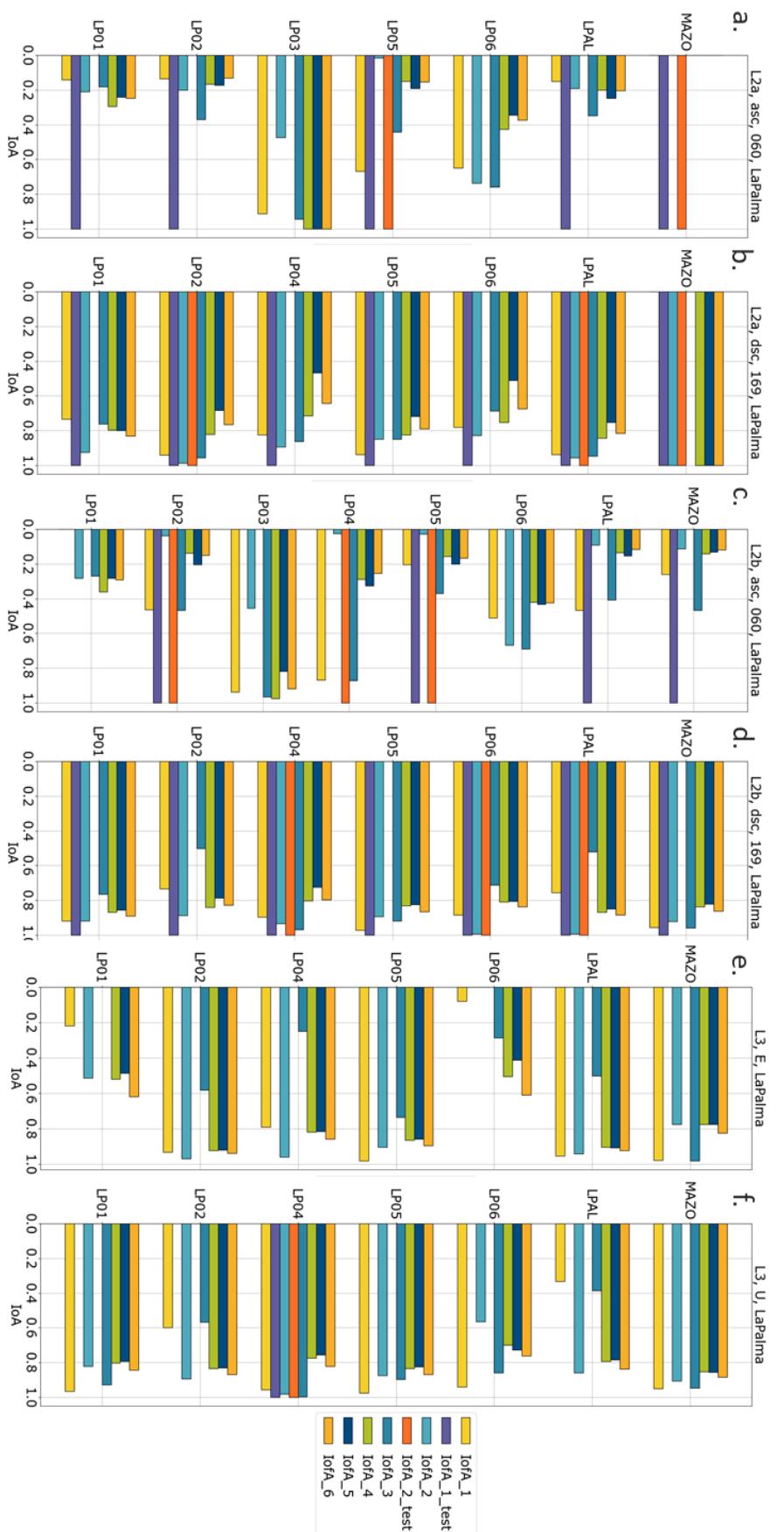


Figure 105: Summary of all IoAs per station. Reference station MAZO. From table 9: IoFA_1 (time series correlation); IoFA_1_test (overall model test); IoFA_2 (velocity differences); IoFA_2_test (t-test for velocity); IoFA_3 (Seasonality/correlation); IoFA_4 (Seasonality/Standard deviation); IoFA_5 (Seasonality/Mean differences); IoFA_6 (Seasonality/RMS)



REFERENCES

- Bru, G.; González, P.J.; Mateos, R.M.; Roldán, F.J.; Herrera, G.; Béjar-Pizarro, M.; Fernández, J. A-DInSAR Monitoring of Landslide and Subsidence Activity: A Case of Urban Damage in Arcos de la Frontera, Spain. *Remote Sens.* **2017**, *9*, 787. <https://doi.org/10.3390/rs9080787>
- Congalton, Russell. (2001). Accuracy assessment and validation of remotely sensed and other spatial information. *INTERNATIONAL JOURNAL OF WILDLAND FIRE*. **10**. 321-328. 10.1071/WF01031.
- Vradi, A., Sala, J., Solari, L., & Balasis-Levinsen, J. (2023). VALIDATING THE EUROPEAN GROUND MOTION SERVICE: AN ASSESSMENT OF MEASUREMENT POINT DENSITY. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **48**, 247-252.
- European Environment Agency, 2021. European Ground Motion Service (EGMS) Quality Assurance & Control Report – Harmonisation Tests. land.copernicus.eu/user-corner/technical-library//quality-assurance-and-control-report-2013-harmonisation-test
- Fabris, M, Achilli, V, Menin, A, Estimation of Subsidence in Po Delta Area (Northern Italy) by Integration of GPS Data, High-Precision Leveling and Archival Orthometric Elevations. *International Journal of Geosciences*, 2014, **5**, 571-585 <http://dx.doi.org/10.4236/ijg.2014.56052>
- Fabris, M., Battaglia, M., Chen, X., Menin, A., Monego, M., Floris, M., 2022. An Integrated InSAR and GNSS Approach to Monitor Land Subsidence in the Po River Delta (Italy). *Remote Sensing*. **14**. 5578. <https://doi.org/10.3390/rs14215578>.
- Cenni, N., Fiaschi, S., Fabris, M. Monitoring of Land Subsidence in the Po River Delta (Northern Italy) Using Geodetic Networks. *Remote Sens.* **2021**, *13*, 1488. <https://doi.org/10.3390/rs13081488>
- Barra A, Solari L, Béjar-Pizarro M, Monserrat O, Bianchini S, Herrera G, Crosetto M, Sarro R, González-Alonso E, Mateos RM, Ligüerzana S, López C, Moretti S (2017) A methodology to detect and update active deformation areas based on Sentinel-1 SAR images. *Remote Sens* **9**: 1002. <https://doi.org/10.3390/rs9101002>.
- Ezquerro, P., Tomás, R., Béjar-Pizarro, M., Fernández-Merodo, J.A., Guardiola-Albert, C., Staller, A., Sánchez-Sobrino, J.A. Herrera, G. Improving multi-technique monitoring using Sentinel-1 and Cosmo-SkyMed data and upgrading groundwater model capabilities. *Science of the Total Environment* **703** (2020) 134757 13
- Boni, R.; Pilla, G.; Meisina, C. Methodology for Detection and Interpretation of Ground Motion Areas with the A-DInSAR Time Series Analysis. *Remote Sens.* **2016**, *8*, 686. <https://doi.org/10.3390/rs8080686>
- Brewer, C.A.; Marlow, K. A. Color representation of aspect and slope simultaneously, Conference: Eleventh International Symposium on Computer-Assisted Cartography (Auto-Carto-11), Minneapolis, Minnesota, 1983.
- Pfeiffer, J., Zieher, T., Schmieder, J., Rutzinger, M. Strasser 2Hyndman, R., Newnham, G. & Culvenor, D. Spatio-temporal assessment of the Hydrological drivers of an active deep-seated gravitational slope deformation: The Voegelsberg landslide in Tyrol (Austria). *Earth Surf. Process. Landforms*. **2021**;1–17.
- Hofmann, R.; Sausgruber, J.T. Creep behaviour and remediation concept for a deep-seated landslide, Navistal, Tyrol, Austria, *Geomechanics and Tunnelling* **10** (2017), No. 1. <https://onlinelibrary.wiley.com/doi/10.1002/geot.201600066>.
- Collilieux, X., Courde, C., Fruneau, B., Aimar, M., Schmidt, G., Delprat, I., Pesce, D., and Wöppelmann, G.: Radar corner reflector installation at the OCA Geodetic Observatory (France). In EGU General Assembly Conference Abstracts (p. 5201).
- Collilieux, X., Courde, C., Fruneau, B., Aimar, M., Schmidt, G., Delprat, I., Pesce, D., and Wöppelmann, G. (2022). Validation of a Corner Reflector installation at Côte d'Azur multi-technique geodetic Observatory. *Advances in Space Research*, **70**(2), 360-370.
- Vick, L. M., Berg, J. N., Eggers, M., Hormes, A., Skrede, I., & Blikra, L. H. (2021). Keynote Lecture: The Jettan Rockslide—An Engineering Geological Overview. *Understanding and Reducing Landslide Disaster Risk: Volume 6 Specific Topics in Landslide Science and Applications* 5th, 289-315.
- Rouyet, L., Lilleøren, K. S., Böhme, M., Vick, L. M., Delaloye, R., Etzelmüller, B., ... & Blikra, L. H. (2021). Regional morpho-kinematic inventory of slope movements in northern Norway. *Frontiers in Earth Science*, **9**, 681088.



Hermanns, R. L., Oppikofer, T., Böhme, M., Dehls, J. F., Molina, F. Y., & Penna, I. M. (2018). Rock slope instabilities in Norway: First systematic hazard and risk classification of 22 unstable rock slopes from northern, western, and southern Norway. In *Landslides and Engineered Slopes. Experience, Theory and Practice* (pp. 1107-1114). CRC Press.

Aslan G., Foumelis M., Raucoules D., de Michele M., Bernardie S., Cakir Z., 2020, « Landslide Mapping and Monitoring Using Persistent Scatterer Interferometry (PSI) Technique in the French Alps », *Remote Sensing*, 12(8), 1305

Teunissen, P. J. G. (2000a). *Adjustment theory; an introduction* (1 ed.). Delft: Delft University Press.,

Teunissen, P. J. G. (2000b). *Testing theory; an introduction* (1 ed.). Delft: Delft University Press.

Varnes, D.J., 1978. Slope movement types and processes. Special report, 176, pp.11-33.

Hungr, O., Leroueil, S. and Picarelli, L., 2014. The Varnes classification of landslide types, an update. *Landslides*, 11, pp.167-194.

Reyes-Carmona, C.; Barra, A.; Galve, J.P.; Monserrat, O.; Pérez-Peña, J.V.; Mateos, R.M.; Notti, D.; Ruano, P.; Millares, A.; López-Vinielles, J.; et al. Sentinel-1 DInSAR for Monitoring Active Landslides in Critical Infrastructures: The Case of the Rules Reservoir (Southern Spain). *Remote Sens.* 2020, 12, 809. <https://doi.org/10.3390/rs12050809>

Carvalho, J., Pinto, C., Dias, R., Rabeh, T., Torres, L., Borges, J., Torres, R., Duarte, H., 2017. Tectonic Evolution of an Intraplate Basin: the Lower Tagus Cenozoic Basin, Portugal. *Basin Research*. 29. n/a-n/a. 10.1111/bre.12193.

Heleno, S.I.N., Oliveira, L.G.S., Henriques, M.J., Falcão, A.P., Lima, J.N.P., Cooksley, G., Ferretti, A., Fonseca, A.M., Lobo-Ferreira, J.P., Fonseca, J.F.B.D., 2011. Persistent Scatterers Interferometry detects and measures ground subsidence in Lisbon. *Remote Sensing of Environment*, Volume 115, Issue 8, 2152-2167, ISSN 0034-4257, <https://doi.org/10.1016/j.rse.2011.04.021>.

Pereira, N., Carneiro, J.F., Araújo, A., Bezzeghoud, M., Borges, J. 2013. Seismic and structural geology constraints to the selection of CO₂ storage sites—The case of the onshore Lusitanian basin, Portugal, *Journal of Applied Geophysics*, 102, pp. 21-38, <https://doi.org/10.1016/j.jappgeo.2013.12.001>.

Reyes-Carmona, C., Galve, J.P., Pérez-Peña, J.V. et al. Improving landslide inventories by combining satellite interferometry and landscape analysis: the case of Sierra Nevada (Southern Spain). *Landslides* **20**, 1815–1835 (2023). <https://doi.org/10.1007/s10346-023-02071-1>



GLOSSARY

ADA	Active Deformation Area
ASC	Ascending
ATS	Automatic Total Station
CLC	Corine Land Cover
CLMS	Copernicus Land Monitoring Service
CR	Corner Reflector
CRS	Coordinate Reference System
IoA	Index of agreement
DEM	Digital Elevation Model
DESC	Descending
DSGSD	Deep-Seated Gravitational Slope Deformation
EEA	European Environment Agency
GMS	Ground Motion Service
GNSS	Global Navigation Satellite System
InSAR	Interferometric Synthetic Aperture Radar
LOS	Line-of-Sight
MAE	Mean Absolute Error
MP	Measurement Point
PS / DS	Persistent Scatterer / Distributed Scatterer
R²	Coefficient of Determination
RMSE	Root Mean Square Error
S1	Sentinel-1
TS	Time Series

ANNEX: InSAR concepts summary

This section is intended as a summary for those unfamiliar with radar-based satellite data products and their geometric aspects.

SAR basics

A radar is a ranging technology, and the satellite with such an instrument onboard needs to look to one side to build a two-dimensional picture. Hence, images are acquired in the direction perpendicular to the flight direction, which is north-south. Therefore, we can only measure the projection of relative displacement along the vector between the satellite and the ground, which is named Line-of-Sight (LOS). Thus, the true direction of motion in the three-dimensional space is ambiguous, without some other form of information. Later in this section, it is explained how the EGMS 3D Ortho product is composed. Figure A1 illustrates the Sentinel-1 acquisition geometry:

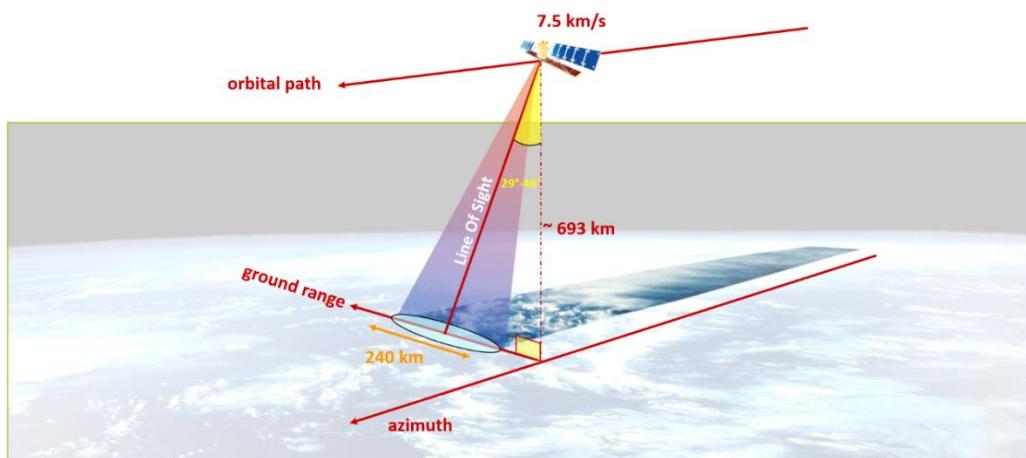


Figure A1: Data acquisition geometry (Sentinel-1)

Radar satellites are active systems that emit pulses of electromagnetic radiation. They are able to measure the strength of the return signal, the time-delay and the phase related to the angle of the signal's sinewave as it returns to the satellite. Unlike optical satellites, which are passive systems, radar satellites acquire images regardless of the time of day and level of cloud-cover; please see Figure A2 for an example of radar and optical images over the same area. EGMS products are made from hundreds of Sentinel-1 SAR image acquisitions over the same locations across the European territory.

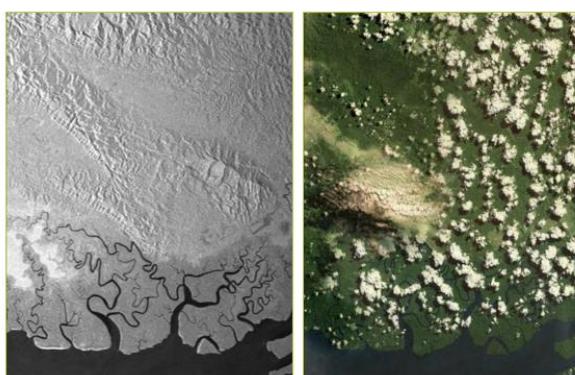


Figure A2: Radar (active system) versus Optical (passive system)

Acquisition geometry

Figure A3 illustrates how the MPs measured in the ascending and descending orbits (L2 products, Basic and Calibrated) cover different sides of a north oriented valley, as a consequence of the non-perpendicular satellite acquisition geometry). Figure A3 also shows the limitations of the Ortho/L3 product in very steep valleys where the absence of overlapping ascending and descending MPs prevents the decomposition into East-West (horizontal) and Vertical (vertical) movements.

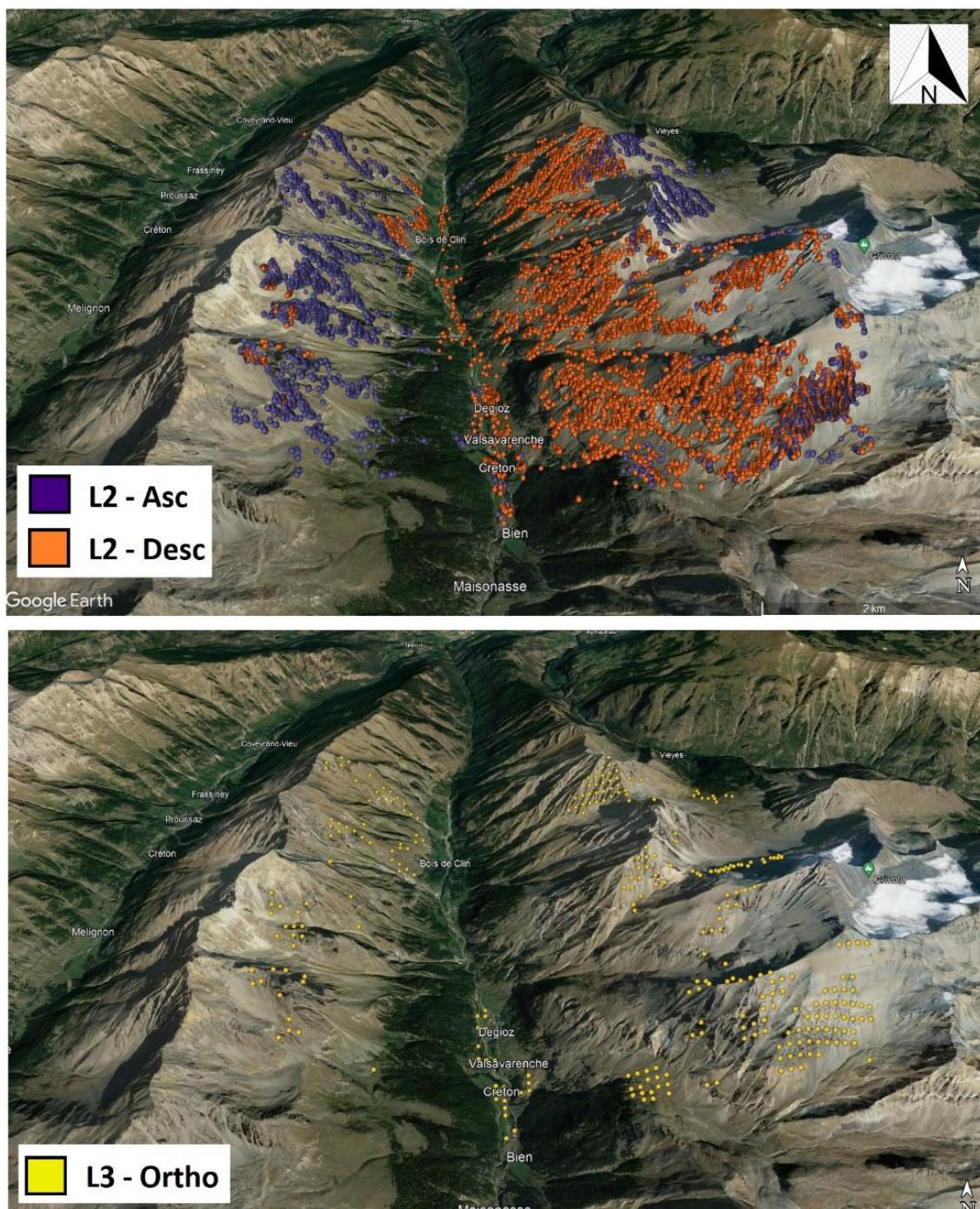


Figure A3: Different Measurement Point densities for L2 Ascending/Descending products (top) versus the Ortho product (bottom);
(basemap: google)

Ortho/L3 product

Ortho/L3 products are produced on a square grid with 100 metres spacing (Figure A4), with a six-days regular temporal sampling. For each grid cell, all available Calibrated/L2b is averaged, considering the different LOS, to produce separate ascending and descending displacement time series. Grid cells with non-existent or not enough data are excluded.

In the grid cells where sufficient ascending and descending orbits overlap, the vertical and eastward motion components are estimated. It is important to note that local north-south movements cannot be estimated due to the geometry of the satellite acquisitions. In the decomposition phase, then, the observed north-south displacement is neglected.

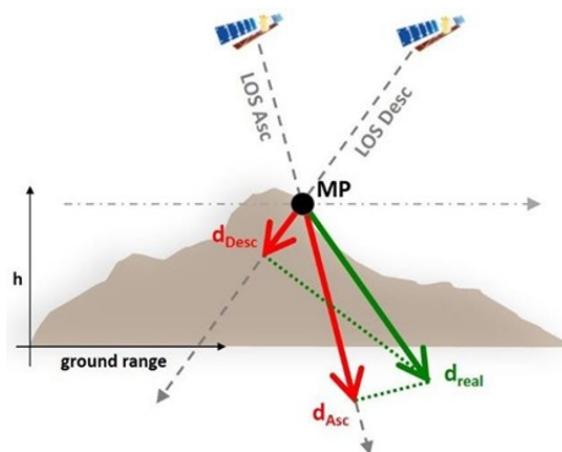
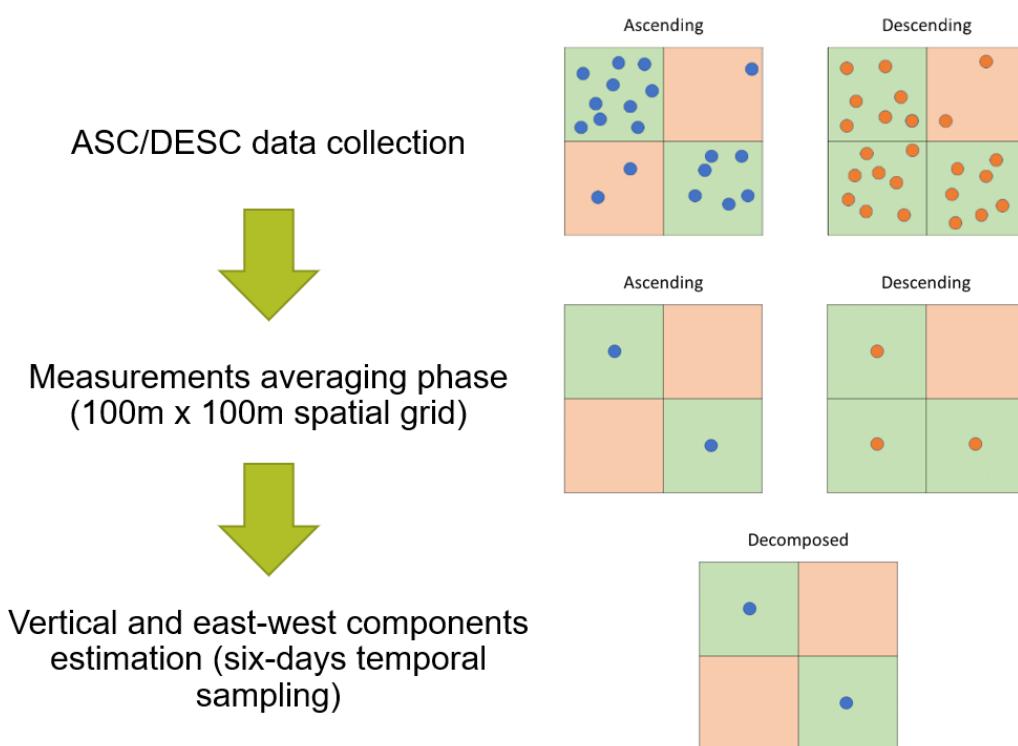


Figure A4: Otho/L3 product composition

EGMS Validation Report 2018-2022 update

Artificial corner reflectors

Corner reflectors (CRs) are designed to reflect radar signals back to the satellite antenna (Figure A5). They are normally deployed on locations that offer poor reflectivity (e.g. – densely vegetated or covered in snow). They are made of metal and oriented to the satellite to provide the strongest return possible.

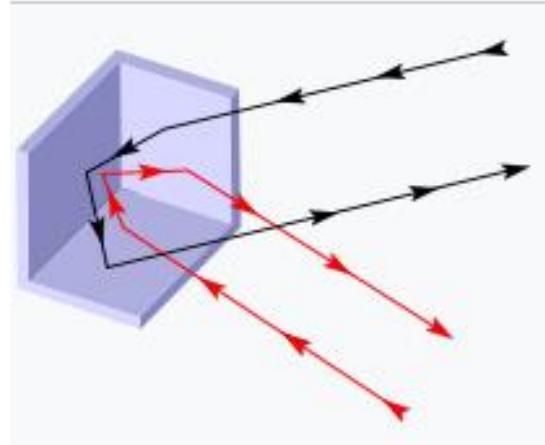


Figure A5: Left (Corner reflector), Right (working principle of CR) – source: Wikipedia