Remote Sensing Applications: Society and Environment 37 (2025) 101452

Contents lists available at ScienceDirect

Remote Sensing Applications: Society and Environment

journal homepage: www.elsevier.com/locate/rsase

Applications based on EGMS products: A review

M. Crosetto [a,*], B. Crippa [b], M. Mróz [c], M. Cuevas-González [a], S. Shahbazi [a]

[a] Centre Tecnològic de Telecomunicacions de Catalunya - CERCA (CTTC-CERCA), Av. Carl Friedrich Gauss 7, 08860, Castelldefels, Spain
[b] Department of Earth Sciences, University of Milan, Via Botticelli 23, I-20133, Milan, Italy
[c] Department of Geodesy, University of Warmia and Mazury in Olsztyn, ul. Oczapowskiego 1, 10-719, Olsztyn, Poland

ARTICLE INFO

Keywords:
PSI
Deformation
Monitoring
European ground motion service

ABSTRACT

The European Ground Motion Service (EGMS) represents the largest wide area Persistent Scatterer Interferometry service ever conceived. It is part of the Copernicus Land Monitoring Service's product portfolio. Thanks to its technical characteristics, and the fact that EGMS products are made available on a full, open, and free-access principle, the EGMS has the potential to become a game changer in the way ground motion data are used in Europe. Three years after the publication of the first EGMS products, this initial review studies the scope and impact of this service in terms of applications. After a brief introduction to the service, the paper describes the main EGMS trends, including the procedures to analyse and exploit its data, and a review of its main applications. The quantity and quality of the applications are useful ways to show the potential of the service. This can open the door to a future widespread use of EGMS data. Next, the paper features a technical discussion on the main characteristics of the EGMS products, the main EGMS validation activities, and future research lines.

1. Introduction

Wide area monitoring of land deformation is key to achieve a synoptic view of the deformations occurring over large regions. Persistent Scatterer Interferometry (PSI) offers unmatched capabilities to perform such monitoring with millimetre-per-year precision (Crosetto et al., 2016). This technique is the core of the so-called PSI-based Ground Motion Services (GMSs). These are the factors that make GMSs possible:

- The availability of systematic Synthetic Aperture Radar (SAR) acquisitions over wide areas, especially by using Sentinel-1 sensors.
- The readiness of mature PSI processing and analysis tools.
- The accessibility of powerful computational resources.
- The development of effective visualization platforms to display and analyse PSI data (Rucci et al., 2023).

Today, the Copernicus European Ground Motion Service (EGMS) is the most important GMS (Crosetto et al., 2020), and is the subject of this review. This service covers the 30 Copernicus participant states (Crosetto and Solari, 2023). However, several other initiatives at national and regional levels have been proposed in recent years. The most relevant initiatives are briefly listed below. All

* Corresponding author.
E-mail addresses: mcrosetto@cttc.cat (M. Crosetto), bruno.crippa@unimi.it (B. Crippa), marek.mroz@uwm.edu.pl (M. Mróz), mcuevas@cttc.cat (M. Cuevas-González), sshahbazi@cttc.cat (S. Shahbazi).

https://doi.org/10.1016/j.rsase.2025.101452
Received 3 August 2024; Received in revised form 3 January 2025; Accepted 7 January 2025
Available online 8 January 2025

but the first are based on Sentinel-1 imagery.

- Italy. A GMS precursor was launched in 2007, exploiting ERS-1/2, Envisat and CosmoSkyMed data (Costantini et al., 2017).
- Norway. The first national GMS based on Sentinel-1 images was launched in November 2018 (Bredal et al., 2019; Dehls et al., 2019). It can be accessed at https://insar.ngu.no/.
- Germany. Several papers refer to this GMS, including Kalia et al. (2017, 2021), Wagener and Kalia (2021), and Even et al. (2023). The German GMS is accessible at https://bodenbewegungsdienst.bgr.de.
- The Netherlands. It is accessible at https://bodemdalingskaart.nl/en-us/.
- Denmark. The GMS for Denmark is described in Bischoff et al. (2020). It is not accessible online.
- Sweden. The GMS for Sweden is described in Darvishi et al. (2022) and Nilfouroushan et al. (2022). It is accessible at https://insar.rymdstyrelsen.se/.
- Romania. A nationwide deformation map of the country originating from a private initiative (Toma et al., 2021). It is accessible at http://pstool.terrasigna.com/.
- In addition to the national GMS, there are several regional initiatives, such as those described in Confuorto et al. (2021) and Raspini et al. (2019), which cover Tuscany,[1] Veneto,[2] and Valle d'Aosta (Italy). In Spain, a regional GMS covers the Catalonia region.[3]

These additional initiatives are also worth mentioning:

- Greece. A nationwide product is described in Papoutsis et al. (2020), though it is not available online.
- Canada. An early-stage GMS is described in Poncos et al. (2023), accessible at http://c-gms.com/.
- Australia. A wide area land subsidence product covering the Eastern States of Australia is described in Du et al. (2023). It is not accessible online.

The EGMS represents the most significant service devoted to land deformation measurement ever realised worldwide. Its products are made available on a full, open, and free-access basis. The implementation and maintenance of EGMS require a major economic and technical effort. For this reason, it is worth investigating the scope and impact of this service, particularly in terms of the applications based on its data. This paper aims to review the use of EGMS three years after the publication of its first release of products. The next section briefly outlines the main characteristics of the EGMS. Section 3 analyses the main EGMS trends, including tools and procedures to analyse and exploit EGMS data, and a review of the main applications published in the literature. Section 4 provides a discussion of the technical characteristics of the EGMS products. Section 5 summarizes the main EGMS validation activities, while Section 6 describes the need for future research. The paper concludes with a number of key findings.

2. The EGMS

The EGMS aims to provide reliable information that is standardized and harmonized across national borders, on both natural and anthropogenic ground motion phenomena over Europe. Processing full resolution Sentinel-1 SAR data of ascending and descending passes, and exploiting both point-like and distributed scatterers, EGMS offers three types of products:

- Basic product. This product delivers line-of-sight[4] (LOS) deformation velocity and deformation time series for each PSI measurement point[5] (MP). There are two sets of Basic products, corresponding to the complementary ascending[6] and descending geometries. The measurements are referenced to a local reference point.[7]
- Calibrated product. This product provides LOS deformation velocity and time series, with two sets corresponding to the ascending and descending geometries. Unlike the Basic product, measurements in the Calibrated product are referenced to a deformation model derived from GNSS data (Dehls et al., 2022), offering absolute deformation values rather than relative measurements.
- Ortho product. This product includes two motion components for each MP: East-West horizontal[8] and up/down vertical. Each MP provides the deformation velocity and time series, referenced to the same GNSS deformation model used in the Calibrated product. The MPs of the Ortho product differ from those of the previous products since it is resampled to a 100 m grid.[9] The EGMS Explorer displays the Ortho product by default, although users can access higher resolution data through the Basic and Calibrated products.

[1] https://geoportale.lamma.rete.toscana.it/difesa_suolo/#/viewer/openlayers/326.
[2] https://idt2.regione.veneto.it/idt/webgis/viewer?webgisId=185.
[3] https://visors.icgc.cat/subsidencia-projectes/#/0419.
[4] PSI measures the deformation along the radar line-of-sight, i.e. the line that connects the SAR sensor and the MP.
[5] PSI can only obtain an MP where the phase noise in the input SAR data is below a certain threshold.
[6] The ascending data are acquired by a satellite in polar orbit that moves from south to north, while the descending data are acquired by a satellite moving from north to south.
[7] The PSI deformation estimates are relative measurements that must be referenced to a reference point.
[8] Note that the PSI measurements are not sensitive to horizontal North/South displacements due to acquisition geometry using polar orbits.
[9] It is, in fact, an irregular grid: there can only be an MP where, at least two MPs exist in a 100 m by 100 m cell: one ascending and one descending.

The EGMS products are accessible through the EGMS Explorer, available at https://egms.land.copernicus.eu/. The platform offers two main functionalities: (1) an interactive WebGIS that allows users to visualize EGMS products and perform basic data analysis operations (registration is not required to access and use the WebGIS); and (2) an interface to search and download EGMS products, which can only be accessed by registered users. The EGMS Explorer offers comprehensive technical documentation[10], a Frequently Asked Question section,[11] and a Service Desk.[12]

The EGMS products are updated yearly, resulting in several available datasets:

- Baseline processing: covers the 2015–2020 period, published in 2021.
- First update: extends the temporal coverage to include 2021 (2015–2021), published in 2022.
- Second update: covers the 2018–2022 period, published in 2023. This update introduced a 5-year window processing approach.
- Third update: will cover the 2019–2023 period, scheduled for release in Q4 of 2024.

Only the most recent update is visible in the EGMS Explorer. However, previous versions remain available for downloading.

3. Main trends in EGMS

The EGMS is a relatively new service, with its first product release published in 2021. After approximately three years' accumulated experience, two main aspects are now discussed in this section:

- The methods and tools to analyse the EGMS products, especially considering the instruments and techniques that can handle large EGMS datasets. These tools are essential for promoting the widespread use of EGMS products. This point is addressed in Section 3.1.
- The main applications developed so far. Understanding the primary applications of EGMS products is fundamental to inspire their use in different scenarios and stimulate the development of new application fields. This topic is addressed in Section 3.2.

3.1. Methods and tools to analyse the EGMS data

The EGMS products represent an extensive dataset, requiring suitable tools and procedures for effective analysis and exploitation. The most relevant tools and methods are reviewed in this section, and can be classified as follows:

1. Extraction and conversion of data. A self-contained application (EGMStream) to facilitate the extraction, cropping, and conversion of EGMS products is described in Festa and Del Soldato (2023). This freely-available application downloads the original EGMS CSV[13] files and converts them into geospatial data formats, such as ESRI shapefiles or GeoPackage. EGMStream enables users to download, customize, and convert ground movement data for specific single bursts[14] or areas of interest selected through the application interface. A similar tool, named EGMS-toolkit, is described in Hrysiewicz et al. (2024), see https://github.com/alexisInSAR/EGMStoolkit.
2. Data clustering. A clustering procedure to filter and reduce the volume of large PSI datasets, with the objective of facilitating their interpretation and exploitation, especially for non-expert PSI users, is described in Barra et al. (2017). Starting from the EGMS products, this method identifies clusters of neighbouring MPs or ADAs (Active Deformation Areas) with deformation velocities above a specified threshold (ADAFinder[15]). Each ADA is assigned a quality index, which accounts for the noise of the deformation time series and the spatial homogeneity of the clustered MP deformations. An application of the ADAFinder to EGMS data for monitoring the structural health of urban areas is described in Mele et al. (2023). A Europe-wide map (European ADA web map), derived from filtering the EGMS Basic data of the baseline EGMS dataset (Fig. 1) lets users focus directly on the active deformation areas with absolute deformation velocities exceeding 5 mm/yr.

3A. A step forward with respect to the ADA Finder is described in Navarro et al. (2020). These authors propose an automatic ADA classification system, known as ADAClassifier, with identifies the geological or anthropogenic processes that cause the deformation. The classification system, based on a decision tree, can be a useful tool to speed up the interpretation of the EGMS products, especially over wide areas. In the original paper, the ADAs are classified into six main phenomena: landslide, sinkhole, subsidence, construction settlement, expansive soil, and thermal expansion. This classification can be achieved using external data sources such as a Digital Terrain Model (DTM), a geologic map, a landslide inventory, etc. Along with the ADAFinder, the ADAClassifier is part of the ADA Tools, available at the same address as the ADAFinder: https://adatools.cttc.es. Cuevas-González, 2024 describe an application of the ADAClassifier across Spain, using all available ascending and descending

[10] https://land.copernicus.eu/en/products/european-ground-motion-service.
[11] https://land.copernicus.eu/en/faq.
[12] https://land.copernicus.eu/en/contact-service-helpdesk.
[13] A CSV file is a text file that stores tabular data using commas to separate values, and newlines to separate records. The EGMS products are distributed as large CSV files.
[14] A Sentinel-1 SAR image is divided into three swaths, and each swath is divided into nine bursts or sub-images.
[15] This tool is available at https://adatools.cttc.es.

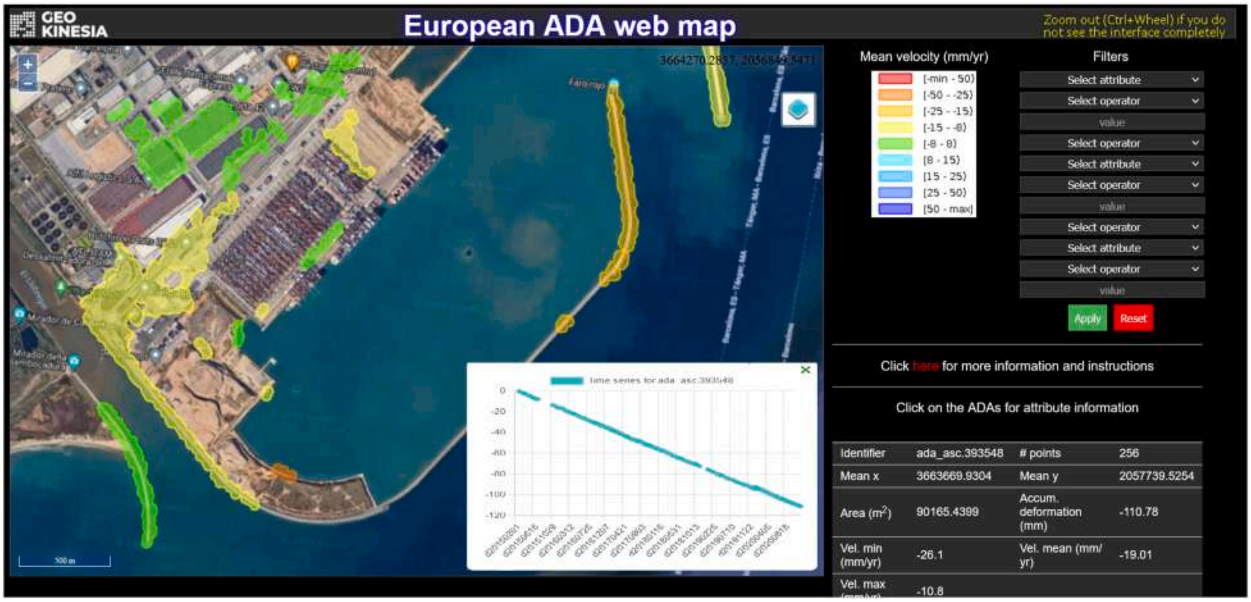

Fig. 1. Example of the European ADA map of the port of Barcelona. Each ADA corresponds to a polygon, colour-coded according to its velocity. This map includes a deformation time series representative of each ADA. It is accessible via a webmap at http://groundmotionADAs.com.

datasets from the EGMS Basic product. An example of this work, concerning a relatively small area of less than 10 km^2, is shown in Fig. 2. However, the procedure's potential becomes more evident when applied to large areas, such as processing more than half a million km^2 of Spain.

3B. Another ADA classification approach is described in Palamà et al. (2024). These authors propose a supervised classifier to categorize the ADAs into different deformation classes. They implemented a machine learning classifier that employs the Extreme Gradient Boosting technique. The method uses the ADAFinder output, a DTM and a land cover map of the analysed area as inputs. Landslide and subsidence inventories are employed as ground truth for training and validation purposes. The paper describes the analysis of the Italian territory based on the EGMS Basic product, with the aim of extending the analysis to all Europe. The paper describes the classification into three deformation classes: deep-seated gravitational slope deformation, landslide, and subsidence. However, the final goal is to extend the analysis to multiple classes. Another interesting classification approach based on machine learning is described in Rivera-Rivera et al. (2024).

4. A natural evolution of the ADAFinder and ADAClassifier is the assessment of the potential impact of the detected ADAs, known as ADA Impact, as described by Zêzere et al. (2024). This approach aims to provide decision makers with tools to assess exposure and the potential impact of the detected active hazards, thereby supporting risk assessment. These authors assess the potential impact by estimating the process magnitude and the exposure efforts. The process magnitude depends on factors such as the ADA surface area, absolute deformation velocity, type of phenomenon, and deformation time series. The exposure considers the population, buildings, roads, railways and other critical equipment and infrastructure existing within a given ADA polygon. The potential impact is categorized in three classes: low, medium, and high. An example of a potential impact map is shown in Fig. 3.

5A. Evers et al. (2023) describe a procedure called PSDefoPAT to associate each EGMS time series with a best-fitting time series model. In this approach, the periodic and trend components of the deformation data are treated separately. The periodic component is modelled using a sine function, while the trend component is fitted using linear, quadratic, and piecewise linear regression models. This tool is fully automatic and capable of analysing large data sets. The authors discuss various case studies to demonstrate how their analysis reveals new information on the temporal behaviour of deformation. This information complements the data provided by deformation velocity maps.

5B. Kuzu et al. (2023) propose a method for detecting anomalies in PSI time series data related to buildings. For this task they introduce an unsupervised learning method that employs a long short-term memory autoencoder model and a time series reconstruction loss function named soft-DTW (soft variant of the Dynamic Time Warping). The authors illustrate their method using EGMS data over Rome (Italy) which detected various types of building displacements and is scalable to support urban monitoring and infrastructure management at the continental level.

6. Krzepek et al. (2023) propose the transformation of vector data, specifically point data, from the EGMS products into raster data. They claim that this transformation achieved through a standard point-to-raster operation using a GIS (Geographic Information System) software, such as ArcGIS Pro, increases the usability of this type of data. In addition, they introduce a tool to detect large-scale ground motion hot spots and discuss the exploitation of time series. Although EGMS data are mentioned in this work, the discussed examples concern German GMS data.

Fig. 2. Example of output from the ADA Classifier covering a coastal area in southern Spain. In this region, most of the ADAs are classified as "Landslide" (LAN). However, there are a few ADAs classified as a "Settlement" (SET) or "Settlement/Landslide (SET/LAN).

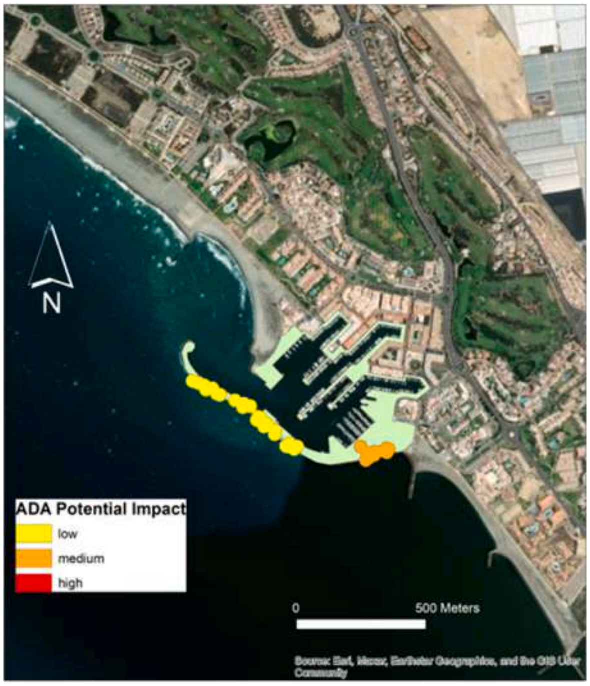

Fig. 3. Example of an output of the ADAImpact over Almerimar Marina (Granada, Spain). This image is taken from Zêzere et al. (2024).

7. Shahbazi et al. (2022, 2024) focus their analysis on spatial differential deformations, or the spatial gradient of deformation, which is directly related to damages to structures and infrastructures. In fact, such damages depend on the deformation pattern: the most significant ones are associated with high spatial differential deformations, i.e. high spatial deformation gradient values. The procedure, which is called Building Differential Deformation (BDD), requires the EGMS Basic product and a vector map of buildings and infrastructures as inputs. For all buildings covered by enough MPs, it computes the slope (gradient) and aspect of the deformation field, highlighting the local maximum deformation slopes. The BDD can be a useful screening tool to analyse large PSI datasets. The reliability of the procedure depends on the number of MPs falling inside a given building. An example of BDD output is shown in Fig. 4, which illustrates several buildings in the study area characterized by low to high gradient intensity. The BDD procedure has been used to assess the potential building damage map of Spain, available at http://groundmotionADAs.com. This map identifies hundreds of buildings affected by low to high gradient intensity. For several of them, in situ validation has been carried out (Shahbazi et al., 2024).

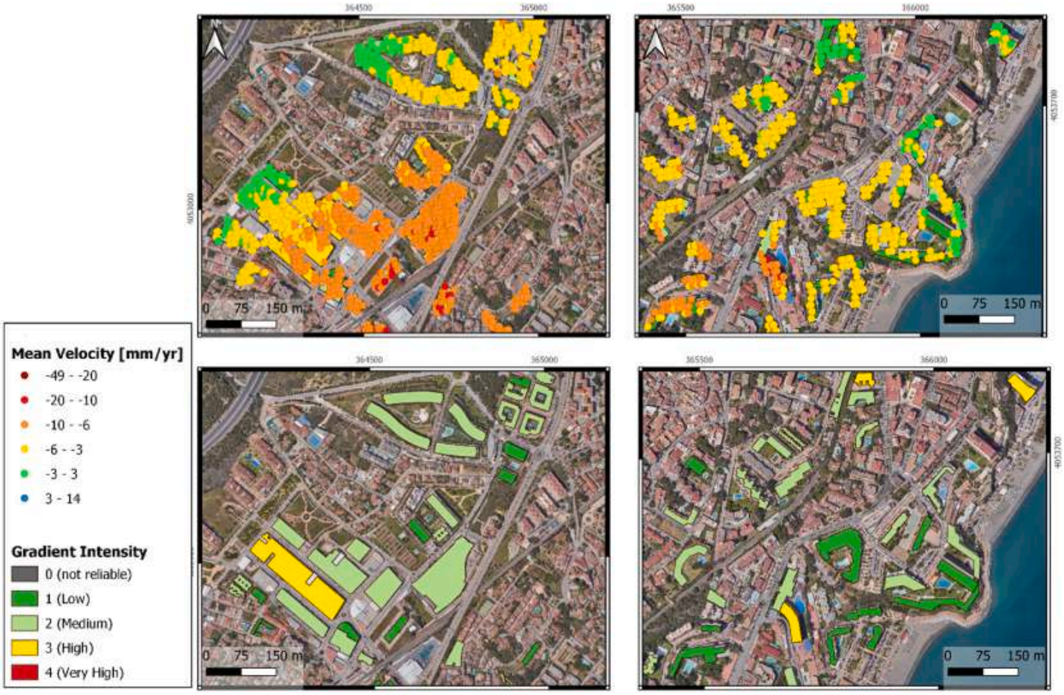

Fig. 4. Example of BDD output. Two deformation velocity maps (above) and the corresponding potential damage maps (below), i.e. maps of the building affected by differential deformations. The potential damage is colour-coded according to the deformation gradient intensity.

3.2. Application review from literature

Three years after the release of the EGMS baseline, several applications exploiting this dataset have been described. These are the main trends that have been deduced from the review of such applications.

- In general, most of the published papers concern known PSI applications that are run with EGMS data, which were largely published in the last 25 years. However, there are important exceptions, where the analysis fully exploits the wide-area nature of the EGMS products. This is the case of Cuevas-González, 2024 and Palamà et al. (2024) that perform a nation-wide ADA classification

Table 1
Classification of the EGMS applications published in the literature. In the References column, **-B** indicates the use of the EGMS Basic, **-O** the Ortho, and **-C** the Calibrated product. Product type is not specified in cases in which it is not mentioned by the authors.

Main topic	Sub-topic	References
Land subsidence	Coastal areas and relative sea level rise	Antoniadis et al. (2023) **-O**, Thiéblemont et al. (2023) **-O**, Melet et al. (2021) **-O**, Evelpidou et al. (2023) **-O**
	Groundwater exploitation	Hasan et al. (2023) **-O**, Mateos et al. (2024), Khan et al. (2024), Beccaro et al. (2023) **-O**, Ghaderpour et al. (2024) **-C,O**
Landslides	Local studies	Yishu (2022) **-O**, Nikolakopoulos et al. (2023) **-O**, Godone et al. (2023) **-C**, Dabiri and Nilfouroushan (2024) **-B,C,O**, Torre et al. (2024), Lau et al. (2024) **-C,O**
	Landslide inventories	Necula and Niculiță (2023) **-C**, Necula and Niculiță (2024) **-C**, Guinau et al. (2024) **-C**, Medici et al. (2024) **-C**
Geodynamics and tectonics	–	Atanasova and Nikolov (2023), Metzger et al. (2023) **-O**, Mildon et al. (2024) **-O**, Melichar et al. (2024) **-O**
Mining	Underground mining	Pawłuszek-Filipiak et al. (2023) **-O**, Ilieva et al. (2024)
	Open pit mining	Motagh et al. (2024), Tzampoglou and Loupasakis (2023) **-O**
	Abandoned mines	Yang et al. (2023) **-O**, Tinagli et al. (2024) **-O**
Infrastructures	Bridges	Tonelli et al. (2023) **-O**, Eskandari and Scaioni (2023) **-C,O**
	Dams	Ruiz-Armenteros et al. (2023), Costantini et al. (2022) **-B,C,O**
	Civil infrastructure	Milenova Vasileva (2023) **-O**, Zêzere et al. (2024), Wang (2023) **-O**
	Gas storage	Fibbi et al. (2023) **-C,O**, Fibbi et al. (2024) **-O**, Rigamonti et al. (2024)
	Landfills	Negula et al. (2023) **-O**
Urban areas. Buildings	–	Mele et al. (2023) **-C**, Hlaváčová et al. (2023) **-C,O**, Shahbazi et al. (2022) **-C**, Shahbazi et al. (2024) **-C**, Rodríguez-Antuñano et al. (2023)
Archaeology and cultural heritage	–	Antonioli et al. (2023) **-O**, Agapiou et al. (2023) **-O**, Ioannidis et al. (2024) **-O**

using the Basic product; Shahbazi et al. (2022, 2024) that describe a nation-wide BDD; Thiéblemont et al. (2023) that propose a new coastal pan-European relative sea-level product; Hasan et al. (2023) that study subsidence data over 15 regions of Europe; Yishu (2022), which describes the analysis of several landslides; and Necula and Niculiță (2023, 2024) and Medici et al. (2024) that propose a nation-wide national inventory and landslide mapping, respectively.
- Several applications concern local studies that cover relatively small areas. Among such applications, it is worth noting that some of them are related to thin or small features. This is clearly at the limit of the applicability due to the resolution of the original Sentinel-1 data and hence the MP density that characterize the EGMS products. Examples of these applications can be found in Table 1 under landslides/local studies; infrastructures; urban areas and buildings, and archaeology and cultural heritage.
- In some cases, the published studies mainly rely on the EGMS data. In most cases the EGMS data are complemented by other types of data. Sometimes, the EGMS products operate with data originating from additional ad hoc PSI studies.
- It is interesting to discuss the types of EGMS products used. The Basic is the less elaborated product and is expected to be used by experts. This is not corroborated by the numbers. Most of the research studies use the Ortho product (27 out of 37 listed in Table 1, with 22 exclusively based on this product). This is followed by the Calibrated product (15 out of 37, with 10 exclusively based on this product), and the Basic product (2 out of 37, with none exclusively based on this product). Use of the Ortho product, especially its vertical component, is straightforward, especially its vertical component. This explains, at least partially, its widespread use. However, it is worth remembering that this product has a much smaller resolution than the other two ones.

The main EGMS applications that are described in the literature are briefly reviewed below and are summarized in Table 1. The percentage of each type of application is shown in Fig. 5, while the geographical distribution of the applications is illustrated in Fig. 6. It is worth noting that most of the applications are concentrated in Southern Europe: Italy (12 studies), Greece (10 studies) and Spain (7 studies).

3.2.1. Land subsidence

1. Coastal areas and relative sea level rise.

Antoniadis et al. (2023) study two coastal cities and identify the subsidence mechanism (consolidation of the compressible soil layers) by combining a multi-source dataset. Thiéblemont et al. (2023) present a pan-European analysis of relative sea level changes considering vertical ground motion from EGMS. Melet et al. (2021) provide an overview of the Copernicus products and services to inform on sea level rise adaptation. Evelpidou et al. (2023) investigate relative sea-level changes of eustatic/tectonic origin in the Corinth Gulf (Greece), focusing on the combination of geomorphological (long-term) and geodetic (short-term) data as key in this study.

2. Groundwater exploitation.

Hasan et al. (2023) explore the interrelation at global scale between groundwater stress, aquifer depletion, and land subsidence using remote sensing and model-based datasets with a machine learning approach. Mateos et al. (2024) assess groundwater level depletion and its associated subsidence rates in future scenarios using machine learning techniques. Khan et al. (2024) integrate artificial intelligence techniques with PSI-derived data to create comprehensive pre- and post-event multi-temporal deformation inventories and susceptibility maps. This fusion allows the authors to model and predict ground deformation events. Beccaro et al. (2023) study a subsidence affecting infrastructures and urban areas in northern Italy. Ghaderpour et al. (2024) perform ground deformation monitoring of an industrial area.

3.2.2. Landslides

1. Local studies.

Yishu (2022) describes the analysis of several landslides located in Northern Italy. Nikolakopoulos et al. (2023) perform a local study of a landslide that affects a village in western Greece using UAV, GNSS and EGMS data. Godone et al. (2023) study a large, slow-moving landslide phenomenon using methodology that couples long-term PSI data analysis with intensive in situ monitoring. Dabiri and Nilfouroushan (2024) demonstrate the advantage of using advanced PSI time series analysis for a better understanding of surface deformation before a landslide event. Torre et al. (2024) analyse a complex active movement using EGMS, geological and geomorphologic data. Lau et al. (2024) monitor deep-seated landslides.

2. Landslide inventories.

Necula and Niculiță (2023) propose the creation of an inventory of active landslides in Romania using EGMS data and geomorphological inventories. Necula and Niculiță (2024) study slow-moving landslides in the Moldavian Plateau (Romania). Guinau et al. (2024) perform landslide mapping by integrating EGMS data and landscape evolution analysis through geomorphological indices. Medici et al. (2024) describe a semi-automatic procedure for landslide mapping.

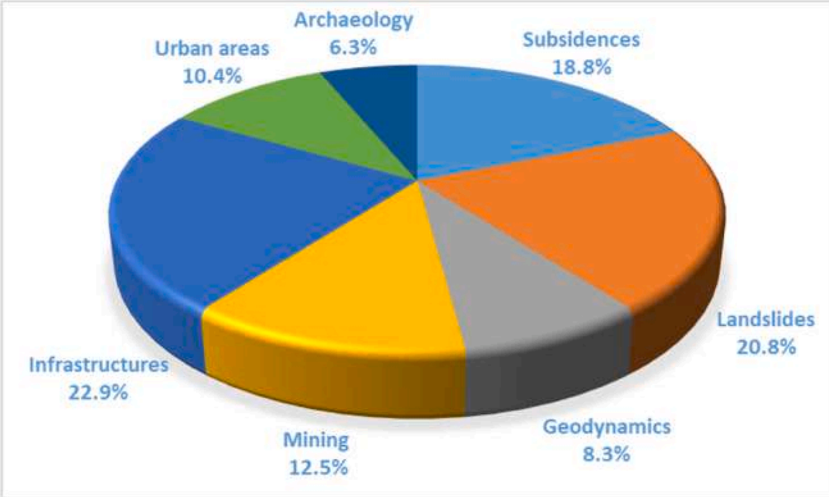

Fig. 5. Distribution (%) of the main types of EGMS applications described in the literature.

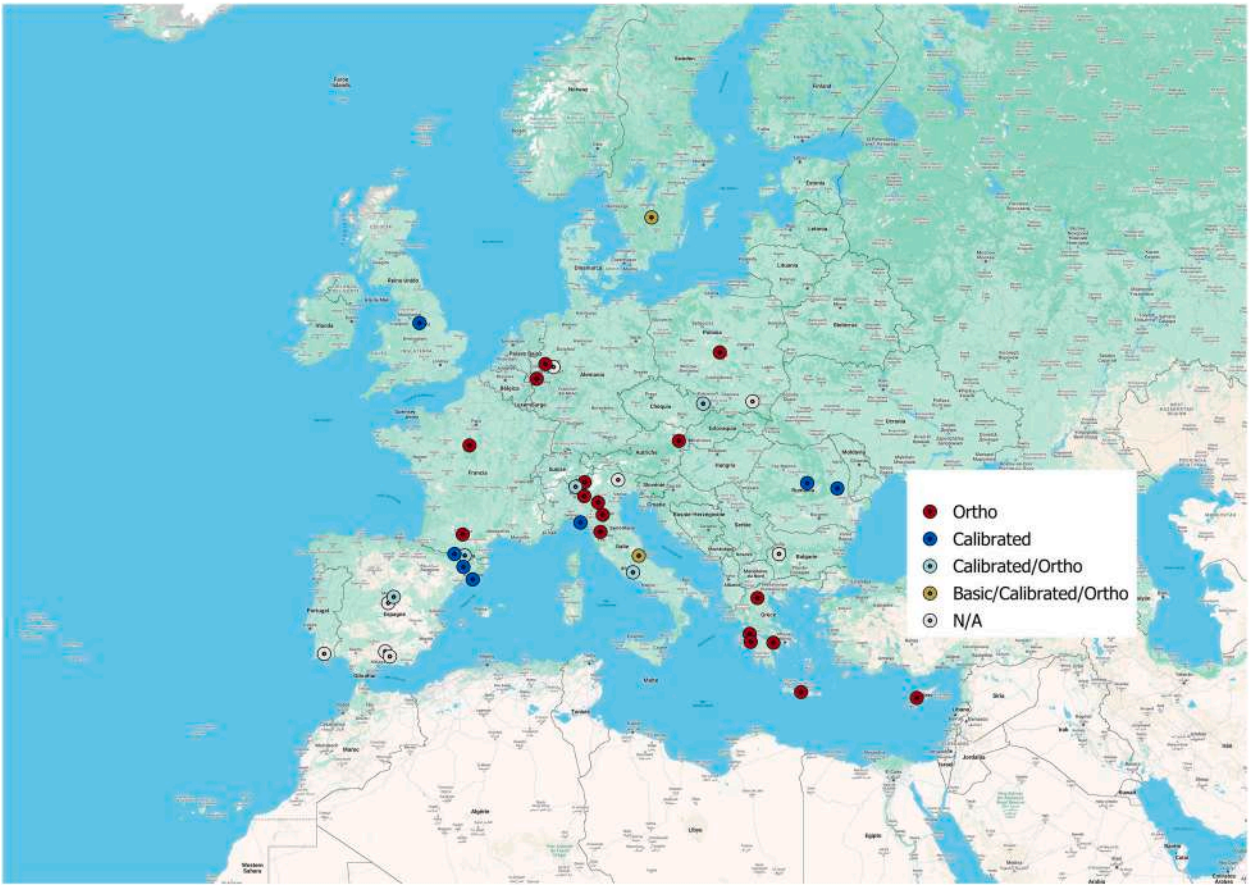

Fig. 6. Geographical distribution of the EGMS applications reviewed in this paper.

3.2.3. Geodynamics and tectonics

Atanasova and Nikolov (2023) study the effect of hazardous geodynamic processes in the area around the city of Sofia (Bulgaria). Metzger et al. (2023) investigate recent kinematics of Crete (Greece). Mildon et al. (2024) assess the aseismic vertical deformation during the inter-seismic cycle across a normal fault in the Gulf of Corinth (Greece). Melichar et al. (2024) observe unusual fault kinematic behaviour before, during, and shortly after a series of earthquakes in Austria.

3.2.4. Mining

1. Underground mining.

Pawłuszek-Filipiak et al. (2023) monitor the deformation caused by underground mining operations using EGMS, other PSI data, and corner reflectors. Ilieva et al. (2024) address the long-term PSI monitoring of mining induced deformations in Southern Poland.

2. Open pit mining.

Motagh et al. (2024) perform an analysis of ground surface deformation around an open pit mine in Germany. Tzampoglou and Loupasakis (2023) investigate hydrogeological hazards in open pit coal mines in Greece.

3. Abandoned mines.

Yang et al. (2023) evaluate the ground movements in the post-mining phase. Tinagli et al. (2024) reconstruct the spatial and temporal evolution of ground deformation around a sinkhole-prone area in an abandoned mining district.

3.2.5. Infrastructures

1. Bridges.

Tonelli et al. (2023) apply EGMS for the remote monitoring of road bridges and interpret the results from a structural viewpoint. Eskandari and Scaioni (2023) evaluate the EGMS data for bridge monitoring, in terms of the response of bridge structures to temporal and thermal deformations.

2. Dams.

Ruiz-Armenteros et al. (2023) discuss the use of EGMS to monitor dams, large ponds, and their surrounding areas. Costantini et al. (2022) describe a dam-monitoring case based on exploiting EGMS data.

3. Civil infrastructure.

Milenova Vasileva (2023) describes the applicability of EGMS to monitor civil infrastructure. Zêzere et al. (2024) illustrate examples of potential impact of deformation on a road network and a port. Wang (2023) studies the damage to infrastructure, including highways and railways, caused by ground motion in Italy.

4. Gas Storage.

Fibbi et al. (2023) describe an underground gas storage monitoring. Fibbi et al. (2024), more in general, address the analysis of ground deformation patterns in underground gas storage activities. Rigamonti et al. (2024) study several underground gas storage reservoirs located in Italy.

5. Landfills.

Negula et al. (2023) assess the suitability of the EGMS Ortho Product to perform a systematic observation of landfill areas, in which several solid waste landfills located across Romania are considered.

3.2.6. Urban areas. Buildings

Mele et al. (2023) propose a methodology for monitoring the deformations of urban settlements, based on the application of the ADAfinder tool with EGMS products. Hlaváčová et al. (2023) address the multidimensionality of urban resilience and demonstrate the utility of EGMS and other PSI data in supporting the assessment of geotechnical hazards in urban or post-mining environments. Several examples of differential deformation of buildings are described in Shahbazi et al. (2022, 2024). Rodríguez-Antuñano et al. (2023) propose a methodology for large-scale infrastructure monitoring and vulnerability assessment in which four case studies of recently-collapsed infrastructures are analysed. They claim the proposed methodology has potential to predict and prevent structural collapses.

3.2.7. Archaeology and cultural heritage

Antonioli et al. (2023) study an archaeological structure carved entirely in bedrock, which can be recognized and measured using remote sensing data. Agapiou et al. (2023) investigate the EGMS ground motion data over western Cyprus, which is home to 147

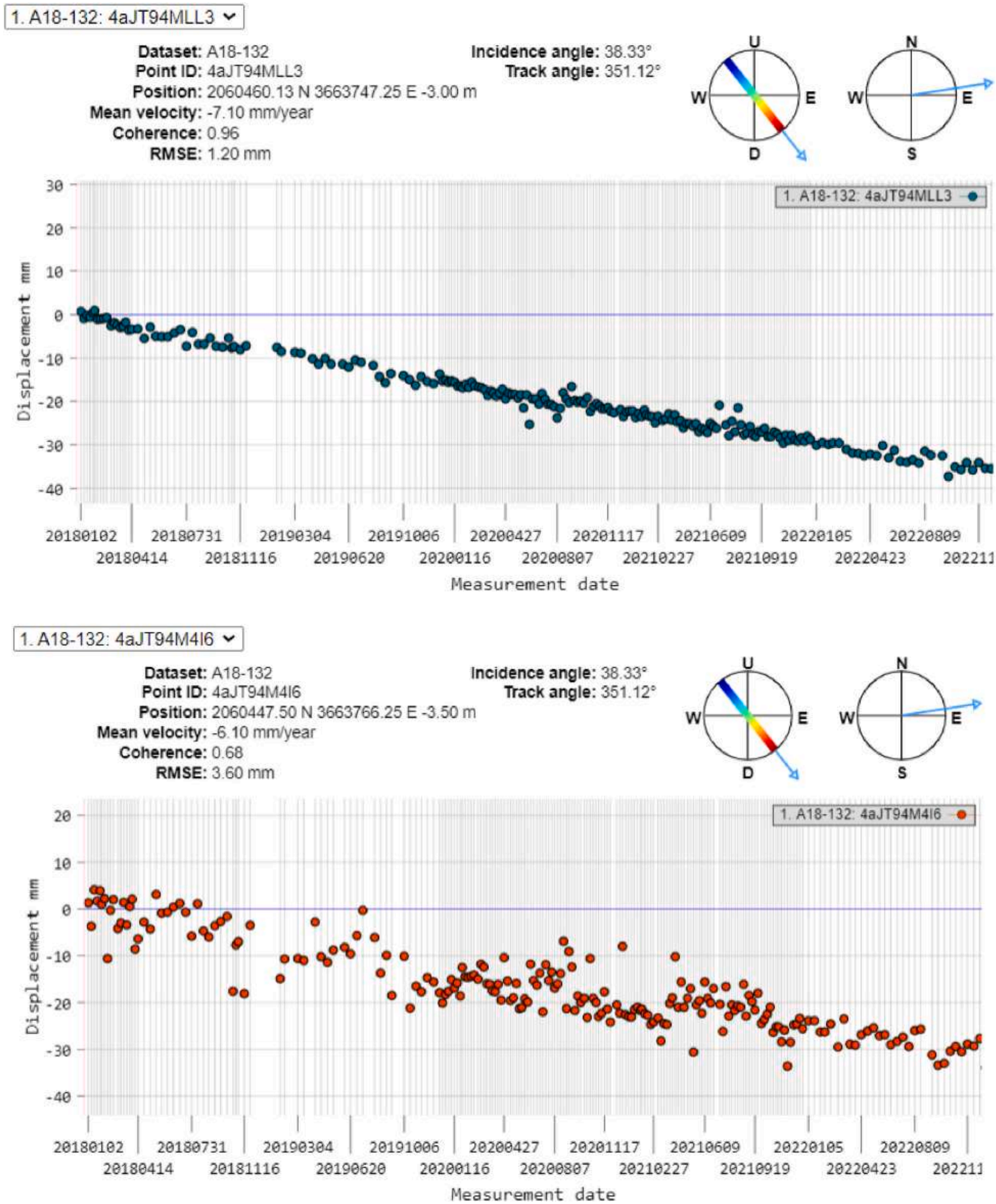

Fig. 7. Example of MP time series from the EGMS Calibrated product. The time series above has a very high temporal coherence (0.96), while the other has a medium temporal coherence (0.68).

ancient monuments and archaeological sites. Finally, Ioannidis et al. (2024) propose a methodological framework for tackling climate change risks and natural hazards threatening cultural heritage in the most efficient way possible.

4. Technical discussion

In this section we discuss some technical characteristics of the EGMS products. Understanding these aspects can help users to better understand and exploit this type of data.

1. **Global blind processing versus ad hoc processing.** One criticism of EGMS is its use of blind processing, which can lead to sub-optimal results because an ideal PSI processing requires an identifiable end-user, a set of user requirements, and tailored data analysis to satisfy such requirements. However, the EGMS is designed to be a general-purpose, continental-wide service. Its user requirements are based on the characteristics of Sentinel-1 SAR data and state-of-the-art PSI techniques, reflecting a technology-driven approach to cover wide areas, instead of targeted applications. This is because the EGMS is basically the result of a technology push. This notwithstanding, we believe that the EGMS product can be suitable for many applications, as discussed in the previous section. More demanding applications may require complementary ad hoc processing using the same Sentinel-1 data or other SAR data with different characteristics, such as very high-resolution X-band or higher-coherence L-band. This can be done by companies or research centres specialized in PSI processing.
2. **About the claimed 1-mm accuracy of EGMS.** Several key documents, including the original EGMS White Paper (White Paper, 2017), claim that EGMS delivers deformation estimates with a 1-mm accuracy. This statement contains at least two errors. In optimal conditions (good set of images, good and non-isolated MPs, linear deformation, etc.), 1-mm is true in terms of deformation velocity, not deformation itself (Crosetto et al., 2016). Thus, the correct claim would be "1 mm per year", not "1 mm": the difference is important. Additionally, the 1 mm per year refers to precision (i.e. a standard deviation of 1 mm/yr) rather than accuracy. This distinction is correctly reported on the EGMS website: https://land.copernicus.eu/en/products/european-ground-motion-service.
3. **Performance varies from MP to MP.** All MPs in an EGMS product meet specific selection criteria, but their performance varies. This variability is evident in the MP time series, due to different levels of noise associated with each MP and varying noise associated with different dates. For this reason, some time series appear very clean (e.g. Fig. 7 above), while other contain dispersed values (e.g. Fig. 7 below), which can complicate the interpretation of the corresponding motion. In the examples in Fig. 7, the temporal coherence with respect to the linear regressed velocity is 0.96 and 0.68, respectively. Similar information can be derived from the RMSE (1.2 vs. 3.6 mm), which is evaluated on the time series residuals after applying a regression model of a third order polynomial plus a seasonal component. Aside from the noise, the time series can be affected by other error sources, the most important one of which is the residual atmospheric component. This component is usually smaller, if not negligible, in areas with high MP density (e.g. urban and peri urban areas), while it is usually higher in isolated areas with low MP density (e.g. countryside or mountain areas). These aspects should always be considered when interpreting EGMS measurements.
4. **The impact of deformation uncertainty varies from application to application.** It is worth noting that deformation uncertainty impacts EGMS applications differently. Applications relying on very few points, a single MP in the most extreme case, are more exposed. Such cases include the analysis of single houses, thin infrastructures, localized landslides, etc. There are at least two critical aspects related with these applications. First, they critically depend on the location of the MPs (see the following point). Second, they are vulnerable to errors and outliers in the deformation time series. Careful interpretation is required in these instances, though the analysis of even single MPs can be very valuable, despite its difficulties, especially where no other type of measurement is available.

   In contrast, analyses based on multiple MPs typically offer greater precision and reliability. Such analyses are well-suited for examining large buildings and infrastructures, broad subsidence areas, or large landslides. In these cases, one can exploit the redundancy of deformation measurements. In cases where simple models are employed (e.g. a subsidence model), the typically low number of model parameters can be estimated from hundreds or even thousands of MPs.

5. **MP positioning.** Accurate 3D positioning (e.g. east, north and height) of MPs is fundamental for the interpretation and exploitation of the EGMS products. It is worth recalling that the precision of MP positioning is three orders of magnitude worse than the precision of deformation measurements (meters vs millimetres). EGMS specifications require 3D geolocation precision to be better than 10 m. This precision is critical for EGMS interpretation, particularly in analyses involving small or thin objects. For instance, such precision is important to understand if an MP is inside or outside the perimeter of a given building or, more generally, of a given deformation phenomenon. Besides the planimetric positioning, the height of the analysed MPs is also worth considering. For instance, if an MP comes from the roof of a building, its elevation will be key to discriminate between the building and its surroundings.
6. **Delay in product delivery.** Due to processing load, EGMS products are published annually. If, for example, the release occurs in early September, there can be a delay of 8–20 months between the date of the last processed image (typically the end of the year) and the present. For this reason, EGMS data are not suitable for monitoring recent deformation events. However, this gap can be addressed by processing the most recent Sentinel-1 data, filling the gap between the date of the last EGMS processed image and the present time, or using other SAR imagery to complement EGMS products. High-resolution SAR data (TerraSAR-X, TanDEM-X, PAZ, and Cosmo-SkyMed) offer the additional advantage of obtaining a much higher MP density.

5. EGMS validation

In order to ensure the EGMS acceptability at the scientific, technical, and commercial levels, different efforts have been devoted to the validation of the EGMS products. A comprehensive validation report related to the first EGMS update (2015–2021) is available on the EGMS website.[16] We discuss its main characteristics in the following paragraphs.

The first aspect is the completeness of the EGMS products in terms of spatial coverage and MP density. The density can be low outside urban areas and where fast motions occur (with 6-day revisit time this occurs with absolute deformation velocity over pairs of MPs above 2 mm/day). The validation shows that the MP density ranges from 110 MP/km^2 for the forest class to 145 MP/km^2 for the permanent crop class, while it achieves 7800 MP/km^2 over continuous urban fabric. All of these values satisfy the EGMS technical specifications. More information on the measurement density is provided in Siegmund et al. (2022), Vradi et al. (2023) and Sala et al. (2023).

The second aspect is the precision and accuracy of the EGMS products. This analysis has been performed over many sites scattered over Europe, using heterogeneous ground truth (topography, levelling, and GNSS). Some of the results show a good agreement between EGMS and the ground truth, both in terms of deformation velocity (absolute differences below 1–2 mm/yr) and time series (standard deviation of differences below 5 mm). However, this cannot be said generally. In some cases, the differences in the deformation velocities (EGMS vs. ground truth) are far from the millimetre-per-year precision, which is sought. For instance, differences in the range of 5–10 mm/yr can be found. The same is true for the time series, where biases up to 10–20 mm or peaks of the same order of magnitude occur.

These discrepancies can be due to several factors. First, the EGMS footprint and the ground truth location might not completely coincide spatially, because a search radius of 50 or 100 m is used. Depending on the deformation pattern, this can influence the validation. Second, the differences can be due to errors in the EGMS data. For instance, they can be due to temporary low coherence (e.g. affecting a subset of the acquisitions), or to outliers that affect even a single image (i.e. a single date of the time series). The single outlier can be also due to residual atmospheric effects. Third, the difference can be due to errors in the ground truth data. Finally, they can be due to inconsistencies in the reference points used for EGMS and the ground truth. All of these aspects must be borne in mind when analysing the validation results.

The third aspect concerns the usability of the data for different types of applications, including the estimation of the appropriateness of the EGMS data, the metadata, and the dissemination platform. This involved: (i) assessing the consistency of the EGMS data with the environmental, urban, and geological context of the given validation site; (ii) evaluating the usefulness of the EGMS products for specific applications, and (iii) highlighting the added value of the EGMS data for the targeted applications. The EGMS validation report describes several applications in which the EGMS proved its usefulness and added value.

Other external validation activities have been devoted to the EGMS data. Even et al. (2023, 2024) describe the inter-comparison of EGMS and the German GMS. The results show a good agreement. However, it is worth mentioning that these results were generated using the same software from GAF AG, with only some differences in the processing parameters. The EGMS and German GMS data were also validated against levelling and GNSS data. Although an exception was reported in a site with pronounced spatio-temporal deformation gradients where significant errors were found, good overall validation results were obtained.

6. Future research

The EGMS is a service in continuous evolution. We will briefly discuss some key future research aspects for the progress of the service.

- **Improvement in PSI processing.** There are several technical features of the current EGMS that could be improved. We will now outline a few of them. New algorithms need to be used to increase the MP density. In line with this, the service could include intermittent or partial scatterers. The phase unwrapping in the presence of non-linear motion must be improved. The atmospheric filtering requires further refinement, especially for the low MP density and mountain areas. Finally, the positioning accuracy must be increased. Considering sub-pixel MP image location would contribute to this. It is worth underscoring that all of the above aspects require an in-depth feasibility analysis. In fact, the service implementation requires careful consideration of the computational load and data storage constraints of generating Europe-wide PSI products.
- **Improvement in the product visualization.** The current visualization of the Calibrated and Ortho products displays the PSI and GNSS deformation signals together. On occasion, this can make deformation interpretation more difficult. It would be helpful to let the users know what the separate deformation contributions of PSI and GNSS are. Additionally, the current EGMS Explorer background is rather poor and could be improved.
- **Inclusion of L-band data.** Looking to the mid-term, the scope of EGMS could evolve regarding the SAR missions to be used. Of particular interest are the forthcoming L-band data from NISAR (NASA ISRO Synthetic Aperture Radar) and ROSE-L (Radar Observing System for Europe in L-band). The SAR data from these missions will have enhanced interferometric coherence, especially in areas of vegetation coverage where the longer L-band wavelength can penetrate the canopy, therefore improving the MP coverage and density.

[16] https://land.copernicus.eu/en/technical-library/validation-report-2015-2021-dataset/@@download/file.

- **Boosting automated analysis.** As discussed above, EGMS products are often used to perform local deformation studies. However, the full potential of such products is exploited by analysing wide areas, up to an entire European coverage. This calls for appropriate tools to automate the data analysis and support a systematic data interpretation. Section 3.1 reviews some of the existing tools. Future research should address the evolution of such methods and tools.
- **Continuous validation.** Further validation is needed to increase the credibility of EGMS products and promote user uptake. A global characterization of deformation quality is needed. Ideally, a set of key numbers should be derived from future validation activities, e.g. to describe the precision of deformation velocity, deformation time series, MP positioning, etc. A comprehensive inter-comparison with national ground motion services could contribute to this goal. In addition, a validation of the EGMS GNSS model would be necessary.

7. Conclusions

Three years after the release of the EGMS baseline products, this first review paper explores the scope and impact of EGMS across different fields of application. First, a brief overview of the principal characteristics of the EGMS has been provided. Then the main trends of EGMS have been analysed. This includes the methods and tools to analyse the EGMS products, and a review of the main applications developed so far. A technical discussion of the main characteristics of the EGMS products has been provided. The main validation activities for EGMS, which are crucial for its acceptance at the scientific, technical, and commercial levels, have been discussed. Some key aspects related to EGMS evolution have been addressed. Finally, the main applications based on EGMS data have been reviewed.

In this paper, 48 different articles describing practical EGMS application cases have been identified, which have been organized into seven main categories, as shown in Table 1. In several of these applications, ground motion data are treated as a standard commodity. In most cases, information from the EGMS is an essential component in developing these applications, highlighting the potential of the service. We foresee a continued expansion of applications in the years to come. They will help raise awareness about EGMS and its products, and attract new users, especially outside the community of PSI data experts.

CRediT authorship contribution statement

M. Crosetto: Writing – original draft, Supervision, Conceptualization. **B. Crippa:** Software, Formal analysis. **M. Mróz:** Writing – review & editing, Supervision. **M. Cuevas-González:** Writing – review & editing, Visualization, Conceptualization. **S. Shahbazi:** Visualization, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

The author is an Editorial Board Member/Associate Editor for *ISPRS Journal of Photogrammetry and Remote Sensing* and was not involved in the editorial review or the decision to publish this article.

Acknowledgements

This work has been partially funded by AGAUR, Generalitat de Catalunya, through the Consolidated Research Group RSE, “Geomatics” (Ref: 2021-SGR-00536). The work of Saeedeh Shahbazi has been funded by AGAUR, Generalitat de Catalunya, through a grant for the recruitment of early-stage research staff (Ref: 2021FI_B 00077).

Data availability

No data was used for the research described in the article.

References

Agapiou, A., Kyriakidis, P., Hadjipetrou, S., Kyriakides, N., Votsis, R., 2023. European Ground Motion Service for built heritage: a case study from Cyprus. In: International Symposium on Digital Earth.
Antoniadis, N., Alatza, S., Loupasakis, C., Kontoes, C., 2023. Land subsidence phenomena vs. Coastal flood hazard—the cases of messolonghi and aitolikon (Greece). Rem. Sens. 15 (8), 2112.
Antonioli, F., Furlani, S., Spada, G., Melini, D., Zomeni, Z., 2023. The lambousa (Cyprus) fishtank in a quasi-stable coastal area of the eastern mediterranean, a notable marker for testing GIA models. Geosciences 13 (9), 280.
Atanasova, M., Nikolov, H., 2023. Application of SAR data time series for monitoring of geodinamic processes in the Sofia region. Int. Multidiscip. Sci. GeoConference: SGEM 23 (2.1), 283–290.
Barra, A., Solari, L., Béjar-Pizarro, M., Monserrat, O., Bianchini, S., Herrera, G., et al., 2017. A methodology to detect and update active deformation areas based on Sentinel-1 SAR images. Rem. Sens. 9 (10), 1002.
Beccaro, L., Cianflone, G., Tolomei, C., 2023. InSAR-based detection of subsidence affecting infrastructures and urban areas in emilia-romagna region (Italy). Geosciences 13 (5), 138.
Bischoff, C.A., Ferretti, A., Novali, F., Uttini, A., Giannico, C., Meloni, F., 2020. Nationwide deformation monitoring with SqueeSAR® using Sentinel-1 data. Int. Assoc. Hydrol. Sci. 382, 31–37.

Bredal, M., Dehls, J., Larsen, Y., Marinkovic, P., Lauknes, T.R., Stødle, D., Moldestad, D.A., 2019. The Norwegian National Ground Motion Service (InSAR No): Service Evolution. AGU Fall Meeting. G13C-0559.
Confuorto, P., Del Soldato, M., Solari, L., Festa, D., Bianchini, S., Raspini, F., Casagli, N., 2021. Sentinel-1-based monitoring services at regional scale in Italy: state of the art and main findings. Int. J. Appl. Earth Obs. Geoinf. 102, 102448.
Costantini, M., Ferretti, A., Minati, F., Falco, S., Trillo, F., Colombo, D., Novali, F., Malvarosa, F., Mammone, C., Vecchioli, F., et al., 2017. Analysis of surface deformations over the whole Italian territory by interferometric processing of ERS, Envisat and COSMO-SkyMed radar data. Remote Sens. Environ. 202, 250–275.
Costantini, M., Minati, F., Trillo, F., Ferretti, A., Passera, E., Rucci, A., et al., 2022. EGMS: Europe-wide ground motion monitoring based on full resolution InSAR processing of all Sentinel-1 acquisitions. IGARSS 2022, 5093–5096.
Crosetto, M., Monserrat, O., Cuevas-González, M., Devanthéry, N., Crippa, B., 2016. Persistent scatterer interferometry: a review. ISPRS J. Photogrammetry Remote Sens. 115, 78–89.
Crosetto, M., Solari, L., Mróz, M., Balasis-Levinsen, J., Casagli, N., Frei, M., Oyen, A., Moldestad, D.A., Bateson, L., Guerrieri, L., Comerci, V., Andersen, H.S., 2020. The evolution of wide-area DInSAR: from regional and national services to the European Ground Motion Service. Rem. Sens. 12 (12), 2043.
Crosetto, M., Solari, L., 2023. Satellite Interferometry Data Interpretation and Exploitation: Case Studies from the European Ground Motion Service (EGMS). Elsevier.
Dabiri, Z., Nilfouroushan, F., 2024. Enhancing landslide preparedness: leveraging EGMS products and SBAS-InSAR for pre-event ground deformation monitoring along the E6 highway near stenungsund in southern Sweden. In: EGU General Assembly Conference Abstracts. EGU24-12802.
Darvishi, M., Eriksson, L.E., Edman, T., Toller, E., Nilfouroushan, F., Elgered, G., Dehls, J., 2022. InSAR-based Ground Motion Service of Sweden: evaluation and benefit analysis of a nationwide InSAR service. Nordic Geodetic Commission, General Assembly.
Dehls, J.F., Larsen, Y., Marinkovic, P., Lauknes, T.R., Stødle, D., Moldestad, D.A., 2019. INSAR. No: a national InSAR deformation mapping/monitoring service in Norway–From concept to operations. IGARSS 2019, 5461–5464.
Dehls, J.F., Kenyeres, A., Tóth, S., Larsen, Y., Marinkovic, P., 2022. Towards geodetically robust datum connection of large-scale InSAR results-EGMS perspective. IGARSS 2022, 5097–5100.
Du, Z., McCubbine, J., Garthwaite, M., Brown, N., Ng, A.H.M., Deane, A., Wang, L.W., 2023. Towards a wide-scale land subsidence product in Eastern states of Australia. IEEE Trans. Geosci. Rem. Sens. 61.
Eskandari, R., Scaioni, M., 2023. European ground motion service for bridge monitoring: temporal and thermal deformation cross-check using cosmo-skymed InSAR. Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci. 48, 1235–1241.
Evelpidou, N., Ganas, A., Karkani, A., Spyrou, E., Saitis, G., 2023. Late quaternary relative seasea-level changes and vertical GNSS motions in the Gulf of Corinth: the asymmetric localization of deformation inside an active half-graben. Geosciences 13 (11), 329.
Even, M., Westerhaus, M., Kutterer, H., 2023. A comparison of the German and the European ground motion services. IGARSS 2023, 7898–7901.
Even, M., Westerhaus, M., Kutterer, H., 2024. German and European ground motion service: a comparison. PFG–journal of Photogrammetry. Rem. Sens. Geoinformation Sci. 1–18.
Evers, M., Thiele, A., Hammer, H., Hinz, S., 2023. PSDefoPAT—persistent scatterer deformation pattern analysis tool. Rem. Sens. 15 (19), 4646.
Festa, D., Del Soldato, M., 2023. EGMStream, a desktop app for EGMS data downstream. Rem. Sens. 15 (10), 2581.
Fibbi, G., Beni, T., Fanti, R., Del Soldato, M., 2023. Underground gas storage monitoring using free and open source InSAR data: a case study from yela (Spain). Energies 16 (17), 6392.
Fibbi, G., Beni, T., Del Soldato, M., Fanti, R., 2024. EGMS insights into ground deformation patterns in Underground Gas Storage (UGS) activities. In: EGU General Assembly Conference Abstracts. EGU24-8610.
Ghaderpour, E., Mazzanti, P., Bozzano, F., Mugnozza, G.S., 2024. Ground deformation monitoring via PS-InSAR time series: an industrial zone in Sacco River Valley, central Italy. Remote Sens. Appl.: Soc. Environ., 101191
Godone, D., Allasia, P., Notti, D., Baldo, M., Poggi, F., Faccini, F., 2023. Coexistence of a marginal mountain community with large-scale and low kinematic landslide: the intensive monitoring approach. Rem. Sens. 15 (13), 3238.
Guinau, M., Fernández-Jiménez, C., Barra, A., Viaplana-Muzas, M., Flores, A., Ortuño, M., , et al.Abancó, C., 2024. Multi-technique analysis and landscape evolution: implications for landslide-fluvial cascading hazards assessment. In: EGU General Assembly Conference Abstracts. EGU24-14955.
Hasan, M.F., Smith, R., Vajedian, S., Pommerenke, R., Majumdar, S., 2023. Global land subsidence mapping reveals widespread loss of aquifer storage capacity. Nat. Commun. 14 (1), 6180.
Hrysiewicz, A., Khoshlahjeh Azar, M., Holohan, E.P., 2024. EGMS-toolkit: a set of Python scripts for improved access to datasets from the European Ground Motion Service. Earth Sci. Informatics 1–13.
Hlaváčová, I., Kolomazník, J., Struhár, J., Orlitová, E., 2023. InSAR ground motion mapping in support of urban resilience and regional landscape planning. In: 2023 Joint Urban Remote Sensing Event (JURSE), pp. 1–4.
Ilieva, M., Pawłuszek-Filipiak, K., Teodorczyk, D., Wielgocka, N., Balak, P., Stasch, K., , et al.Tymków, P., 2024. EPOS-PL+ project-infrastructure for long-term InSAR monitoring of mining induced deformations in Southern Poland. In: EGU General Assembly Conference Abstracts. EGU24-19176.
Ioannidis, C., Verykokou, S., Soile, S., Istrati, D., Spyrakos, C., Sarris, A., , et al.Anyfantis, G.C., 2024. Safeguarding our heritage—the TRIQUETRA project approach. Heritage 7 (2), 758–793.
Kalia, A.C., Frei, M., Lege, T., 2017. A Copernicus downstream-service for the nationwide monitoring of surface displacements in Germany. Rem. Sens. Environ. 202, 234–249.
Cuevas-González, et al., 2024. Semi-automatic classification of unstable areas detected by the European Ground Motion Service (EGMS) at national level. Submitted Rem. Sens. Environ..This paper is under review: not yet published.
Kalia, A.C., Frei, M., Lege, T., 2021. BodenBewegungsdienst Deutschland (BBD): Konzept, Umsetzung und Service-Plattform. ZfV-Zeitschrift für Geodäsie. Geoinformation und Landmanagement 4 (in German).
Khan, J., Rosi, A., Raj Meena, S., Floris, M., 2024. The role of artificial intelligence in modeling and predicting ground deformation using advanced InSAR data. In: EGU General Assembly Conference Abstracts. EGU24-13026.
Krzepek, K., Rudolf, M., Homuth, B., Henk, A., Iwaszczuk, D., 2023. Raster representation of ground motion service data and automated hot-spot detection. Joint Urban Remote Sensing Event (JURSE) 1–4.
Kuzu, R.S., Bagaglini, L., Wang, Y., Dumitru, C.O., Braham, N.A.A., Pasquali, G., et al., 2023. Automatic detection of building displacements through unsupervised learning from InSAR data. IEEE J. Sel. Top. Appl. Earth Obs. Rem. Sens. 16, 6931–6947.
Lau, R., Seguí, C., Waterman, T., Chaney, N., Veveakis, M., 2024. InSAR-Informed In-Situ Monitoring for Deep-Seated Landslides: Insights from El Forn (Andorra), vol. 2024. EGUsphere, p. 1.
Mateos, R.M., Collados-Lara, A.J., Pulido-Velazquez, D., Baena-Ruiz, L., 2024. Assessing potential future subsidence due to groundwater depletion in “Alto Genil” Basin (Southern Spain). In: EGU General Assembly Conference Abstracts. EGU24-20678.
Medici, C., Novellino, A., Dashwood, C., Bianchini, S., 2024. Semi-automatic analysis of InSAR large datasets for landslide mapping and monitoring: the Great Britain case study. In: EGU General Assembly Conference Abstracts. EGU24-6191.
Mele, A., Crosetto, M., Miano, A., Prota, A., 2023. ADAFinder tool applied to EGMS data for the structural health monitoring of urban settlements. Rem. Sens. 15 (2), 324.
Melet, A., et al., 2021. European Copernicus Services to inform on sea-level rise adaptation: current status and perspectives. Front. Mar. Sci. 8, 703425.
Melichar, R., Baroň, I., Rowberry, M., Jelének, J., Sokol, Papí, Isaba, M.D.P., , et al.Bürgmann, R., 2024. Unusual fault kinematic behaviour and near-surface crustal stress variations before and during an earthquake series in the Vienna Basin (Austria) in spring 2021. In: EGU General Assembly Conference Abstracts. EGU24-7664.
Metzger, S., Aftab Uddin, M., Mouslopoulou, V., Begg, J., Nicol, A., Saltogianni, V., Oncken, O., 2023. Recent kinematics of Crete, observed by InSAR, reveal complex, curved-forearc deformation and aquifers changes. In: EGU General Assembly Conference Abstracts. EGU-13785.

Milenova Vasileva, S., 2023. PS-DInSAR processing of Sentinel-1 images in the Hambach mine, Germany, and its applicability in civil infrastructure monitoring. Master thesis. Universidad Pública de Navarra (Spain).
Mildon, Z., Diercks, M., Roberts, G., Walker, J.F., Ganas, A., Papanikolaou, I., , et al.Mitchell, S., 2024. Transient Aseismic Vertical Deformation during the Interseismic Cycle across the Pisia-Skinos Normal Fault (Gulf of Corinth, Greece). EGU General Assembly Conference Abstracts. EGU24-16153.
Motagh, M., Haghighi, M.H., Piter, A., Vassileva, M., 2024. Mining-induced subsidence and fault reactivation due to open pit lignite mining in the Hambach region, North Rhine-Westphalia, Germany: insights from Sentinel-1 based European Ground Motion Service (EGMS) and field surveys. In: EGU General Assembly Conference Abstracts. EGU24-11866.
Navarro, J.A., Tomás, R., Barra, A., Pagán, J.I., Reyes-Carmona, C., Solari, L., Vinielles, J.L., Falco, S., Crosetto, M., 2020. ADAtools: automatic detection and classification of Active Deformation Areas from PSI displacement maps. Int. J. Geo-Information 9, 584.
Necula, N., Niculiță, M., 2023. Towards national active landslide inventory using EGMS datasets. Revista de Geomorfologie 25, 16.
Necula, N., Niculiță, M., 2024. Active landslides inventory update based on EGMS data for slowing moving landslides in a hilly environment. In: EGU General Assembly Conference Abstracts. EGU24-14387.
Negula, I.D., Moise, C., Dediu, F., Gheorghe, M., Tudor, G., Sefercik, U.G., 2023. Assessment of the European ground motion service Ortho products for landfill systematic observation. Scientific papers. Series E. Land reclamation. Earth Observ. &; Surv., Environ. Eng. 12.
Nikolakopoulos, K.G., Kyriou, A., Koukouvelas, I.K., Tomaras, N., Lyros, E., 2023. UAV, GNSS, and InSAR data analyses for landslide monitoring in a mountainous village in western Greece. Rem. Sens. 15 (11), 2870.
Nilfouroushan, F., Gido, N.A., Darvishi, M., 2022. Cross-checking of the nationwide ground motion service (GMS) of Sweden with the previous InSAR-based results: case studies of uppsala and gävle cities. EGU General Assembly,. EGU22, 5293.
Palamà, R., Barra, A., Cuevas-González, M., Monserrat, O., Crosetto, M., 2024. Ground motion classification from European ground motion service data using extreme gradient boosting. IGARSS, 2024.
Papoutsis, I., Kontoes, C., Alatza, S., Apostolakis, A., Loupasakis, C., 2020. InSAR Greece with parallelized persistent scatterer interferometry: a national ground motion service for big Copernicus Sentinel-1 data. Rem. Sens. 12 (19), 3207.
Pawłuszek-Filipiak, K., Wielgocka, N., Tondaś, D., Borkowski, A., 2023. Monitoring nonlinear and fast deformation caused by underground mining exploitation using multi-temporal Sentinel-1 radar interferometry and corner reflectors: application, validation and processing obstacles. Int. J. Digital Earth 16 (1), 251–271.
Poncos, V., Cusson, D., Welch, A., Teleaga, D., Toma, S.A., 2023. C-GMS-The Canadian Ground Motion Service, vol. 2023. IGARSS, pp. 1716–1719.
Raspini, F., Bianchini, S., Ciampalini, A., Del Soldato, M., Montalti, R., Solari, L., Tofani, V., Casagli, N., 2019. Persistent Scatterers continuous streaming for landslide monitoring and mapping: the case of the Tuscany region (Italy). Landslides 16, 2033–2044.
Rigamonti, S., Dattola, G., Ciantia, M.O., Crosta, G.B., 2024. A multivariate time series analysis of underground gas storage deformations using InSAR data. In: EGU General Assembly Conference Abstracts. EGU24-19174.
Rivera-Rivera, J.S., Béjar Pizarro, M., Aguilera Alonso, H., Ezquerro, P., Guardiola-Albert, C., Monserrat, O., 2024. Automated classification of ground deformation processes in Spain: a machine learning approach using a novel national InSAR-based database. EGU General Assembly,. EGU24, 8369.
Rodríguez-Antuñano, I., Martínez-Sánchez, J., Cabaleiro, M., Riveiro, B., 2023. Anticipating the collapse of urban infrastructure: a methodology based on Earth Observation and MT-InSAR. Rem. Sens. 15 (15), 3867.
Rucci, A., Ferretti, A., Fumagalli, A., Passera, E., 2023. Large-scale InSAR monitoring: status and challenges. In: EGU General Assembly Conference Abstracts. EGU23-14963.
Ruiz-Armenteros, A.M., Marchamalo-Sacristán, M., Lamas-Fernández, F., Hernández-Cabezudo, Á., Delgado-Blasco, J.M., Bakon, M., , et al.Sousa, J.J., 2023. Utilizing the land monitoring Copernicus program as a regular method for observing dams, large ponds, and surrounding areas. IGARSS 2023, 8010–8013.
Sala, J., Vradi, A., Vöge, M., Raucoules, D., de Michele, M., Martins, J., , et al.Andersen, H.S., 2023. European ground motion service validation: InSAR big data analytics. In: IGARSS 2023, pp. 2394–2397.
Shahbazi, S., Crosetto, M., Barra, A., 2022. Ground deformation analysis using basic products of the Copernicus ground motion service. Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci. 43, 349–354.
Shahbazi, S., Barra, A., Gao, Q., Crosetto, M., 2024. Detection of potential building damage using differential deformation maps. ISPRS J. Photogrammetry Remote Sens. 218, 57–69.
Siegmund, R., Brcic, R., Kotzerke, P., Eineder, M., 2022. The European ground motion service EGMS-processing central Europe with first results on quality and point densities. In: IGARSS 2022, pp. 5105–5108.
Thiéblemont, R., Le Cozannet, G., Raucoules, D., Rohmer, J., Wöppelmann, G., Calkoen, F., Nicholls, R.J., 2023. Contribution of subsidence on relative sea level in Europe. In: EGU General Assembly Conference Abstracts. EGU23-7227.
Tinagli, L., La Rosa, A., Paoli, G., 2024. Spatial and temporal evolution of mining-induced sinkholes in the Gavorrano area (Tuscany, Italy): insights from remote sensing and field data. Geomorphology 453, 109137.
Toma, S.A., Teleagă, D., Poncoş, V., Grozea, C., 2021. Ground motion patterns analysis from the national persistent scatterer deformation map of Romania. IGARSS 2021, 6237–6239.
Tonelli, D., Caspani, V.F., Valentini, A., Rocca, A., Torboli, R., Vitti, A., , et al.Zonta, D., 2023. Interpretation of bridge health monitoring data from satellite InSAR technology. Rem. Sens. 15 (21), 5242.
Torre, D., Galve, J.P., Reyes-Carmona, C., Alfonso-Jorde, D., Ballesteros, D., Menichetti, M., , et al.Azañón, J.M., 2024. Geomorphological assessment as basic complement of InSAR analysis for landslide processes understanding. Landslides 1–20.
Tzampoglou, P., Loupasakis, C., 2023. Hydrogeological hazards in open pit coal mines–investigating triggering mechanisms by validating the European ground motion service product with ground truth data. Water 15 (8), 1474.
Vradi, A., Sala, J., Solari, L., Balasis-Levinsen, J., 2023. Validating the European ground motion service: an assessment of measurement point density. Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci. 48, 247–252.
Wagener, N.J., Kalia, A.C., 2021. Unsupervised learning applied to Persistent Scatterer Interferometry datasets for the characterisation of ground motion patterns in northern Germany. Microwave Rem. Sens.: Data Process. Appl. 11861, 10–17. SPIE.
Wang, Z., 2023. Risk Evaluation of Ground Motion Using Machine Learning Models for the Lombardy Infrastructure. Master Thesis. Politecnico di Milano (Italy).
White Paper (2017). Available online: https://land.copernicus.eu/en/products/european-ground-motion-service/egms-white-paper (accessed on 10 July 2024).
Yang, C.H., Stemmler, C., Müterthies, A., 2023. Ground movement analysis in post-mining city using MTInSAR with help of European ground motion service. ISPRS annals of the Photogrammetry. Rem. Sens. Spatial Inform. Sci. 10, 739–745.
Yishu, Y., 2022. Assessment of Landslides in Sondrio Province, Italy Based on EGMS: European Ground Motion Service. Master Thesis. Politecnico di Milano (Italy).
Zêzere, J.L., Mileu, N., Oliveira, S., Garcia, R., Melo, R., Santos, P., Reis, E., 2024. ADA impact tools user manual. Deliverable D5.2 of the RASTOOL Project. https://rastool.cttc.es.