End-to-end implementation and operation of the European Ground Motion Service (EGMS)

Product User Manual

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ABBREVIATIONS

CLC	CORINE Land Cover
CLMS	Copernicus Land Monitoring Service
CRS	Coordinate Reference System
DEM	Digital Elevation Model
DS	Distributed Scatterer
DInSAR	Differential Interferometric Synthetic Aperture Radar
EEA	European Environment Agency
EGMS	European Ground Motion Service
ETRF2000	European Terrestrial Reference Frame 2000
ETRS89	European Terrestrial Reference System 89
EU	European Union
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
InSAR	Interferometric Synthetic Aperture Radar
IW	Interferometric Wide
LAEA	Lambert Azimuthal Equal Area
LOS	Line-of-Sight
MP	Measurement Point
PS	Persistent Scatterer
PUM	Product User Manual
RD	Related Document
RMSE	Root Mean Square Error
SCE	Copernicus Snow Cover Extent
STD	Standard Deviation
UK	United Kingdom
USCB	Upper Silesian Coal Basin
WAP	Wide Area Processing

1. INTRODUCTION

EGMS - the European Ground Motion Service – serves a wide user community and provides new and unique, calibrated, and harmonised ground deformation products at Pan-European level.

The definition phase for a European Ground Motion Service started in November 2016 and involved 13 Copernicus participating states. In a series of meetings user needs and requirements were consolidated, defined and subsequently specified in a white paper in September 2017. This document formed the basis for the European Commission to implement the EGMS in the framework of Copernicus. A product that is not bound by national borders was requested explicitly by the user community based on their specific needs.

The EGMS adds a new and unique European-wide geospatial layer to the Copernicus Land Monitoring Service (CLMS) portfolio, enabling further value-adding through both public and private sector downstream applications. All 29 countries contributing to Copernicus and the United Kingdom (UK) are covered during the first end-to-end implementation and operation of the service. The newest add-on to the Copernicus Land Monitoring Service comprises continental-scale, homogeneous maps of ground motion in mm-per-year precision measuring ground and infrastructure displacements, including those caused by landslides, subsidence and tectonics. The products are generated by high volume and high performance Interferometric Synthetic Aperture Radar (InSAR)-processing of data from Copernicus' Sentinel-1 Earth observation mission, providing a new and innovative European geospatial dataset from which other value-added products and services can be derived. These are based on project-specific targets and the technical feasibility of both the data and its processing and implementation. A dedicated viewer and downloader give access to the products of EGMS on a free- and open-to-all policy.

The Product User Manual (PUM) gives an overview of the EGMS and provides all relevant information about its products and their potential usage to the user community. The PUM is the primary document that users are recommended to consult before using the product and enables users to understand and efficiently use the EGMS products. The PUM serves various user groups with InSAR knowledge and expertise and includes elements such as use cases and sections dedicated to the general public, experts, and InSAR experts:

- Chapter 2 answers basic questions about the product and its application
- Chapter 3 provides a product description and an introduction to the methodology followed to produce the products
- Chapter 4 presents possible EGMS applications and the strengths & limitations of the products
- Chapter 5 introduces some use cases to the users
- Chapter 6 presents basic terminology and explanations of InSAR
- Chapter 7 provides information about the terms of use
- Chapter 8 presents the EGMS help desk

The PUM will guide the user to the practical use of the various EGMS products, elaborating the utilisation of the data, informs about potential applications, and highlights the limitations of the data.

Interested users that are new to the topic of interferometric ground motion measurement or users with basic knowledge will find high level information about the methodology, the products and their use complemented with practical guidance in this manual. Expert users who require in-depth information or exhaustive theoretical and technical background information should consult the relevant EGMS reference documents listed in Chapter 1.1.

1.1. References and Related Documents

Table 1 Reference Documents

ID	Reference or Related Document	Date	ID	Source or Link/Location
RD1.	Algorithm Theoretical Basis	20/12/2021	EGMS-D3-ALG-SC1-2.0-006	EGMS ORIGINAL Consortium
RD2.	Product User Manual	15/10/2021	EGMS-D4-PUM-SC1-2.0-007	EGMS ORIGINAL Consortium
RD3.	End User Interface Manual	15/10/2021	EGMS-D5-UIM-SC1-2.0-008	EGMS ORIGINAL Consortium
RD4.	Product Description and Format Specification	20/12/2021	EGMS-D6-PDD-SC1-2.0-009	EGMS ORIGINAL Consortium
RD5.	Product Archive and Dissemination system description	20/12/2021	EGMS-D9-PADS-SC1-2.0-011	EGMS ORIGINAL Consortium
RD6.	Quality assurance and control report	03/05/2022	EGMS-D10.4-QCR-SC2--042	EGMS ORIGINAL Consortium
RD7.	User Uptake Plan	15/10/2021	EGMS-D14-UUP-SC1-8.0-016	EGMS ORIGINAL Consortium
RD8.	End User Requirements	15/10/2021	EGMS-D15-URD-SC1-8.0-017	EGMS ORIGINAL Consortium
RD9.	GNSS calibration report	20/12/2021	EGMS-D19.1-GCR-SC1-3.0-031	EGMS ORIGINAL Consortium

2. Frequently Asked Questions

This section gives a first impression of the EGMS and answers basic but important questions concerning its implementation and characteristics.

What is EGMS?

EGMS is an acronym which stands for European Ground Motion Service, the latest component of the Copernicus Land Monitoring Service.

For what period does the service provide data and products?

Baseline from February 2015 to December 2020. Three annual updates are planned for 2021-2023.

Which areas and regions are covered by the data?

Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden & United Kingdom.

Figure 1 Overview of the countries for which data and products are available in the EGMS

What is the methodology or the approach behind the products?

The underlying methodology utilises mature and state-of-the-art techniques of SAR Interferometry specifically multi-interferogram techniques analysing time series of differential full-resolution Sentinel-1-based SAR interferograms to minimise noise related to different sources and to derive displacements over time and average velocities for individual Measurement Points (MPs). Refer to [RD1] to access detailed information on the InSAR approach.

What products are made available to the user?

- *Basic* - provides InSAR displacement data provided in the satellite Line-of-Sight (LOS), with annotated geo-localisation and quality measures per measurement point
- *Calibrated* - is considered the main EGMS product as it serves the needs of most users. It is fundamentally the same as the *Basic* product but enhanced by the InSAR MP displacement values

being referenced to model derived from Global Navigation Satellite System (GNSS) time-series data, thereby making the InSAR measurements absolute

- *Ortho* - exploits the discrete look-angles provided by the *Calibrated* product to derive two further layers; one of purely vertical displacements, the other of purely east-west displacements

A more detailed description of the products can be found in Chapter 3 and [RD4].

How to assess the quality of the individual products?

The quality evaluation of the products and a statistical evaluation of the achieved accuracies etc. are listed in [RD6]. The trustability of the products rely on the effective quality assurance procedures put in place by the EGMS with the implementation of both internal and external validation protocols under the coordination of the European Environment Agency (EEA).

For which users are the products suitable?

The data are freely available to everyone who is interested in ground motion data and can be used for different purposes (see Chapter 5 of this document). Moreover, the products of the EGMS are suitable for users who wants to access precise measurements of ground motion such as e.g. engineers, local authority planners/developers, insurers, etc. An overview of expected users of the Service is provided in [RD7].

Where are the limitations in the data sets and the applicability of the products?

The products of the EGMS can be used in many different ways, but there are also limitations and restrictions in their application and usability, as described in Chapter 4.

What are the minimum requirements for the user to work with EGMS?

Only a device with an Internet connection is required. The data can be accessed directly via laptops, PCs, cell phones or tablets.

How do I get access to the products?

EGMS products are provided via the dedicated Dissemination & Archive System. Through this viewer and download interface, it is possible to both visualise and download the data. A detailed introduction of the portal and explanation of its use can be found in [RD3].

Are the data and products also available for download?

The *Calibrated* product is determined as the main EGMS [RD4] product and therefore of main interest to the common user community. Together with the *Ortho* product the *Calibrated* product can be retrieved in the WebGIS viewer, as well as downloaded from archive, while the *Basic* product is only available via the archive facility of the EGMS dissemination system. The use and functions of the download interface are explained in [RD5].

What are the costs for usage and download?

The land monitoring products and services are made available through the CLMS website on a principle of full, open and free access (ref. Privacy policy and terms of use and Chapter 6). Search and download functionality will be available through the Product Archive, and will require user registration. The authorisation system is based on the EU Login, while registration occur on the main Copernicus land portal.

Where can I get help or support if problems occur or users have questions?

In case of any problems or questions with the EGMS products or viewer, the user can reach the Copernicus Land Monitoring Service helpdesk. More information is given in Chapter 8 of this document.

3. Product Description

The following sections will briefly explain the production workflow and the main characteristics of EGMS products. For a detailed insight into the technical background of the products the interested user should refer to the documents [RD1] and [RD4]. An overview of the EGMS products and their characteristics is shown in Figure 2 below. Each product is presented in Chapters 3.4, 3.5 and 3.6.

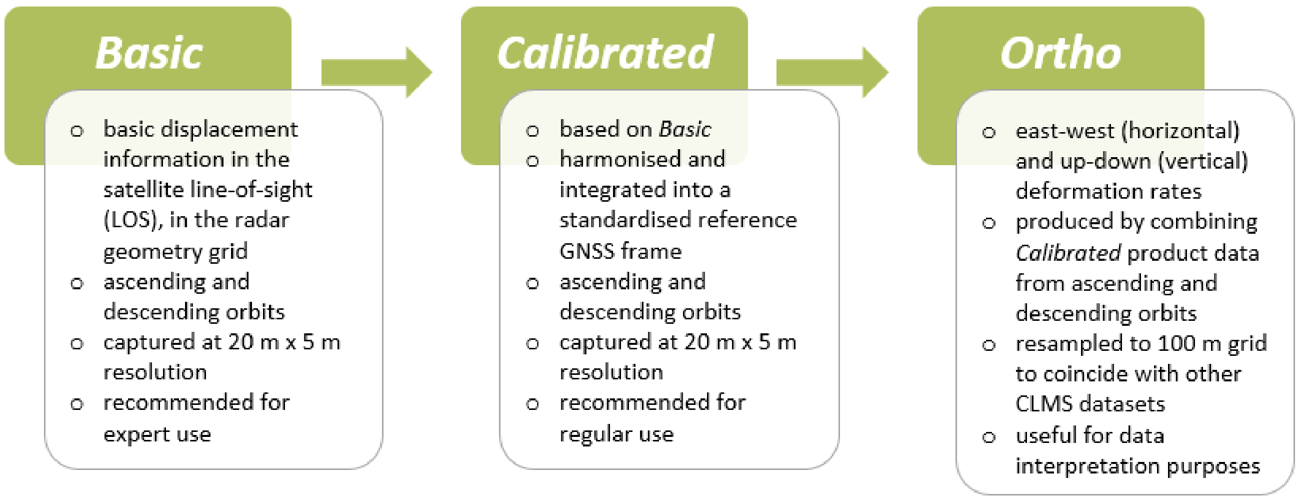


Figure 2 EGMS product overview and the main product characteristics

3.1. Product Quality Control

Each of the EGMS products has undergone an extensive quality control protocol in order to generate the best possible results. For this purpose, a variety of criteria were examined, including in addition to format demands [RD4], e.g. sufficient point density in selected CORINE Land Cover 18 (CLC) classes as well as other requirements listed in Table 2 below followed by a brief description of each quality parameter.

Table 2 EGMS product specifications and requirements

Specifications	*Basic*	*Calibrated*	*Ortho*
3D Geolocation accuracy	<10m	<10m	<10m
Mean velocity STD	0.7 mm/yr	0.7 mm/yr	0.7 mm/yr
Displacement STD	4 mm	8mm	8mm
Measurement Density	CORINE Land Cover 18: Class 1.1.1 > 5000 MP/km² Class 1.1.2 > 1000 MP/km² Class 1.2 > 1000 MP/km² Class 3.3 > 100 MP/km²	The same as *Basic*	Reduced due to resampling

3D Geolocation accuracy

SAR interferometry is able to determine the corrections to be applied to the reference Digital Elevation Model (DEM) in order to reconstruct the 3D position of the observed targets. As for displacement information this correction is relative.

In order to avoid bias in the geolocation, a common procedure was adopted to anchor the to the *a priori* digital elevation model: Copernicus GLO-30 DEM. It was assumed that the elevation of most MPs differ minimally from the reference DEM, and the common mode was removed from the elevation correction before geocoding.

Mean velocity standard deviation (STD)

After compensating atmospheric effects, the mean velocity is calculated for each MP from the time series of displacements based on a linear model with a corresponding estimation of the standard deviation of the mean velocities over the time series. Mean velocity STD is represented in the LOS for *Basic* and *Calibrated* products and along the horizontal (east-west) and vertical (up-down) components for *Ortho* product.

Displacement standard deviation (STD)

The displacement of an MP between the individual acquisition dates is the fundamental information characterizing the behavior of the MPs over time. It is calculated and recorded in a time series for each MP and represented in Line-of-Sight for product levels *Basic* and *Calibrated* and decomposed in vertical and East-West components for *Ortho* products. The corresponding standard deviation of displacements in the time series is estimated and provided in the metadata.

Measurement Density

A comparison of the measurement density for the *Basic* product against different CORINE Land Cover 18 classes represents another significant quality feature to evaluate the products quality. Separate quality checks for the *Calibrated* products are not required since this product is derived from the *Basic* product without affecting the MP position and therefore the MP density.

CLC is a standardised and harmonised land cover and land use dataset across Europe. Since the beginning of the 1990s, the entire European land surface has been classified into a variety of land use classes, regularly updated and made freely available to the user. Further information can be found in [RD1] and at: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018

EGMS products are validated high quality products. That means MPs are reliable and can even be assessed by annotated quality indicators, such as temporal coherence and RMSE. Even though the density of points might decrease over specific land cover classes or specific structures, all MPs found in EGMS products in these areas are representative and can be regarded as similar to “ground truth”.

3.2. Production Methodology

The overall objective of EGMS is to provide Pan-European, consistent and harmonised, ground deformation measurements derived from the complete satellite data archive of the European Sentinel-1 mission and generated with mature and state-of-the-art interferometric techniques. Using all available and relevant Sentinel-1 acquisitions with precise orbits, data processing is performed on defined processing units to achieve maximum efficiency, accuracy and precision of the deformation measurements [RD1].

The analysis is covering the period from February 2015 to December 2020 in the first baseline analysis, with three consecutive annual updates that are foreseen.

Generation of the EGMS baseline and updates will follow the basic stages logic symbolised by Figure 3 below. The reader will find detailed information about data processing in [RD1].

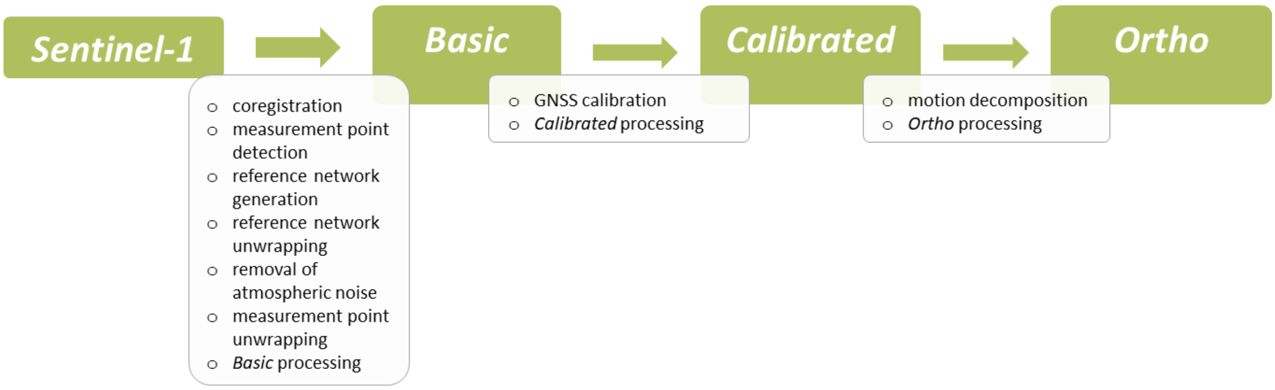


Figure 3 EGMS product flow for baseline analysis

Due to an accurate calibration process EGMS *Calibrated* represents a unique reference dataset, available at European level and comparable across national borders [RD1]. To achieve this, thousands of individual overlapping *Basic* products were harmonised and integrated into a standardised reference frame by using a velocity model derived from GNSS network measurements as an absolute referencing of large-scale deformation processes [RD9].

3.3. Satellite Data Input

EGMS utilises a vast data basis of radar images comprising Level-1 SLC data products acquired by the two twin satellites Sentinel-1A and Sentinel-1B. Each satellite platform carries a Synthetic Aperture Radar operating at C-band, i.e., a wavelength of approx. 5.5 cm (5.405 GHz). In the Interferometric Wide (IW) swath mode, which is the main acquisition mode over land, data is acquired at a spatial resolution of 20 m in azimuth and 5 m in range (single look). IW mode acquires three sub-swaths per image, with each sub-swath composed of a series of 9 bursts stacked in the azimuth direction. Each burst is approximately 80 Km (range) per 20 Km (azimuth), resulting in an overall 250 Km by 180 km image.

Snow-cover can compromise the quality of InSAR results by increasing the noise of time series. Snow-cover is a factor either seasonally or quasi-permanently at high latitudes and over mountain regions, e.g. the Alps, parts of Scandinavia, Iceland. To produce reliable InSAR coverage and filter out images with extensive snow coverage, it is sometimes required to use prior information such as the Copernicus Snow Cover Extent (SCE) product. For example, time series over Norway will contain only images acquired between May/June and October.

The availability of an earthquake catalogue of European events can allow the selection of appropriate processing strategies to deal with such events. In particular, the processing and quality parameters have been adapted in areas where strong earthquakes have been recorded (e.g. central Italy earthquake sequence in 2016-2017). More information is available in [RD1].

3.4. The EGMS *Basic* product

<u>Product overview:</u>

- The deformation data are accurate, reliable and representative, nevertheless interpretation of these is feasible for local phenomena only due to the representation of displacement information in the satellite LOS.

- Measurement point density is high, especially in urban areas. The number of MPs can be reduced where large areas are to be analysed. This can be achieved using Geographic Information System (GIS) operations on product attributes (e.g. coherence threshold) without degrading quality.
- In terms of time series the *Basic* products are temporally sampled at a 6 day cycle using two satellites (Sentinel-1A and 1B) from April 2016 onwards and 12 days before Apr. 2016. From December 2021 the temporal sampling is again 12 days due to the loss of contact with Sentinel-1B.

The EGMS *Basic* product provides InSAR displacement data in the satellite LOS, with annotated geolocalisation and quality measures per measurement point. Satellite LOS means that measurements are projected along the imaginary line which connects the satellite to the target.

The product is provided as a 2D map of InSAR measurement points, colour-coded by average velocity. A time series plot is associated with each point.

Significantly, *Basic* products are spatially referenced to a virtual reference point, whose time series is derived by a statistical analysis of the dataset. As a consequence, the provided measurements are meaningful just considering the processed area. It is not possible to compare deformations from adjacent areas belonging to different tiles of the same product. The time series are temporally referenced to the value of the deformation model at time T_0=0. Please refer to [RD1] for a description of the reference point rationale.

EGMS *Basic* is provided as two discrete datasets; one made from the SAR data acquired orthogonal to the satellite ascending trajectory (south to north), the other from data acquired orthogonal to the descending trajectory (north to south).

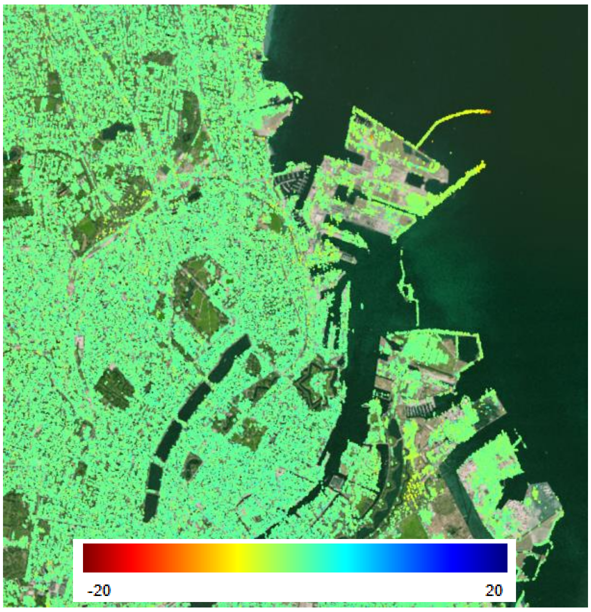


Figure 4 Example of EGMS *Basic* product (City of Copenhagen - Denmark)

The product itself can be regarded by the user as a base product that provides accurate deformation information at a high level of detail or maximum measurement density. It is considered for expert usage and shall be evaluated with appropriate expertise, tools and potentially auxiliary data.

3.5. The EGMS *Calibrated* product

Product overview:

- Analogous to EGMS *Basic*, all products are generated at the highest possible spatial resolution and contain the full Line-of-Sight deformation history.
- *Calibrated* products comprise displacement time series and metadata.
- Displacement values of *Basic* and *Calibrated* time series differ by the magnitude of the components compensated by the calibration process. Differences represent the effect of low pass trends (e.g. glacial rebound) on the MP deformation.
- Prior to April 2016 the temporal sampling is every 12 days. From April 2016 onwards the temporal sampling is every 6 days. From December 2021 the temporal sampling is again 12 days due to the loss of contact with Sentinel-1B.
- Differently from EGMS *Basic*, deformation measurements are calibrated, therefore absolutely referenced and consistent across space and time.
- Analysis of deformation data in areas with events such as earthquakes need special attention, since single measurements or single products could eventually render an induced deformation phenomenon inappropriately, e.g. due to a heavy displacement. A comparison of multiple *Basic* or *Calibrated* products of different acquisition geometries is mandatory in that case. A record of significant earthquake events affecting various GNSS networks is systematically maintained by the GNSS community.

The EGMS *Calibrated* product is considered the main EGMS product as it serves the needs of most users. It is fundamentally the same as the *Basic* product but enhanced by the InSAR MP displacement values being referenced to model derived from GNSS time-series data, thereby making the InSAR measurements **absolute** (with reference to an Earth centred reference frame). *Calibrated* products overcome the intrinsic limits of the *Basic* ones, hence making it possible to compare deformations from adjacent areas belonging to different products of the same level. The harmonization process makes all EGMS *Calibrated* components equivalent and comparable at common spatial (above 50 km) and temporal (mean velocity) scales by removing low-pass components e.g. tectonically induced trends. EGMS *Calibrated* combines the features of the underlying *Basic* product with the accuracy and consistency of existing geodetic networks. Therefore, the technical characteristics of EGMS *Basic* are valid for EGMS *Calibrated* as well.

As with *Basic* products, the *Calibrated* product is provided as two discrete datasets, one in ascending geometry, the other in descending geometry.

Some isolated islands and the oversea departments and regions of France may not have GNSS data available. For these areas, *Calibrated* products are produced by harmonizing *Basic* products with respect to each other, and then adjusting the mean ground velocity to zero. Measurements of any displacements on such islands are not referenced against the GNSS-derived datum, but to a local reference point.

Compared to the *Basic* product shown on the left side of Figure 5, a change in the velocity values due to the inclusion of the GNSS signal is notable by the change in colour of multiple MPs of the *Calibrated* product on the right side. The reason for this is a glacial rebound by ~+2 mm/yr at city of Kotka.

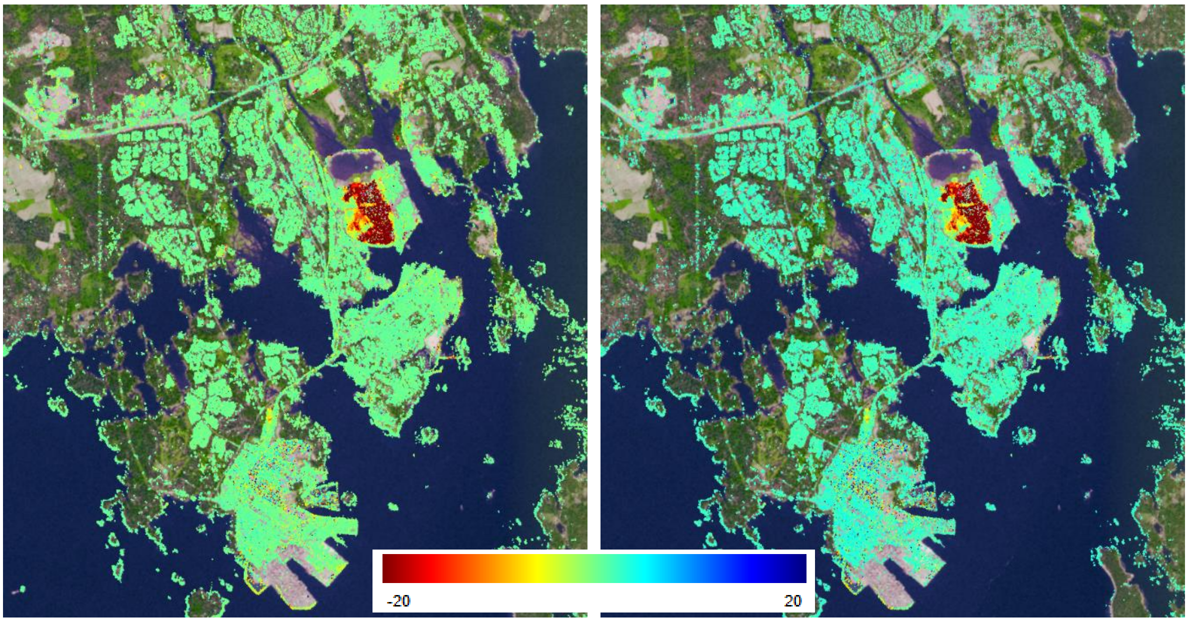


Figure 5 Comparison of *Basic* and *Calibrated* product (City of Kotka - Finland)

3.6. The EGMS *Ortho* product

Product overview:

- The data product is provided as two separate data layers containing respectively purely vertical and purely east-west displacements.
- It's represented in 100 m x 100 m output resolution cells to provide robustness plus reliability and match other existing CLMS datasets.
- Allows an analysis of displacement and deformation phenomena of the earth surface independent of the radar look geometry.
- The horizontal component of the *Ortho* product reflects displacements in just east-west direction due to the SAR acquisition geometry along a polar orbit which leads to a lesser sensitivity of the measurement of motion in north-south direction. EGMS processing compensates the north-south component of motion through the calibration with GNSS data.

EGMS *Ortho*, see an example in Figure 6, is a unique geospatial dataset of absolute displacement measurements, anchored to a common GNSS framework. The product exploits the discrete look-angles provided by the *Calibrated* product to derive two further layers; one of purely vertical displacements, the other of purely east-west displacements. Both layers are resampled to a 100 m grid comparable with other CLMS products. Vertical and east-west displacement components can be estimated taking advantage of the prior information coming from GNSS data. Refer to RD1 for more details about the *Ortho* products generation process.

The main benefit of *Ortho* products is ease of understanding to those new to InSAR as the data-acquisition geometry need not be considered. However, such *decomposed* data can still prove valuable even to InSAR experts when considering phenomena that might include non-vertical displacements such as those relating to tectonics or landslides.

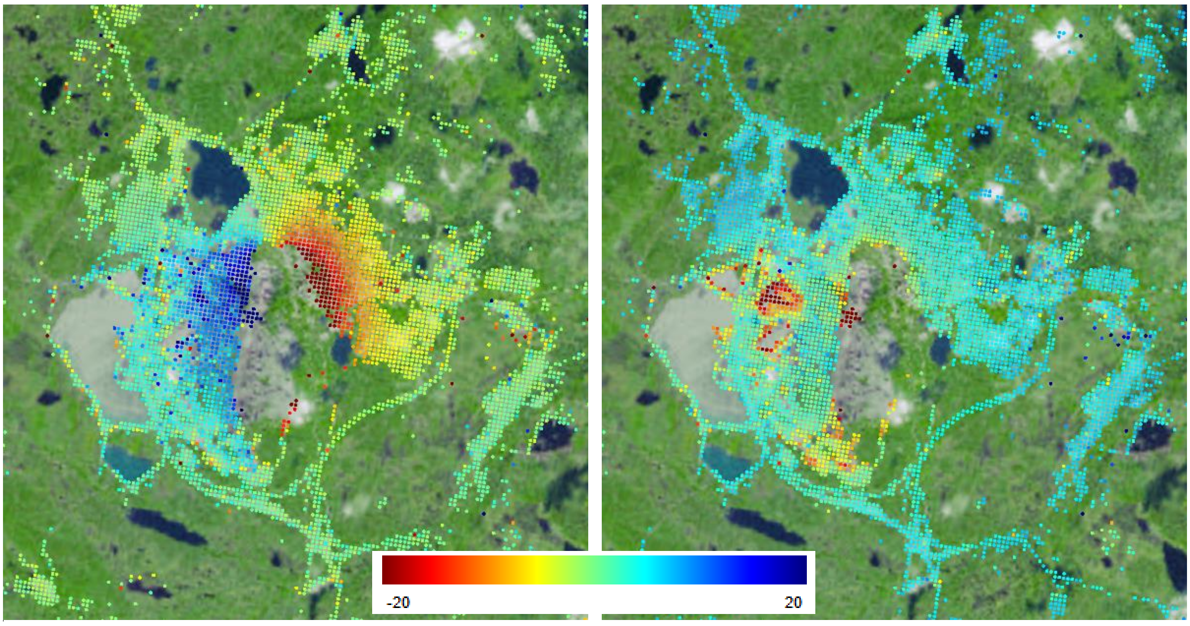


Figure 6 Example of an *Ortho* product – horizontal / East-West (left) and vertical / Up-Down (right) (City of Kiruna - Sweden)

The information given by the *Ortho* product is easier to understand by the end-user compared to *Basic* or *Calibrated*, due to the representation of surface motion and displacement in a standard coordinate system – independent of the inherent satellite geometry. *Ortho* products are consistent across all tracks and, in addition, the east-west and up-down velocities can be recombined to produce a true movement direction vector within an east-west or vertical plane, which is essential to understand specific types of real world deformation phenomena, e.g. landslides. *Ortho* will be the product the users will see first when opening the EGMS viewer.

Peculiarities of EGMS *Ortho*:

- **Spatial sampling:** The ascending and descending *Calibrated* products that make the *Ortho* product have different acquisition geometries, meaning that the distribution of MPs is not identical between the two datasets. To ensure that both datasets represent the same area of ground, the data is averaged to a common 100 m grid, this particular spacing chosen to coincide with other CLMS services and it is a good compromise between resolution and spatial coverage of the database.

- **Coverage:** To make the *Ortho* product, *both* ascending *and* descending geometry *Calibrated* products are needed. In some areas of high topographic relief, the usual geometric artefacts associated with radar remote sensing (layover, foreshortening and shadow – see chapter 6) prevent 100% coverage. In such areas, there are no EGMS *Ortho* measurements.

- **Not full-3D:** Each Sentinel-1 satellite is near-polar-orbiting with a side-looking radar. The echoes of the SAR instrument consequently become less sensitive as the direction of any ground displacement approaches that of the satellite flightpath, i.e., north-south. Importantly, any ground movements in these directions will not be measured directly by InSAR but reintroduced from the GNSS data (please refer to [RD1]). In fact, north-south displacement components are not available for any MP, since they are estimated from GNSS data, characterized by a much lower spatial resolution than InSAR measurements. Therefore, vertical, and east-west components are estimated thanks to a spatial interpolation of the information available. This approach, however, does not introduce a significant bias in the measurements, apart from area affected by strong spatial variations of north-south displacements.

- **Temporal sampling:** In general, the temporal sampling of the satellite tracks contributing to the *Ortho* product is not aligned. This happens because *Calibrated* products, from which *Ortho* are derived, exhibit acquisition patterns shifted in times on a track basis. Moreover, there may be holes in the datasets (e.g., missed acquisition, especially in 2015). In order to define a common temporal grid, for the baseline all time-series will start on January 2016 and end on December 2021, with regular six-day temporal sampling with origin on 3-April-2014 (launch date of S1A). A regular sampling will be maintained whenever possible, even if, in correspondence of huge gaps in the *Calibrated* products time series used to generate the *Ortho* level, customized solutions may be adopted. Please refer to document [RD1] for further details on *Ortho* product generation.

3.7. Important Product Attributes

All available products are provided together with a variety of attributes. This information is indispensable for the evaluation of the quality and uncertainties of the EGMS products and assists the user in understanding and analysing the products. All essential attributes are shown below together with a practical explanation of their meaning and use. For a detailed description of all attributes per product the reader should refer to [RD4].

MP Type

Provides the user with information on whether the ground motion was derived from a persistent / point scatterer or a distributed scatterer extending to the area provided in this attribute in m^2 (0 means point-like scatterer, > 0 distributed scatterer respective area of the DS).

This attribute is available for *Basic* and *Calibrated* products.

Temporal Coherence

Indicates the stability of the reflection characteristics associated with the MP over the time series. It therefore represents a measure of quality or reliability of the measurement. For the EGMS *Ortho* product, the temporal coherence results from the average coherence of the input MPs of one grid cell. In general coherence is calculated in terms of the correlation coefficient given in the range 0 to 1. High coherence with values close to 1 indicates high stability and reliability, whereas stability and reliability degenerates with coherence values lower than 0.5. Pixels with low coherence values are usually excluded from data processing. The user can regard this attribute as a quality measure allowing the user to filter the products according to the coherence values, e.g., analysing and visualising only MPs with a coherence of ≥ 0.8.

This attribute is available for *Basic* and *Calibrated* products.

RMSE (Root Mean Square Error)

Residual error or variation of the displacement over the time series in *mm*. It represents a measure of the precision of the displacement.

This attribute is available for *Basic*, *Calibrated* and *Ortho* products.

Mean Velocity

It describes the mean velocity of the MP without acceleration or seasonal trends measured in the temporal frame of the time series. Velocity is calculated along in the LOS for EGMS *Basic* and *Calibrated*; this means that the motion can realise towards the satellite or away from it. Therefore, positive values for mean velocity indicate a movement towards (e.g. uplift) and negative values a movement away (e.g. subsidence) from the sensor (see Figure 7). The LOS velocity for EGMS *Ortho* represents the motion in the vertical or east-west directions.

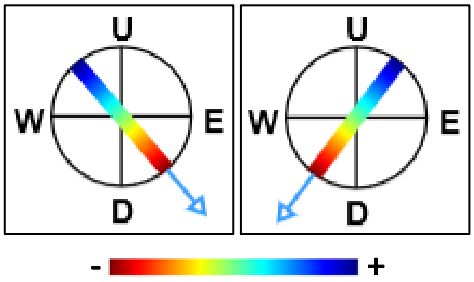


Figure 7 Representation if Line-of-Sight displacement (left: ascending & right: descending)

This attribute is available for *Basic*, *Calibrated* and *Ortho* products.

Seasonality

Characterises the magnitude of seasonal displacement over the period of one year. The seasonal oscillation is a sinusoidal signal in the displacement time series that results from cyclic processes over the year. It can be related to e.g. rainfalls or temperature variations between winter and summer. The magnitude of this oscillation, recorded here for an MP, is dependent on the characteristics of the surface or the object and its response to temperature variation. In realistic scenarios values for the seasonality of an MP are found in the range between 5 mm and 10 mm.

Available for *Basic*, *Calibrated* and *Ortho* product.

Time-series

This attribute describes the displacement or ground deformation of an MP related to the primary image as the zero-point for each SAR acquisition date. A record of the complete displacement history for each MP over the temporal sampling period is provided here. From the displacement history, all effects over the time span, e.g. seasonal signal, linear trend or acceleration from a given date on, can be visualised and statistically derived. The data itself is temporally referenced to the primary acquisition in the stack and spatially referenced to a reference point (*Basic*), or the reference GNSS network (*Calibrated* and *Ortho*). The data record can be utilised to describe or separate effects over time. The mean velocity of an MP or an ensemble of MPs gives a linear trend of the surface motion and lets the user identify spatial patterns of similar trends and the strength of surface motion. Superimposed higher order effects, e.g. acceleration (2nd order) or a seasonal (periodic) signal in the time series can then be separated.

Available for *Basic*, *Calibrated* and *Ortho* product.

4. HOW BEST TO USE EGMS PRODUCTS

All EGMS products serve a variety of applications. Basically, all of them deal with dynamic processes versus nearly stable conditions of the earth's surface on different scales. The EGMS represents a new and unique source of data, valid as ***reference information*** since:

- Calibration of displacement data to a standard geodetic reference frame results in a harmonised and consistent data product.
- Even on a Pan-European scale data are coherent with a comparably dense MP distribution for similar surface types, consistent across European regions and national borders.
- Provision of a densified Pan-European GNSS data model as a by-product of EGMS ensuring the traceability of deformation patterns and separability of superimposed deformation signals. The GNSS model is a value added product compiling available geodetic networks, e.g., EUREF, NGL, etc.
- EGMS provides validated products that undergo in-depth and independent validation. For details of the validation concept, see https://land.copernicus.eu/user-corner/technical-library/validation-approach-of-the-egms-product-portfolio. The external validation process will be completed at the end of 2022.

According to these features users are able to reference their individual deformation studies or investigation to EGMS, validate their processing results or even compare in-situ findings with EGMS information and products.

4.1. Fields of application of EGMS products

Besides the characterisation as a baseline dataset, EGMS products provide a unique data source as is for the user community. Since all products are validated the information can be used for the analysis of dynamic phenomena and their evolution, e.g. subsidence patterns due to changes in groundwater production, or for estimating ongoing deformation of single targets e.g. infrastructures. For an analysis of the spatial features of surface motion, such as areas or clusters of points with comparable motion trends, deformation patterns can be identified according to the **mean velocity** or the seasonal components. This allows any user to indicate areas with significant motion or displacement of interest and therefore trigger further evaluation of the indicated phenomenon by analysing the complete temporal history of the MPs, utilising when needed other high/very high resolution products or other sources of displacement data (e.g. in situ instruments).

Thanks to the relatively long **time series of terrain displacement** recordings in all EGMS products, temporal characteristics and patterns, such as linear subsidence, or specific phenomena, such as accelerated subsidence linked to underground construction works, are detectable. The accessibility of different temporal displacements allows the user to address specific problems, such as geohazards studies by tracing the evolution of the deformation or projecting trend analyses based on the displacement history.

In the following, a brief overview of the areas of application is presented, for which the products from the EGMS are suitable on different levels for investigations and where the specific main purpose to the user is. An estimate of the potential user groups interested in the EGMS products for each application is given in the Annex.

Suitable	
Possibly Suitable	
Partly Suitable	
Not Suitable	

Geohazards

Subsidence

Natural Subsidence
- Consolidation
- Suberosion in karst and salt domes

Anthropogenic
- Groundwater fluctuations & exploitation
- Urbanization

Basic
Calibrated
Ortho

The type, characteristics and intensity of ground movements are closely related to geological and hydrogeological conditions. The interpretation of the EGMS data depends on the scale, quality and completeness of ancillary data and measurements. For example, ground water time series can be compared to EGMS time series to link groundwater exploitation and motion recorded.

Landslides

- Identification of potentially risky and/or critical areas
- Mapping of new landslides or other types of slope dynamics
- Monitoring of state of activity
- Improved natural hazard risk mapping for urban planning and civil protection purpose
- Update landslide database, catalogues and geological maps

Basic
Calibrated
Ortho

Double orbit analysis, decomposition of vertical and horizontal displacement and Integration of DEM-based topographic analysis are necessary. Major events (landslide collapses) often result in low coherence and might not be detected. Not all landslide types can be measured, and the motion rate must be smaller than 2 mm/day. The MP coverage on the landslide body depends on land cover and geometric effects.

Tectonics

- Identification of large area tectonic motion

Basic
Calibrated
Ortho

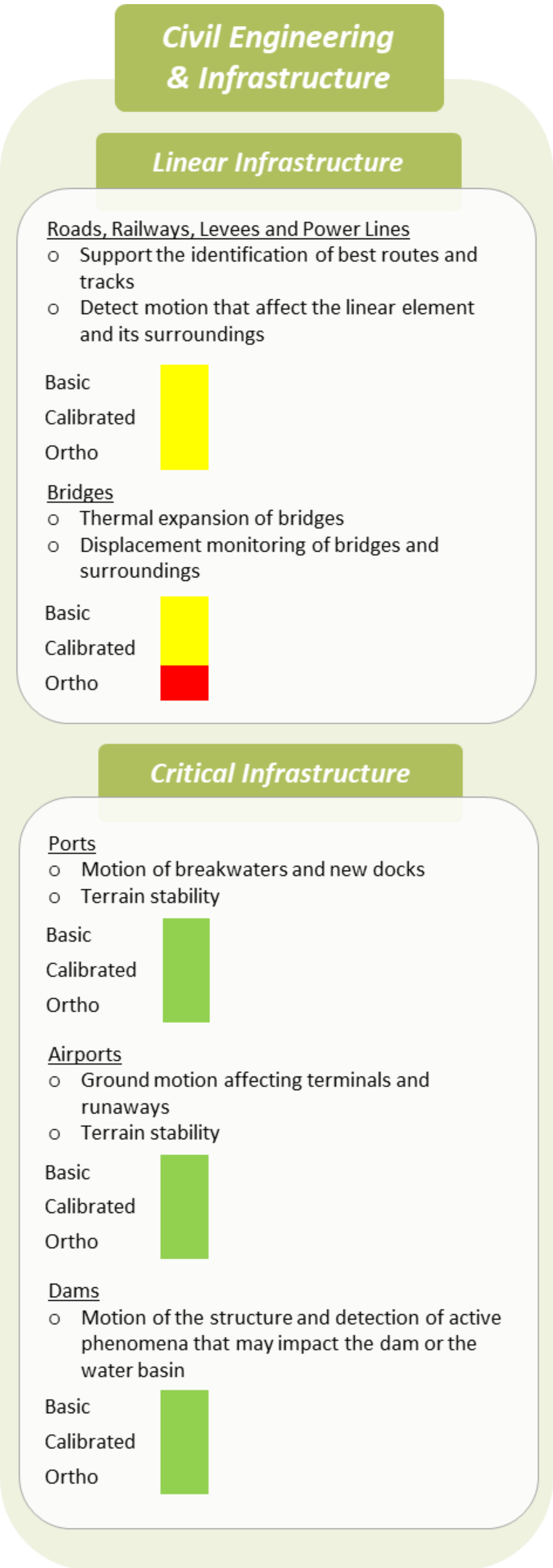
Suitability to monitor wide area ground movements, strain at faults, and support to identify and quantify differential movement across tectonic boundaries and therefore improving understanding of large-scale tectonic deformation. The EGMS products cannot be used for forecasting earthquakes.

Volcanoes

- Monitoring of volcanoes (e.g. inflation/ deflation)

Basic
Calibrated
Ortho

Baseline data useful for assessing the status of a volcanic area. Suitability to detect deformation of the volcanic edifice prior to an eruption or after an eruption. EGMS data cannot be used as sin-eruption tools or to monitor active lava flows.



EGMS products are a baseline for the investigation of active movements along linear infrastructure and in their surroundings. EGMS can offer an overview of active phenomena that may endanger and damage an infrastructure. They can also offer information about the stability of single elements through few but reliable MPs. EGMS is not providing data for structural investigations and may be not accurate enough for specific and single elements appraisals. Detailed scale analysis may require the processing of very high resolution images. The suitability of the *Ortho* product depends on the type of analysis. If individual elements are under consideration, it is not suitable, but if, in turn, the movement in the area around these elements is investigated, the *Ortho* product could possibly be suitable as well.

The detectability of ground movements is dependent on the size of the single structure and on the presence of nearby constructions which may interfere the receiving signal. The EGMS will provide a baseline and will facilitate the monitoring of urban areas and critical infrastructure like nuclear power plants, chemical storage or refineries or water gas and power distribution facilities. For example they can be used to detect subsidence affecting airport runways or breakwaters in ports. EGMS data may be used to assess the presence of differential displacements but are not a tool for detailed structural investigations. Point density and accuracy may not be enough for specific users and applications.

The EGMS products are excellent to monitor the surroundings of a critical infrastructure. For example, they can be profitably used to detect active landslides that may interfere with dam basins.

Civil Engineering & Infrastructure

Buildings

- Monitoring of the structure and surroundings
- Possible detection of differential displacement
- Terrain stability

Basic
Calibrated
Ortho

Engineering

- Monitoring of dewatering processes
- Tunneling & earthworks
- Monitoring of the structure and surroundings
- Possible detection of differential displacement
- Terrain stability

Basic
Calibrated
Ortho

The EGMS products can be used to detect the effects of engineering works of various type, such as dewatering for foundation excavation or tunnelling.

Time series can be used to evaluate the effect of engineering works over time and as deferred time monitoring tools.

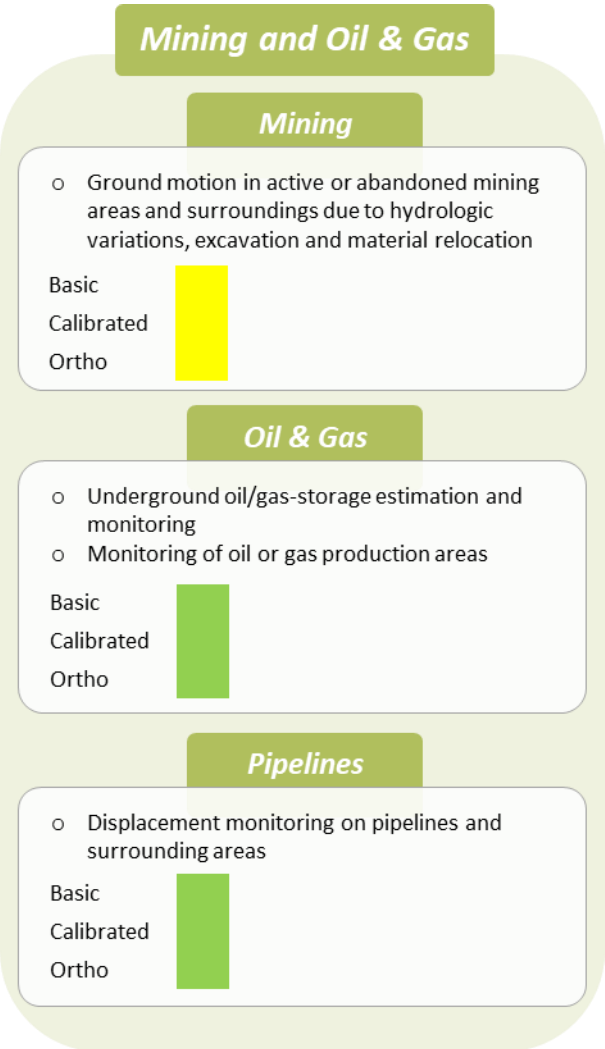
The EGMS data cannot follow in real time any kind of engineering operation and has limitations in vegetated areas and may not be accurate enough for the structural assessment of single structures affected by the motion induced by engineering work.

Cultural Heritage

- Monitoring and mapping ground motion in cultural heritage areas and UNESCO sites

Basic
Calibrated
Ortho

Suitability to detect ground motion in cultural heritage sites and provide valuable information for heritage management and protection. The EGMS is optimized for urban heritages .



Suitability to detect ground motion induced by surface and sub-surface mining in active or abondoned mining sites. For example, subsidence due to subsurface coal excavation or assessment of residual motion in abandoned mining sites. Measurement points coverage is highly dependent on coherence loss for frequent surface changes (e.g. in open pit mines) or strong non-linear motion.

Suitability to detect ground movements related to gas and oil extraction and gas storage. Potential integration of the EGMS data in reservoir models.

Pipeline damage and leaking are usually caused as a result of ground movement. The EGMS gives valuable information about active movements along the track and in the surroundings of a pipeline. For subsurface pipelines the trajectory of the pipeline has to be known for association of encountered MP. EGMS is not suitable for investigating the structural integrity of the pipeline.

4.2. Limitations

The previous sections provided an overview of the applicability and the potential of the EGMS data for a wide variety of applications. Nevertheless, limitations exist for EGMS products which are inherent for interferometric techniques but essential to know for the user and need to be regarded before starting an analysis of the data, thereby preventing interested users new to the topic from incorrect or inadequate use. Main limitations result from:

Natural conditions of the earth's surface

On certain surfaces that are particularly characterised by a changeable texture or by the absence of strong reflectors, no information can be obtained since no MPs are detected, namely

- **Topography**: Slope and orientation of a mountain flank directly affect the radar imaging geometry that way that, at an extreme, no information can be retrieved in certain areas that are aligned to the SAR look direction (shadow or layover areas) and lead to a different coverage of MPs between orbits. This impact also the detectability of the motion between orbits.
- **Hydrosphere**: in general PS-Interferometry is not applicable here, due to surface motion (wind and waves). Therefore, applications like monitoring of water (rivers, lakes, and ocean) or measurement of surface motion, currents and direct sea level changes are not feasible.
- **Vegetation & crops**: Vegetation is characterised by its growth, changing appearance throughout the seasons or vegetation cycle. Besides the diffuse backscattering mechanism of vegetation layers, changes of the geometric state of vegetation (plant growth, motion due to wind, harvest, foliage, falling leaves, etc.) prevent the applicability of EGMS products in those areas. Applications such as measurement of plant/tree growth, terrain deformation monitoring under forest areas or grassland are not realistic. Topography often determines the vegetation state of the surface, e.g. appearing vegetation areas in increasing terrain heights and steepness of low mountain ranges in Europe are limited for EGMS due to a lack of detectable MPs. In higher and steeper regions, such as high alpine terrain, cragged and rocky features are dominant and the number of natural reflectors increases; therefore, there is a potential increase in MP density.
- **Coastal areas**: The coastal areas should be treated with care. Deformation measurements over temporally flooded areas, e.g. the tidal flat system of the Wadden Sea, is not feasible even though falling dry for a period of hours. In terms of sea level rise the landward subsidence rates measured by EGMS products along the coast are a significant information source for climate change studies or risk grading.
- **Snow cover**: A layer of snow is a disturbing entity for the applied processing technique and therefore periods with seasonal or perpetual snow cover are excluded in the time series. In addition to excluding snow from the input data used for the products, changing terrain elevations due to snow cover would also make long-term monitoring impossible. Therefore, the products cannot be used for snow- or ice-specific applications and analyses and are outside the scope of EGMS.

Methodological Constraints

Besides ground coverage, methodological constraints due to the sampling design, the processing concept or the acquisition system of the satellite set limitations on the use of the generated products. In brief limitations are due to

- Even in areas where no measurement points appear in the EGMS products, real or natural ground movements can still be present, which were not detected by the processing algorithm. This results from the inherent requirement of a coherent measurement in processing, excluding certain natural surface types (e.g. forest) where points cannot be detected.

- With the progress of EGMS over the upcoming years new reflectors and corner reflectors or targets will appear throughout the production area, e.g. due to finalised construction works. These reflectors will not appear as an MP in the EGMS products immediately with each new Sentinel-1 acquisition, due to the MP selection technique in PSI processing and is therefore depending on the updating approach of EGMS.
- Small scale and fast moving objects such as vehicles, trains, etc. are not sampled with the time series, excluded and not regarded in the process and in general not in the scope of the technique in use.
- The processing technique utilises an existing time series of past acquisitions and provides therefore a record of the displacement history of according MPs up to a certain date. It allows the user to backtrack deformation events or phenomena prior to the latest acquisition data of the product. Predictions are not feasible and out of scope of EGMS and its products itself. An integration of these products in modelling or analysis exercises, e.g. in volcanology observations needs to be performed by users with specific expertise and appropriate auxiliary data.
- The geolocation accuracy is quantified with a threshold value of <10m, see Table 2. Therefore, the localisation of a scatterer (determining the measurement point) is only possible in that range, so that an exact relation of the MP and the real reflecting object may not always be possible for single points. Instead, MPs in close physical proximity of an object can be related according to their spatial distribution and context. Considering the radar imaging geometry plus geolocation accuracy the topologic structure of the reflectors rendering the real object remains in the product. E.g. MPs detected along a series of lamp poles or over multiple window elements over a multi-storey façade of a building might appear shifted, but equidistantly distributed, in a PSI product.
- Even though the north-south component of motion is modelled and retrieved from GNSS for calibration, it is assumed that this component does not exist for decomposition of *Ortho* information. Since polar orbits are used with orthogonal look (aligned predominantly in east-west) direction, the technique is sensitive to motion parallel to east-west direction while the north-south direction is not determined.
- In general, the temporal sampling of the satellite tracks contributing to the *Ortho* product is not aligned. This happens because *Calibrated* products, from which the *Ortho* product is derived, exhibit acquisition patterns shifted in times on a track basis. Moreover, there may be holes in the datasets (e.g., missed acquisition, especially in 2015).
- With the failure in Sentinel-1Bs power system late December 2021 and subsequent fruitless recovery actions the Sentinel-1 system was and is still not able to acquire data in its full capacity and according to the acquisition plan, reducing the repetition rate over Europe from 6 days (with two satellites) to 12 days (with one satellite). The baseline product that covers the timeframe between 2015 and Dec 2020 is therefore not affected, the same holds for the first update until Dec 2021 where only few acquisitions are missing at the end of the time series. Updates utilising data after Dec 2021 can still be processed with the lower repetition rate, accounting for a lower coherence between the acquisitions. Finally, the period of reduced capacity (operating Sentinel-1A only) needs to be determined and the update method to be adapted to this restriction (length of input time series vs. lower repetition) – plus provision of a quantification of the effect on measurement accuracy and point density in the update products.
- In areas with strong or significant non-linear motion, measurements could be inaccurate and MP density decreased due to the loss of points in those areas. These effects are caused by a loss of coherence and discrepancies between real deformation and the (non-linear) motion model applied during processing. Therefore, maximum deformation rates for an area can be derived to provide an indication for the reliability of the measurements.

5. USE CASES

The products made available within EGMS have a wide range of possible applications in the most diverse fields of application. These use cases illustrate and describe classical examples of InSAR usage to facilitate the work of future EGMS users.

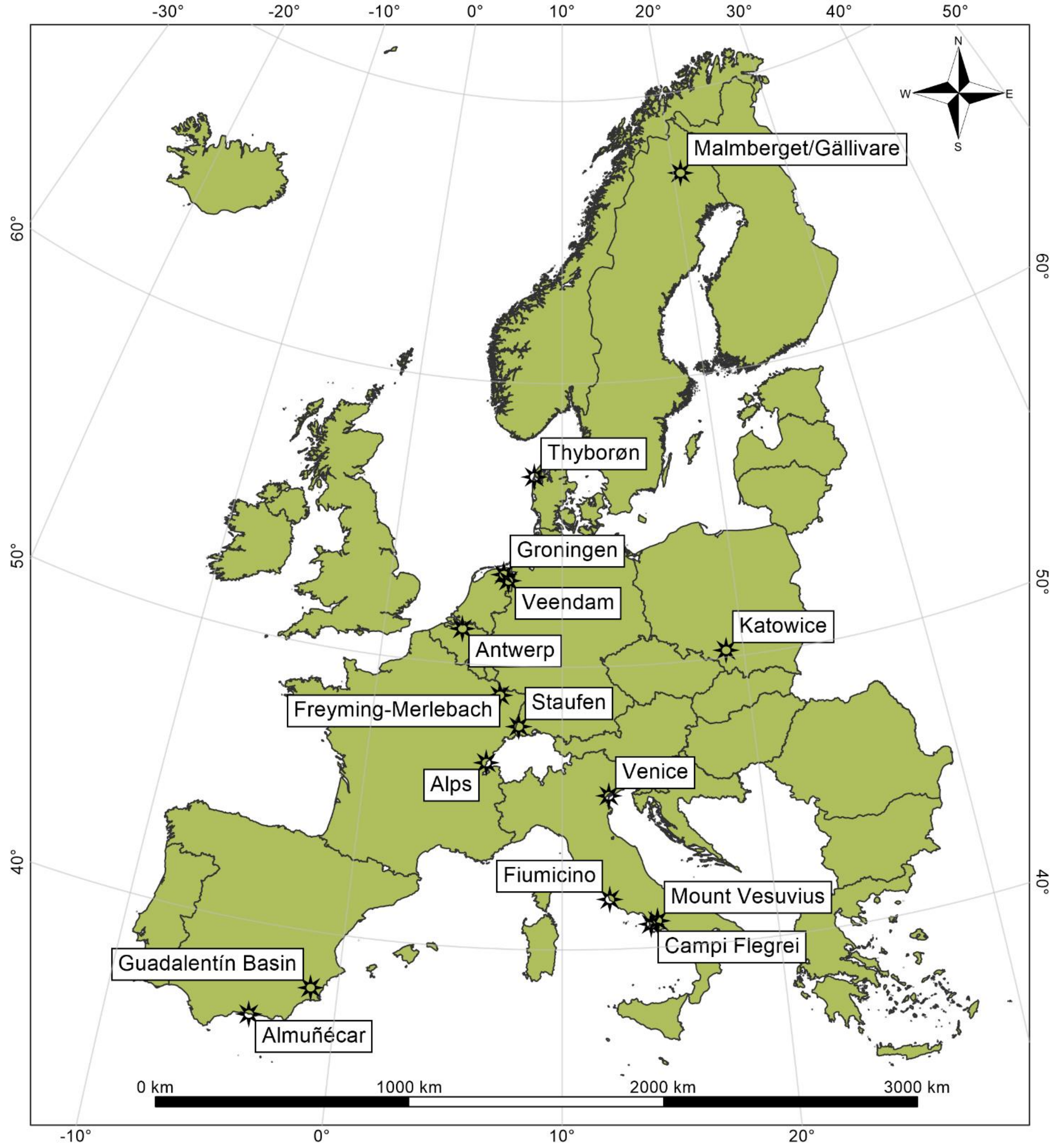


Figure 8 Overview map of the use cases locations presented in the following sections

5.1. Geohazards

5.1.1. Landslides

In the last decades, a significant increase in terms of quantity and magnitude of landslide events has been reported that caused damage or threatened society.

Available landslide inventories are a more or less accurate representation of the past landslide locations built upon spatially incomplete and positional inaccurate landslide information (Lima et al. 2021). Additional information on the spatial accuracy of events, their temporal occurrence and mapping uncertainties can further enhance the usability of inventory data. In traditional usage, the term landslide has been used to cover almost all forms of mass movement of rocks and regolith at the Earth's surface. Landslides occur when the slope (or a portion of it) undergoes some processes that change its condition from stable to unstable.

InSAR analysis at regional scale has been proven to be an efficient complementary tool to identify active slopes, which are probably potential landslides. InSAR data permits to determine factors like movement velocity, acceleration, age of movement (within the period covered by the InSAR time series) and geographic location. However, it shall be emphasised that conclusive classification of landslide types also requires knowledge or auxiliary information such as geological conditions, topographic information (slope, convexity, slope height, aspect, among others), climate, water saturation and cause of the movement. Especially the integration of ground displacement information of slopes and their temporal component are increasing the quality of landslide susceptibility maps and can be used also as source to monitor instable slopes.

Regarding the topographic or geometric fact that most of the landslides are characterised by vertical and horizontal motion, the combined usage of *Basic*/*Calibrated* and *Ortho* products enhance the detection accuracy and precision.

According to studies in the French Alps and the addressed landslides inventory EGMS products provide new information source to analyse and interpret landslides. For the studied areas in the French Alps, EGMS data show a consistent spatial characteristics and localisation with velocities in down direction between 5 mm/yr and 18 mm/yr. The horizontal motion of the landslides is in the range of 8 - 27 mm/yr in east direction.

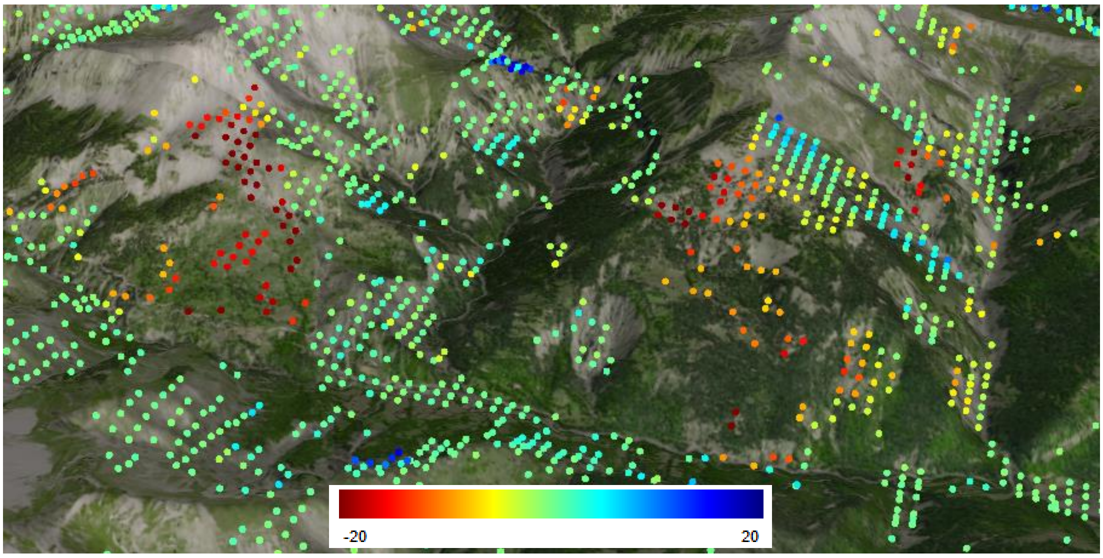


Figure 9 *Ortho* product for French Alps in horizontal / East-West direction

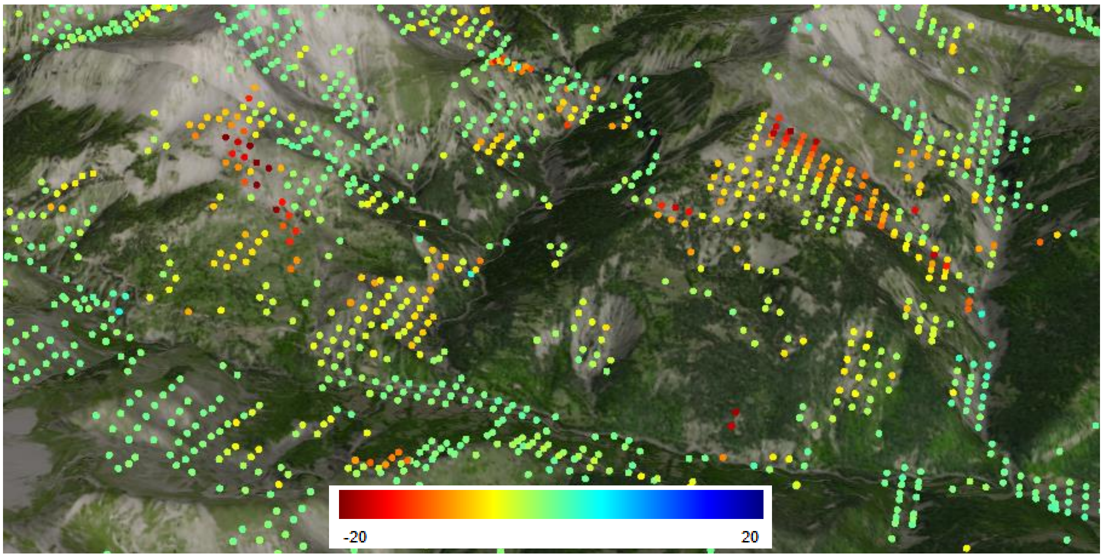


Figure 10 *Ortho* product for French Alps in vertical / Up-Down direction

A comparison of EGMS *Ortho* and *Basic* products illustrate the dependence of the measurements from local and look geometries and finally the rendering of deformation effects in the satellite based EGMS data. Examples derived in the area of Marina del Este in the municipality of Almuñécar, see Figure 11, illustrate the localisation of landslides along two flanks extending from the ridge of the promontory (aligned north-south) along the slope towards the coast in i) west and ii) east direction. Local geometry plays a role for the measurement when imaging i) and ii) in ascending Figure 11 (left) and descending Figure 11 (right) direction.

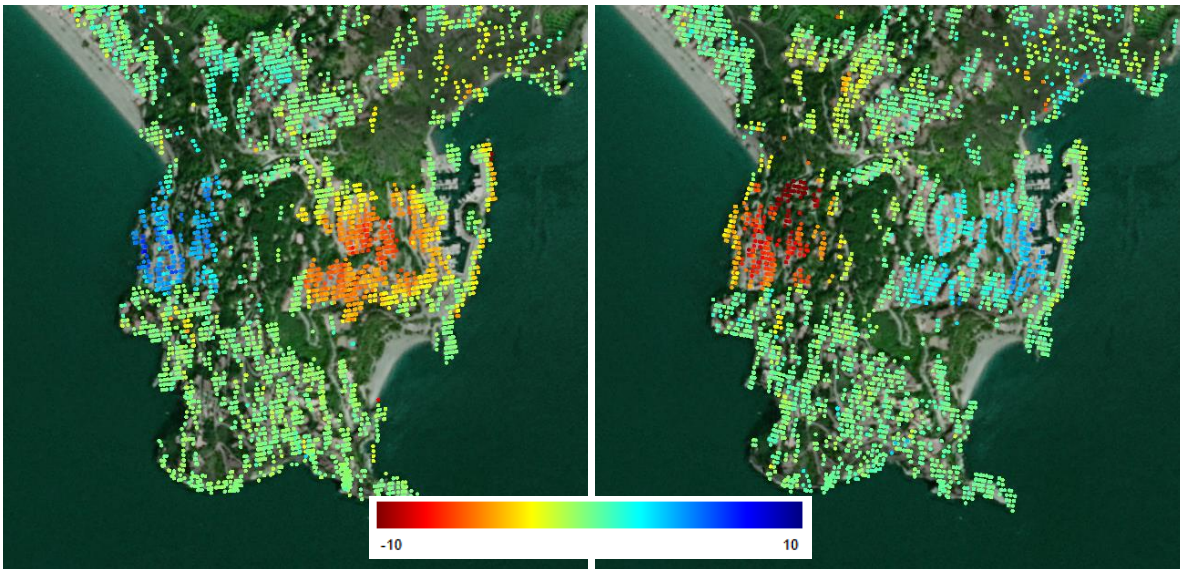


Figure 11 Comparison between ascending (left) & descending (right) *Basic* product in Almuñécar

Movement of the landslides is mapped here with the opposite sign, meaning away or towards the antenna (in LOS). In real world geometry this effect expresses the dominant east or west component of motion, as illustrated in Figure 12.

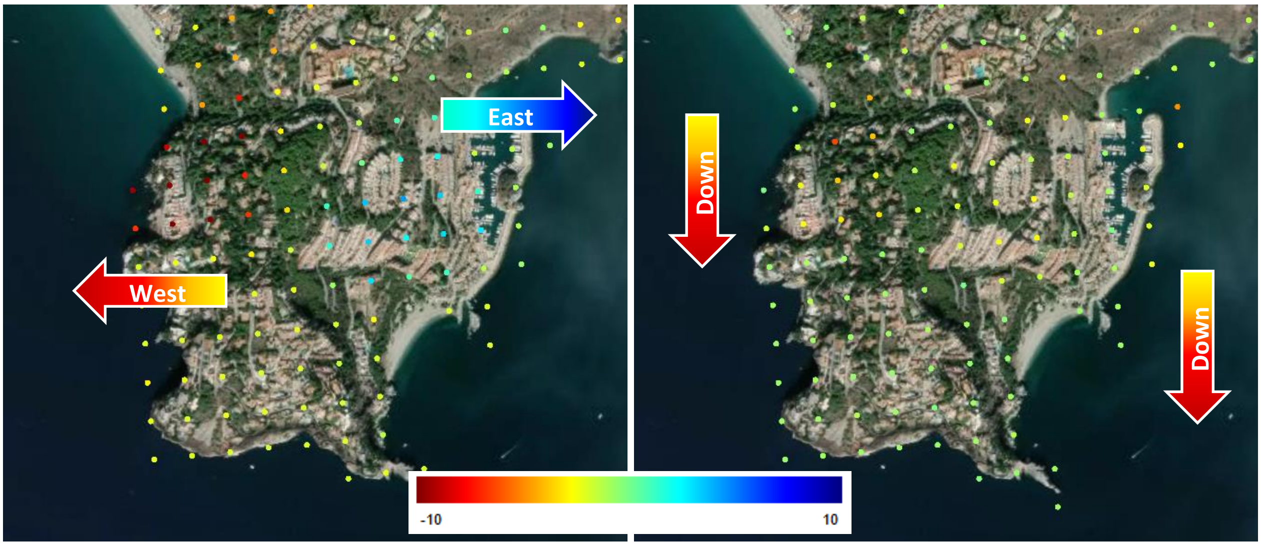


Figure 12 Comparison between East-West (left) & Up-Down (right) *Ortho* product in Almuñécar

References:

- 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).
- Lima, P., Steger, S., Glade, T. (2021). Counteracting flawed landslide data in statistically based landslide susceptibility modelling for very large areas: a national-scale assessment for Austria. Landslides, 18.

5.1.2. Subsidence - Ground movements due to groundwater depletion

Ground movements due to groundwater fluctuations represent an increasing problem all over the world and may occur, among others, as result of excessive water extraction, flooding of inactive mining sites and significant seasonality of rainfalls.

Especially in urban and peri-urban areas, groundwater fluctuations appear as anthropogenic processes causing land subsidence due to excessive groundwater extraction for agriculture or industry. The Guadalentín basin in the Múrcia region in Spain serves as the perfect example of progressive terrain motion reaching LOS velocities of up to -100 mm/yr and imposing significant risk to economy, flooding and infrastructure (Jover 2016). The Guadalentín Basin is filled by Neogene-Quaternary sediments transported by the Guadalentín River along an intramontane depression located in the eastern part of the Baetic Cordillera, which is an ENE-WSW-oriented alpine orogenic belt.

Since 1960, agricultural development has required the exploitation of the aquifer system and in 1988, the amount of extraction reached a maximum historical value of 77.6 hm^3/a. After 1988, a general reduction in extraction of wells was recorded due to CO^2 pollution of groundwater resources but also because of water transfer from the Tajo River to the Segura River.

Strong impacts on groundwater levels were also caused by the major drought from 1990 to 1995 and excessive water extraction in the Múrcia urban area from 2005 to 2007. A deficit in the groundwater reserve was recorded from 1965 to 2009, corresponding to an annual rate of decline of the aquifer of 33 hm^3 (Alonso and Aróstegui, 2014).

Also the present analysis, black circled area of interest in Figure 13 are confirming the tendency appointed by former investigations with LOS displacement in the range of -30 mm/yr with a maximum mean velocity in this area up to -46.30 mm/yr.

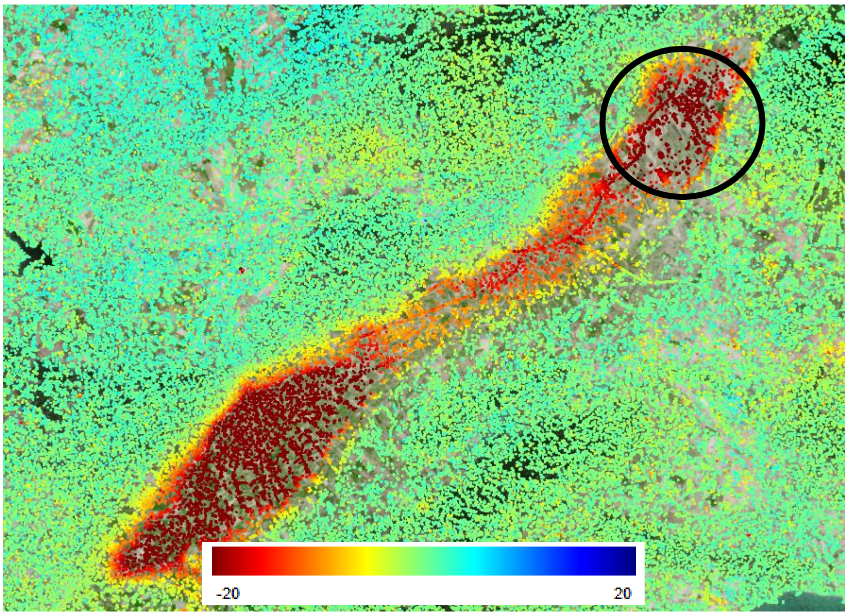


Figure 13 Continuous subsidence caused by excessive water extraction for agriculture in the Guadalentín Valley, Murcia

In previous studies the evolution of land subsidence in the Alto Guadalentín Basin (southeast Spain) was monitored using multi-sensor SAR imagery between 1992 and 2012 of C- and X-Band systems and analysed utilising advanced differential interferometric synthetic aperture radar (DInSAR) techniques (Bonì et al. 2015). The DInSAR derived surface displacement reveal a direct correlation with the thickness of the compressible alluvial deposits. Bonì et al. (2015) state that "Detected ground subsidence in the past 20 years is most likely a consequence of a 100–200 m groundwater level drop that has persisted since the 1970s due to the overexploitation of the Alto Guadalentín aquifer system. The negative gradient of the pore pressure is responsible for the extremely slow consolidation of a very thick (> 100 m) layer of fine-grained silt and clay layers with low vertical hydraulic permeability (approximately 50 mm/h) wherein the maximum settlement has still not been reached".

Following up the findings of the InSAR exercises in Guadalentín Basin, especially for C-Band, the monitoring is continued with EGMS products comparing spatial characteristics (distribution, density), motion rates and temporal trends in relevant areas.

References:

- Alonso, M.S., Aróstegui, J.L., G. (2014). Sobreexplotación de acuíferos en la cuenca del Segura, ISBN: 978-84-92988-22-8.
- Bonì, R., Herrera, G., Meisina, C., Notti, D., Béjar-Pizarro, M., Zucca, F., Mora, O. (2015). Twenty-year advanced DInSAR analysis of severe land subsidence: The Alto Guadalentín Basin (Spain) case study. Engineering Geology, 198.
- Jover, R. T. (2016). The Valley of Guadalentín in Lorca, the deepest in Europe according to research in collaboration with the University of Alicante. (U. o. Alicante, Editor) Acessed at 11.02.2022, available at University News: https://web.ua.es/en/actualidad-universitaria/2016/julio16/18-24/the-valley-of-guadalentin-in-lorca-the-deepest-in-europe-according-to-research-in-collaboration-with-the-university-of-alicante.html.

5.1.3. Subsidence - Ground movements due to groundwater level recharge in abandoned mines

The city of Freyming-Merlebach is suffering significant uplifts due to natural water filling in former underground coal mines. It is worth to know that the last panel of Lorraine French coalmines has been closed in 2004. To limit the extent of the rise in groundwater and to protect built-up areas suffering from subsidence, a recently installed pumping station injects fresh water into the mine galleries to reduce concentrations of iron, manganese and suspended solids before being discharged into the natural environment (BRGM - French Geological Survey, 2015).

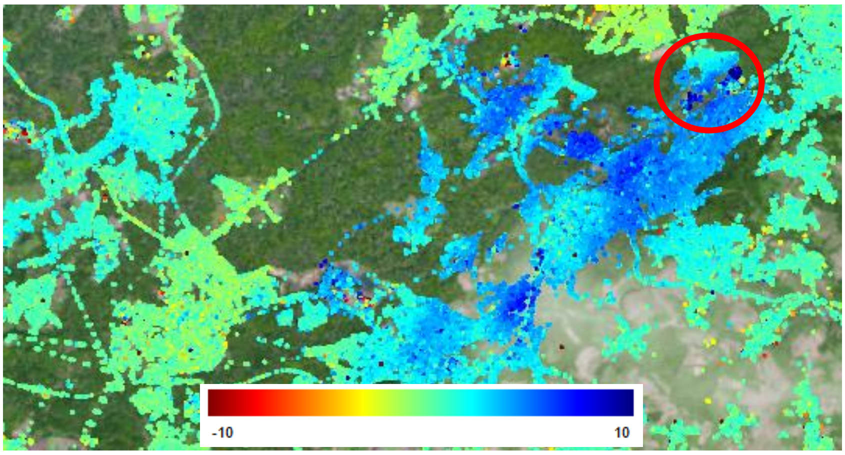
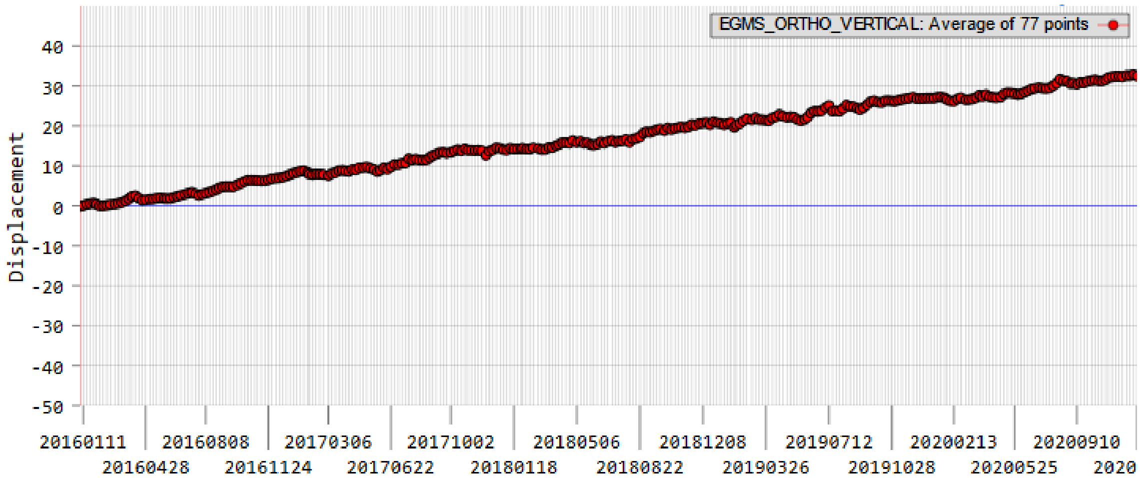


Figure 14 Increased water level in former coal mines led to significant uplifts in Freyming-Merlebach

A strong relation to hydrologic condition with increased uplift in spring and autumn is observable due to the natural overflow from Germany. Aside from this, a mean velocity of 3.02 mm/yr in ascending was measured for the entire area averaged over approx. 30000 points. When measuring the areas with the highest uplift, the mean rate of lifting processes is measured up to 6 mm/yr, with occasional peaks of 10 mm/yr.

If the *Ortho* products are additionally analysed for the area circled in red, a clear directional trend in the movement becomes visible, see Figure 15. Vertical motion is characterised by an uplift of approx. 7.3 mm/yr following a linear trend over the time series. Horizontally, considering the *Ortho* East-West components (lower graphs), a motion pattern varying in east-west is observed, with westward movement along the western edges of the uplift area of approx. 3 mm/yr and eastward movement of approx. 9.3 mm/yr at the eastern ones.



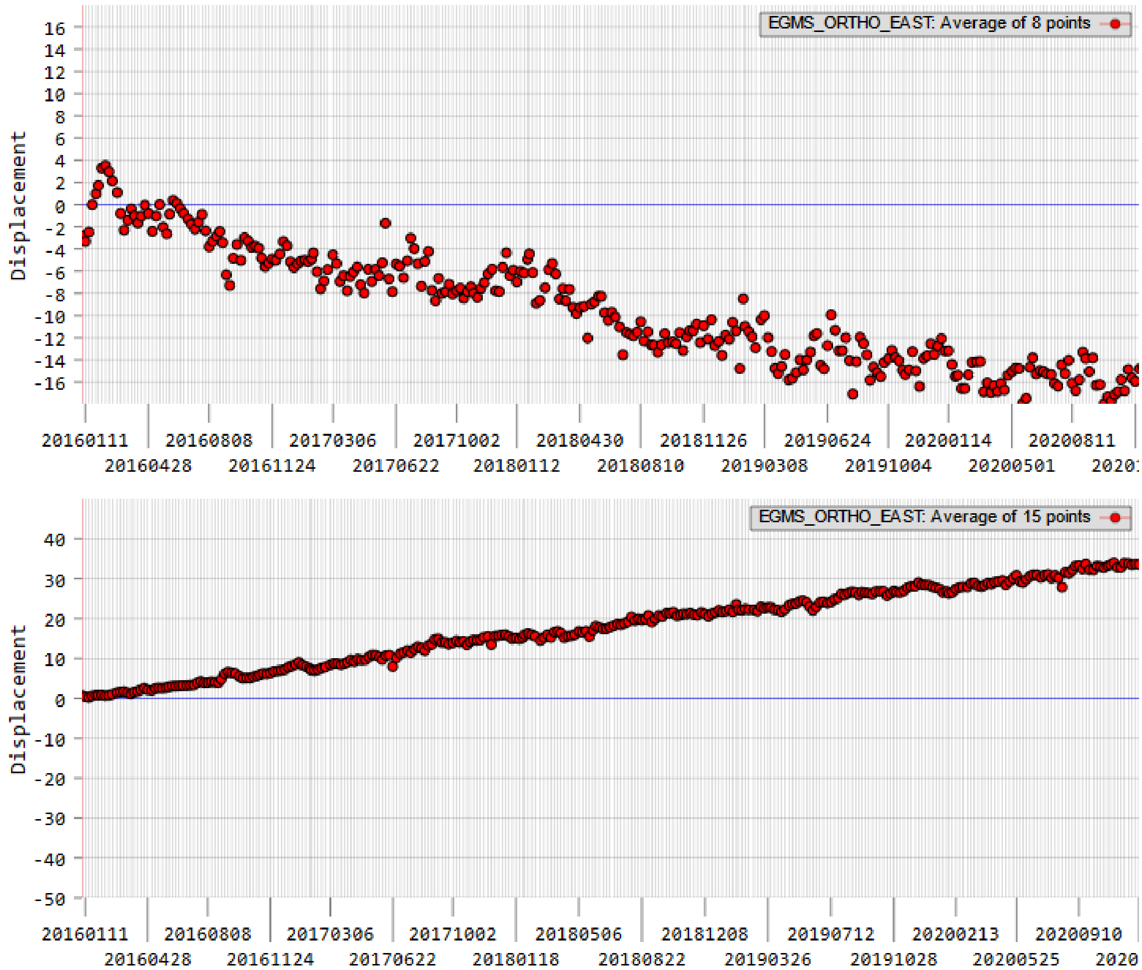


Figure 15 Average time series for *Ortho* products in Freyming-Merlebach
(top: vertical / Up-Down direction & middle/bottom: horizontal / East-West direction)

References:

- *BRGM - French Geological Survey* (2015). https://www.brgm.fr/en/news/press-kit/lorraine-coal-basin-management-water-municipality-freyming-merlebach
- Fuhrmann, T. (2016). Surface Displacement from Fusion of Geodetic Measurement Techniques applied to the Upper Rhine Graben. DGK - Deutsche Geodätische Kommission der Bayerischen Akademie der Wissenschaften.

5.1.4. Subsidence - Due to consolidation of organic layers/reclamations

The municipality of Fiumicino with the largest airport in Italy - "Leonardo da Vinci-Fiumicino Airport" - is located in the middle of Tiber delta West of Rome. “This region is characterized by a complex geological setting (alternation of recent deposits with low and high compressibility) and has been subjected to different urbanisation phases starting in the late 1800s, with a strong acceleration in the last few decades” (Bozzano et al. 2018).

The entire river delta is characterized by slight subsidence processes, which can be explained by the natural consolidation of the sediments of the delta. In the inner delta plain there are two reclaimed marshes, named Maccarese and Ostia ponds, which have been reclaimed over several decades, starting in 1884, with the help of a pumping plant network. InSAR based investigations provide a possibility to measure and evaluate the development, velocities and intensity of the subsidence.

Previous studies based on ERS 1/2, ENVISAT and RADARSAT-1 in the period from 1992 to 2006 have impressively shown that very strong subsidence processes of up to 20 mm/yr can occur, especially in the Maccarese and Ostia peatlands. This is remarkable since the two northern runways of the airport are partly located on these unstable areas.

And it is in these areas that the relevance of both *Ortho* products can be seen very impressively in. The East-West product does not show any relevant motion, whereas the vertical component shows mean velocities up to -8.0 mm/yr, arriving to -20.0 mm/yr along the northern runaway. But not the entire runway is affected by ground motion. In the northern third, the runway no longer is located on the reclaimed peatlands and just in the transition between the peatlands and the sand barrier a clear stabilization can be noticed. “A clear correlation between the observed deformation pattern and the geological features is observed: for instance, the abrupt change in the deformation rate along the NS runway of the airport corresponds to the transition from […] stiff sediments to 1–2 soft organic and inorganic clays” was also stated out by Del Ventisette et al. (2015). Further strong subsidence processes are visible in the vertical product along the highway A91 which connects the airport with the city of Rome.

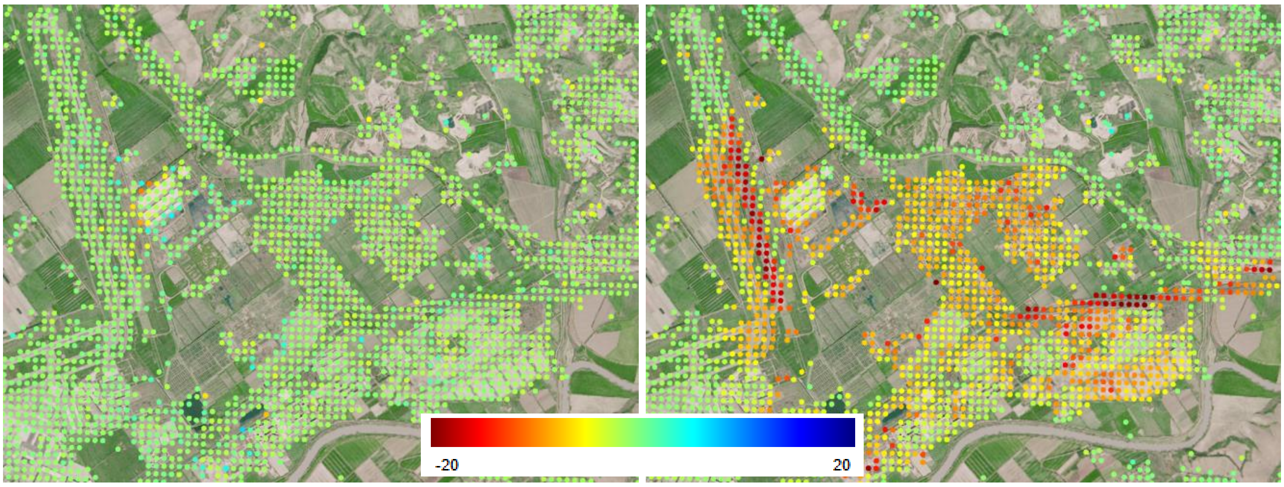


Figure 16 Subsidence processes over Maccarese peatlands in *Ortho* product
(left: horizontal / East-West & right: vertical / Up-Down)

References:

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5.1.5. Subsidence - Due to local geology and climate change on coastal sites

The 10 largest Danish cities are located along the coast and about 80% of the Danish population lives within 3 km of the North Sea and the Baltic Sea. Climate change and rising sea levels could, in connection with the geological asset and land use of the areas, lead to potential risk areas for subsidence.

Coast line shifts or changing coastal dynamics due to climate change and rising sea levels is, in contrast to land subsidence caused by gas or groundwater extraction, has been a minor topic in Denmark in the past. Potential reasons for this include the fact that the effect was assessed as comparatively low, therefore not determined as a prominent challenge so far and that data availability for analysing this problem was limited or even not existent.

The harbour of the fishing village of Thyborøn, located on the North Sea, was the subject of the study by Sørensen et al. (2016), who investigated ground motion including satellite data from Sentinel-1. The research showed that the use of InSAR techniques in combination with existing investigations adds a significant additional value to the monitoring of harbour infrastructure and coastal protection and leads to a deeper understanding of coastal phenomena. However there is still a need for an increased information base such as density or coverages to monitor the extensive area along the coast and its site specific dynamics.

The EGMS products provide long-term national coverage and can help to better understand and analyse subsidence processes due to climate change. Besides protection measures for harbour infrastructure, coastal cities and harbours are prone to risks due to climate change and sea level rise. Settlements like the fishing village Thyborøn, that are located in a coastal subsidence area could be especially affected. With a subsidence rate of up to -30 mm/yr in the vertical *Ortho* that amplifies the effect of a rising sea level, EGMS products give an indicator for risk areas which can directly be included in the planning process or the risk grading along the Danish coast.

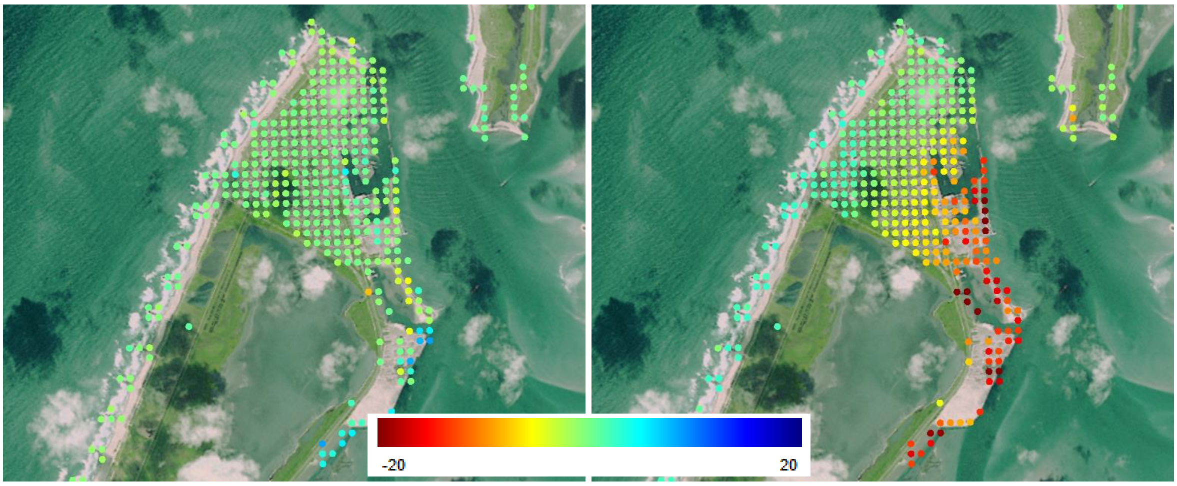

Figure 17 Port of Thyborøn with *Ortho* products (left: horizontal / East-West & right: vertical / Up-Down)

References:

- Sørensen, C. S., Broge, N. H., Mølgaard, M. R., F. Levinsen, J., Okkels, N., Knudsen, P. (2016). Advancing Coastal Climate Adaptation in Denmark by Land Subsidence Mapping using Sentinel-1 Satellite Imagery. Geoforum Perspektiv, 15(28).

5.1.6. Volcanoes and volcanic-related deformation

Ground movements in volcanic areas can have different origins related to their depth under the terrain surface. Volcanic activity is a prominent example for the complexity of ground deformation in a delimited area with a variety of displacement phenomena.

Campi Flegrei

This caldera, located in the Gulf of Pozzuoli in the west of Naples, is one of the most studied volcanic fields in Europe and is described as “one of the most dangerous quiescent volcanic systems in the world” (Piochi et al. 2008).

Troise et al. (2019) state that “Since 1950, it has undergone four episodes of caldera-wide uplift and seismicity, which have raised the coastal town of Pozzuoli, near the centre of unrest, up to 4.5 m and triggered the repeated evacuation of some 40,000 people”. The unrest phases lasted for different lengths of time and are followed by phases of subsidence; the current uplift phase started in 2005. "Complex mechanisms involving magma, geothermal system, tectonic stresses” (Troise et al. 2019) are responsible for the undergoing continuous unrest.

Since the beginning of the time series in 2015 until the end of 2020, uplift processes have been detected and estimated in a maximum of 70 mm/yr visible in *Ortho* product. The current uplift phase has been running since 2005 associated with an increase of the seismicity rate and of the degassing activity in the phlegraean fields (Tramelli et al. 2021). Despite the continuing unrest and the shift between uplift and subsidence phases, the last eruption of the caldera dates to 1538.

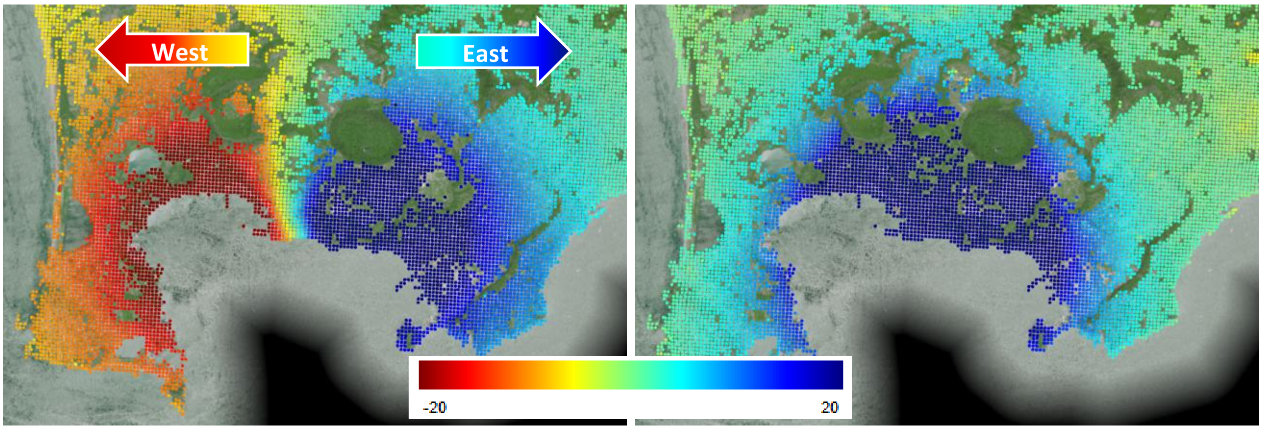

Figure 18 *Ortho* products at Campi Flegrei with strong uplift process (left: horizontal / East-West & right: vertical / Up-Down)

The Campi Flegrei area is located in a densely populated area so that the knowledge of active ground motion is of paramount importance for civil protection activities. Currently, the Italian Civil Protection Department manages the seismic, geochemical and deformation monitoring of the area. Global positioning system data and interferometric products are part of the monitoring system (Casu et al., 2019). The products of the EGMS offer an additional contribution to the knowledge of this complex volcanic system.

The examples of EGMS ortho data, shown in Figure 18, represent an ideal illustration of a significant and intensive uplift area or dome rendered in its horizontal (east-west) and vertical motion. Vertically strong upward motion is found in the nearly circular uplift area in the right image of Figure 18 with its maximum velocity (up) in the centre of the area and decreasing velocities towards the edge. Horizontal movement, namely in east-west direction as shown in the left image of Figure 18, shows the expected pattern of eastward and westward directed components of the velocity field over the uplift dome. Here eastward motion dominates on the eastern flanks and westward motion on the western flanks of the uplift dome.

Mount Vesuvius

The cone region and crater of Vesuvius in the east of Naples is also characterized by ground movements over time. But these are not steady uplift processes as in the caldera; on the contrary subsidence with small periodic uplifts with an overall mean displacement rate of -13 mm/yr is recorded. Although these two systems are considered to be separated, some authors suggest a possible interconnection with the seismic processes of one that may have a direct or indirect effect on a neighbouring volcano (Walter et al. 2014).

Thus, even years later, the EGMS *Basic* and *Ortho* product shown in Figure 19 confirm the studies who observed "long term subsidence with a nearly constant rate and well-defined seasonal oscillations" (Samsonov et al. 2014) since the beginning of the 2000s at Vesuvius.

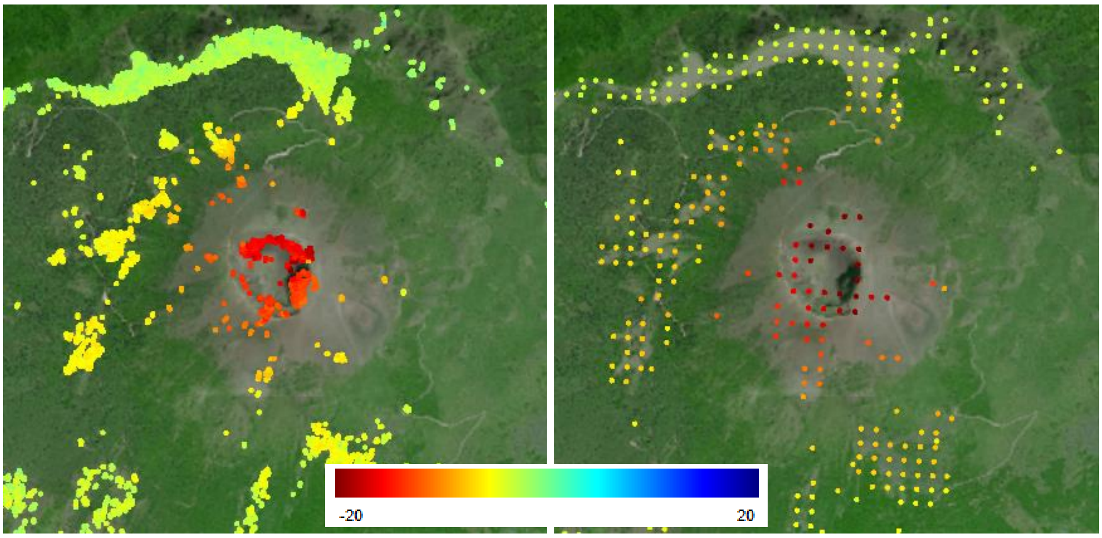

Figure 19 *Basic* and *Ortho* product of Mount Vesuvius with long term subsidence (left: ascending & right: vertical / Up-Down)

References:

- Beccaro, L., Tolomei, C., Gianardi, R., Sepe, V., Bisson, M., Colini, L., De Ritis, R., Spinetti, C. (2021). Multitemporal and Multisensor InSAR Analysis for Ground Displacement Field Assessment at Ischia Volcanic Island (Italy). Remote Sens. 2021, 13.
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- De Novellis, V., Atzori, S., De Luca, C., Manzo, M., Valerio, E., Bonano, M., Cardaci, C., Castaldo, R., Di Bucci, D., Manunta, M., Onorato, G., Pepe, S., Solaro, G., Tizzani, P., Zinno, I., Neri, M., Lanari, R., Casu, F. (2019). DInSAR analysis and analytical modelling of Mount Etna displacements: The December 2018 volcano-tectonic crisis. Geophysical Research Letters, 46.
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5.2. Civil Engineering & Infrastructure

5.2.1. Buildings - Ground movements as a result of geothermal drilling

In the small German town of Staufen im Breisgau, located in the state of Baden-Württemberg, geothermal drilling with a final depth of 163m was carried out in the summer of 2007 under the local town hall. The purpose was to take advantage of geothermal energy to heat and cooling the two buildings during the renovation of the town hall.

The local geological asset created several problems after the realisation of the geothermal exploitation system. In fact, a deep-lying anhydrite layer is found directly beneath the historic old town; by absorbing the hot fluids from the depths like a sponge, anhydrite is converted into gypsum. “The swelling process occurred relatively slowly due to its kinetics and medium-to-low hydraulic permeability in this zone. The swellable anhydrite layers were located at a depth between 61.5 and 99.5 m below ground level” (Fleuchaus et al. 2017). This increases the volume of the rock and a surficial uplift of 60 cm in 10 years has been recorded in the city centre with an additional lateral displacement of 43 cm. This process has not come to an end and have damaged about 270 houses and caused costs of several million euros. As a countermeasure, for example, pumps were installed to keep the groundwater level low so that further swelling and thus ground motion are prevented. “The uplift rate was reduced from initially 11.0 to 3.5 mm per month. Since it is not possible to recover penetrated water from sulphate-bearing layers, swelling will stop only when there is no more inflow of groundwater" (Fleuchaus et al. 2017).

The following figures show that the ground motions in the EGMS *Basic* and *Ortho* products are clearly visible and that displacement and uplift processes, in average of 11 mm/yr, are still not completed. In the *Basic* product, however, phases of stabilization can be detected every spring, which are then again characterized by uplift of about 4 mm from summer to winter months. These data can therefore be easily used to identify trends in displacement processes, to assess the impact of measures taken, evaluate potential risk and dangers or to justify an entirely new planning to handle situations like these.

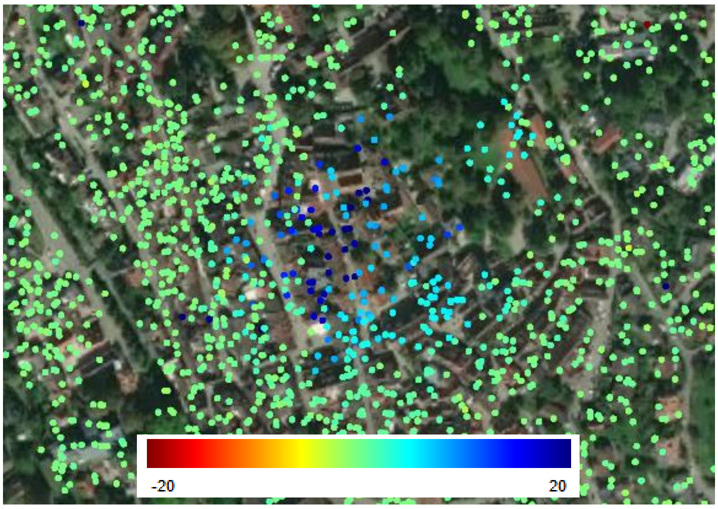

Figure 20 Uplift processes visible in *Basic* (ascending & descending orbit) in the city of Staufen im Breisgau

The results in *Ortho*, indicates the direction of the motion. In the east-west direction a mean velocity of -2.95 mm/yr is determined, which indicates a westward movement of the surface. In contrast, the vertical component is estimated in around 4 mm/yr.

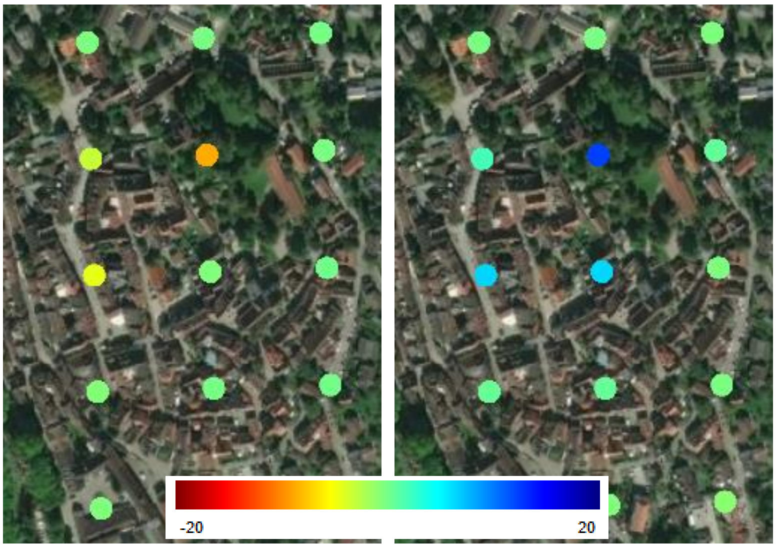

Figure 21 Westward shift in horizontal (left) and uplift in vertical (right) *Ortho* product for the city of Staufen im Breisgau

References:

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- Fleuchaus, P. and P. Blum (2017). Damage event analysis of vertical ground source heat pump systems in Germany. Geotherm Energy 5, 10.
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5.2.2. Linear and Critical Infrastructure - Detection of motion of the structure and surroundings

The city of Antwerp located along River Scheldt is the second-largest metropolitan area of Belgium and is home of the second largest port in Europe in terms of annual cargo volume, and additionally home of the second largest chemical industrial park in the world. Utilisation of EGMS products potentially provides the basis to detect and analyse movements in the area of the port itself and its vicinity, opening up topics in a variety of applications such as monitoring critical and linear infrastructures or buildings, risks along transport logistics chains, etc.

Ship berths, quays, cargo storage areas, ships locks and also transport infrastructure are subjected to heavy loads continuously for a long period of time in order to handle the millions of tons of cargo day-by-day. In order to continue to manage the increasing load, the port is being extended, continues to grow and therefore induces an enormous impact on natural characteristics of the harbour and surrounding area, which makes these areas vulnerable for ground motion.

The products of the EGMS represent an additional information source useful to detect, understand, analyse or evaluate the effects of ground motion directly on linear and critical infrastructures plus to assess second order effects on port operation or transport logistics. Therefore “deformation monitoring of critical infrastructure assets is of major importance for preventing damage and losses” (Schlögl et al. 2021).

Areas with potential risks for critical infrastructure are found to a huge degree in the port area of Antwerp, characterised by medium subsidence in a range of 2.5 to 3.5 mm/yr downwards and negligible motion in East-West direction with subsidence peaks of up to 10 mm/yr in parts of the port with velocities of up to 6 mm/yr in E-W. In terms of the spatial context subsiding areas with different magnitude of deformation are distributed in the port area, potentially effecting the stability of the port infrastructure or leading to structural stress. Subsidence areas are furthermore present around the port area comprising the logistics infrastructure, such as railway and road networks. Along those linear structures both components of motion need to be analysed to indicate potential damages.

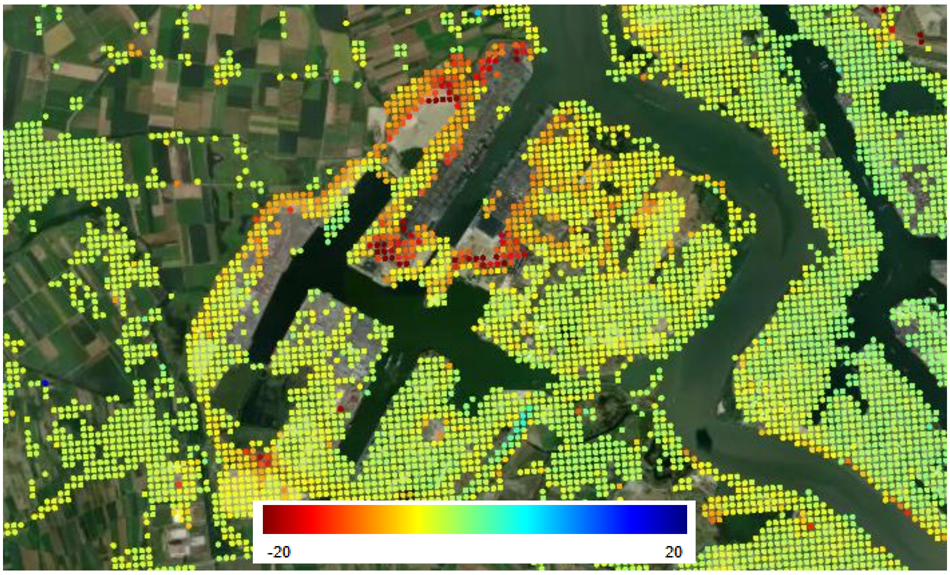

Figure 22 Port of Antwerp with vertical / Up-Down *Ortho* product

References:

- Declerqc, P.-Y., Gérard, P., Pirard, E., Walstra, J., Devleeschouwer, X. (2021). Long-Term Subsidence Monitoring of the Alluvial Plain of the Scheldt River in Antwerp (Belgium) Using Radar Interferometry. Remote Sensing, 13(6).
- Schlögl, M., Widhalm, B., Avian, M. (2021). Comprehensive time-series analysis of bridge deformation using differential satellite radar interferometry based on Sentinel. Journal of Photogrammetry and Remote Sensing, 172.

5.3. Mining and Oil & Gas

5.3.1. Mining - Ground motion as a result of mining activities

Mines, both surface and underground, exist all over the world to extract resources from the ground and "remote monitoring of ground deformation from radar satellites has become an operational tool for mines world-wide" (Colombo & MacDonald 2015). While above-ground mines can be monitored using both optical and radar-based systems, underground mining areas are a particular challenge. It is irrelevant whether the mines are active or abandoned. The influences and consequences of mine activity can sometimes occur years later or are difficult to measure and detect only on a small scale.

In the last years, the potentials to use InSAR and associated techniques have steadily improved. Not only the spatial but also the temporal resolution has improved significantly, so it "has brought InSAR technology to the forefront of mine site deformation monitoring" (Colombo & MacDonald 2015). Therefore the products of EGMS with their temporal coverage rate of up to 6 days and a high spatial resolution offer the possibility to detect different effects of mining to the surrounding area and the mine at itself.

One use case covers mining activities and dynamics in the region Ostrava/ Katowice extending from Czech Republic to Poland. The Upper Silesian Coal Basin (USCB) reaches from the Ostrava region in Czech Republic to Katowice in Poland. It forms an industrial region dating its activity back to the 12th century. With the 19th century's underground coal mining, ironworks and coal fired power plants were intensified and have left a significant imprint on the local environment. About 30 underground coal mines are still in operation within the USCB area. Active mines as well as closed mines are found in close vicinity, and both affect the water and groundwater regime. In addition to environmental impacts deformations due to mining activities and a changing groundwater regime pose a risk to industrial and human infrastructure. Finally the use case covers issues of an essentially dynamic area in terms of deformations and complex patterns. Besides mining operations it's of high relevance for environmental and geo-risk impacts as well as planning or transformation plus inter border issues.

Deformation phenomena in the USCB show high dynamics at explicit features and with a high magnitude of motion. These characteristics can be summarised in depression cones with subsidence in a range of up to 15 – 20 mm/yr down and approx. 8 mm/yr eastward on the western flank and approx. 15 mm/yr westward on the eastern flank of the cone. There are also uplift areas with velocities up to a range of 10 – 15 mm/yr together with maximum velocities of 5 mm/yr westward on the western flank and 5 mm/yr eastward on the eastern flank of the dome.

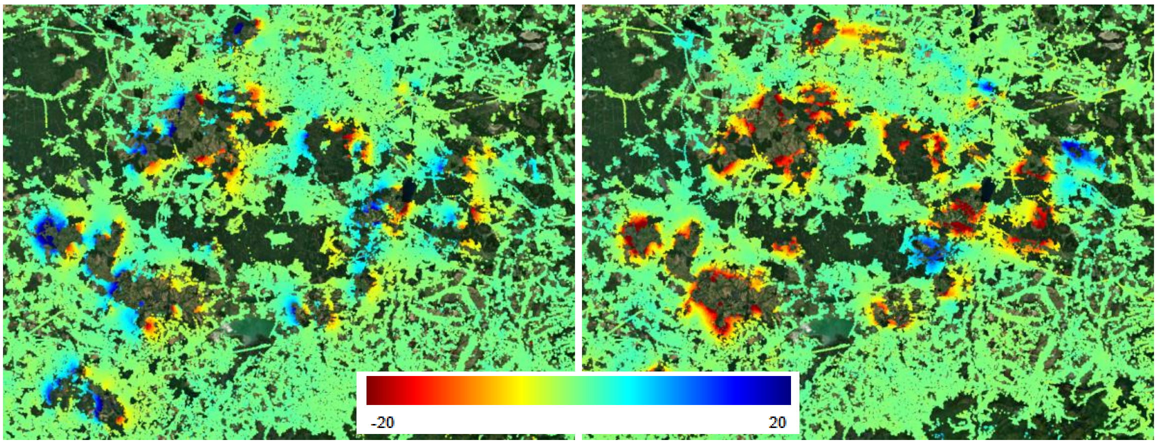

Figure 23 Mining related ground motions at USSB (left: horizontal / East-West & right: vertical / Up-Down)

Another example of ground movements as a result of mining activities is found in northern Sweden in the Malmberget/Gällivare area and was investigated by Makitaavola et al. (2018). Initially, mining was carried out above ground, but was then gradually moved underground. Because of these different methods, this mining region represents a particularly high potential for ground movement. This is also confirmed by geological investigations, which show that the area has several potential large-scale deformation zones. As both the adjacent settlements and the mining area continue to expand, houses have to be relocated and the mining area moves further and further under the towns and settlements, so that since 2009 it has been necessary to monitor the ground movements throughout with GPS support to monitor the transformation of these area. Currently, these measurements only take place once a quarter, which means a total of 4 measurements per year. The EGMS products can therefore support the on-site measurements by providing movement information at significantly shorter intervals and also enable long-term monitoring with comparatively significantly shorter intervals between measurements.

As shown in Figure 24, the Ortho product indicates that the horizontal movements (peaks up to -24.60 mm/yr) are intensive especially in the western and eastern parts of the subsiding area that tends to move down with maximum -18.1 mm/yr at the core of the mining area. This significant motion in this site indicates potential risk areas where damages to infrastructure and settlement areas can be expected.

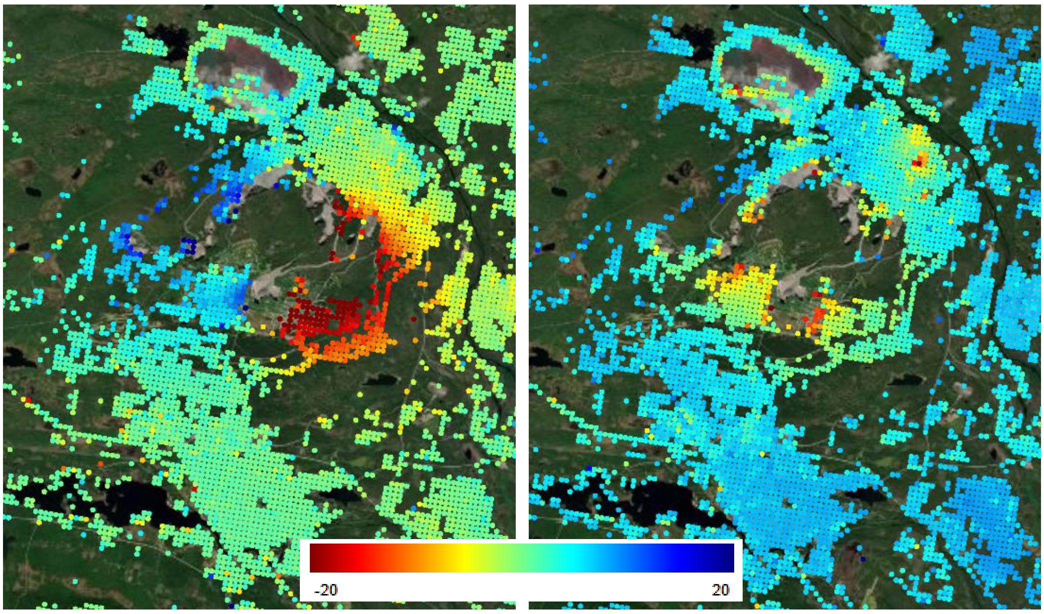

Figure 24 Mining related ground motions at Malmberget/Gällivare (left: horizontal / East-West & right: vertical / Up-Down). The positive ground motion signal surrounding the mine in the Up-Down component is given by the regional uplift due to post-glacial rebound.

References:

- Colombo, D., MacDonald, B. (2015). Using advanced InSAR techniques as a remote tool for mine site monitoring. The Southern African Institute of Mining and Metallurgy, Slope Stability 2015.
- Makitaavola, K., Stockel, B.-M., Savilahti, T., Sjoberg, J., Dudley, J., McParland, M.A., Morin, R. (2018). InSAR as a practical tool to monitor and understand large-scale mining-induced ground deformations in a caving environment. Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving, Australian Centre for Geomechanics.

5.3.2. Mining - Ground motion as a result of salt solution mining

Salt is extracted from the salt layers of the Zechstein Unit at a number of sites in Poland, Germany and the Netherlands.

EGMS data helps to understand the dynamics occurring during Salt deformation processes in the Veendam salt pillow located at the southern boundary of the Groningen district and contributes an efficient means of monitoring compliance with the maximum permitted subsidence rates.

A producer of calcium chloride, magnesium chloride, magnesium oxide and magnesium hydroxide, uses solution mining to extract carnallite and bischofite salt near Veendam. This technique injects water into the salt layers and pump out the resulting brines. Twelve wells have been drilled at a depth ranging from 1.400 to 1.800 meters. This mining activity triggers subsidence.

A subsidence bowl is created near Veendam due to solution salt mining between 1972 and 1991. Dissolution of the salt results into overburden that is not fully supported from below causing surface subsidence (Raith 2017). Satellite radar interferometric measurements performed by TU Delft over the period 1992-2003 revealed subsidence of about 120 mm (Hanssen 2006)

As shown in Figure 25 continuous negative LOS displacement with mean velocities of -25mm/yr could be observed, exceedingly the rates derived by TU Delft in former periods. Moreover, an acceleration of displacement starting from spring 2018 is notable.

The independence of the measurements in the ortho data from the viewing geometry render the deformation effects the salt mining area in a way that is easier to interpret for the user. The subsidence cone in the central part of Figure 25 (right) is represented by a downward velocity of approx. 20 mm/yr. The extent of the cone can be estimated along MPs following linear features and indicating similar subsidence rates, e.g. roads heading northwest from the subsidence area and showing downward motion.

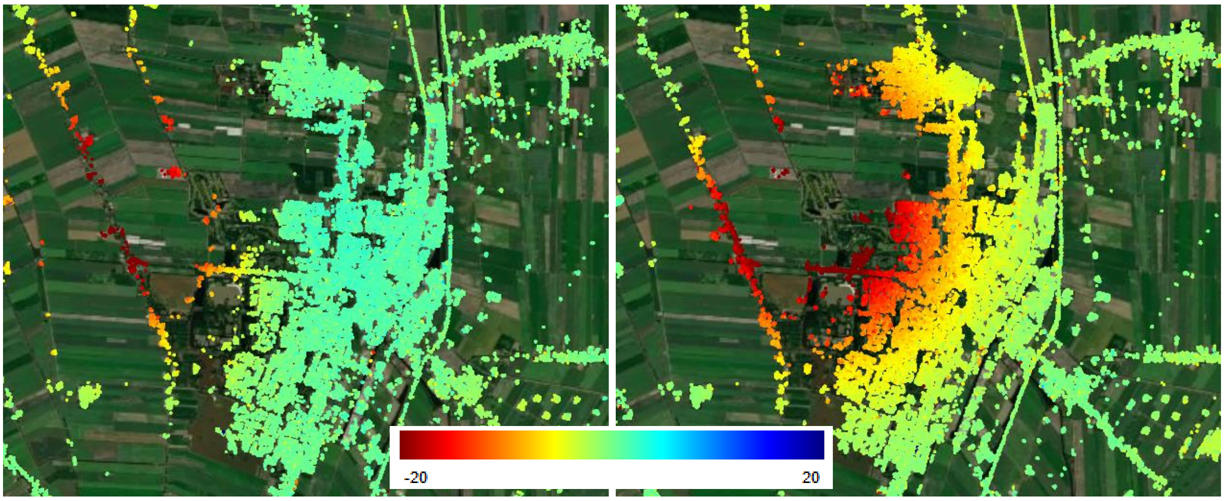

Figure 25 *Basic* product for Veendam (Netherlands) ground deformation due to salt solution mining
(left: ascending & right: descending)

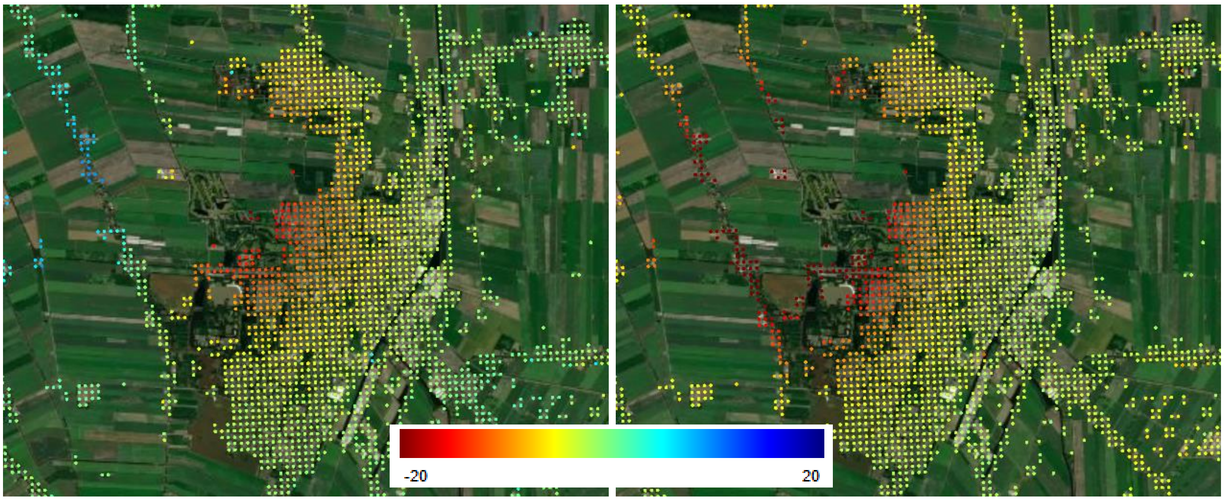

Figure 26 *Ortho* product for Veendam (Netherlands) ground deformation due to salt solution mining
(left: horizontal / East-West & right: vertical / Up-Down)

References:

- Hanssen, R. F. (2006). Salt Mining Deformation.
- Raith, A. S. (2017). Internal deformation of salt bodies with large mechanical contrast: a case study of the Veendam salt Pillow, the Netherlands.

5.3.3. Gas - Linear and seasonal trends in ground motion

The largest natural gas field in Europe and the 10th largest field in the world is located near the Dutch city of Groningen. This field opened in 1959 and exploited since 1963 for half a century. It represents an important economic factor and has a significant role in the energy supply for the Netherlands as well as the surrounding countries which obtain gas from this field. During production the risk of seismic events became evident with a series of earthquakes beginning with 1986 and with increasing frequency since 1991. Earthquakes with largest magnitudes caused damage to roads, buildings, etc. and altered the production and operation of the field with the goal of decommissioning the field.

The EGMS products offer a unique possibility to analyse ground movements during production, storage and depletion retrospectively from 2015 onwards and to monitor the consequences of the closure of the gas field with the annual updates in the future. Besides the technical complexity this case illustrates topics of public interest, such as seismic risk and risk exposure to the inhabitants, inter-border relations in terms of gas production and storage as well as geopolitical issues with the future use and transport of gas.

The gas field at Groningen, here visualised with *Ortho* products, shows specific characteristics, such as that the gas extraction areas subsiding at 5.0 to 15.0 mm/yr down and 2.0-11.0 mm/yr westward in the eastern parts of the field and 1-6 mm/yr eastward in the western parts of the field.

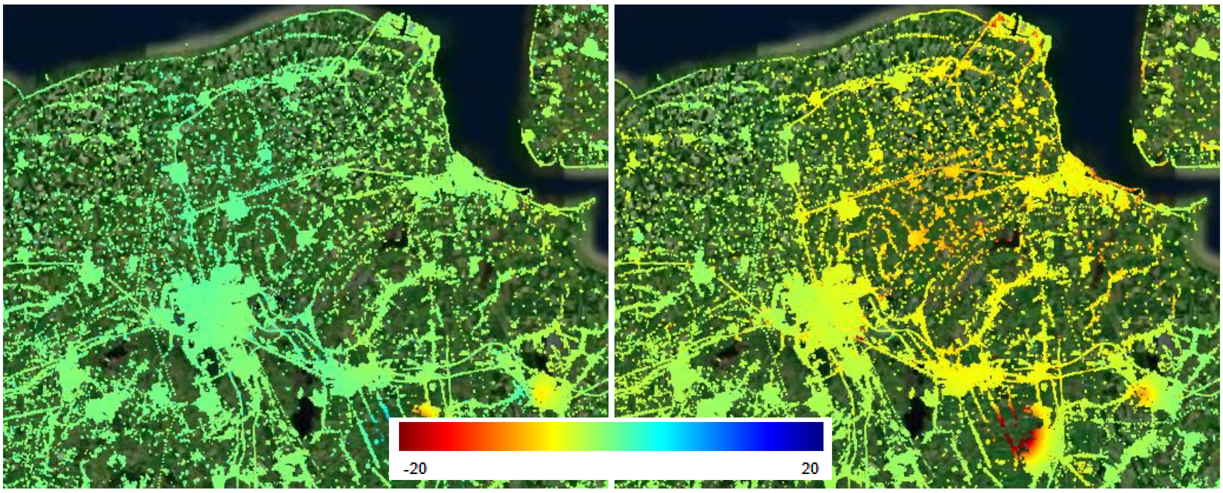

Figure 27 Groningen gas field with *Ortho* products
(left: horizontal / East-West & right: vertical / Up-Down)

Nevertheless, as the plots for the *Ortho* products in Figure 28 indicates, the area of the gas reservoir shows an explicit seasonal signal, which could be correlated to its fuel state. The signals clearly show that there is subsidence of up to -16 mm, especially in the vertical direction, which is due to the storage tanks being drained in winter. In summer, on the contrary, the empty reservoirs are filled up again and uplift processes of 12-13 mm can be recognized. Despite this, there is a downward trend visible over the entire time series from 2016-2020 in the affected area.

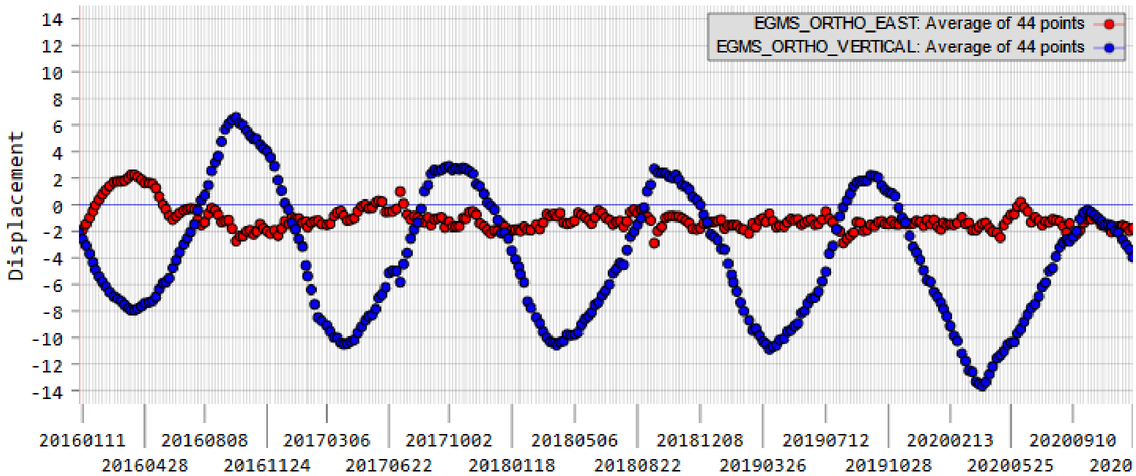

Figure 28 Plots for *Ortho* products over UGS Norg in southwest of Groningen

References:

- Thienen-Visser, K. van, Pruiksma, J.P., Breunese, J.N. (2015). Compaction and subsidence of the Groningen gas field in the Netherlands. Proc. IAHS, 372.

5.4. Cultural Heritage

5.4.1. Venice

The Venice Lagoon and the city itself have been on the UNESCO World Heritage List since 1987 and are therefore subject to special care and protection. "The city of Venice and its surrounding lagoon is presently one of the sites most sensitive to land subsidence worldwide. Even a few mm loss of ground elevations with respect to the mean sea level can significantly change the natural lagoon environments and threaten the city's survival" (Tosi et al. 2018). Research based on high resolution X-band Data concluded that short repetition intervals in SAR data allow measurable changes in the sub-millimeter accuracy and high spatial resolution helps to detect the large variability of ground deformations, captures motions that no other measurement techniques can detect and that a wide number of ground motion points reveal large-scale ground motion patterns as well as dynamics at both local and regional scales.

Both the *Ortho* product in Figure 29 and the corresponding time series plot in Figure 30 show a subsidence processes of the entire lagoon and for the area circled in red with a mean velocity of -2.36 mm/yr and occur without any particular peaks or unusual outliers.

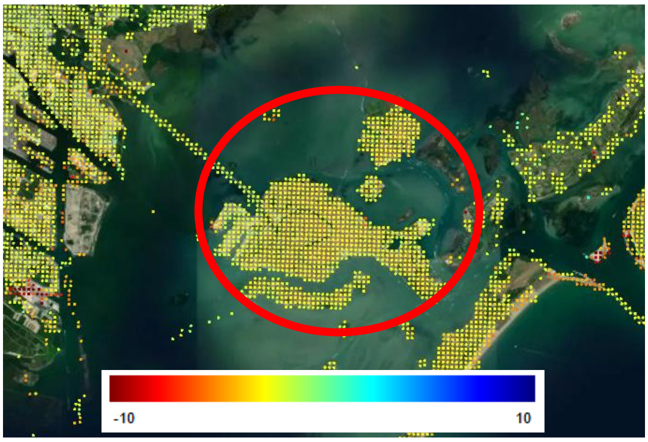

Figure 29 Vertical / Up-Down *Ortho* product for Venice (Italy)

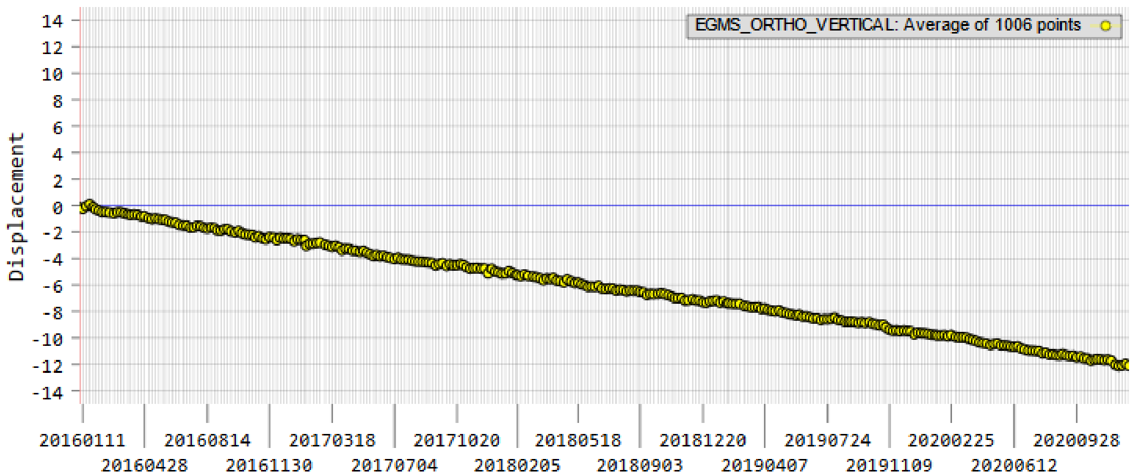

Figure 30 Average time series for Vertical / Up-Down *Ortho* product for Venice (Italy)

References:

- Tosi, L., Da Lio, C., Teatini, P., Strozzi, T. (2018). Land Subsidence in Coastal Environments: Knowledge Advance in the Venice Coastland by TerraSAR-X PSI. Remote Sensing, 10(8)

6. InSAR Definitions

Describing and specifying EGMS products necessitates the use of various technical terminology (i.e. InSAR "jargon"). The following glossary, presented in alphabetical order, defines those terms used in this document that are InSAR-specific and may not be immediately understandable by the non-specialist.

For those who want a deeper understanding of the principles and theories behind InSAR and the processing behind EGMS products, please see the EGMS *Algorithms and Theoretical Basis* [RD1].

Accuracy vs. precision

These terms are used with specific meaning in EGMS documentation (and in space geodesy) and can be confused. *Accuracy* refers to how close a measurement is to the true value, while *precision* refers to how close measurements of the same item are to each other, so a clock can be very precise and keep time to within fractions of a second each day, but if it's set to be three hours out, it's still not very accurate. Figure 31 below provides a different example:

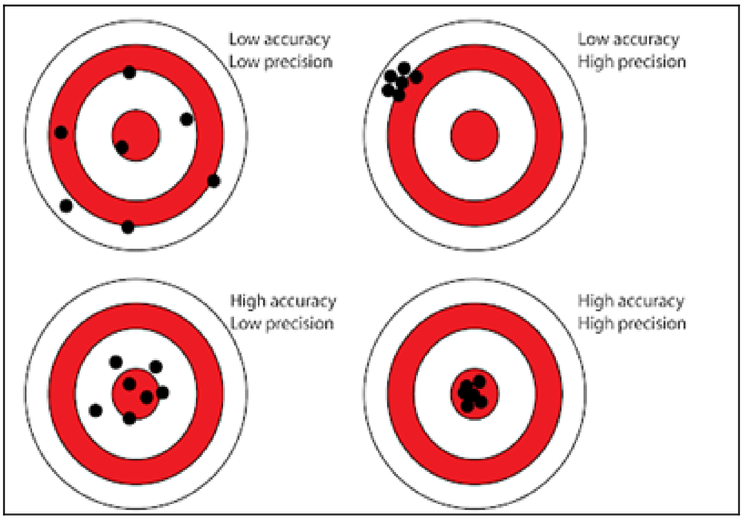

Figure 31 Accuracy vs. precision (from http://www.antarcticglaciers.org)

EGMS *Basic* products are *relative* to one of the InSAR measurement points within the same dataset, and the tolerances in any measurement therefore represent a ***precision***. EGMS *Calibrated* and *Ortho* products are anchored to a real-world, GNSS-controlled, geodetic reference frame, and any tolerances in InSAR measurement consequently relate to the 'real world' and are presented as an ***accuracy***.

Ascending & descending geometry

Sentinel-1 is a near-polar-orbiting mission, and 'ascending' and 'descending' are terms relating to the direction of satellite travel during a particular image acquisition (see Figure 32). As the SAR instrument aboard the satellite is right-looking, two distinct geometries of SAR data are acquired when the satellite is flying from north to south as opposed to south to north. These two geometries of InSAR measurements are available in the EGMS *Basic* and *Calibrated* products as two discrete datasets. In the EGMS *Ortho* product, they are combined to constrain measurements to either purely vertical or east-west ground displacements in two discrete datasets.

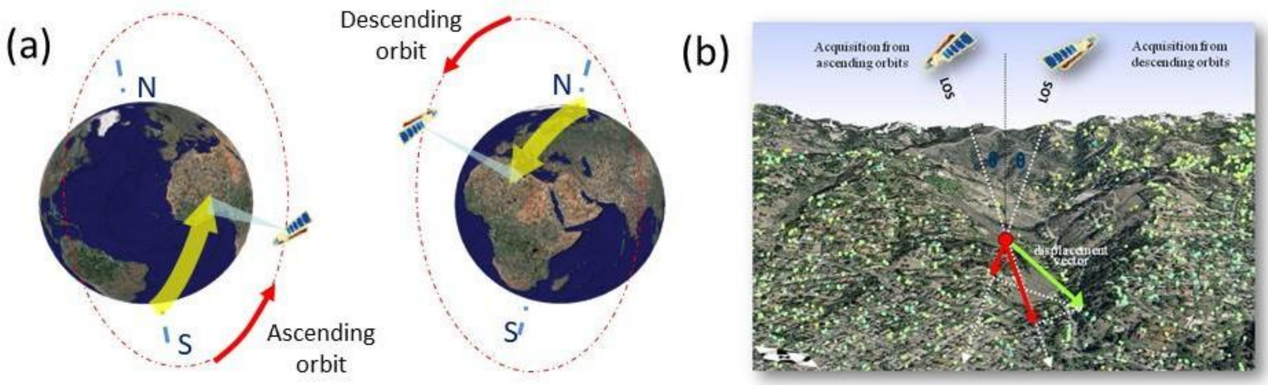

Figure 32 a) All modern satellite SAR sensors orbit the Earth in a near-polar orbit. b) By combining the rotation of the Earth and the orbital paths of the satellites, the entire surface of the Earth is illuminated by two different satellite geometries. When the satellite travels in a descending orbit (from north to south), it views a target area looking westward (in right-looking mode), while during its ascending orbit, that is, when it moves from south back to the north, it views the same target area looking eastward

Azimuth

The flight direction of the satellite. Normally orthogonal to the SAR instrument's direction of look (see Figure 33):

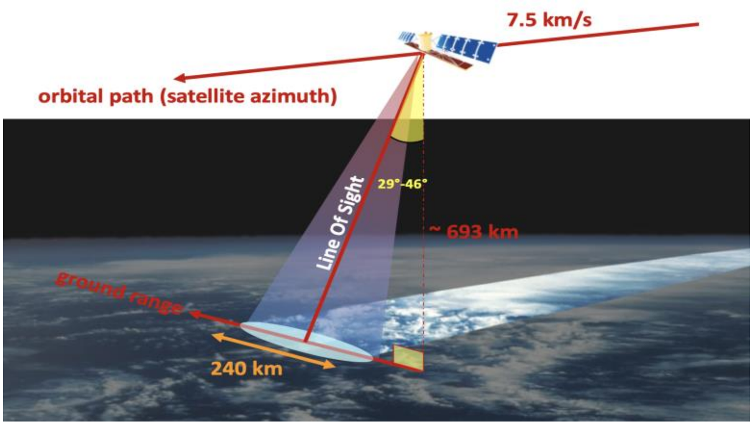

Figure 33 Image acquisition geometry of Sentinel-1

Azimuth of Basic & Calibrated InSAR measurements

The compass direction of the InSAR Line-of-Sight (see Figure 33) measurement (also orthogonal to the satellite flight path).

(Temporal) Coherence

A measure (from 0-1) of the scattering similarity between corresponding pixels in a multi-temporal SAR-image data stack. Growing and moving vegetation typically reduces coherence and prevents reliable InSAR measurement. The lower the coherence, the more noise, the higher standard deviation in the measurement, the overall less precision. Poor coherence is the main reason that InSAR measurement point distribution is not regular. The built environment typically provides high levels of coherence and a corresponding increase in measurement point density.

Colour-map

InSAR measurement points in InSAR velocity maps are colour-coded by average velocity in mm per year. The 'colour-map' legend defines what colour corresponds to what velocity. In practice the variance of velocities is shown as a continuous rainbow of colours, their extremes corresponding to the upper and lower limits of average velocity within the area. EGMS convention follows the norm that green points are stable, red and orange points are moving *away* from the satellite and blue points are moving *towards* the satellite (see Figure 34).

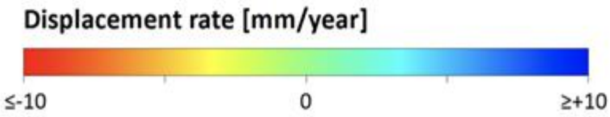

Figure 34 Example EGMS velocity colour-map

Displacement resolution

The minimum amount of displacement (in millimetres) that can be reliably measured by the system between two SAR acquisitions.

Epoch

A time instant or a specific period of time in a succession of temporal events. In InSAR analyses an epoch correspond to a specific acquisition time of a SAR image.

(Geo) locational / positional accuracy

The positional accuracy of an InSAR measurement point in the xy plane (i.e., ground coordinates). Note, the radar response from the many scattering features within each Sentinel-1 20 m x 5 m ground-cell is integrated into a single response, which is then mapped to the centre of each pixel, where in fact the absolute location of scattering dominance is usually unknown without some additional information. Whenever a dominant, pointwise, scatterer is present, surrounded by low-reflectivity objects, it is possible to apply specific algorithms to provide sub-pixel geolocational accuracy. Other variables such as the satellite orbit data and radar system parameters also influence positional accuracy.

Global Navigation Satellite System (GNSS)

A system of (systems of) of satellites providing signals that transmit positioning and timing data to receivers. The concept enables estimation of the absolute (i.e. relative to the WGS84 geodetic datum and within certain tolerances) 3D positioning over time. In order to exploit the strengths of both InSAR and GNSS data, the reference model contains average velocities in 3D (east, north, up) on a 50-km grid. Deviations from the constant velocity model, as well as motion on shorter spatial scales than the reference model, will be estimated from InSAR data with high spatial density.

Line-of-sight / SAR incidence angle

Orbiting SARs are side-looking instruments to enable range measurement. This look angle is defined as the angle between the vertical and the radar beam at the radar platform. Due to the curvature of the Earth, the look-angle is not the same as the *incidence angle*, defined as the angle between the vertical and the radar beam propagation-vector at the surface. Depending on location and range across the imaged swath, Sentinel-1 incidence angle ranges from about 21 to 46 degrees. InSAR measurements are therefore projected in the satellite's 'line-of-sight', an important consideration when considering displacements of unknown direction.

(InSAR) Measurement point

The MP is the InSAR measurement of displacement as represented on a map. Individual EGMS InSAR measurement points can emanate from the radar scattering from either a *single,* high amplitude ground resolution cell (where a dominant, pointwise, scattering centre is present: a Persistent Scatterer - PS), or from *several*, contiguous, amalgamated cells (Distributed Scatterer - DS) if the ground cover is less reflective.

MP density and distribution

MP density and distribution relates to the coverage of InSAR measurement points within a given area of analysis. MP density varies as a function of land cover (e.g., scattering features, coherence, topography), and statistics are available for comparisons of EGMS data against CORINE land cover data. Generally, MP density increases with a built environment where *point scatterers, represented by strong and stable reflectors such as poles and structures,* will dominate, as opposed to a sparser coverage of *distributed scatterers corresponding to relatively stable ensembles of targets such as bare soil or cragged/rocky surfaces,* in more rural landscapes. The spatial density of InSAR measurement points depends heavily on terrain cover: vegetated areas exhibit a low density, while urban areas are more favourable. Also, no measurement points can be identified over water, and, in general, where radar reflectivity changes with time.

Depending on the number of available Sentinel-1 scenes and the dispersion of temporal and geometrical baseline values, *2 m accuracy* can be achieved on the absolute elevation value of each MP, while, depending on the time-span of the dataset, the velocity field can be estimated with a precision *better than 1 mm/yr*. In general, the standard deviation is *better than 4-5 mm* [RD1]. Finally, depending on the radar sensor used for the analysis, the geographic coordinates of the PS can be estimated with an error of a just few meters.

Geometric effects

Side-looking radars are intrinsically limited by the geometric effects of *layover*, *foreshortening* and *shadowing* which make parts of the Earth surface invisible to the satellite. These effects only affect areas of steeper topography (see Figure 35) and prevent or strongly limit the identification of measurement points. The geometric effects are somewhat reduced by the combination of two, opposing look-angles. Refer to [RD1] for a technical explanation of geometric effects.

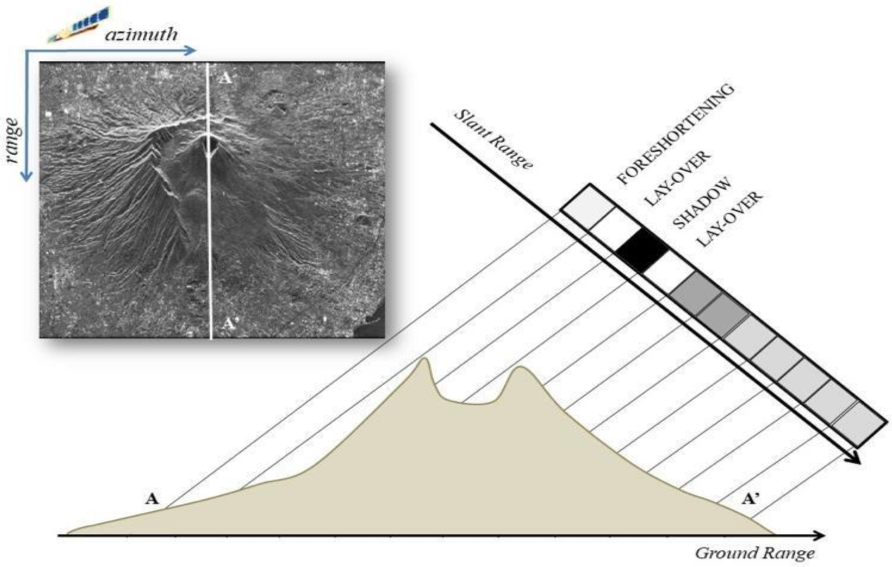

Figure 35 SAR amplitude image acquired over the Vesuvius volcano. Studying a range line passing through the volcanic edifice (section A-A') shows pixels affected by foreshortening, layover, and shadowing, as well as areas with low reflectivity values along the slides facing away from the sensor

(Coordinate) Reference System

A coordinate-based system used to locate geographical entities and involving a specific map projection in relation to a specific Earth ellipsoid. In EGMS, in agreement with other Copernicus services, the Coordinate Reference System (CRS) is ETRS89-LAEA Europe, also known in the EPSG Geodetic Parameter Dataset under the identifier: EPSG:3035. The Geodetic Datum is the European Terrestrial Reference System 1989 (EPSG:6258). The Lambert Azimuthal Equal Area (LAEA) projection is centred at 10°E, 52°N. Coordinates are based on a false Easting of 4321000 meters, and a false Northing of 3210000 meters. The WGS84 reference is used that is based on the *European Terrestrial Reference System 89* (ETRS89), and its version the *European Terrestrial Reference Frame 2000* (ETRF2000).

Reference point

In InSAR, the 'reference point' commonly refers to the InSAR measurement point within a Basic-type InSAR dataset that is assumed to be stable, and to which all other measurement points are relative. The precision of InSAR measurement point time series is statistically dependent on distance from the reference point due to the influence of uncompensated tropospheric and ionospheric components that typically increase with distance. The criteria for reference point selection include: high radar amplitude, high coherence, and central location within the radar image under study, absence of local displacement. The final localisation of the reference point is retrieved by an optimised selection process minimising potential induced trends in the displacement. Reference points are only relevant to EGMS *Basic* products as *Calibrated* and *Ortho* products are made with reference to a GNSS-derived reference frame. Refer to [RD1] for a technical explanation of the role and importance of the reference point in InSAR.

Spatial resolution

The minimum size of feature that can be discerned by the system. In practice with Sentinel-1, this is determined by the dimensions of the acquisition ground-cell which are about 20 m in azimuth by 5 m in ground-range. Only one InSAR measurement is calculated for each ground-cell.

Temporal sampling of Sentinel-1 data

The total number, and distribution over time, of the SAR acquisitions processed to produce the InSAR result under analysis. A regular and dense distribution of acquisitions is preferred for higher quality results. Note, Sentinel-1 data are nominally acquired every six days over Europe.

The temporal resolution relates to the rate at which the Sentinel-1 mission, with two satellites flying 180 degrees apart, re-acquires imagery over the same place. Each satellite acquires repeat data every 12 days, and so together, acquisitions over the same place are made every 6 (six) days.

Time-series data

A *time-series* is a series of data points indexed in time order. An *InSAR time-series* relates to a single measurement point and shows the displacement of that point over time according to each SAR data acquisition with reference to the first acquisition within the epoch analysed (see Figure 36 below). MPs are evaluated according to a displacement model. The *average velocity* of each measurement point given in an InSAR velocity map is derived from the time-series of measurements for each point. Time series data are useful in revealing deviations from the average velocity, e.g. accelerations, and assist in understanding motion trends and evolution (see Figure 36).

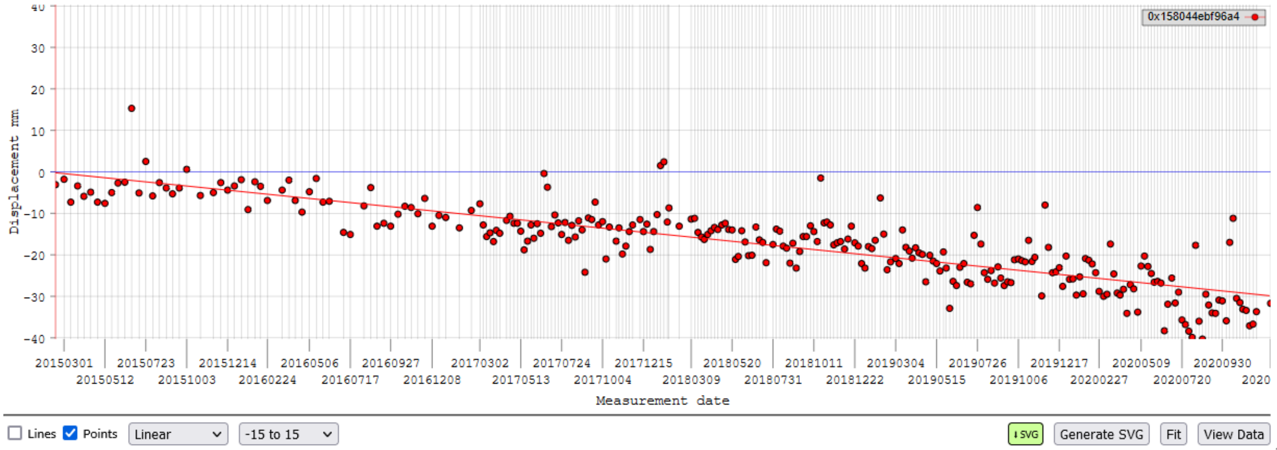

Figure 36 Example InSAR time-series plot. Each point relates to a SAR acquisition and all together they reveal the overall evolution of motion for that measurement point during the time period spanned by the dataset under analysis

Wide area processing vs local analyses

An important fact which should not be neglected when working with InSAR measurements obtained from Wide Area Processing (WAP) is that they are the result of a processing specifically *designed for wide areas*. Processing parameters are carefully tuned to meet project requirements, including those about computational time and memory allocation. These constraints, together with obvious limits on manual quality checks when dealing with *millions* of MPs, creates a differentiation between *local* InSAR analyses customised to a specific application, and WAP results. For instance, in local analyses, the thresholds on phase coherence used to identify MPs are usually set to lower values, since manual interventions can then fix possible phase unwrapping errors [RD1] and/or remove some points that appear as statistical outliers to the processing operator. Therefore, it is not impossible that an *ad hoc* processing of the same dataset used to generate a WAP result but limiting the area of interest to a few tens of square kilometres, to identify different MPs coverages and densities.

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7. TERMS OF USE

The Copernicus programme is governed by Regulation (EU) No 2021/696 of the European Parliament and of the Council of 28 April 2021 establishing the Union Space Programme and the European Union Agency for the Space Programme and repealing Regulations (EU) No 912/2010, (EU) No 1285/2013 and (EU) No 377/2014 and Decision No 541/2014/EU. Within the Copernicus programme, a portfolio of land monitoring activities has been delegated by the European Union to the EEA. The land monitoring products and services are made available through the Copernicus land portal on a principle of full, open and free access, as established by the Copernicus data and information policy Regulation (EU) No 1159/2013 of 12 July 2013.
The Copernicus data and information policy is in line with the EEA policy of open and easy access to the data, information and applications derived from the activities described in its management plan.

8. SUPPORT AND HELP DESK

Product technical support is provided by the product custodian through Copernicus Land Monitoring Service helpdesk at copernicus@eea.europa.eu. Product technical support doesn't include software specific user support, data interpretation or general GIS or remote sensing support.

ANNEX

Table 3 Possible applications of EGMS products for Geohazards

Geohazards	Users	Action	Relevant products
Subsidence	• Energy companies • Urban planning offices • Insurance companies • Military • Cargo and logistic companies • Transport companies • Industry • Estate Agents • Public authorities • Civil Protection	• Construction • Deconstruction • Monitoring • Planning • Risk assessment • Appraisal management	• *Basic* • *Calibrated* • *Ortho*
Landslides	• Urban planning offices • Insurance companies • Transport companies • Industry • Public authorities • Civil Protection	• Construction • Deconstruction • Monitoring • Planning • Risk assessment • Appraisal management	• *Basic* • *Calibrated* • *Ortho*
Earthquake	• Aid organizations • Public authorities • Military • Healthcare • Urban planning offices • Insurance companies • Civil Protection	• Assessing • Help management • Risk assessment • Damage mapping	• *Calibrated* • *Ortho*
Volcanic Activity	• Aid organizations • Public authorities • Military • Healthcare • Urban planning offices • Insurance companies • Civil Protection	• Monitoring • Help management • Risk assessment • Damage mapping	• *Calibrated* • *Ortho*

Table 4 Possible applications of EGMS products for Civil Engineering & Infrastructure

Civil Engineering & Infrastructure	Users	Action	Relevant products
Buildings	• Urban planning offices • Insurance companies • Estate agents • Civil engineering and construction companies • Engineering consultancy companies • Energy supplier	• Construction • Expansion • Renovation • Teardown • Maintenance • Monitoring	• *Basic* • *Calibrated*

Roads	• Urban planning offices • Business enterprise • Road departments • Transport companies • Logistic companies • Toll companies • Tourism sector • Engineering design companies • Insurance companies	• Design • Construction • Expansion • Renovation • Maintenance • Monitoring	• *Basic* • *Calibrated*
Tunnels	• Highway and Railway companies • Insurance companies • Design and Construction companies	• Construction • Expansion • Maintenance • Monitoring	• *Basic* • *Calibrated*
Bridges	• Urban planning offices • Road departments • Transport companies • Logistic companies • Toll companies • Tourism sector • Asset managers • Insurance companies	• Design • Construction • Expansion • Change detection • Maintenance • Monitoring	• *Basic* • *Calibrated*
Railways	• Railway companies • Urban planning offices • Insurance companies • Civil engineering and construction companies • Engineering consultancy companies	• Design • Construction • Expansion • Maintenance • Deconstruction • Recommissioning • Monitoring	• *Basic* • *Calibrated*
Airports	• Airline companies • Military • Transport companies • Government agencies • Civil engineering and construction companies • Engineering consultancy companies	• Design • Construction • Expansion • Maintenance • Deconstruction • Monitoring • Planning	• *Basic* • *Calibrated* • *Ortho*
Ports	• Port operators • Shipping companies • Shipyards • Cargo and logistic companies • Transport companies • Industry • Tourism industry • Energy supplier	• Design • Construction • Expansion • Maintenance • Deconstruction • Monitoring • Planning	• *Basic* • *Calibrated*

Table 5 Possible applications of EGMS products for Energy & Natural Resources

Energy & Natural Resources	Users	Action	Relevant products
Oil & Gas	• Energy suppliers • Industry • Military • Environmental agencies • Cargo and logistic companies	• Construction • Maintenance • Deconstruction • Planning	• *Basic* • *Calibrated*
Power Plants	• Energy companies • Military • Society	• Construction • Maintenance • Deconstruction • Monitoring • Planning	• *Basic* • *Calibrated*
Wind Farms	• Energy companies • Agriculture sector • Urban planning offices	• Construction • Maintenance • Deconstruction • Monitoring • Planning	• *Basic* • *Calibrated*
Power Lines	• Energy companies • Urban planning offices • Military • Society	• Construction • Maintenance • Deconstruction • Monitoring • Planning	• *Basic* • *Calibrated*
Dams	• Urban planning offices • Road departments • Transport companies • Energy supplier • Society • Insurance companies	• Construction • Maintenance • Deconstruction • Monitoring • Planning	• *Basic* • *Calibrated*
Mining	• Energy companies • Mining companies • Risk managers and civil protection	• Mining • Closure • Opening • Excavations • Planning	• *Calibrated* • *Ortho*

Table 6 Possible applications of EGMS products for Cultural Heritage

Cultural Heritage	Users	Action	Relevant products
Heritage management	• Government • Municipalities • Archaeologist • Cultural heritage organisations • No-profit organisations	• Maintenance • Monitoring	• *Basic* • *Calibrated* • *Ortho*