

# COPERNICUS

## LAND MONITORING SERVICE



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## Glossary

1D	1 Dimensional
3D	3 Dimensional
Anc.	Ancillary
API	Application Programming Interface
APS	Atmospheric Phase Screen
ASCII	American Standard Code for Information Interchange
AWS	Amazon Web Services
AWS EC2	Amazon Web Services Elastic Compute Cloud
AWS S3	Amazon Web Services Simple Storage Services
Cal/Val	Calibration and Validation
CLC2018	Corine Land cover 2018
CORINE	Coordination of Information on the Environment
CPC30	Copernicus Participating Countries (of which there are 30)
CPU	Computer Processing Unit
CR	Corner Reflector
DEM	Digital Elevation Model
DIAS	Data Information and Access Services
DS	Distributed Scatterer
ECMWF	European Centre for Medium Range Weather Forecasts
EEA	European Environment Agency
EEA39	European Environment Agency (of which there are 33 member and 6 participating states)
EGMS	European Ground Motion Service
ENVISAT	Environmental Satellite
ERS	European Remote sensing Satellite
ESA	European Space Agency
EO	Earth Observation
EPOS	European Plate Observation System
EPSG	European Petroleum Survey Group

ERA5	ECMWF Re-Analysis 5 (5 meaning fifth major global reanalysis)
ETRS89	European Terrestrial Reference System 1989
EU	European Union
EUDEM	European Union Digital Elevation Model
EUGMS	European Union Ground Motion Service
EUREF89	European Reference System 1989
FAQ	Frequently Asked Questions
GB	Gigabyte
GeoJSON	Geographic JavaScript Object Notation
GIS	Geographical Information System
GMS	Ground Motion Service
GNSS	Global Navigation Satellite System
GUI	Graphical User Interface
H(DS)	Homogenous Distributed Scatterers
HLOP	High Level Operations Plan
InSAR	Interferometric Synthetic Aperture Radar
INSPIRE	Innovation in Science Pursuit for Inspire Research
ISO	International Organisation of Standardisation
ITRS	International Terrestrial Reference System
KMZ	Keyhole Markup language Zipped
LOS	Line of Site
MP	Measurement Point
MB	Megabyte
NWP	Numerical Weather Prediction
PS	Point-like Scatterer
PSI	Point Scatterer Interferometry
QA	Quality Assurance
QC	Quality Control
RAM	Random Access Memory
RMSE	Root Mean Square Error
S1	Sentinel-1

S1A	Sentinel-1A
S1B	Sentinel-1B
S1C	Sentinel-1C
S1D	Sentinel-1D
SAR	Synthetic Aperture Radar
SBAS	Small Baseline Subsets
SLC	Single Look complex
TB	Terrabyte
TBD	To be defined
TOPS	Terrain Observation with Progressive Scans
Web-GUI	Web based Graphical User Interface
WGS84	World Geodetic System 1984

## EXECUTIVE SUMMARY

This document presents the combined Product Specification Document and Service Implementation Plan for the Preparation of the Implementation of the European Ground Motion Service (EGMS). This is considered a dynamic report, representing the current position of EGMS within the InSAR and General user communities while being aware of future developments that may have an impact on the usage and scope of EGMS as it develops. Some key elements considered and represented within this document are highlighted below:

- EGMS, like with any other Copernicus service, should not compete with commercial business but to complement those services to provide an adequate, and in many cases, much needed baseline on top of which valuable, detailed commercial information can provide a next level of information.
- With that in mind, the discussions included within this document focus heavily on the value of EGMS in the context of user requirements considering its advantage to support existing, and potential future advancements in the commercial InSAR domain that are out of bounds of EGMS.
- The users are the primary focus of EGMS not just in terms of user uptake but more so with respect to breadth of usage considering both Direct (experienced InSAR users) as well as Community user groups. EGMS is a service that must be useful to all users. It, therefore, has to be designed considering the widest range of uptake across local, national, regional scales while being valuable to those who use it.
- Users drive the focus and desire for EGMS while also challenging the approach to data dissemination and specification which must be broad enough while also accurate enough to meet a range of requirements.
- This dissemination of data and how a user will interact with EGMS is discussed at length while allowing flexibility in the final approach selected. The recommendations presented outline considerations with respect to accessibility, longevity and ensuring service continuity to the user groups from a proposed ramp up to full implementation phase.
- A ramp up phase has been presented as a first phase of EGMS. This phase, designed to build momentum with the service, will also focus primarily on the elements of most interest to the users while allowing an opportunity to gauge usability, access and breadth of application prior to a perhaps wider rollout. The ramp up focus is described with respect to user groups, applications, methodology, coverage and dissemination.
- As Copernicus services grow, it is expected that EGMS will also grow and evolve to best meet an expected wider community and wider application base. Familiarity and acceptance of ground motion products continues across the industry while also finding a place in new industries such as analytics.
- The ability for EGMS to adapt to future changes in need and desire within the scope and spirit of Copernicus services, as well as future evolution with respect to technology, growing Sentinel constellation etc., is a critical aim of the service that is also touched upon within this document.

The EEA Aurora consortium presents views from across key players within the commercial InSAR community along with InSAR research and value added service providers. This combination of partners has provided a range of inputs, experience and knowledge that is truly complementary while also allowing all parties to consider the most suitable approach for this EGMS service. Experience from similar national services provide the consortia with a breadth of knowledge to engage with and present a comprehensive and dynamic report that is as reflective as possible on current and expected future position while also allowing and expecting adaptations within a future service.

## 1. INTRODUCTION

Copernicus is a European system for monitoring the Earth. Data is collected from different sources, including Earth observation satellites and in-situ sensors. The data is processed and provides reliable and up-to-date information in six thematic areas: land, marine, atmosphere, climate change, emergency management and security. The Land Monitoring Service provides data at scales ranging from local to global. EGMS falls naturally within the Pan-European products provided by the land service, although it could provide local products for specific ground motion problems if required.

Several European countries are developing their own ground motion services. However, Copernicus data acquisition does not follow national borders, and neither do many ground motion processes that are of interest. Processing at a pan-European scale is, therefore, an efficient solution, providing a uniform product for the entire area of interest. Individual nations will be able to take advantage of EGMS data and provide enhanced, harmonised products to their citizens. EGMS will also help disseminate technical experience with the use of operational ground motion data and bridge the gap to user communities in those Copernicus participating states lacking the capability to process and analyse such data by themselves.

The Sentinel missions were designed to supply the data needs of Europe's Copernicus programme. The Sentinel-1A/B satellite constellation carries radar instruments designed to supply images of the Earth in all weather, day and night. An unprecedented amount of Copernicus Sentinel-1 data is continuously being acquired over Europe, with great potential. The European Environment Agency (EEA) has been entrusted to implement a European Ground Motion Service (EGMS), as part of the Copernicus Land Monitoring Service's product portfolio. EGMS will provide ground motion time-series information with full spatial and temporal resolution based on interferometric analysis of Sentinel-1 radar data.

This document builds upon previous work by the members of the EU-GMS Task Force, and has been compiled for the EEA under contract EEA/DIS/R0/19/003, to provide support and guidance for the preparation of the resulting procurement for the European Ground Motion Service.

It is presented in two parts to cover both the specification of the service products (Product Specification Document, PSD) as well as recommendations for how that service could be implemented (Service Implementation Plan, SIP). These separate components have been combined here to provide context and complementarity, and to reduce unnecessary overlap in technical details.

At the core of the considerations within this document, and in the eventual service, is the user. This service should be applicable to as many users as possible. While user requirements are described in detail in Section 3, including several case examples, the following application areas have been identified:

- Natural and man-induced geohazard risk assessment
- Geodesy
- Land management, urban and rural planning
- Climate services
- Infrastructure development and management
- Mining and other natural resources extraction
- Dam and groundwater monitoring
- Insurance topics and litigations
- Structural and civil engineering
- Cultural heritage
- The property market
- Railway and road management

Either directly, or indirectly (via downstream services), the main user communities will include:

- Geological and geodetic surveys
- Road, railway and mining administrations
- Regulators and planners
- Public authorities at European, national, regional and municipal levels
- Industry (infrastructure management, engineering, oil and gas, insurance etc.)
- Academia
- Citizens of Copernicus participating states

It is well understood, and expected, that the end-user community needs will vary, and likely evolve, in terms of size of the area of interest, frequency of updates and precision of measurement. The product types and focus may also change. Section 4 describes the product level considerations, where the main products considered are summarised as:

Level 2a (as an intermediate product):

- Basic displacement information provided in the satellite line-of-sight (LOS) in the original radar geometry grid, with annotated geolocalisation and quality measures per measurement point.
- The product delivered for individual and consistent processing units within each relative orbit of satellite image stacks.
- Produced using community best practices and state-of-the-art algorithms.

Level 2b:

- The level 2b product is based on Level 2a products, integrated into a standardised reference frame using external information such as GNSS network measurements.
- For products integration and mosaicking, best geodetic practices are utilised.
- EUREF network is exploited for datum connection purposes.
- **This is the core product and main deliverable of the EGMS.**

Level 3:

- East-West and Up-Down deformation rates produced by combining Level 2b data from ascending and descending orbits.
- This product will be produced on a grid with 100 m x 100 m pixels.

The core of this document seeks to provide consideration for all major factors associated with a ground motion service on this scale including a proposed timetable for implementation which considers an overview of the eventual service and how it could mature from demonstration to operational status. This information can then allow for appropriate decisions to be made with respect to the eventual scope and requirements that will be translated into the procurement documents.

The rest of this document is structured into the following distinct sections:

- Section 2, Background to technology
- Section 3, Service Implementation Plan including user needs
- Section 4, Product Specification Document
- Sections 5 to 11, Appendices A to H, providing additional and detailed technical information for reference

## 2. BACKGROUND ON TECHNOLOGY

This section provides the technological background on which EGMS is based. The section focuses on giving the reader an overview of the InSAR technique; its basis and limitations. Since EGMS is strongly linked to the Copernicus program, also an introduction to the key features of the program and its relevant satellites is included.

Several of the aspects sketched in this section are addressed in a more rigorous and academic way in the Technical Appendices.

*Definition of time series InSAR: Spaceborne time series Synthetic Aperture Radar Interferometry (InSAR) is an engineering technique for the extraction of information from sets of satellite radar images, enabling measurement of millimetre-scale movements from space.*

The InSAR technique has been developed and applied over several decades, for the purpose of mapping and monitoring the movements of natural and anthropogenic features from space. The technique is nowadays well established in several sectors, ranging from civil engineering to the energy sector.

### 2.1. Ground motion mapping with Spaceborne Radar

As remote sensing geodetic observations become increasingly available, and the frequency of satellite acquisitions continues to increase, spaceborne monitoring techniques have gained a stable role in a number of sectors. Spaceborne monitoring provides a non-invasive way to map and monitor small and large areas at comparable cost (in comparison to in-situ conventional survey techniques). Ground motion information from spaceborne missions is used to optimise the conventional survey process by supporting in prioritising and managing frequency and density of in-situ measurements.

#### 2.1.1. Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) is a microwave imaging system with cloud-penetrating capability. Due to the active nature of a radar, it has day and night operational capabilities. SAR is a versatile technology, with its key capability to not only create images of features but rather to provide remote measurements over large geographic areas.

A SAR instrument transmits an electromagnetic signal and records the backscattered energy from the earth's surface. The recorded data are processed into a two-dimensional image in radar coordinates: one dimension is the travel time along the satellite orbit (azimuth time), and the other is the closest-approach distance from the satellite to each pixel (slant range).

The signal contained in each pixel is a complex value. The pixel value is related to the sum of backscattered signals from all the individual scatterers within the pixel. With corresponding interpretation for an:

- The *amplitude* of a SAR image: a measure of the nature of the scattering from the pixel
- The *phase* of a SAR image: a measure of (two-way) distance from the radar to the pixel on the earth's surface.

Both characteristics play important roles in the context of ground motion estimation.

## 2.1.2. Interferometric SAR (InSAR)

As mentioned, the phase signal contains the necessary information about the distance from the satellite to target, which as a time series would indicate ground motion. However, it is in practice only possible to determine the absolute satellite-to-target distance with decimeter-scale precision and comparable accuracy. Thus, high precision measurements of *absolute* ground motion are not directly available.

However, by using a technique called *Interferometric SAR (InSAR)*, we may derive very accurate information about *relative* ground motion between two points on the ground during the period between two image acquisitions. This is achieved by exploiting the phase *change* between two SAR images acquired in the same satellite geometry at different times, known as an *interferogram*. It is possible to derive ground motion maps over large areas with high spatial resolution and millimetric accuracy.

Due to the periodic nature of the phase signal, differential distances that differ by an integer multiple of the wavelength introduce exactly the same phase change. In other words, the phase of the SAR signal is a measure of just the last fraction of the two-way travel distance that is smaller than the transmitted wavelength. This phase ambiguity (i.e. phase wrapping) is the source of one of the hardest challenges faced by interferometric processing systems.



Figure 2-1. Image of an earthquake. It shows the surface displacement associated with the June 1992 magnitude 7.3 earthquake in Landers, seen by interferometric processing of two images from the ERS-1 C-band satellite, [Massonnet 1993]. One full colour cycle in the interferometric fringes represent a change of 28 mm in the ground-to-satellite range between pre- and post-earthquake images. Solid lines show the surface rupture as mapped in the field. The picture shows the cover page of Nature, Vol 364, 8 July 1993 Issue no. 6433.

### 2.1.2.1. Mapping millimetric ground motion with InSAR

The phase of a SAR signal is influenced by many more components than just the ground motion. To isolate the ground motion, the other phase components must be mitigated, most importantly:

- Atmospheric variations (ionosphere and troposphere)
- Topography
- Number of phase cycles

Some of these components can be removed with auxiliary information, e.g. a Digital Elevation Model (DEM) that can be used to remove the influence of topography, while numerical weather model data can be used to mitigate the effects of atmospheric variations. However, we will always be left with some components that cannot be modelled, and therefore need to be estimated from data. These include:

- Residual topographic contribution due to DEM inaccuracy, typically due to buildings not being included in the DEM. This contribution is necessary to estimate the correct 3D position of each pixel, which is a very important part of the final product.
- Turbulent atmospheric components that cannot be predicted with weather models.
- Residual long-wavelength atmospheric components
- Spatial and temporal unwrapping of the phase signal related to ground motion

Since we have several unknowns per phase observation, the problem of separating these phase components is inherently ill posed, and needs to be resolved using assumed constraints.

Using certain assumptions on the statistical properties of the atmospheric phase contribution, as well as a smoothness assumption about the desired ground motion signal, it is possible to constrain to a numerical solvable problem. A single interferogram is not sufficient for this. Thus, a time series of SAR images from the same satellite geometry is required in order to:

- Capture variations in the ground motion signal over time,
- Reliably exploit the statistical properties of atmosphere for mitigation of errors.

### 2.1.2.2. Time-series InSAR: tool for reliable estimation of ground motion

During the last two decades, a large variety of InSAR time series analysis methods have been published. Broadly speaking, these fall into three main categories, with different characteristics:

- Methods for analysis of pointlike scatterers (PS)
- Methods for analysis of distributed scatterers (DS)
- Methods that exploit both PS and DS

These methods may employ different approaches for time series analysis, but they all generate ground motion estimates, which can be compared. However, each of the methods inherently possesses unique strengths and weaknesses, and no method can provide optimal results for all use cases. This means that for a generic service, it is foreseen that a set of complementary methods will need to be applied.

Many different scattering mechanisms can be identified in SAR images and can create good radar targets, suitable for interferometric analysis. Simple, basic, mechanisms originate from single, double or trihedral reflection from material whose electromagnetic characteristics do not vary with time (at least compared to the duration of the InSAR analysis) are typically referred to as persistent scatterers.

Pointlike Scatterers (PS) typically belong to the family of persistent targets and correspond to single dominant scatterers within their resolution cells, exhibiting a very stable value of reflectivity as a function

of time and possible variations in acquisition geometry. Many PS are usually available in urban areas and most of them correspond to man-made structures (poles, antenna, metallic objects, buildings, etc.).

Distributed scatterers (DS), exhibiting fairly good coherence in some interferograms but not all, are identified from homogeneous ground, scattered outcrops, debris flows, non-cultivated lands and desert areas. They typically correspond to natural targets and originate by a multitude of individual scattering centres distributed over a volume or a surface and can be described only in statistical terms. DS are characterised by lower reflectivity values compared to PS, but their information content can be improved by spatially averaging neighboring samples with similar statistical properties. A comparison of the results of DS and PS processing is shown in Figure 2-2.

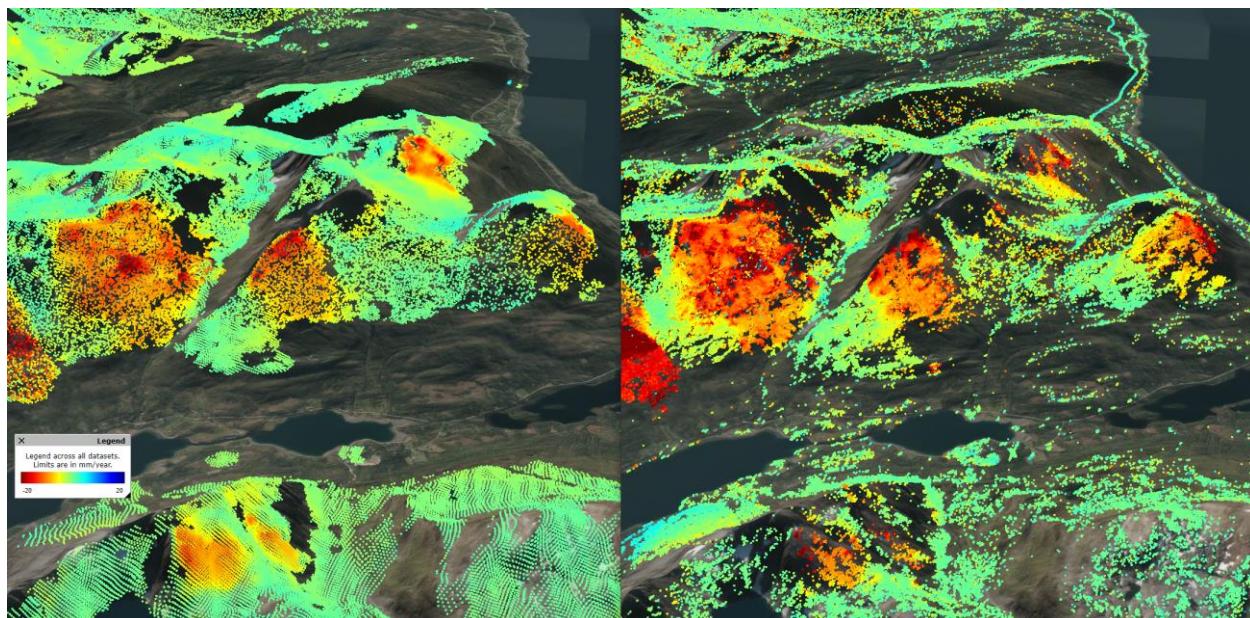


Figure 2-2. Comparison of DS (left) and PS (right) based processing of a mountainside in northern Norway with moving landslides. Although the input C-band datasets differ in resolution (Radarsat-2 fine mode, 2009-2018 on the left; Sentinel-1, 2015-2018 on the right), it is clear that DS processing increases the area with recovered velocities.

The most recent multi-interferogram techniques can identify both families of measurement points, PS and DS. We refer to these as hybrid PS/DS techniques. The advantages of adding DS to the results of a typical PS analysis depends on the area of interest and the type of land cover. The improvement is quite modest over urban areas, where most of the radar targets suitable for InSAR analysis are deterministic and therefore corresponding to PS, but it can be significant over non-urban areas. An example is shown in Figure 2-3.

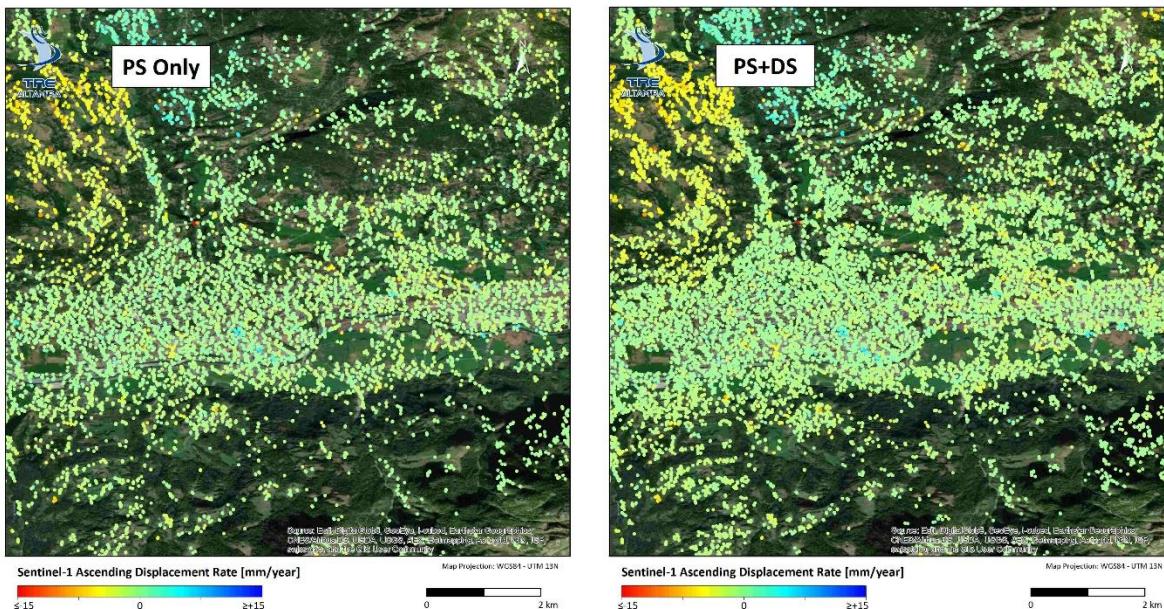


Figure 2-3. Visual comparison of the results obtained from the processing of 150 Sentinel-1 scenes acquired over Aosta valley, using a standard PS analysis vs a hybrid technique, where both PS and DS targets are both properly identified.

Despite challenges and limitations, InSAR provides a unique perspective for mapping and monitoring ground motion. It is remote and therefore non-invasive in nature, and its capability to provide displacement measurements over wide areas makes it a cost-efficient resource and a perfect technique for implementation in an operational service. Moreover, with the introduction of the Sentinel-1A/B satellites, the accuracy of the measurements has reached unprecedented levels (provided that the technique is properly applied) that no conventional in-situ method can offer.

### 2.1.2.3. InSAR based Ground Motion Products

The basic product output of any InSAR based ground motion estimation is a database of measurement points, each with a time series of line-of-sight ground motion measurements relative to a local reference point and a given reference time. In addition, each point has associated metadata, including a 3D position, and other annotations (line-of-sight vector, quality measures, etc.). This product is also frequently referred to as Level 2a product.

For many typical single use cases, this basic product is sufficient. However, for a large-scale service, it is necessary to harmonise all basic products with respect to a well defined datum. Using overlapping analysis areas, it is possible to do this in a relative manner, leaving only a single reference point. However, it is preferable to exploit external information, which in practice, considering the spatial scale of the problem, is only available from GNSS networks. Assuming a uniform model for ground motion on a 10+ km spatial scale, it is possible to harmonise all basic products. This product is referred to as Level 2b.

A 2D product with components in East-West and vertical directions can be derived for all areas with measurements in at least two line-of sight geometries. Due to different coverage of measurement points for different line-of-sight, gridding to lower resolution is generally needed. This product is referred to as Level 3.

#### 2.1.2.4. Quality Standards & Validation

In order to successfully exploit InSAR derived ground motion products in an end-user application, it is important to associate quality information with the product.

Typically, a user will need to know:

- The accuracy of each measurement time series and/or its parametrisation.
- The location of the measurement point

While a complete error model for InSAR ground motion estimates is not straightforward and subject to assumptions, it is possible to derive a number of representative measures that can serve as a proxy for quality. Common for all such measures is that some assumptions or apriori information about the motion are needed.

InSAR also faces the resistance frequently encountered for acceptance and adoption of disruptive technology, especially considering the significant investments made in the past in alternative survey technologies. To overcome this resistance, a number of validation campaigns took place over the past decades, showing to the users that InSAR provides comparable reliability with respect to conventional in-situ techniques for all scenarios applicable to EGMS.

### 2.1.3. Challenges, Limitations & Opportunities

As any other geodetic technique, InSAR has its limitations. This section outlines the most crucial ones that will have to be considered in the context of the deployment of an operational service.

#### 2.1.3.1. Geolocalisation

Measurement points in InSAR depend on a large number of factors (e.g. materials, geometric shape, orientation, etc.). The precise localisation of the measurement points is a necessary part of any InSAR processing workflow. One of the conundrums of InSAR time series analysis is that the ground motion is available with millimetric precision under favourable conditions, while it is not always well known what object on the ground you measure or where exactly it is located. Typical location uncertainty is in the interval 1-15 meters, depending on satellite configuration.

#### 2.1.3.2. Relative nature of the technique

InSAR measures the relative motion between points on the ground with very high accuracy, but cannot directly measure an absolute motion. This implies that external data is needed in order to reference the ground motion estimates to an absolute frame of reference. Typically, GNSS networks are exploited for resolving this issue.

#### 2.1.3.3. Opportunistic nature of the technique

InSAR exploits so called “targets of opportunity”, meaning that reliable ground motion can only be derived for certain pixels. Whether ground motion data can be derived for a given pixel, depends on many factors. But in summary, a pixel can be used for ground motion estimation if the contributing scatterers within a single pixel don’t change their relative position over long periods with more than a fraction of the radar wavelength (5.6 cm in the case of Copernicus Sentinel-1 constellation), which is called *coherent scattering*. Such targets of opportunity typically include urban infrastructure, bare soils, and rocky terrain. On the other hand, water bodies and dense vegetation will not be possible to measure. In addition, changing snow cover will exclude large regions from InSAR based ground motion analysis for part of the year. For

EGMS, this mostly has implications for the Nordic countries, and in mountain regions in other parts of Europe.

#### 2.1.3.4. One-dimensional motion estimates

A radar only measures the distance from antenna to target, not the direction the signal comes from. We can derive the absolute location of each pixel using a 3D model of the earth, with precision in the metre range or better. However, measuring the absolute motion is not directly possible. Motion in a direction that does not change the distance from the radar is not observable with millimetric precision. This means that from a single InSAR analysis, we can only measure the change in distance, i.e. the motion component along the direction from antenna to target, the so called *Line of Sight (LoS)*. The ground motion estimates are thus measures of a one-dimensional (1D) component of the true three-dimensional (3D) motion. However, since multiple 1D components are present for each location, it is possible to derive motion in two directions: vertical and east/west. SAR sensors in polar orbits are unfortunately largely insensitive to motion in the north/south direction.

### 2.2. Copernicus Program & Sentinel-1 Mission

Copernicus is the world's largest Earth observation programme, directed by the European Commission in partnership with ESA ([www.copernicus.eu](http://www.copernicus.eu)). The programme went live in 2014 with the launch of the first of the Copernicus Sentinel satellites, Sentinel-1A, a high-quality radar specifically configured for operational InSAR service provision. It was joined a year later by Sentinel-1B, an identical sister satellite placed in orbit 180° apart.

Together, the two satellites provide at least two InSAR-capable measurements of the entire European continent every six days. In addition, almost all parts of the world's land masses outside Europe are imaged with regular intervals of 6, 12 or 24 days.

Sentinel-1 has embodied a positive step-change for InSAR technology. The Sentinel-1 satellites provide reliable global coverage, combined with a free and open data policy, a revisit time of six days from at least two different look angles, an overall high coherence between acquisitions and an innovative acquisition mode. Furthermore, since follow-on satellites are already planned, robustness and continuity of the mission are already confirmed for the next decade.

The technical impact of the Sentinel-1 characteristics on InSAR, in context of EGMS, is explained in detail in the technical appendices.

### 2.3. Large-scale Applications: Opportunities & Challenges

The task of running an InSAR analysis on a stack of hundreds of SAR images is not a trivial one. It requires a complex processing chain with many challenging steps. The workflow developed to analyse SAR images covering a small area of interest is in practice often not scalable to the dimensions of an entire country, let alone a continent. The computational requirements and the post-processing requirements are strongly dependent on the number of images, the extent of the area and the number of acquisition geometries. Moreover, the complexity of the process and the number of intermediate steps require a carefully thought through quality control process.

However, when properly set-up and managed, the application of InSAR on large scales brings a considerable added value to a large cross section of users; added value that can not be provided in any other way at the same price tag.

EGMS can represent a game changer for many users providing a completely new and extremely valuable information layer to them. However, it requires, just as many other techniques, true experts to be properly deployed for operational use. This is even more applicable when looking at the scales relevant for EGMS.

## 2.4. Summary

InSAR has proven to be a remarkable technology and an indispensable operational tool for mapping and monitoring of ground motion in many fields. Within a large number of use cases, InSAR has over the last 20 years proven to be complementary, supplementary, disruptive and cost-efficient capability with respect to conventional in-situ techniques. The Copernicus mission, with free and open data, high coverage and operational nature, is a game changer that has rendered the 'idea' of a continental scale service like EGMS a realistic product.

Just as with any other techniques, InSAR has its limitations. However, these limitations can be mostly accounted for and partially overcome by the experience, knowledge and on-going research, of the InSAR experts. With proper analysis, invaluable information can be derived about the ground motion on a very large number of measurement points Europe wide.

## 2.5. References

[Colesanti 2003]: Colesanti C., Ferretti A., Prati C., Rocca F. Monitoring landslides and tectonic motions with the Permanent Scatterers Technique, *Engineering Geology*, Volume 68, Issues 1–2, 2003, Pages 3-14, ISSN 0013-7952, [https://doi.org/10.1016/S0013-7952\(02\)00195-3](https://doi.org/10.1016/S0013-7952(02)00195-3).

[Massonnet 1993]: Massonnet, D. et al. The displacement field of the Landers earthquake mapped by radar interferometry. *Nature* 364, 138–142 (1993)

### 3. SERVICE IMPLEMENTATION PLAN (SIP)

#### 3.1. Introduction

The service implementation plan below provides necessary guidelines for the implementation of EGMS. The ambition for EGMS is to meet the needs of as many end-users as possible, given reasonable boundary conditions, such as coverage and update frequency while also considering future evolution of the service. This section summarises the end-user requirements and evaluates how EGMS can or cannot meet them, either during the production phase or future evolution of the service. We present a processing methodology based upon the InSAR community consensus and describe the necessary production system. Quality of both the service and the end products need to be assured, and we suggest methods for both internal quality control and external validation. Finally, EGMS will only be successful if potential end-users can find and can use the data for its purposes. For this reason, we discuss end-user requirements for data access and recommend solutions for dissemination and visualisation. We also discuss how the service can evolve to meet the needs of more users.

#### 3.2. End-user requirements

##### 3.2.1. User types

End-user community needs will vary, in terms of size of the area of interest, frequency of updates and precision of measurement. However, two crucial characteristics shall be ensured for the EGMS service:

- The service shall be designed and deployed to allow unrestricted and timely access to ground motion information for all citizens in the EU and Copernicus participating nations.
- The products delivered by the service will be standardised in order to be useful for as many applications as possible.

Either directly, or indirectly (via downstream services), the main user communities will include:

1. Geological and geodetic surveys
2. Road, railway and mining administrations
3. Regulators and planners
4. Public authorities at European, national, regional and municipal levels
5. Citizens of Copernicus participating states
6. Industry (infrastructure management, engineering, oil and gas, insurance, etc.)
7. Academia

##### 3.2.2. Benefits of EGMS and use cases

Many potential end-users of ground motion data are not currently aware of InSAR and the information it can provide. An example of this is the monitoring of deformation related to construction projects such as tunnels. In a typical tunnel project, millions of euros are spent monitoring the stability of buildings and infrastructure around the tunnel path, using in situ measurements. These costs could be reduced dramatically by supplementing with InSAR-based ground motion data. However, knowledge of its existence and capability are often largely limited. Such applications typically require the purchase of costly SAR data, and satellite acquisitions often must be planned. A potential end-user may have to wait two or more years before there is sufficient data to provide reliable ground motion data can be produced. By

leveraging the data provided by EGMS, InSAR providers can concentrate on offering monitoring services based on high-resolution radar sensors (such as TerraSAR-X and COSMO-SkyMed), which are more suitable than Sentinel-1 for monitoring individual structures or local phenomena. Thus, EGMS will stimulate the extended and applied use of satellite-based ground motion data, both in the public and commercial downstream sectors in Europe.

EGMS will also begin to turn ground motion data into a standard commodity. Engineering and geodetic service companies often act as value-added providers of ground motion data to end-users who might not be able to use the data directly. EGMS ground motion data will act as an important complementary information source within their analyses. In addition, EGMS data will reveal many previously unknown locations with movements causing infrastructure problems and challenges where countermeasures need to be implemented by the public or private sector, hence leading to new business opportunities within risk management and protection of assets. It is expected that once ground motion data is made widely available, new downstream products and services will appear.

Note that with InSAR it is not possible to directly provide a measure about the integrity of infrastructure, but it is possible to monitor the target objects and the area around them, and based on the observed results, formulate a hypothesis about infrastructure health.

The InSAR technique used as a basis for the EGMS service has a variety of possible applications. In the following sections, several applications are described. However, it is to be expected that with the evolution of the technique also the application possibilities for the EGMS service could be extended. Below are listed some possible use cases and their technical requirements.

### 3.2.2.1. Civil engineering

Measuring and monitoring movements and/or deformation of infrastructures on a national, regional or local level. Infrastructures are affected by natural and anthropogenic phenomena such as thermal variations or soil type and groundwater variations influencing the stability of foundations. In many situations, the responsible entity may not be aware that the motion is occurring. In all cases, there will be concerns about changes in motion, whether unstable infrastructure begins to move, or known motion accelerates. Local and regional subsidence effects have been observed over areas where the extraction of water from natural underground aquifers outpaces the natural or assisted recharge of the aquifers. This phenomenon has the potential to cause widespread damage to below- and above-ground infrastructure, due to rapid or differential settlements.

For infrastructure construction projects the EGMS will provide baselines of ground motion, which can be used in the planning phase. This will help to assess the risk for ground motion induced damages to the planned infrastructure, as well as it will provide an overview over pre-existing ground motion.

The effects on several types of infrastructures could be monitored within the EGMS scope.

#### Use cases

- Buildings
- Power plants
- Roads
- Bridges
- Railways
- Airports
- Ports
- Dams

- Dikes
- Reservoirs
- Levees
- Canals
- Tunnels
- Pipelines
- Sewage Systems
- Groundwater aquifers
- Water protection infrastructure

#### Benefits

- Support site selection processes by providing information on existing surface motion
- Provide assets stability information
- Select and prioritise maintenance for critical infrastructure
- Create a common picture across stakeholders involved in budgeting and management of maintenance projects

#### **3.2.2.2. Mining**

Monitoring mining sites before, during and after the extraction activities take place. In particular, it is worth noting that across Europe hundreds of coal mines, most no longer active, have led to subsidence. In many cases, once the mining operations have been suspended, groundwater filling the mine workings leads to rebound. There have been many cases of ground collapse over abandoned mine shafts. Many of these mines are poorly documented, or completely undocumented. Sites used for storing tailings have to be carefully monitored in order to identify potential leakages in a timely manner.

#### Use cases

- Active underground and open pit mines (metals and minerals)
- Abandoned mines
- Tailings and stockpiles

#### Benefits

- Provide a map of the mining sites (active and inactive)
- Support early warning, monitor sites for possible risks
- Tailor deployment of surveillance crews

#### **3.2.2.3. Energy sector**

The InSAR technique is widely applied in the energy sector to monitor production-induced phenomena. Such activities have an impact on the local and regional level by potentially causing subsidence and therefore affecting local infrastructures.

#### Use cases

- Mapping of subsidence at and around the extraction sites
- Geothermal activity

- Gas extraction
- Hydropower dam/reservoir monitoring
- Underground gas and CO<sub>2</sub> storage
- Production plant stability monitoring
- Fine-tuning injection strategies
- Integrity monitoring of pipelines, production plants, etc.
- Fracking

#### Benefits

- Cost-effective monitoring
- Establish baseline of ground motion before start of development
- Better understanding of the effect of activity on surroundings

#### **3.2.2.4. Motion of landforms**

Catastrophic slope failures of various types have claimed the lives of hundreds of people in Europe over the last century. Often, these failures show many years of slow movement, followed by an acceleration phase prior to collapse. It is important to identify such unstable slopes and evaluate their risk to society. Once potential failure areas are detected, they must be monitored over time to identify any acceleration. Typical landslide applications are mapping, monitoring and state of activity estimation.

A periglacial landform is a landscape feature resulting from the action of intense frost, often combined with the presence of permafrost. Examples include rock glaciers, solifluction sheets, pingos and thermokarsts.

#### Use cases

- Landslides
- Periglacial landforms

#### Benefits

- Provide a baseline for the identification of potentially risky and/or critical areas to prioritise on a more localised monitoring technique.
- Mapping of new landslides or other types of slope dynamics to update existing databases and catalogues.
- Monitoring of state of activity for active landslides (or other types of slope dynamics)
- Improved natural hazard risk mapping for urban planning or the planning phase of infrastructure projects.

#### **3.2.2.5. Seismic and tectonics**

Monitoring of areas prone to earthquakes, to tectonics shifting and/or volcanic activity.

#### Use cases

- Volcanic inflation/deflation
- Tectonic movements

## Benefits

- Provide a better understanding of the zones surrounding volcanoes and their hazard zones.
- Identifying and quantify differential movement across tectonic boundaries and therefore improving understanding of large-scale tectonic deformation.

### 3.2.3. Use case categories

In Table 3-1, many of the use cases listed above are categorised by their feature type and typical rates of movement. Naturally, as many of these types of ground motion are highly variable and can fit several categories of movement. The table is meant to be illustrative, not exhaustive.

Table 3-1. Categorisation of use cases in the context of EGMS. The list is not exhaustive.

Time scale	Localised feature [< 5 km]	Linear feature	Extended feature [> 5 km]
<b>Stable</b>	Stable infrastructure Bedrock	Stable roads, railways, dikes, levees, canals, etc.	Bedrock / bare soil
<b>Slow [&lt;30 mm/yr]</b>	Subsidence of any type of infrastructure: Buildings, Airports, Ports, Dams, Dikes, Pipelines, Power plants, Reservoirs, Tunnels, Sewage Systems, Groundwater aquifers, etc.  Landslides  Abandoned and active mines	Roads, Railways, Dikes  Levees, canals, and other water protection infrastructure  Pipelines  Geothermal activity	Large landslides  Volcanic inflation/deflation  Activities associated with shale gas  Postglacial rebound  Sealevel changes  Abandoned and active mines  Geothermal activity
<b>Fast [30-200 mm/yr]</b>	Landslides  Salt mine	Levees, canals, and other water protection infrastructure	Large landslides  Volcanic inflation/deflation  Oil and gas extraction  Active mining
<b>Rapid [200++ mm/yr]</b>	Active rock glacier  Debris flows  Rock avalanches	Precursor to infrastructure failure  New landfill for road/railroad	Gas storage  Groundwater overexploitation
<b>Seasonal or weak nonlinear</b>	Aquifer  Groundwater affected areas  Tailing dams	Linear infrastructure on groundwater affected land  Precursor to linear infrastructure failure	Gas storage  Aquifers

	Dikes Bridges Precursors to landslides, mudslides, infrastructure failure, etc. Periglacial landforms		
<b>Transient or strong nonlinear</b>	Precursor to infrastructure failure Settlement of new landfill Closed/abandoned mine collapse Tank storage (water, gas, oil) Tailing dams Active rock glacier Failing landslide/mudslide/rockslide	New landfill for road/railroad Precursor to linear infrastructure failure	Open-pit mining
<b>Instantaneous</b>	Catastrophic failure of building infrastructure Failing landslide/mudslide/rockslide Sinkhole	Catastrophic failure of road/railroad segment	Earthquake Volcanic eruption

### 3.2.4. Technical requirements categories

Each of these user groups has requirements specific to the applications described above, and five main categories of requirements can be identified:

- Spatial Resolution
- Temporal Resolution
- Accuracy
- Coverage
- Update frequency

Spatial resolution is considered according to the scale of displacement patterns. Low resolution (100 m) would be sufficient for regional-scale displacements, while medium resolution (20 m) would be needed for localised displacement patterns, e.g. landslides, mining sites or a group of houses. High resolution (<5 m) is considered when the displacement is on a building or sub-building level.

Temporal resolution refers to the acquisition frequency, i.e., the revisit period by the satellite for the same orbit configuration. The temporal resolution affects the maximum displacement velocity that can be observed. Low temporal resolution refers to a revisit period of 30 days or more; medium temporal

resolution refers to a revisit period between 10 and 30 days, while high resolution means a revisit period of less than 10 days.

Accuracy, in a general sense, refers to how representative the measurement is of a real-world process (i.e. deformation on the surface of the Earth). The accuracy of a measurement is determined by comparison with external reference measurements (i.e. ground-based geodetic surveys). In radar remote sensing applications, the term 'accuracy' may encompass both the accuracy and precision of a measurement. Precision is often confused for accuracy when, in reality, precision is simply a measure of the quality (i.e. repeatability). While some user groups require only sub-meter accuracy, others require sub-centimeter or better accuracy for measurements to be useful. Current earth observation capabilities outpace most end-user groups' desired accuracy threshold.

Coverage refers to both the locality and the spatial extents of the measurement. Many user groups' applications focus on urban or built environments, the rural-urban interface, or other anthropogenic activities, while other applications are related to natural or geologic processes. In the example of urban infrastructure monitoring, targeted coverage with limited spatial extent is required. In another example of monitoring regional subsidence, wider coverage across urban and natural terrains is required to provide continuous results.

Update frequency refers to the frequency with which the displacement data is updated, although the full deformation history is recorded for each data point. A bi-yearly or yearly update frequency is considered low update frequency. Medium update frequency refers to bi-monthly or monthly updates. For high update frequency, bi-weekly or weekly updates would be necessary. For applications that require a higher update frequency, a short latency period between the last data acquisition and publication of the end-user product is also important.

EGMS will provide consistent data at a continental scale. Spatial resolution, accuracy and coverage will, therefore, need to be maximised based on this while also considering the applicability to as many users as possible. The EU-GMS white paper (2017) and the Ground Motion cost-benefit analysis (PwC 2018) both suggest an annual update frequency. The future evolution of the service may provide a higher update frequency to support some monitoring applications. However, it should be noted that increased updates of the EGMS service may have an impact on the market of commercial InSAR service providers.

### 3.2.5. Requirements analysis

The use cases have been grouped in Table 3-1 above, based on the size and/or nature of the features addressed and of the type of root cause. Given the objective and scope of the EGMS, this analysis focuses typically on mapping and monitoring activities for which ground motion information can be provided within months of latency. Table 3-2 below provides the technical requirements for each group of end-users.

Table 3-2. Technical requirements for selected end-user categories.

Description	Spatial resolution	Temporal resolution	Accuracy	Coverage	Update frequency	Relevant product(s)
<b>Localised infrastructure:</b> buildings, airports, ports, dams, bridges, dikes, power plants, tank storage, ...	0.1 - 20 m	1-30 days	Equivalent with other geodetic techniques: ~mm scale relative to local reference	Localised	<6 months	Level 2a Level 2b PS

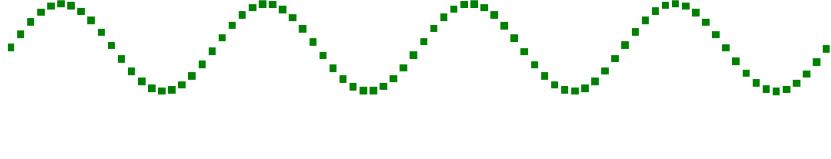
<b>Linear infrastructure:</b> roads, railways, tunnels, pipelines, dikes, ...	0.1 - 20 m	1-30 days	Equivalent with other geodetic techniques: ~mm scale relative to local reference	Extent of linear infrastructure (0-1000+ km)	<6 months	Level 2b PS
<b>Extended features:</b> reservoirs, groundwater aquifers, sewage systems, airport runways, gas extraction fields, gas storage, mines, ...	20 - 100 m	30+ days	Equivalent with other geodetic techniques: ~mm scale relative to local reference	10+ km	6+ months	Level 2b Level 3 PS DS
<b>Natural disasters:</b> Earthquake, volcanic eruption	100 – 200 m	1-15 days	cm-scale	10-1000+ km	Per repeat cycle, On demand (depending on type of volcanic activity)	Level 2b Level 3 PS DS
<b>Motion of landforms:</b> landslides, periglacial landforms	10 - 200 m	1-30 days	Equivalent with other geodetic techniques: ~mm/yr scale over long spatial scales	10-1000+ km	6+ months	Level 2a Level 2b Level 3 PS DS
<b>Tectonic phenomena:</b> postglacial uplift, tectonic fault creep	200+ m	30+ days	Equivalent with other geodetic techniques: ~mm/yr scale over long spatial scales	50-1000+ km	6+ months	Level 2b Level 3 PS DS

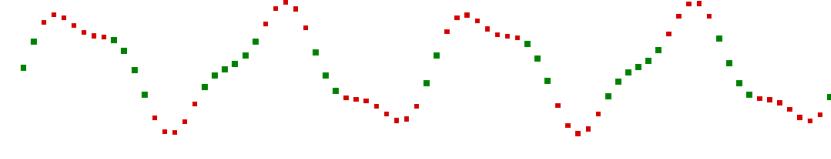
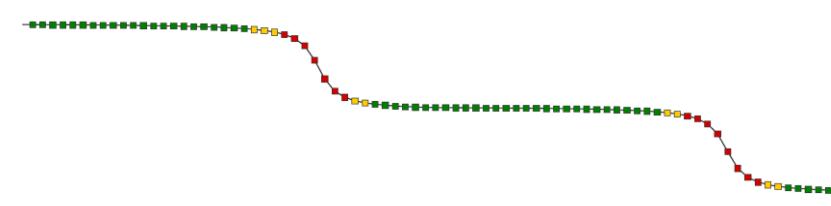
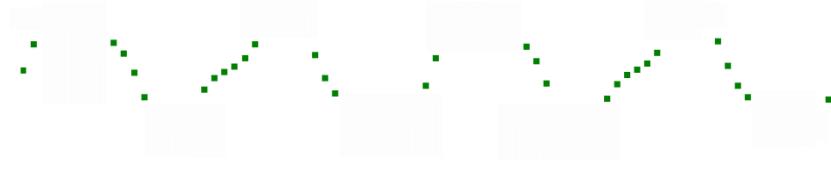
### 3.2.6. Deformation regimes

In order to increase understanding of the various deformation regimes being addressed in this section (e.g. stable, linear, quasilinear, etc.) and to better define the EGMS service, it is important to understand the possibilities and limitations of the InSAR technique, with regard to temporal patterns of deformation. The main deformation regimes are presented in Table 3-3. Note that these deformation regimes must be interpreted for a difference between two spatially separated points.

Table 3-3. Deformation regimes vs observability by InSAR

Deformation regime	Observability by InSAR	Visual Representation
<b>Stable</b>	<u>Yes</u>	
<b>Linear</b>	<u>Yes, up to a threshold.</u> Upper bound for motion relative to nearby pixels in noiseless case: <ul style="list-style-type: none"> <li>• a quarter of SAR system wavelength per repeat cycle (~2.3 mm/day for Sentinel-1)</li> </ul> Note that for spatially smooth motion, larger rates can be resolved. In practice, the observability threshold is lower due to: <ul style="list-style-type: none"> <li>• Missing observations</li> <li>• Noise</li> </ul>	
<b>Quasilinear</b>	<u>Yes, up to a threshold.</u> Depending on noise level, some unwrapping errors may still occur when $\text{abs}(\text{residual} + \text{noise})$ is larger than 1/4 of SAR system wavelength	

<b>Settling</b>	<u>Partially</u>  Only after settlement velocity falls below the observability threshold for linear rate.	  Green: observable regime; Yellow: Can only be unambiguously resolved (e.g., phase unwrapped) when the signal-to-noise-ratio (SNR) is very high; Red: Cannot be unambiguously resolved (e.g., phase unwrapped) without external information
<b>Progressing</b>	<u>Partially</u>  After the observability threshold for linear rate is exceeded, we need external information to unambiguously resolve. Eventually, this ground motion regime will likely lead to catastrophic failure of the monitored object.	  Green: observable regime; Yellow: observable in some cases with SNR very high; Red: Fast motion that cannot be unambiguously resolved without a priori deformation.
<b>Seasonal (sinusoidal)</b>	<u>Yes</u>  Note: a special case of quasilinear	  Green: amplitude < ¼ of the SAR system wavelength.
<b>Seasonal (high variations)</b>	<u>Yes, with specific processing</u>	

	<p>Requires algorithm with full 3D phase unwrapping to resolve, unless external information is available.</p>	 <p>Green: unambiguous, red: needs specialised processing (based on e.g. three-dimensional unwrapping) to resolve</p>
<b>Seasonal (fast-slow)</b>	<p><u>No, over the complete observation span</u></p> <p>Reliable estimate can be obtained for a certain observation timespan (i.e., green points in the figure) but over the whole period an overall estimation may be unreliable, because in some cases the deformation can be too fast to be observed, as in the “red dots interval”</p>	 <p>Example: Acceleration in spring (yellow), slowdown/stable in summer/autumn/winter (green/yellow). In red jumps between stable seasons can be very rapid, resulting in incorrect estimation. Pattern is repeating seasonally.</p>
<b>Seasonal (missing observations due to snow cover)</b>	<p><u>Yes, with a priori information/assumption</u></p> <p>For reliable estimation assumption (e.g. quasilinear) or external information is needed</p>	

### 3.2.6.1. Discussion on linear and non-linear motion

InSAR phase measurements are inherently ambiguous, providing only the last fraction of a phase cycle (section 2.1.2). The objective of InSAR time series analysis is a reliable estimation of the deformation time series of as many measurement points as possible. The only situation for which this is inherently impossible is when a group of nearby points is moving with respect to all other points by more than a quarter-wavelength between two consecutive temporal samples. All other deformation patterns are theoretically resolvable using a priori assumptions about the smoothness, and external information if available, of some of the involved phase components (section 6.5.3). In particular, the degree of nonlinearity of the deformation signal plays an important role.

The process of resolving the phase ambiguities is referred to as phase unwrapping, a crucial step in any InSAR processing workflow (section 8.3) that can be carried out in many different ways. Common to all of them is that some assumptions are needed. For a reliable and efficient workflow, the most important assumptions are:

- Nearby points experience similar atmospheric disturbances;
- The deformation is not deviating significantly from a linear function of time.

The latter assumption allows for the use of very efficient algorithms that scale well, and this assumption is valid for the vast majority of measurement points that can be analyzed with InSAR. However, many important use cases for InSAR based deformation monitoring are concerned with precisely the relatively few measurement points that belong to a strongly nonlinear regime (section 3.2.2). A major design goal for the EGMS service is to be able to reliably meet the needs of many of these use cases, if at all possible, within reasonable restrictions in terms of production latency and capacity. An example is shown in Figure 3-1, where a large landslide has experienced several phases of acceleration.

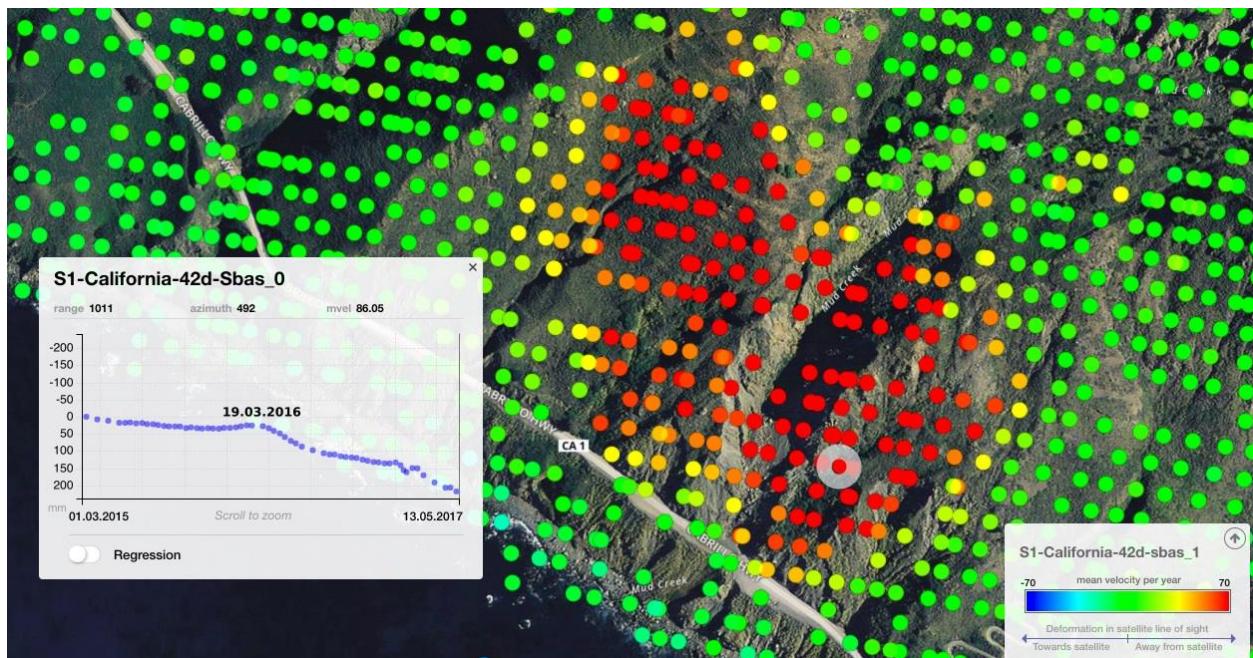


Figure 3-1. A DS based Sentinel-1 time series analysis of a large landslide along California's Highway 1 along the Pacific coastline in the Big Sur region,

([https://www.esa.int/ESA\\_Multimedia/Images/2017/06/Landslide\\_on\\_the\\_radar](https://www.esa.int/ESA_Multimedia/Images/2017/06/Landslide_on_the_radar)). After several decimeters of motion over a short time span, the landslide failed on May 20, 2017. The road was cut off, and 5 hectares of new land added to the shoreline. Note that during the last few months before the failure, the deformation velocity was too large for correct unwrapping.

In InSAR literature, (e.g. [SpaansHooper 2016] and references therein), many ways of handling nonlinear motion have been studied (section 8.3). While in theory their performance was demonstrated, in practice they are all characterized by potentially intractable computational requirements, typically involving a quadratic increase in computation time as a function of the number of input data points. In the context of the EGMS continental-scale product, there will be limitations in terms of computational resources (i.e., allocated hardware budget). This requires compromises in order to ensure that the applied workflows scale well, both in terms of algorithms and processing workflows, given the extent of the service (section 3.3). Production and algorithmic scalability are further detailed in section 3.4.3.

In the following, typical deformation regimes encountered in practice will be elaborated, with potential algorithmic scalability issues in mind.

### 3.2.6.2. References:

[SpaansHooper2016] K. Spaans and A. Hooper, "InSAR processing for volcano monitoring and other near-real time applications" *JGR Solid Earth*, vol. 121, pp. 2947-2960. 2016

### 3.2.7. Summary: Assessment of EGMS feasibility for use cases

Based on the technical requirements presented above and considering the use cases categorisation presented in Table 3-4. It is possible to assess the feasibility (i.e. the extent to which EGMS fulfils the requirements).

Table 3-4. Assessment of EGMS feasibility and applicability for the use cases.

- Green – full compliance and applicability of the EGMS foreseen specifications with requirements
- Yellow – a partial fulfilment of the requirements
- Red – EGMS not suitable for the specified requirements

Time / Space	Localised feature [< 5 km]	Line feature	Extended feature [> 5 km]
Stable	Stable infrastructure Bedrock	Stable roads, railways, dikes, levees, canals, etc.	Bedrock / bare soil
Slow [<30 mm/yr]	Subsidence of any type of infrastructure: Buildings, Airports, Ports, Dams, Dikes, Pipelines, Power plants, Reservoirs, Tunnels, Sewage Systems, Groundwater aquifers, etc.  Landslides	Roads, Railways, Dikes Levees, canals, and other water protection infrastructure Pipelines Geothermal activity	Large landslides Volcanic inflation/deflation Fracking Postglacial rebound

<b>Fast [30-200 mm/yr]</b>	Landslides Salt mine	Levees, canals, and other water protection infrastructure	Large landslides Volcanic inflation/deflation Oil and gas extraction
<b>Rapid [200+ mm/yr]</b>	Rock glacier	Precursor to infrastructure failure New landfill for road/railroad	Gas storage Groundwater overexploitation
<b>Seasonal or weak nonlinear</b>	Aquifer Groundwater affected areas Tailing dams Dikes	Line infrastructure on groundwater affected land	Gas storage Aquifers
	Bridges Precursors to landslides, mudslides, infrastructure failure, etc. Periglacial landforms	Precursor to linear infrastructure failure	
<b>Transient or strong nonlinear [periods with motion faster than ~ 2.5 mm/day (C-band)]</b>	Precursor to infrastructure failure Settlement of new landfill Closed/abandoned mine collapse Tank storage (water, gas, oil) Tailing dams Rock glacier	New landfill for road/railroad  Precursor to linear infrastructure failure	Open-pit mining
<b>Instantaneous</b>	Catastrophic failure of building infrastructure Failing landslide/mudslide/rockslide Sinkhole	Catastrophic failure of road/railroad segment	Earthquake Volcanic eruption

### 3.3. Geographical coverage

Two scenarios must be considered for the geographic coverage of EGMS; the 30 Copernicus Participating Countries (CPC30), or the 39 EEA member and cooperating countries (EEA39). As the EEA is the Entrusted Entity in charge of the Copernicus Land Monitoring Service, of which EGMS will be a part, it is natural that EGMS eventually have the same coverage as the other Land Monitoring Service thematic datasets.

The Copernicus Participating Countries are the 28 EU members, plus Norway and Iceland (Figure 3-2). The EEA member countries are the 28 EU members, plus Norway, Iceland, Liechtenstein, Switzerland and Turkey. In addition, six West Balkan countries are cooperating countries: Albania, Bosnia and Herzegovina, North Macedonia, Montenegro, and Serbia.

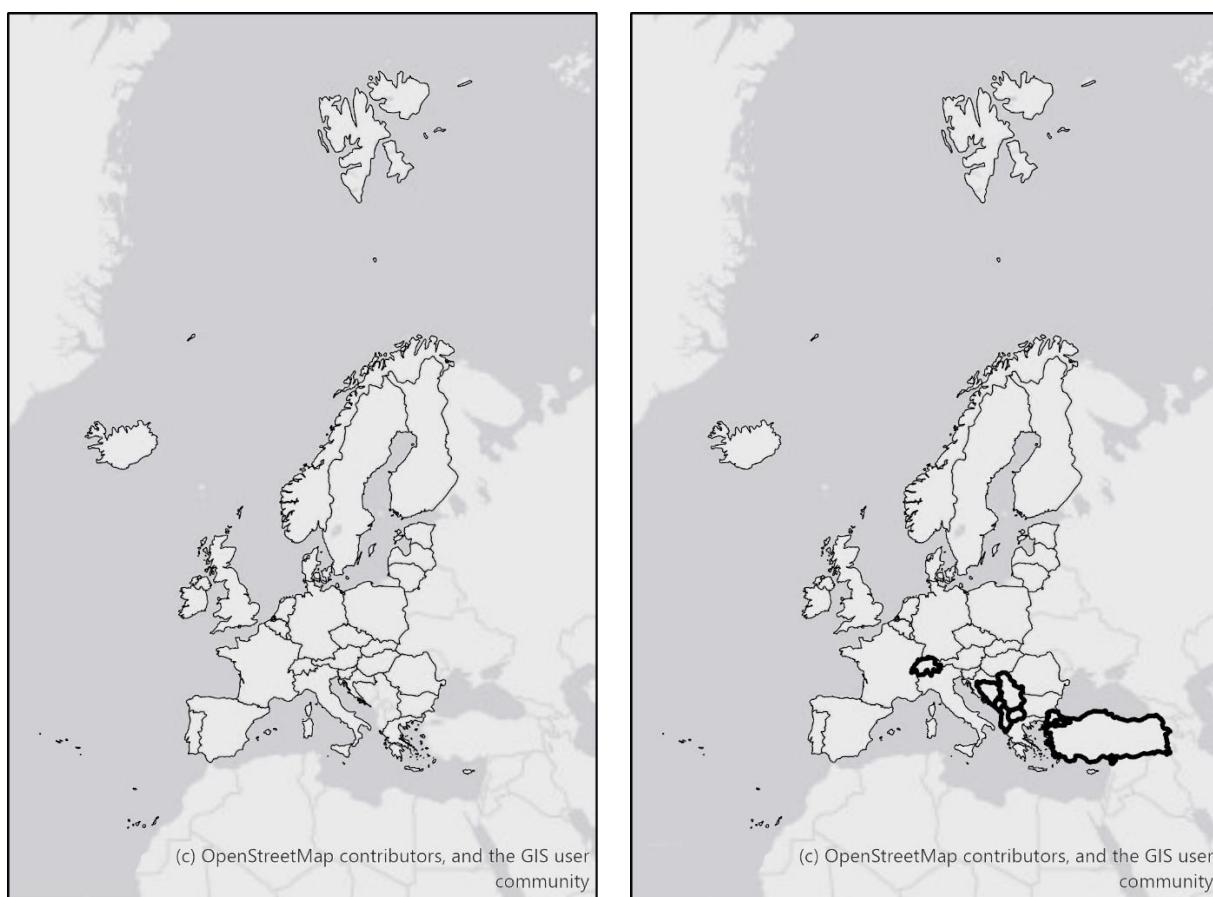


Figure 3-2. (Left) Copernicus participating countries; (Right) EEA countries with the difference in bold.

Liechtenstein, Switzerland and the six West Balkan countries are surrounded by CPC 30 countries. Including these countries in EGMS will have little impact on production requirements. Turkey, however, significantly increases the number of Sentinel-1 scenes that would need to be processed.

Four European countries have overseas regions, not all shown in Figure 3-2; France, Spain, Netherlands and Portugal (Figure 3-3). These include many islands, as well as French Guiana. Although the total area of these regions is not high, the distributed nature of them significantly increases the amount of Sentinel-1 data that needs to be processed. In addition, each island requires some individual attention during processing.

It should be noted that there are also fourteen British Overseas Territories. Although these are under the jurisdiction and sovereignty of the United Kingdom, they are not part of it, and only Gibraltar is included within the European Union.

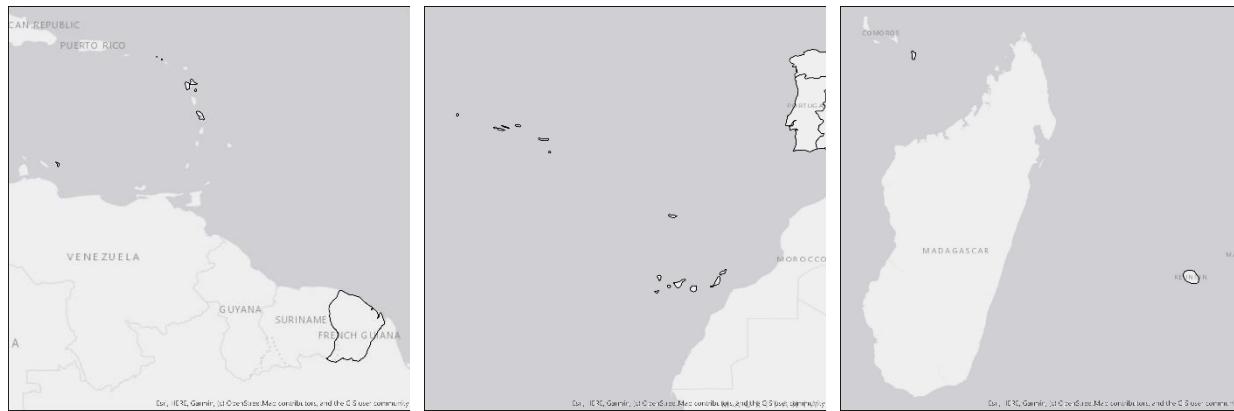


Figure 3-3. Overseas regions of France, Spain, Netherlands and Portugal

Svalbard and Jan Mayen, two remote jurisdictions of Norway, also need special consideration. Jan Mayen is subject to the same issues as the other small islands but also lacks any usable Sentinel-1 data before the summer of 2019. Svalbard has specific processing challenges related to its arctic location. It is largely covered by glaciers and has a very short snow-free season. In addition, the unglaciated areas are subject to complex seasonal deformation due to periglacial processes.

Due to the near-polar orbit of Sentinel-1 there is significant overlap between images acquired along adjacent orbits. This overlap increases with latitude. The result is that each point on the ground is imaged multiple times during a 6-day acquisition cycle. At a minimum, every point is imaged by a single ascending and a single descending acquisition, but at the highest latitude, points may be imaged by as many as four ascending and four descending acquisitions (see Figure 3-4). In principle, this means that EGMS would not have to use every available scene to provide full coverage. However, user needs would be better met if all available data are processed.

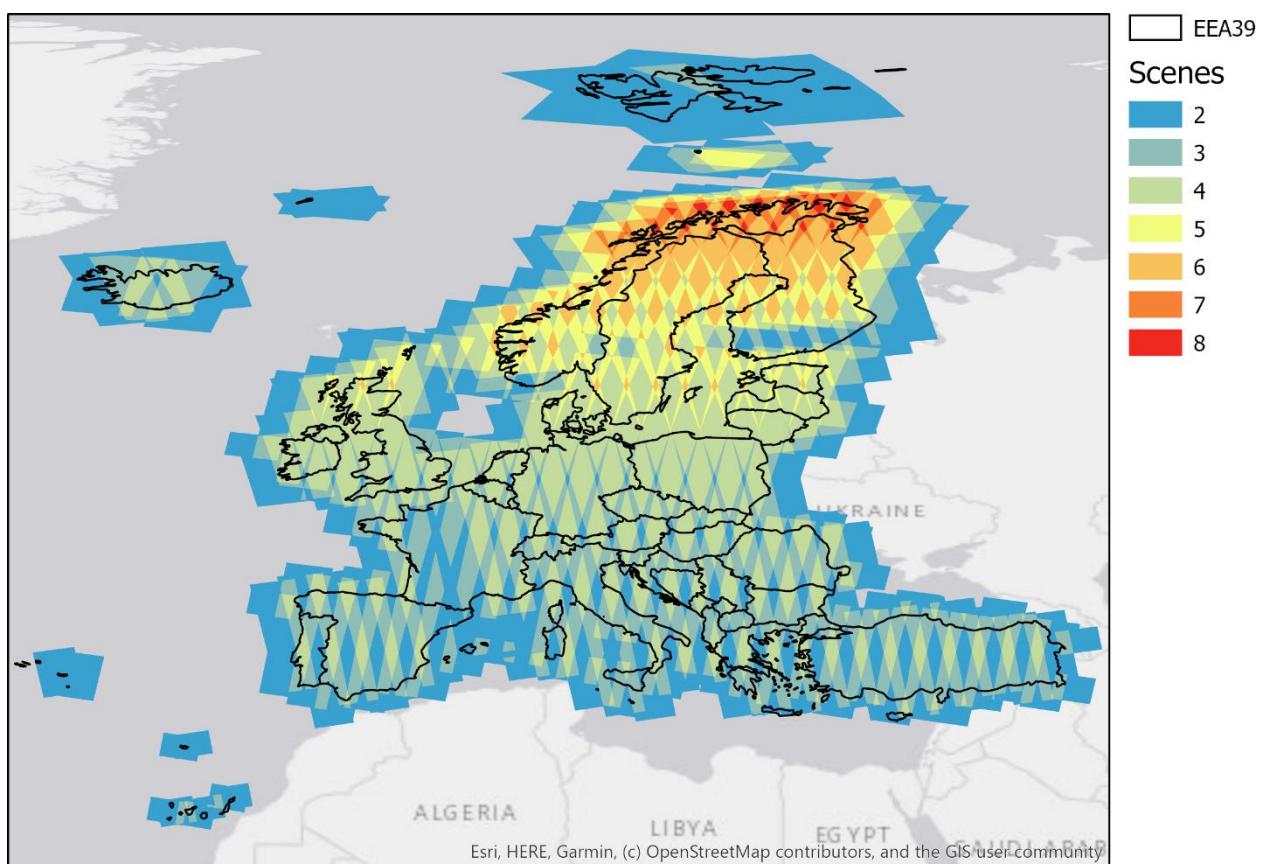


Figure 3-4. Number of Sentinel-1 scenes acquired between June 1 and June 6, 2019.

Sentinel-1 scenes consist of three subswaths, each of which is made up of single *bursts* (see 10.2 for a discussion on the concept of bursts). Based upon the theoretical pattern of Sentinel-1 acquisitions, the full EEA39 coverage, including all overseas regions, would require the processing of approximately 18,700 bursts, including both ascending and descending acquisitions. (In reality, not all tracks are acquired, especially over Svalbard and Iceland.)

The following options could be considered for the ramp-up of EGMS:

- EEA39, without overseas regions, Svalbard and Jan Mayen, Turkey and Cyprus
  - Requires processing of approximately 15,500 bursts.
  - Alleviates the need for special handling of remote islands.
- EEA39, without overseas regions, Svalbard and Jan Mayen
  - Requires processing of approximately 17,200 bursts.
  - Alleviates the need for special handling of remote islands.
- EEA39, including all overseas regions, but not Svalbard and Jan Mayen
  - Requires processing of approximately 17,600 bursts.
- EEA39, including all overseas regions and limited, feasible areas of Svalbard

The impact of these options will be discussed further in Section 2.6.

## 3.4. Production system

### 3.4.1. Introduction

The production system described in this section has as its main goal to address the requirements from the end-users, as described in Section 3.2. For the production system there are, however, also other user needs that must be addressed. These other users may be addressed as internal for the Production system but may also be seen as external users or entities that may support the operations of the production system. The identification of such users and their needs will be described in Section 3.4.2, Production flow. In that section, an outline of a suggested production flow, and how the components in the flow may be grouped will also be given.

Section 3.4.3, will address the needs for processing and storage capacities.

Section 3.4.4, Production system deployment models, will provide potential solutions for how to deploy the production service. In this section, models involving cloud computing and hybrid solutions will be reflected upon.

In Section 3.4.5, aspects related to maintaining an operational production system and quality assessments will be addressed. The need for human interactions for the Production system will also be analysed here.

### 3.4.2. Production flow

The core production flow of a production system for EGMS services may be described through a simplified figure as below where the Production system is seen from the external actors

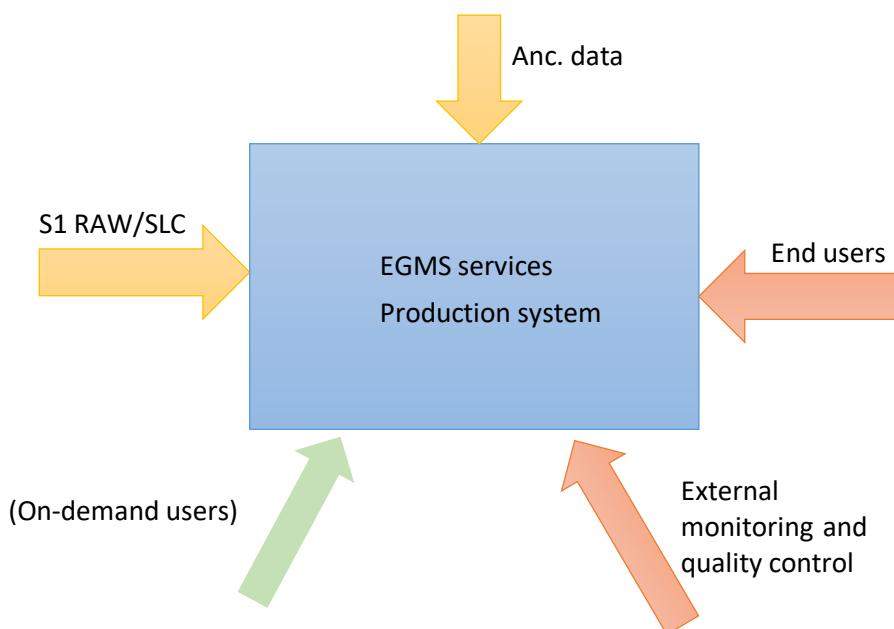


Figure 3-5. Production flow external view.

The figure represents a simplified view that serves to identify the boundaries for the production system. A brief description of the entities of the figure is as follows

- **S1 RAW/SLC** data products represent the core input to the production system. Note that the potential need for local storage and communication with the external source will be revisited in detail later.
- **Anc. data** represents the ancillary datasets needed to provide the service. The potential need for internal storage will be revisited later.
- The **end users** represent the main user community as described in Section 3.2. Note that these users are seen as “passive” users in the production system context, as they only retrieve available data from the system without influencing the internal production operations of the production system. The interfaces for data access are discussed in Section 3.6.1.
- The **external monitoring** and **quality control** represent the need for retrieval of information about the status of the production system, and potential use of more detailed interfaces for assessing quality by an external user. The potential need of external quality control will be revisited later. The user interface for external monitoring may be represented through web interfaces with statistical reporting from the production system.
- **On-demand users** represent authorised users that require access to information from the Production system before a 12-month cycle is completed. The on-demand users are separated from the end users, as these users will have different requirements in regard to area of interest and temporal sources used by the Production system. The on-demand users should not influence the basic production operations that serves the end users. A potential on-demand service component will be briefly discussed in Section 0.
  - **NOTE:** This potential service component shall, if present, only be available to a very restricted group of users, e.g. other Copernicus services, through a dedicated activation procedure. Opening an on-demand production option for general users is particularly problematic in terms of impact on the commercial market. Thus, this system component is strongly discouraged but is included here for completeness.

The internal representation of the EGMS Services Production system may be realised in different ways. However, it may be beneficial to separate some key components internally, for easier deployment and long-term maintenance. A figure that represents a realisation of the internal production system is given below.

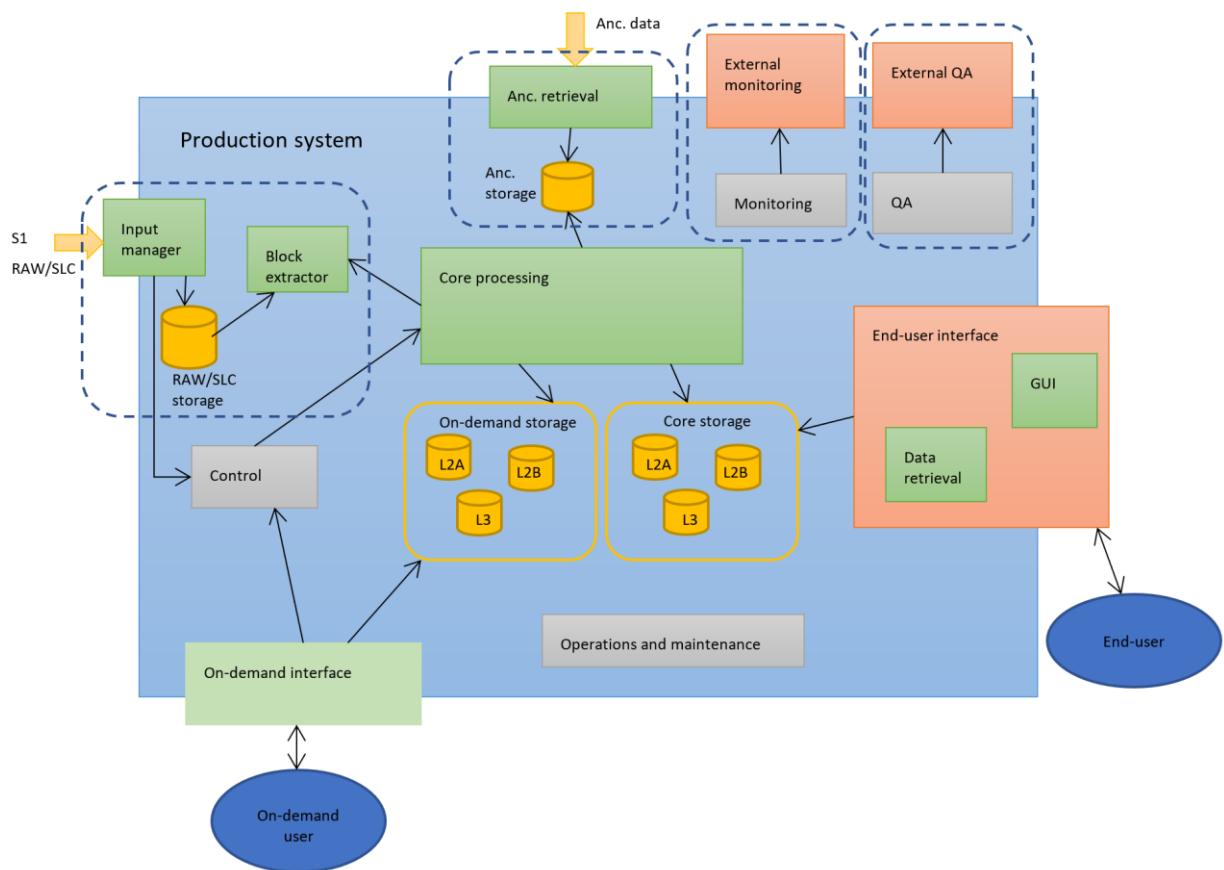


Figure 3-6. Production system - internal components.

The Core processing functionality is seen as the driving component in the Production system. The goal should be to ensure that the system is data driven as much as possible, without any necessary intervention from an internal or external actor. The only exception is a potential on-demand user access option. A potential interface for on-demand usage should, however, be realised so that the on-demand user does not have a direct access to the processing elements. A description of the key components are as follows

- **Input manager** – this entity is responsible for reception, either as an active or passive actor, of S1 data to use in the production system. The functionality should include some basic quality checks of the data before the data is inserted into the local RAW/SLC storage. When data are inserted, the Control unit should be informed in order to plan the actual processing to be done on the received data.
- **Block extractor** – this represents a subsystem that is able to extract single blocks on which to operate. For S1, the most likely granularity of these blocks will be the single bursts. The block extractor is used by the Core processing subsystem but may also include functionality triggered by the Input manager to prepare blocks to be used.
- **RAW/SLC storage** – this represents a local cache of the RAW and/or SLC data. The size of the local cache will depend on the selected time frame of the stacks to be operated on. Other aspects that need to be considered are the potential for long-term reprocessing from earlier 12-month intervals, and the potential of having a close connection to an external storage of the products. An alternative to storage of RAW/SLC in basic product format is to extract blocks to store individually or in repeat-pass stacks. Depending on the storage format, this may reduce the

necessary storage capacity as data that would be thrown away at a later stage may be discarded before storage, e.g. the cross-polarisation channel if not used.

- **Core processing** – this represents the main algorithms that generate the L2a, L2b and L3 products. Note that Figure 3-6 does not consider if RAW or SLC data is needed as input. If RAW is used as input, it is assumed that a SAR processor, generating necessary SLC from the RAW data is included in the Block extractor or Core processing subsystem. The details of the Core processing algorithms are given in 9.3. The Core processing subsystem is the most CPU-intensive subsystem within the Production system. The internal design of this subsystem should be done so that it is scalable and independent on specific hardware. It should utilise functionality in the host system, but not depend on any specific vendors to avoid vendor lock-in.
- **Anc. Retrieval** – this represents the subsystem that communicates with external sources and storages for retrieval of the necessary ancillary data used in the production (section 4.6).
- **Anc. Storage** – this represents a local storage of ancillary data used in the processing. Note that an evaluation has to be done regarding how static the ancillary data is seen from a service delivery. The DEM used may be seen as more static than regularly updated orbital information.
- **Monitoring** – the monitoring includes gathering of key information from the system during operations and for long term analysis. Preferably a database scheme should be used that adheres to common standards for monitoring information. The monitoring should also be used internally by the operations and maintenance unit for supervising the daily operations of the system.
- **External monitoring** – this represents the interface for reporting monitoring information for external reports. The contents and formats should be at a format that makes the report generation as automated as possible.
- **QC** – This represents quality assurance activities to be done internally to ensure that the service is as good as possible. The quality assurance data should be as automated as possible, but it may also include requirements for retrieval of some key information from the subsystems involved directly in the service production (block extractor, core processing, etc.).
- **External QC** – This represents the interface for data that may be fed to an external quality analysis. The detailed needs should be based on the regularity and details of a chosen external quality analysis.
- **End-user interface** – this represents the interface through which the end-users communicate with the production system. The interface should be implemented so that the communication with the internal system is done by polling operations only to remove the potential for end-user actions impacting the production system. The details of the interface should at least involve the following 2 sub-components
  - **GUI** – a graphical interface as described in Section 3.6.2. The GUI should not rely on having specific client software at the premises of the user.
  - **Data retrieval** – an entity that does actual retrieval of L2a, L2b and L3 results. The data retrieval should be possible to trigger both from the GUI and also from a subscription driven interface following standardised API solutions when possible.
- **Core storage** – This represents the local storage of all generated L2a, L2b and L3 products that is generated. The size and long-term storage policy depends on the selected temporal stack sizes and the need for access to intermediate products from earlier production cycles.
- **On-demand storage** – This represents L2a, L2b and L3 products generated when the production system is accessed through a potential on-demand interface. Seen from the core processing, the storage should be similar to the Core storage. On-demand storage is however kept separate from the core storage as the generated products may be generated from a subset of the complete long-term stack of input and output data, and through use of potentially simplified ancillary data.

- **On-demand interface** – This represents the user interface and potential negotiations with the production system when an on-demand access to the service is required. If this service component is implemented, it is likely that access to operations personnel will be required for initiating the processing when an on-demand request over an area is done by an authorised user.
- **Control** – this represents the internal control mechanism that is required for operations and maintenance personnel to run and supervise the production system. The necessary level of control should be kept at a minimum but should nevertheless support the possibility to override and adapt the production to new situations. It should also be noted, as there may be temporal differences between the availability of input RAW/SLC data and necessary ancillary data, that the control unit needs to be able to handle this.
- **Operations and maintenance** – including personnel to supervise and guide users, as well as maintenance personnel that may analyse and potentially update subsystems of the production system when required.

Figure 3-6 also indicates how some key components that are related may be grouped together to provide general functionality that other production system components may require. The potential groupings indicated are

- **Quality assurance** related tasks. The distinction between internal and external quality control may be difficult, and some elements will most likely be reflected in both internal and external QA.
- **Monitoring** tasks. The external monitoring may be seen as a subset of more detailed internal monitoring.
- **Ancillary data retrieval and storage**. This may be seen as a complete entity, which has requirements related to updates and long-term storage capabilities.
- **Input data management and blocking**. The management of the input and extraction of necessary blocks may be seen as a single subsystem with internal requirements related to storage capacity and extraction of relevant data from the original RAW/SLC S1 products.

### 3.4.3. Capacity requirements

The EGMS Production system will need access to a substantial amount of data throughout the processing cycle. The amount of RAW/SLC data generated by the S1 satellites over Europe is massive. The generated S1 SLC products are approximately 8 times larger than the matching S1 RAW data. From a pure storage capacity point-of-view, it would make sense to store the RAW data. However, this would mean that the processing from RAW to SLC products would need to be incorporated into the production system, adding to the overall system complexity.

The local timeline for processing in the Production system depends on the availability of data from the sources; RAW/SLC data and ancillary data. In addition, the algorithms in the Core processing subsystem will influence the timeline for the production system (section 3.4.6). The data from the external data provider (RAW or SLC) will be made available at a semi-continuous rate. The availability of ancillary data is however not in the control of the Production system. The timeliness of the ancillary data depends on the policies of external providers (section 4.6). The Core processing algorithms should be arranged so that preparations and processing steps that do not depend on the availability of the ancillary data is done as soon as possible. This may again lead to a need for available temporary storage capacity. The Production system should be designed to handle availability of data at irregular intervals and have storage capacities to handle this.

ESA provides various models for accessing RAW and SLC products through the Copernicus Mission. In addition, there are several downlink sites that provides data access through downlink and localised processing of the data. However, the most realistic way to ensure a complete access to the necessary data is to go through the official Copernicus Network.

Utilizing the Copernicus Network, there are 2 possible models;

- Access data directly from the Copernicus Network when needed for processing
- Downlink the necessary data when available, and keep copies close to the EGMS Production system for the necessary amount of time.

The first model, depending on the storage being available when needed means that the necessary local storage space will be reduced. In this model the necessary storage space will include L2a, L2b, L3 products, ancillary data, and necessary intermediate data used during the processing. The drawback with this model is however that the processing system will depend on internet access when in production, and the data policy regarding access to potentially older data in the Copernicus system.

The second model will also require local storage space for RAW/SLC data but will eliminate the need for internet access during processing. There still has to be an access to data from an external provider, but this can be handled separately from the central production operations and the timeline of the services.

Another aspect that needs to be considered for the data storage model is the potential need for reprocessing data from earlier processing cycles. If there will be a need for such reprocessing (due to upgrades of the core algorithms or central parameters), the need for long-term storage of local data has to be considered.

#### **3.4.3.1. Input data volume considerations**

The area of interest for the EGMS is covered by 15-20000 individual bursts, depending on specific choices (see Section 3.3). An upper bound for the total data volume can be derived using the following assumptions:

- ~20000 individual bursts = ~750 SLC products
- All data is acquired in dual polarisation
- Current data volume, on average 200 scenes available for any stack
- 60 new scenes every year for any stack

This yields the following:

- Current data volume (end of 2019): 1200 TB uncompressed / 600TB compressed
- New data every year: 45,000 products = ~350TB uncompressed
- Volume around start of service: 1.5 PB uncompressed / 750TB compressed

Note: If the cross polarisation channel is not used, it is possible to reduce all of these numbers by almost a factor of two.

#### **3.4.3.2. Bandwidth requirements**

Assume that:

- Production time is four months for the initial production cycle;
- Transferring of input data to computing nodes will happen over the first 4 months maximum;
- Data are transferred in compressed form (4GB per product).

Then we need a sustained and uninterrupted bandwidth over four months of about 600 Mbit/s (75 MB/s) to be able to download all the data. With 10 Gbit/s bandwitch, the data could be transferred in about three weeks.

From these calculations, it is clear that the only sustainable model is a processing system with high-bandwidth access to the data archive.

### 3.4.3.3. System requirements for core processing system

Regardless of the choice of the processing platform, some general requirements may be put on the processing units.

#### 3.4.3.3.1. Algorithmic considerations

System requirements are strongly dependent on the choice of algorithmic framework, as discussed in section 9.3). In particular, it is important to choose an algorithmic framework (Figure 3-7) that scales well over time to avoid drastically increasing costs from one production cycle to the next. We will, in this section, derive capacity requirements assuming that a conservative and proven approach is chosen (see Section 3.7.5.2). Note that the Level 2a production dominates all other processing steps to such a degree that only this block needs to be considered in terms of processing capacity requirements.

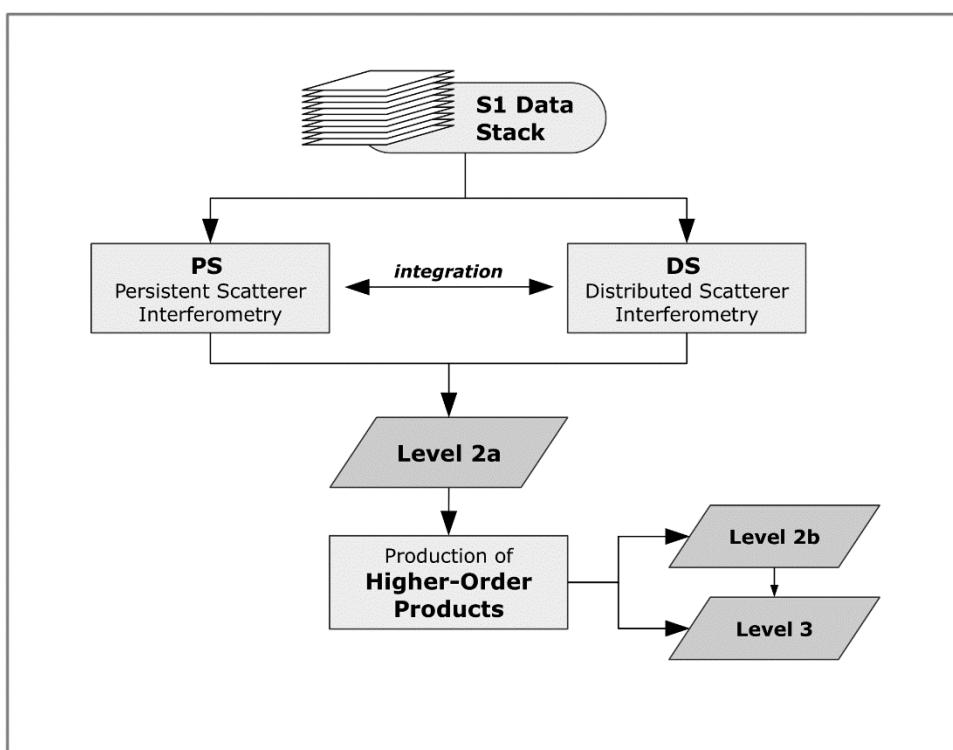


Figure 3-7. Generic algorithm flow of EGMS, with a detailed breakdown of algorithmic steps given in Appendix D.

### 3.4.3.3.2. Processing units

As discussed in the previous section, some parts of standard InSAR processing algorithms do not scale well with increasing size of the processing unit. It is recommended to define manageable processing units that are small enough to be processed on commodity hardware. The following is a conservative choice that will allow commodity hardware to be used:

- Full resolution PS analysis:
  - ~ 10 km x 10 km
  - 2500 x 800 full resolution pixels
- Low resolution DS analysis:
  - 250 km x 250 km, 80m resolution
  - 3000 x 3000 low-resolution pixels

This suggestion is based on existing workflows (APPENDIX H: LARGE SCALE CAPACITY EXAMPLES) but should be regarded as a guideline only. Larger processing units may often be feasible, and sometimes this will simplify the subsequent L2b/L3 production, but at the cost of more expensive hardware.

To avoid performance loss, it is paramount that input data are loaded into memory once, and that as few steps as possible need to store intermediate results to disk. For full-resolution PS based processing, we assume that we need room for two RAM buffers the size of the entire data stack, plus the corresponding amount for other precalculated data, the following calculation yields an upper bound on memory consumption per processing block:

- Complex double precision = 16 bytes/pixel
- Block size: 1-2M pixels
- 300 scenes max for initial production cycle
- Total buffer size = 5-10 GB
- Overall memory need = 16-32 GB / processing block

DS-based analysis will in principle have similar needs, but due to the multimaster nature with up to  $\sim N^2/2$  potential interferogram combinations for a stack of N scenes, it is common to use intermediate disk storage of multilooked interferograms since the full multimaster dataset is not guaranteed to fit in memory. This allows flexibility in RAM usage and parallelism in subsequent processing steps, at the cost of need for more temporary disk storage and slower input/output (I/O) than in-memory. Thus, we will assume that PS, DS and PS/DS workflows can all use the same commodity hardware, see Section 3.4.3.3.3.

InSAR processing workflows suitable for continental-scale production must scale well with the number of available scenes per processing unit. In particular, any non-trivial processing step with quadratic or higher complexity in the number of scenes must be avoided to keep the processing capacity needs on a reasonable level over time. In the following analysis, we outline processing capacity needs for single processing units. For a workflow that scales properly over time, these numbers can simply be extrapolated over a set of processing units covering the entire EGMS area of interest.

Note that the production of L2a is by far the most demanding processing step, with high variation between different algorithms. Production of L2b/L3 is expected to consume only a small fraction of the total resources and will be considered negligible in this context

### 3.4.3.3.3. Processing nodes

The requirements per processing unit indicated in the previous section, imply that a typical processing node on a cloud service or computing cluster will need to fulfil the following requirements

- N (physical) CPUs
- N x 16-32GB RAM
- Access to data storage with very high bandwidth (input data and output results)
- Enough local storage for all intermediate products

The hardware market is evolving fast, so no specific recommendation on choice of hardware will be made. Example suitable processing nodes currently available from commercial cloud service providers include:

- AWS EC2 platform: See Table 3-5
- Onda DIAS platform: See Table 3-6

Table 3-5. AWS EC2 Platform

i3.16xlarge instance characteristics	
vCPU	64
RAM	488GB
Internal Storage	15.2 TB (8xNVMe SSD)
Network Bandwidth	25 Gbps

Table 3-6. Onda Dias Platform

ONDA-DIAS instance characteristics	
vCPU	64
RAM	512GB
Internal Storage	20 TB (no SSD)
Network Bandwidth	2 Gbps

There are many ways to derive ground motion data from SAR time series. A full capacity analysis for all options is outside the scope of this work, but we will provide some guidelines using examples from:

- Production of the Norwegian Ground Motion Product (PS only)
- Production of Italian territory on AWS (DS only)
- Production of a European-wide SBAS-based product on Onda DIAS (DS only)

For details about these experiments, see Appendix H.

### 3.4.3.3.4. EGMS capacity and scaling considerations

#### 3.4.3.3.4.1 Processing considerations

Choice of the processing units suggested in section 3.4.3.3.2 results in the following approximate number of processing units to cover the entire EGMS area of interest (EEA39):

- PS: 500,000 units
- DS: 500 units

Note that in practise, the actual number may be a bit higher depending on the applied overlap between processing units. Assuming a scalable processing setup, we can extrapolate the numbers achieved in the large-scale studies described in detail in APPENDIX H: LARGE SCALE CAPACITY EXAMPLES to the full EEA39 area. We can summarise ballpark computing needs in order to finish a full production cycle in 4 months as:

- PS processing: About 20 typical processing nodes
- DS processing: About 15 typical processing nodes

#### 3.4.3.3.4.2 Scaling considerations

Here, we have assumed 100% utilisation, meaning that actual needs will be slightly higher. The recommended workflow (section 3.7.5) applies joint PS/DS processing. Due to some synergy in typical PS and DS workflows, it is safe to assume that the sum of the outlined capacity needs provides a reasonable upper bound. Allowing resources for more advanced processing in key areas (typically urban), and some time for postprocessing and L2b/L3 production, we can conclude that a setup with about 40 processing nodes is sufficient for a PS+DS production cycle of 4 months. The production of L2a data for each unit is independent of other units, meaning that the production time scales well with the available hardware. This means that a doubling of the available computing resources results in almost 50% less production time.

#### 3.4.3.3.4.3 Production storage considerations

Three types of storage space should be considered:

- Temporary storage (during production): These files are locally stored on the production nodes during processing only, and discarded when the corresponding L2a product is finished.
- Intermediate storage of data and intermediate products that are needed during a full production cycle.
- Permanent storage for static ancillary data and end products (L2a / L2b / L3), that will be kept indefinitely.

In practise, only the permanent storage is mandatory, while temporary and intermediate storage can be scaled depending on the budget and algorithmic implementation.

### 3.4.4. Production system deployment models

Core processing algorithms for EGMS services traditionally require a significant amount of processing power. For the continuous operations in production cycles of 12 months, the necessary processing power may be predicted, depending on the amount of data and the selected algorithm capacities. Some processing may be done as soon as possible when data and ancillary data are available, while other processing can only be done at the end of the 12-month cycle, preparing for the final delivery.

Traditionally, the processing of EGMS services has been done through dedicated centralised processing centres. With the arrival of cloud computing other options for a distributed processing system have

become available. The following sections address the pros and cons of centralised vs cloud computing for EGMS services. In addition, a model for potential hybrid solutions is also addressed.

#### **3.4.4.1. Centralised processing**

Processing done at dedicated local processing centres sets no limitations to retrieval and exploration of data and algorithms for the local maintainer. Any restrictions to the availability of temporary results for exploration of local phenomena are only limited by the algorithm complexities, and the data made available for local use. If the need for detailed exploration for quality assurance and investigation of localised phenomena is large, a centralised framework with easy access to large amount of intermediate results may be beneficial.

Maintenance and support of a centralised processing framework may require investments in personnel and monitoring processes for hardware surveillance. In addition, the initial investment in hardware may be large, and benefits of development in hardware during the Production system lifetime may require large reinvestments. Scaling a localised processing centre may be difficult, in particular if the need for potential reprocessing of older data is an issue. Processing power inside an 12-month cycle may be predictable, whereas potential reprocessing may require much more processing to be done and consequently a larger need for available processing power.

#### **3.4.4.2. Cloud processing**

Use of cloud computing services reduces the necessary investment in local personnel and hardware for operations. Cloud computing services reduces the need for investments in localised hardware, and availability of necessary processing power may be scaled by the cloud computing provider according to the need of the Production system. A need for resources for reprocessing of older data may be scaled by the cloud platform provider. Hardware monitoring and support are also eliminated and left to the cloud service provider.

The cloud computing services are in continuous development, and their business models are expected to evolve over time. As of today, the most expensive step in a cloud computing system is the need for extracting data from a cloud computing environment. This may set restrictions on the amount of data to be extracted from the processing system. Needs for extraction of a large amount of data for quality assurance and investigations to support local phenomena have to be addressed.

Cloud computing services may further have different standards that are used to benefit the massive parallelism available from cloud computing services. These standards may be varying between the cloud computing providers, and close integration with a given standard may lead to vendor lock-in for a system that utilises specific standards.

The localisation of the data to be used during processing may also have an impact on vendor lock-in. The localisation of data (input RAW/SLC, ancillary storage, L2a/L2b/L3 and potential temporary storage used for quality analysis or local knowledge) close to the processing nodes may be beneficial but may also lead to vendor lock-in with the cloud system provider.

The utilisation of a cloud platform solution should adhere to standards established (i.e. docker, virtual machines, Kubernetes, etcetera), and avoid using vendor-specific standards. When selecting a cloud provider, aspects as guaranteed service up-time, data transport to and from the cloud and geographical localisation should be considered. Other aspects to consider are comparisons between available public and private clouds.

### 3.4.4.3. Hybrid alternatives

Alternatives where some subsystems are deployed locally and others within cloud services should also be considered. The Core processing algorithms, which require more processing power, may be deployed through cloud solutions, whereas quality assurance, GUI and other subsystems may be provided locally. This does, however, need to be analysed to determine the impact on use and data traffic that may result from hybrid solutions.

The interfaces to external entities (GUI, data access, etcetera) need to be analysed. The need for specific client software at users' premises should be kept at a minimum.

### 3.4.5. System monitoring and maintenance

The EGMS Production system is expected to have a relatively long lifetime, with potential for extensions to reflect the long-term policy for use of Copernicus data. Long term supervision and maintenance must be considered to support the need for quality assurance, monitoring and further development of the Core processing algorithms.

#### 3.4.5.1. Monitoring

System monitoring and reporting need to be established both for internal monitoring at the Processing system, but also to generate the necessary reporting for supervision of the EGMS service at an external level. The amount of data and hence monitoring information will be so extensive that procedures that generate monitoring and reports have to be based on automatic operations. However, in order to investigate potential problems or anomalies, the monitoring system also needs to include options that can extract more detailed information when needed.

#### 3.4.5.2. Human interaction

The service generated by the Production system is not expected to require 24/7 operations. The system should be designed and implemented so that human interactions and supervision should be as little as possible and be able to be undertaken within standard working hours.

The operational functionality of the Production system should not depend on human interactions. The block extraction, core processing and system deliveries should be automated and follow configuration setup established. A certain degree of human interaction and monitoring should be expected at the end of each 12-month cycle. However, during the time leading up to the deliveries the production system should be as automated as possible, and only require supervision if anomalies occur. It is expected that there will be a ramp-up phase with more human interactions when the Production system is deployed. This will also rely heavily on expertise from the EGMS community to address potential outlier areas that require local knowledge for establishment.

The GUI and its interactions with the end-users should be as automated as possible. A certain degree of human expertise is, however, to be assumed for all levels of users. This is addressed in Section 3.6.2.

#### 3.4.5.3. Maintenance and operations

The Production system needs to be designed to support long-term operations and evolution of key components. This suggests establishing a modular design, with clear interfaces between key subsystems

that make it easier to upgrade or replace key components. In particular, the Core processing algorithms are expected to evolve over time, and the integration of this subsystem should be as modular as possible.

The various subsystems should be as automated as possible, but with some potential for being manually overridden if anomalies or a need for reprocessing occurs. Maintenance operations for the subsystems (debug operations, extraction of monitoring status, upgrading) should be as simple as possible, making it easy for maintenance personnel to do operations.

### 3.4.6. Production plan and implementation timetable

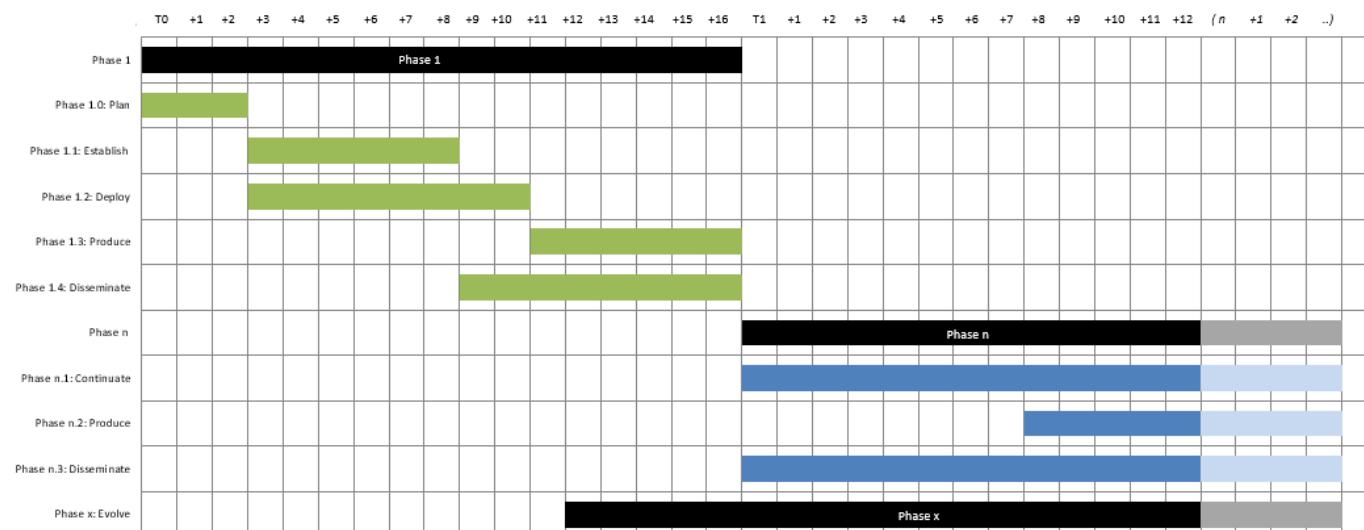
The following production and implementation timetable is based on the experience of the consortia. It builds on the technical recommendations as well as the proposal for the geographical coverage of the EGMS, and their implication on the expected production time. However, in particular the production phases 1.3 and n.2 can be shortened using more hardware resources. This is a tradeoff that needs to be considered.

The plan considers two main phases:

- **Ramp-up Phase** the Service is being established, tested, and approved
- **Production Phase:** the Service is declared operational, i.e. the service starts delivering products to the end user, including the production of the baseline deformation map

The proposed timeline (Table 3-7) is a sketch, and should be considered provisional. It is expected to evolve during the course of the EGMS service's lifetime and be subject to a revision process similar to other Copernicus Services.

Table 3-7. Provisional GANTT chart illustrating the production and implementation phases



T0 = project kickoff

T1 = end of phase 1 = T0 + 16

Phase n = an iterative process with a 12-month period covering one release per cycle.

Phase x = periodic iterative evolution phase during the course of the project.

Note that Production phase includes production setup, four months of production, and quality control.

### 3.4.6.1. Initial phase: first production cycle

#### Phase 1.0: PLAN

- Timeline: [T0, T0+2]
- Phase: Ramp-up phase
- Objective: Consolidation of the Service Implementation Plan

#### Phase 1.1: ESTABLISH

- Timeline: [T0+2, T0 + 8]
- Phase: Ramp-up phase
- Objectives:
  - Choose production platform(s)
  - Organise input data flow:
    - S1 Level 1 data
    - Auxiliary data:
      - Fixed:
        - DEM
        - CORINE land cover
      - Dynamic:
        - S1 precision orbit
        - Numerical weather data
      - In-situ and other:
        - Database of Corner Reflectors
        - “High-quality” GNSS stations

#### Phase 1.2: DEPLOY

- Timeline: [T0+2, T0 + 10]
- Phase: Ramp-up phase
- Objectives:
  - Deploy processing system
  - Test production and system acceptance testing
  - Set up QC system
  - Evaluation data production

#### Phase 1.3: PRODUCE

- Timeline: [T0+10, T1]
- Phase: Production phase
- Objective:
  - Operational production of baseline product portfolio

#### Phase 1.4: DISSEMINATE

- Timeline: [T0+8, T1]
- Phase: Ramp-up and Production phase
- Objectives:
  - Dissemination system acceptance testing [Ramp-up]
  - Evaluation product dissemination [Production]
  - Operational product dissemination [Production]

- User uptake activities [Production]

### 3.4.6.2. Subsequent production cycles

#### Phase n.1: CONTINUE

- Timeline:  $[T1 + 12*n, T1 + 12*(n+1)]$
- Phase: Production phase
- Objectives:
  - Continuous ingestion of input data
  - Preprocessing steps per scene

#### Phase n.2: PRODUCE

- Timeline:  $[T1 + 12*n + 8, T1 + 12*(n+1)]$
- Phase: Production phase
- Objectives:
  - Operational production
  - Packaging of L2b/L3 data update #n

#### Phase n.3: DISSEMINATE

- Timeline:  $[T1 + 12*(n+1), ...]$
- Phase: Production phase
- Objectives:
  - Operational product dissemination
  - User update activities

#### Phase x.x: EVOLVE

- Timeline:  $[T0 + 12*n, ...]$
- Phase: n/a
- Objective:
  - Service (and products) evolution
- Note:
  - Evolution activities run in parallel with production.

## 3.5. Quality control

### 3.5.1. Definitions

#### 3.5.1.1. Definition of “Internal QC”

In this document, we define *internal quality control* as the process of internally ensuring product quality, preferably in a semiautomatic way. This can be done in the form of automatically generated quality overall reports and maps, that will be manually inspected by the Production Quality Manager, or an operator.

#### 3.5.1.2. Definition of “External QC”

In this document, we will define *external quality control* as semi-manual comparison of end products with external information such as:

- Qualitative knowledge about local ground motion (expert assessment)
  - Observation of damages to infrastructure due to ground motion
  - Knowledge about specific non-quantified deformation phenomena
  - Comparison with nonquantitative related information in a GIS system, e.g. geological structures or location of geothermal power stations.
- Quantitative knowledge about local ground motion, including
  - Other available InSAR products (e.g. national GMS and/or results from high-resolution commercial data)
  - GNSS (using a set of stations not used in production)
  - Levelling
  - Extensometers
  - Tiltmeters
  - Ground water level measurements

External QC is out of scope of this section, but is treated to some extent in section 4.5.6.

### 3.5.2. Pointwise quality measures

When the ground motion model is known, the following two well-known quantities describe the overall quality of the retrieved time series.

#### 3.5.2.1. Temporal coherence

The temporal coherence is a normalised measure for assessing the quality of the retrieved deformation time series. According to the applied algorithm, the formulation can be different. Typically, in single master approaches, it measures the similarity between the retrieved time series and the model. Note that the measure is biased and tends relatively slowly to zero for random input. Thus,

$$\gamma = \frac{1}{N} \left| \sum_n e^{i \frac{4\pi}{\lambda} (d_n - d_n^{\text{model}})} \right|$$

Where  $N$  is the number of samples in the time series,  $d_n$  is the retrieved time series, and  $d_n^{\text{model}}$  is the fitted model, which may be parametric, or nonparametric (e.g. using assumption on the degree of smoothness). This measure may be applied in multiple stages of the processing:

- Identification of robust arcs in an initial network detected from amplitude statistics only
- As weights in a finite difference integration of relative parameters estimated per arc in a sparse network, eg pairwise linear velocities [Costantini2012]
- For acceptance testing of final measurement points. A threshold on the coherence can be derived numerically by applying the coherence estimation on uniform random phase noise and thus estimate the probability density function of the test statistic under the null hypothesis:  $\gamma = 0$ . By selecting an acceptable false alarm rate, e.g.  $\alpha = 10^{-4}$ , one may derive the applicable threshold from the estimated pdf.
- Typically, the coherence is one of the annotated quality measures associated with a time series.
- Gridded average coherence, e.g. at 200-500m resolution, can be automatically generated as part of the production system. Such a product could be a basis for automatic anomaly detection. Areas with unexpectedly reduced or low average coherence might indicate, e.g.
  - The applied algorithm failed to initialise well due to holes in the initial reference network.
  - There is an uncaptured temporal ground motion modelling error, e.g. due to strong nonlinear motion.
  - Like for the measurement point density, see above, a range of expected coherences per land cover class can be defined and used as part of an automatic anomaly detection system.
- In multi master approaches (e.g., SBAS) the redundancy of the interferograms can be profitably exploited to retrieve an alternative formulation of the temporal coherence [Pepe2006], that compares the original wrapped interferograms with the ones reconstructed following the equivalent single master phase estimation step, with no need to consider any a priori parametric model for deformation signals.

### 3.5.2.2. Root-mean-square error

The root-mean-square error (RMSE) of a time series with respect to a fitted model is a measure of the average noise per point. This measure has the same units as the input time series, usually millimetres (mm).

$$\hat{\sigma}_d = \sqrt{\frac{1}{N} \sum_n |d_n - d_n^{\text{model}}|^2}$$

If the ground motion time series model is true, the RMSE is a measure of the standard deviation of the noise of each point in the time series. A typical threshold would be in the range 3-5mm. Note that the standard deviation of uniform random phase noise (converted to ground motion at C-band) is 8mm, meaning that reliable points will have a much lower estimated RMSE than this.

Note that both coherence and RMSE depend on the correctness of the ground motion model fit. This means that using them may result in failing to identify strongly deviating ground motion, e.g. catastrophic failure, or strong variations in velocity.

### 3.5.3. Measurement point density

A typical measure of overall quality for a ground motion dataset is the measurement point (MP) density in units of [1/km<sup>2</sup>]. This is a good way of comparing different algorithms and selection criteria for the same dataset, i.e. as *relative* measure. It can also be used to detect anomalies in case of extremely low point densities in an area where this is not expected. This can, for instance, be implemented in the form of an expected range of densities for a given land cover class. The land cover class can be derived from CORINE land cover (see section 4.6), meaning that such deviation testing can be done automatically, and anomaly reports generated as part of a production QC system. To avoid too high or low anomaly rate, this requires that the expected density range for each CORINE land cover class is well tuned.

Note that care must be taken in order to apply measurement density as an *absolute* quality measure. It depends strongly on geographical area, land cover class, deformation phenomena, selection thresholds and many other factors.

In Table 3-8 the most significant classes of CORINE land cover for SAR interferometry products are reported. For each class, a range of values for PS/DS point density is indicated. The higher value corresponds to the goal not guaranteed, the lower value corresponds to the minimum threshold and, if the density is lower than that value, an anomaly must be flagged and further analysed.

Table 3-8. Most significant classes of CORINE land cover for SAR interferometry

Corinne Land Cover Class (CLC)	Measurement point density (PS-DS/sqkm)
1.1.1 Continuous urban fabric	5,000 – 10,000
1.1.2 Discontinuous urban fabric	1,000 – 5,000
1.2 Industrial, commercial and transport units	1,000 – 5,000
3.3 Open spaces with little or no vegetation	100 – 1,000
Other	N/A

### 3.5.4. Study of Tile / Burst / Swath Overlaps

The individual Level-2a processing units (section 3.4.3.3.1) overlap with each other. In these overlap zones, it is possible to check for consistency. Even though one might observe a slightly different selection of coherent measurement points due to different view angles (if from different bursts), we expect:

- Similar MP density
- Similar primary network MPs
- Similar spatial coherence per interferogram

If there is an unexpectedly large deviation, this might be an indication of, e.g. a poor choice of reference point and/or a low-quality primary network integration in one of the compared tiles.

### 3.5.5. Multiprovider harmonization

The production of continental-scale products, may involve different service providers using different algorithms and processing workflows. Harmonization procedures for results from different providers are needed in order to provide data with homogeneous characteristics in terms of density and accuracy of measurements, and the contiguity of the results.

As a motivating example, we refer to the experience of processing at a national scale, using the entire ERS and ENVISAT archive (1992 - 2010) over Italy. The basic processing unit used was the standard framing of level 1A data (~100 km x 100 km). The large area of overlap between frames belonging to the same or adjacent tracks was exploited in order to perform quality controls and align the mean velocity layer. In the case of legacy ERS and ENVISAT data, the temporal sampling was irregular and the number of images per stack varied from less than thirty up to more than a hundred images. The first two objectives of data harmonization were achieved by fulfilling a number of requirements in terms of accuracy and density of the measurements as a function of the land use class (e.g., see section 3.5.3). The contiguity of the result was obtained by opportunistic filtering of the data, removing large scale spatial artefacts, and applying mosaicking strategies to able to analyse all pairwise corrections between processing tiles and to integrate them [Adam2011, Costantini2012, Manunta2019], in order to minimize the difference at the transition between different processing blocks. The approach was very effective, but with a significant drawback: the LOS of displacement patterns larger than the dimension of the single frame are lost.

In context of EGMS, the situation is much more favourable. The Sentinel-1 data archive is homogeneous over all the European territory, with constant and frequent revisit (6 days starting from September 2016), with hundreds of images per interferometric stack. The constant rate allows the observation of the same range of displacement values everywhere, and the number of available images allows high accuracy velocity determination. Some problems could happen at higher latitudes where the snow coverage has a big impact, and for a long period during the winter season there are no useful acquisitions. In this case, some displacement regimes are not observable (see section 3.2.6), and the density and accuracy may be lower than in areas where the whole archive can be exploited.

### 3.5.6. Quality control plan

As part of the internal product quality control, several characteristics of the products should be reported systematically. Such reports should include quantitative assessments of at least the following:

- Comparison to GNSS
  - statistical properties of long-wavelength component residuals
  - Bias and standard deviation of measurement points close to GNSS stations
- Accuracy of atmospheric correction:
  - Analysis of variograms of short temporal baseline interferograms (to ensure coherence and little deformation) before and after correction, see [Appendix on NWP] for a similar QC of the preremoval of APS based on weather models.
- “Point cloud” comparison between Asc/Dsc:
  - Point density over same area of interest
  - Deformation
  - Localization (Latitude/Longitude/Height)

- Note: Compare to “lower bound” predicted by S1 orbital tube statistics (see section 12.3)
- Analysis of reference point noise:
  - Histogram analysis of consistency of stable targets in the vicinity of the reference point.
- Comparison to other external information where/if available:
  - Using artificial reflectors where possible
  - Known apriori deformation signal

## 3.6. User engagement and support

EGMS data will only be used if it is findable, accessible, usable and understandable. Thus, it is not enough to produce enormous amounts of data; a dissemination and visualisation system must be in place. The system must be intuitive to use, provide sufficient visualisation and analysis capabilities to avoid the need data download, but must also provide such download options to the users that require it. The data provided must be well documented (see section 4.7.2) and sufficient explanatory material must be available for new users to understand how to use the data. Finally, users must have the ability to obtain both technical support and data use support.

Being an open service, the EGMS will attract a wide range of users, which will have very different levels of expertise regarding ground motion processes and satellite-based radar interferometry. In the following discussion, we refer to three roughly defined categories of users: general public, experts and InSAR experts.

1. A general public user could be a private citizen (e.g. interested in using the service to check on his or her property) or a non-technical professional (e.g. with an administrative background).
2. Experts are users who are considered to have a ground-motion related technical background, but who do not have the expertise or extensive knowledge related to SAR interferometry (e.g. geotechnical engineers, geologists, or geophysicists).
3. InSAR experts represent users who have worked with InSAR data before and therefore have prior knowledge about the technique, its value and its limitations.

### 3.6.1. Dissemination and visualisation

EGMS will provide ground motion data for tens of billions of locations, each with hundreds of individual measurement values (summary values plus full deformation time series). Users need an interactive web-based interface (Web-GUI) for easy visualisation of the data. The same system should serve as the interface for search and download functionality.

### 3.6.2. Web-GUI

User requirements for the interface will depend on their skill level as well as the type of application. All users, including the general public, require basic information like mean velocity and displacement time series for particular sites. Experts need more detailed information to make full use of the available data for their applications. This includes, in particular, access to auxiliary data like height correction, line-of-sight definition and quality measures. Experts will also need, to a higher degree, means to select data for the display of time series or statistical measures, both spatially or temporal. They will also need export functionality to apply their own post-processing to the displacement data. Compared to the experts, InSAR

experts have a deeper understanding of the underlying techniques, and thus will utilise auxiliary data to assess the quality of the data and to help with the interpretation.

It is quite possible to meet the needs of all users within a single Web-GUI. The key is to keep the interface as intuitive as possible, while providing the necessary tools for experts to derive the information they require. The following minimum functionality should be available within the Web-GUI.

### 3.6.2.1.1. Time series viewer

The main interface should be map-based, with average velocities displayed in colour over a background map. A choice of background maps should be available. At least one should be a standard vector map containing all features down to a building level. At least one should be image based, either high-resolution optical satellite or orthophoto mosaic. The background map should contain elevation information such that it can be viewed and navigated in 3D. It should be possible to perform a geographic search to zoom to a particular location of interest.

Individual data points should be symbolised by average velocity by default (either LOS or vertical). The user should be able to adjust the limits of the colour scale, as well as the field for symbolisation (e.g. LOS velocity, vertical velocity). A graphical representation of the cumulative deformation should be displayed when a given point is clicked. This should also include all summary values and quality measures. It should be possible to compare multiple data points within the same plot, either by selecting several individual points, or a group of points within a polygon.

Data points representing PS and DS should be differentiated. While PS represents a single point, DS represents an area on the ground. It should be possible to estimate the area covered by the DS measurement. This could be accomplished in several ways. Each DS could be represented by a single point, with attributes indicating the size of the area represented by the point. Each DS could be represented by a polygon, with attached attributes. Each individual pixel making up the DS could have its own point, with common attributes for each DS. Each method has its advantages and disadvantages. Keeping in mind the needs of both the general public and experts, it is preferable that the visualisation be as intuitive as possible, without the need to fully understand the difference between a PS and a DS, and all areas with data covered by points. For this reason, we recommend the latter approach, with multiple individual points representing single DS areas.

Where multiple datasets are available for a given area (e.g. ascending and descending Level 2b), the user should be able to select which datasets will be displayed.

### 3.6.2.1.2. Simple analysis tools

Various simple analysis tools should be available within the Web-GUI. For example, a profile tool could allow the user to draw a line within the map. A graphical representation would then be generated of the mean velocities along that profile. Another example would be the ability for the user to select their own reference point within the map. The velocities and deformation time series for all other points within the display would then be recalculated and redisplayed with respect to that point. Similarly, the user should be able to choose a different reference time, and/or time interval, for the display of average velocities and cumulative deformation time series. Yet another example would be a polygon functionality tool, allowing the user to define an on-the-fly polygon showing average time series for all points located within the polygon.

### 3.6.2.1.3. Export functionalities

All maps and time series graphics should be exportable in common raster and vector formats. Data for individual points and selections of multiple points (e.g. within a user-selected polygon) should be exportable in simple ASCII format. Selections of multiple data points should also be exportable in standard GIS formats such as kmz, shapefiles and GeoJSON.

### 3.6.2.2. API

Some specialist users will wish to integrate EGMS data into their workflows. For relatively small amounts of data, this can be accomplished using the export functionality of the Web-GUI outlined above. However, for advanced users, data download should be possible from within their own tools. For this, an application programming interface (API) should be provided. This API should be based upon standards set by the OpenSearch Community ([github.com/dewitt/opensearch](https://github.com/dewitt/opensearch)), as already used by the Copernicus Open Access hub as well as numerous Collaborative Ground Segment hubs.

### 3.6.3. User uptake

It is important to reach as many end-users as possible. Currently, most ground motion data users tend to be experts. In the future, we hope that ground motion data is findable and understandable by all relevant authorities and citizens. To that end, the data must be well documented and understandable.

#### 3.6.3.1. Documentation/FAQ

General public users, as well as experts, are not intimately familiar with ground motion products based on satellite radar data. It is important to identify any potential mismatch between user expectations and what the EGMS service can and should deliver.

Table 3-9 lists some frequently asked questions from end-users when presented with InSAR-based ground motion data. These and other questions should be answered within a searchable FAQ database.

Table 3-9. Frequently asked questions

	General public	Expert	InSAR expert
What are we measuring? <ul style="list-style-type: none"> <li>• What are the measurements representing?</li> <li>• Why do I see a measurement point here, and why not there?</li> <li>• Why is the measurement point red (yellow), ...?</li> </ul>	X	(X)	
What is the "accuracy" of the measurements? <ul style="list-style-type: none"> <li>• Define precision vs accuracy</li> <li>• Displacement</li> <li>• Height</li> <li>• How big of a movement can we detect?</li> </ul>	X	X	X

● How fast of a movement can we detect?			
What is the location precision of measurements (e.g. on a map)?		X	X
What kinds of ground reference measurements are required? <ul style="list-style-type: none"> <li>● In situ (e.g. inclinometers, extensometers)</li> <li>● Conventional geodetic measurements (e.g. GNSS, total station)</li> </ul>		X	X
What is the spatial coverage of measurements? (incl. shadowing effects)	X	X	X
What is the resolution of measurements? <ul style="list-style-type: none"> <li>● Temporal: how often can I get an update?</li> <li>● Spatial: how many measurement points will my area or target of interest contain?</li> </ul>		X	X
What is InSAR actually measuring? <ul style="list-style-type: none"> <li>● Phase component of backscattered electromagnetic signal</li> <li>● Line of sight vs. vector components (horizontal, vertical)</li> <li>● Side looking geometry</li> <li>● Pointlike vs distributed scatterers</li> </ul>	X	X	
What is the difference between persistent scatterers vs. distributed scatterers? <ul style="list-style-type: none"> <li>● When is decorrelation a problem?</li> <li>● How big of a target do you need?</li> </ul>	X	X	
How does InSAR relate to traditional measurements (i.e. terrestrial surveying)?	X	X	
Are measurements relative or absolute? <ul style="list-style-type: none"> <li>● What is the reference for measurements?</li> </ul>	X	X	
Where does InSAR work? Where does it not work?	X	X	
When does InSAR work? When does it not work? <ul style="list-style-type: none"> <li>● Seasonal periods (gaps in data, e.g. seasonal snow cover)</li> <li>● Historical imagery (How far back can we go?)</li> </ul>	X	X	
How often is the EGMS product updated? <ul style="list-style-type: none"> <li>● How long do we have to wait for results?</li> </ul>		X	X
How long will it take to identify changes indicative of a land surface process? <ul style="list-style-type: none"> <li>● Visual identification</li> </ul>	X	X	

• Monitoring alerts			
• Mean velocity measurements			
• Nonlinear deformation difficult to detect?			
Is there a moving window for the proposed GMS?	X	X	
How long will data be available to users?		X	X
• Data archive policy			
• Long-term data preservation			

The user documentation must fulfil the needs of all users of these groups. General public users require basic information about the service and InSAR, in general, to be easily accessible and understandable. The same applies to experts, who are not familiar with SAR interferometry. Such documentation should, therefore, be available without being cluttered with technical details that are not relevant to these user groups. InSAR experts, on the other hand, need good documentation of all technical details. To get to this information in an efficient way, it should not be buried in too much background information that these users do not require.

### 3.6.3.1.1. Elements of the user documentation:

- **Data disclaimer**

A data disclaimer specifying and delimiting the scope of rights and legal liabilities of the EGMS service.

- **User Guide**

The User Guide should explain the EMGS web interface and help the user to navigate and find the desired information, these should include a selection of references to scientific papers directed to experts and links to relevant websites (e.g. of existing third-party use cases) for non-experts. Multi-language user guides and a selection of multi-language featured use cases should be available.

- **Specifications**

A document is needed that will provide product specifications and details about product validation (possibly integrated into User Guide).

- **FAQ**

Frequently Asked Questions as listed above. These will help, in particular, the non-experienced users to quickly find the answers to their most common questions. The FAQ should be developed and maintained in conjunction with the user support system (section 3.6.3.3).

- **Interpretation guidelines**

In order to guide the user, when interpreting the data published on the EMGS, and to avoid unrealistic expectations (e.g. regarding accuracy or coverage or most importantly misinterpretation), the documentation should provide guidelines. These guidelines should explain theoretical considerations in an as simple as possible manner and further explain their practical meaning using examples generated by the service.

- **Reference documentation**

Especially for the InSAR expert, concise but complete documentation of all relevant details is important. The reference documentation should contain:

- Product Specification
- Product validation documentation

- **Limitations**

Guidance documents must make clear that some types of analysis are beyond the scope of EGMS, but available from industry; other types of InSAR analysis can be contracted, e.g. different epochs, high-resolution based on commercial data, alternative processing regimes, custom processing for highly non-linear deformation, etc.

### **3.6.3.2. Tutorials and other training materials**

No matter how good the documentation is, there will be some need for training, both as part of user uptake and user support. While EGMS cannot provide user training throughout all the user countries, training material must be created. In addition, a basic level of support must be provided to end-users. For EGMS, a website should be created where users can find, at a minimum:

- A description of the service, the Web-GUI platform, links to web-pages about the Copernicus program, a section about InSAR for people familiar to conventional geodetic techniques, a selection of InSAR papers related to the use of Sentinel-1 data for different applications;
- The User Guide, FAQ and other documentation described above;
- Video tutorials about basic InSAR technology, the EGMS service and the visualisation system;
- Links to resources within member countries.

All user material should be made available in multiple languages. This may require support from member countries.

### **3.6.3.3. Support**

User support, while critical, must have a clearly defined scope from the beginning. With millions of potential users, it would be impossible to answer every question regarding specific ground movements. Most user queries should be answered by the documentation and training materials outlined above. Agreements should be made with member countries to provide region-specific support. However, some level of interactive support must be made available centrally within EGMS.

E-mail support should not be encouraged. Rather, an online support system should be provided where support requests can be tracked and answers provided within a reasonable response period (suggested two working days). Support topics should be limited to technical issues regarding the data, Web-GUI and API. Questions and answers should be added to the FAQ.

Alternatively, or additionally, an online User Forum could be created, moderated by EGMS staff. This would allow other users to post questions and discussions on a broader range of topics. Answers could be supplied either by EGMS staff (restricted to technical questions) or other users.

## 3.7. Service recommendation

The scope of this section is to summarise the overall recommendations from the consortium for the implementation of the EGMS service.

### 3.7.1. Overall design goals

A pan-European scale service like the EGMS will only succeed in the long term if it stays relevant for its users. As outlined in Section 3.2, the number and type of users are diverse and potentially evolving. In order to meet as many of the users' needs as possible, the overall principle must be the maximisation of information, which in this context means that the service should not be optimised for a subset of users, but design output products of uniform quality that do not unnecessarily exclude common use cases.

As with any large production service, compromises need to be made due to finite resources and external boundary conditions. We will strive to apply the principle of diminishing returns in order to maximise the usefulness of the service given finite resources. In other words, we will try to find a reasonable balance between necessary capacity and the performance of the resulting service.

The scale of EGMS is unprecedented. Although there are, and have been, a number of national and other large initiatives, none have been remotely close to the scale of EGMS. In order to ensure success, it is paramount to avoid unrealistic goals. Towards that end, our recommendations for the service implementation will be conservative and build on proven and mature technologies and suppliers with proven operational track record. It will be discussed how new research fronts may be incorporated into the service over time in section 0. The specification team consists of many experienced and long-term participants in the InSAR community. We have tried to reach internal consensus on as many topics as possible. While unanimous agreement is hard to achieve on every topic, we believe that most recommendations in this section are shared by both the specification team and the general InSAR community.

We will focus on specifying the properties of the service product portfolio, and the user-facing service components (dissemination system, user support). On the other hand, we will refrain from recommending a specific technology in cases where multiple options exist. We believe it should be up to the consortia bidding for the production tender to prove that their suggested methodology and other technical solutions can meet the laid out requirements.

### 3.7.2. Boundary conditions

The most important boundary conditions to consider are

- Capacity constraints, e.g. hardware, bandwidth and available qualified manpower.
- Consequences of delineation of the service with respect to:
  - Industry
  - National services
  - Copernicus contributing missions
  - Other Copernicus services

Some of these aspects have already been analysed in the EUGMS White Paper [EUGMS\_WhitePaper], and will not be challenged in this document.

### 3.7.3. Geographical coverage

There are only two viable choices for the geographical scope of EGMS.

- Copernicus participating countries:
  - 28 EU member states + Norway + Iceland
  - the countries providing funding for the Copernicus Programme should all have the same level of service
- EEA39
  - 33 members of the EEA:
    - 28 EU member states + Norway, Iceland, Liechtenstein, Switzerland, Turkey
    - 5+1 Balkan states (Albania, Bosnia and Herzegovina, North Macedonia, Montenegro, Serbia, as well as Kosovo under UNSCR 1244/99<sup>1</sup>)

Some special territories should be given special consideration:

- EU member states' overseas territories in Caribbean and Indian Ocean
- Canary Islands
- Small enclaves and remote islands within or close to continental Europe
- Svalbard and Jan Mayen
- Antarctic territories

Recommendation:

- First production cycle:
  - EEA-39 with the exception of Turkey, overseas regions, Svalbard and Jan Mayen. Other special cases mentioned above might be considered case by case, depending on how much resources are needed to include/exclude them.
- Service evolution: In subsequent production cycles, include the full EEA-39 area wherever feasible.

### 3.7.4. Update frequency

Building on the consensus from the EU-GMS White Paper [EUGMS\_WhitePaper], which summarises the work of the EU-GMS Taskforce, it is clear that a too high update frequency will challenge industrial interests. A too low update frequency, on the other hand, will result in failure to meet many user requirements. A reasonable compromise must be found that also takes into account a conservative estimate of the production capacity available.

Recommendation:

- First 2-3 production cycles: update every 12 months
- Service evolution: consider whether 6-month updates is feasible technically and with respect to the evolution of delineation criteria.

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<sup>1</sup> Without prejudice to positions on status, and is in line with UNSCR 1244/99 and the ICJ Opinion on the Kosovo Declaration of Independence.

### 3.7.5. Methodology

#### 3.7.5.1. Choice of algorithmic framework

The main available processing methodologies are discussed in 9.3. To follow the design principle of information maximisation, we recommend a requirement that the production methodology shall be able to exploit both the main classes of scatterers, pointlike targets and distributed targets. It should be left open to the bidding service suppliers to propose a specific methodology, but it must be operationally demonstrated that the proposed methodology achieves the requirements defined in the product specification, in a scalable way.

Recommendation:

- Hybrid methodology, considering both PS and DS shall be used.
- The deformation regimes as outlined in section 3.7.5.2 shall be handled by the chosen methodology.
- The specific choice of workflow should be left to the bidding service suppliers but the choice must be able to fulfil the product specification requirements, as well as the proposed production timeline, including scaling requirements.
- 

#### 3.7.5.2. Ground motion regimes

In principle, the only strict limitation on the type of ground motion that can be observed by InSAR methodology without external information, is that the signal does not change by more than a quarter-wavelength (14 mm for S1) between consecutive temporal and spatial samples (see section 3.2.6). This limit is an upper bound, valid only in the noise-free case. Thus, due to the presence of noise, we will typically only be able to handle motion up to a fraction of this in most cases.

In particular, the following ground motion regimes cannot properly be resolved without external information

- Instantaneous and localised motion faster than ~2 mm/day (e.g. fast landslides),
- Sudden events larger than 14 mm in both space and time (e.g. collapse or sinking of single building),

These two cases are both characterised by a large motion for a point or group of points, independently of their surroundings.

All remaining phenomena can, in principle, be resolved by some 3D phase unwrapping procedure. However, 3D phase unwrapping is in general extremely costly (section 8.2, Appendix D), so practical constraints must be applied. This algorithmic constraint has been taken into account in the following recommendations.

Recommendation:

- For the first production cycle, consider as a minimum requirement, only the class of ground motion that can be resolved using a quasilinear assumption, i.e. the class of deformations such that the residuals, w.r.t. the linear trend, do not exceed 14 mm in the whole period of observation. This will cover a very large proportion of the coherent measurement points. Post-processing,

using higher order deformation models, may be applied to correct the unwrapping for some classes of nonlinearity.

- For subsequent production cycles, consider expanding to other classes of nonlinear ground motion, exceeding the assumption of quasi-linear:
  - *Assume a smoothness criterion in time*, in the sense that no ambiguous changes (<14mm) between consecutive samples in time are allowed. This will allow larger variations to be captured by quasilinear (< 14 mm residuals in the whole observation period). This regime can in practice often be resolved by a piecewise quasilinear approach. Such an approach, however, is currently not applied in many studies, meaning that a demonstration of the concept at large scale must be conducted before considering such an approach for EGMS.
  - *Assume smoothness in space and/or time*, which will allow all signals that can be unwrapped unambiguously in 3D to be resolved if of high enough quality. This will enable successful identification of large jumps in the time series if the data can be successfully unwrapped in space. However, this will require reconsidering quality thresholds since the danger of unwrapping errors increases rapidly with decreasing SNR.
  - *Consider handling of instantaneous events*, including earthquakes and volcanic eruptions. Such events pose a challenge for standard processing, and it is an advantage to be able to estimate and take such events into account when applying time series analysis.
  - *Apply point selection criteria that avoids points with high non-triangularity (DS only)* Soil moisture and other volumetric effects may cause phase inconsistencies. This situation typically happens in agricultural areas and wetlands, and is not well understood. See Section 8.4.3.4 in Appendix C for details. These pixels must be avoided for successful 3D unwrapping.

### 3.7.5.3. Challenging scenarios

There are also some challenging scenarios for consideration which are detailed in the following sections.

#### 3.7.5.3.1. Periglacial landscapes

Arctic regions with significant freeze/thaw cycles is challenging for InSAR time series monitoring due to strong nonlinear motion combined with short snow, see e.g. [Rouyet2019] for a description of permafrost effects on InSAR in a periglacial landscape on Svalbard.

##### Recommendation

- Svalbard and Jan Mayen should not be included in the baseline EGMS service
- If there are user needs, customized processing can be considered for the service evolution. This will require a DS only product customized for strong seasonal motion.

#### 3.7.5.3.2. Snow cover

High altitude regions throughout the area of interest, as well as most of Northern Europe, are affected by seasonal snow cover. This results in loss of data for large parts of the year. The consequence is that

detection of strongly nonlinear motion is an illposed problem due to potential phase ambiguity from one snow free season to the next. Depending on the length of the snowcovered season, this limits the ground motion regimes that can be reliably retrieved to those that are ambiguity free (<20 mm/yr and quasilinear), or strongly linear.

In addition to the ambiguity problem, less data will be available for analysis. This means that the product quality is negatively affected whenever the number of scenes is the key parameter, e.g. the geolocalization, and long-wavelength spatial deformation trends.

Affected areas:

- Norway, Sweden, Finland, Iceland
- High and mid-altitude mountain ranges in all of Europe.

Recommendation:

- Scenes with snow cover must be removed when the duration is more than 1-2 months
- Such scenes can be identified and excluded from the analysis using the Copernicus Land Service's Snow Cover Extent product [SCE]

#### 3.7.5.3.3. Isolated islands

Around Europe, many relatively remote islands exist. When the distance to the closest landmass is significantly larger than the atmospheric correlation length, it is not possible to unwrap the signal reliably across the water body. This means that the island must be analysed in isolation.

Recommendation:

- Islands farther than 5-10 km from the nearest land mass should be analysed separately to avoid error propagation, that may affect both island and the closest land mass due to unwrapping errors across the water body.
- For production of L2b, GNSS is needed. If neither GNSS nor geodetic model is available for an isolated island, it is impossible to absolutely reference the L2b product. In these situations, L2a data covering the data should be calibrated relative to each other, and then statistically adjusted to zero, assuming no average motion. Such products, as well as the corresponding L3 products should be clearly marked as potential anomalies with degraded quality.

#### 3.7.5.3.4. References

[Rouyet2019] L. Rouyet, T. R. Lauknes, H. H. Christiansen, S. M. Strand, and Y. Larsen, "Seasonal dynamics of a permafrost landscape, Adventdalen, Svalbard, investigated by InSAR," *Remote Sensing of Environment*, Volume 231, 2019, 111236, <https://doi.org/10.1016/j.rse.2019.111236>.

[SCE] <https://land.copernicus.eu/global/products/sce>

### 3.7.6. Production system design

#### 3.7.6.1. Input data source

The initial EGMS production cycle will, with few exceptions, require, as input, every single data product acquired over the chosen geographical coverage. Thus, the total required data volume is significant (section 3.4.3.1). In order to download the full data volume to a dedicated server, bandwidth is a serious limitation that will make careful production planning very important to avoid delays in the initial service deployment.

Recommendations:

- The choice of production platform (cloud, dedicated server, combination) should be left open to the bidding suppliers, but whatever the choice, it must be well justified with respect to the requirements, in particular, the production timeline.
- Exploitation of the cross-polarisation channel
  - First production cycle: The cross-polarisation channel of S1 IW products shall not be considered. This will reduce processing and local storage capacity requirements by almost 50%.
  - Service evolution: Unless studies become available in the literature, consider to include a medium to large-scale test activity to assess whether the almost doubled production capacity requirement (CPU, storage) is considered worth the effort. Both full coverage, and urban areas only should be considered.

#### 3.7.6.2. Product quality requirements

To ensure a successful service, it is very important to define product quality requirements to be uniformly enforced. These need to be conservative enough to minimise mismatch with user quality expectations. However, they also cannot be too strict, since this will lead to loss of information also for the best available methodology. Table 3-10 outlines the recommendations for each product level. Note that the quality requirements are subject to change over time due to availability of more data, see Table G-2.

Table 3-10. Quality recommendations

Processing level	Resolution	Quality requirement
Level 2a	As high as possible, without losing measurement points.  <u>For (H)DS: &lt;150 full resolution pixels per DS, &lt;100m largest dimension (**)</u>	<5 mm standard deviation for any constant velocity point wrt local reference point (up to 10 km apart) and wrt a temporal reference.  <u>Note:</u> there is no direct requirement for geolocation accuracy due to the relative nature of this product. However, the requirement for Level 2b puts boundary

		conditions on the precision of the geolocation estimate.
Level 2b	Same as for Level 2a	<10 mm standard deviation (*) between any two constant velocity points up to 50 km apart for the baseline service.  10 m 3D geolocation accuracy (see 12.3).
Level 3	100m x 100m	<10 mm standard deviation (*) for any points up to 50 km apart, for 100 m x 100 m resolution cell with space-homogeneous and time-constant velocities.  <u>Note:</u> The geolocalisation accuracy requirement for L2b products will ensure minimal leakage between grid cells.

\*Note that for L2b and L3 products, the listed quality requirement assumes availability of high-quality GNSS data. The accuracy strongly depends on the external calibration data available, in particular the density of GNSS stations, which is different in the different European countries. The above figures are indicative and must be confirmed, see for example

[F. Rodriguez Gonzalez, A. Parizzi and R. Brcic, "Evaluating the impact of geodetic corrections on interferometric deformation measurements," EUSAR 2018]

[A. Parizzi, F. Rodriguez Gonzalez, R. Brcic, "A Covariance-Based Approach to Merging InSAR and GNSS Displacement Rate Measurements," Remote Sensing, 2020, 12(2), 300, Jan 2020. <https://doi.org/10.3390/rs12020300>]

\*\*HDS refers to homogeneous distributed scatterers. Note that these upper bounds are consequences of the 100m grid recommended for L3 products. It is recommended to keep the dimension of (H)DS smaller than the grid size of L3 products to avoid interpolation of L2b results instead of binning in the production of L3.

### 3.7.7. Core processing system

The computing part of the production system is in principle available off-the-shelf in many variants, including cloud providers, dedicated hardware and distributed solutions. However, some properties of EGMS are relatively demanding.

- Very high data volumes, which lead to high bandwidth requirements.
- Non-trivial processing methodology InSAR processing on the scale of EGMS is tricky, and not that many entities are capable of performing this task on an operational level.

Many possible processing system models are feasible, and the specific choice is left to the bidding team. However, some requirements must be put on the production system.

## Recommendation

- Processing close to data All data must be available to the processing system with low latency and very high bandwidth.
- Avoid vendor lock-in (external) In order to minimise the risk of investing too much in a suboptimal processing platform (bankruptcy, obsolete hardware, ), generic platform software (cluster manager, cluster deployment, cloud middleware) should be used in favour of optimizing for a single platform to ease change of platform if necessary. Open source solutions should be preferred when available.
- Avoid vendor lock-in (internal) To minimise the risk of underperforming subsystems, clear and well-defined interfaces between (potentially) independent subsystems must be specified.

### **3.7.8. Dissemination system**

In order to facilitate user uptake, data must be available in an accessible form. One way of doing this is to engage the users through a Web-GUI system for visual access to the database. Such a system must be scalable enough to serve the entire EEA area to a varying number of users without significant latency.

In addition, to be relevant for expert users, data must be accessible via standardised APIs, such that access from GIS systems can be implemented with reasonable effort.

#### Recommendation:

- Scalable Web-GUI system, with all points available to users
  - Data represented by average velocity
  - Deformation time series, all derived measurements and auxiliary data available upon interactive selection.
- Simple registration procedure only to conform with TC of data/service
- Data access via API for users
- Tools for simple analysis tasks integrated with the Web-GUI
  - Spatial average of a selected polygon
  - Profiles of mean velocities in space and time
  - Selection of new local reference point and time interval, with on-the-fly recalculations of rates of points and time series within the view.
  - Location search (name or coordinates)
- Export to standard GIS formats for limited data amounts.
- Separated from the production system.
- Deployed in cloud infrastructure, with load balancing capability to handle peaks of thousands of simultaneous users without service interruption.
- High-resolution optical background imagery
- Standalone background topographical map featuring roads and buildings, etc.
- Hybrid map/optical background layers.

### 3.7.9. Auxiliary/Ancillary data

#### 3.7.9.1. Digital elevation model

For InSAR production purposes, a very high-resolution DEM is not necessary, since the height of each measurement point above the reference DEM is estimated as part of the processing. It is much more important that the model is free of any anomalies and should have a uniform quality. Buildings should not be included, as the discontinuities in height will complicate numerical procedures.

Minimum requirements:

- <100 m spatial resolution
- <20 m vertical accuracy (excluding buildings)

Recommended requirements:

- < 30 m spatial resolution
- < 10 m vertical accuracy (excluding buildings)

The EU-DEM (currently v1.1) is of sufficient quality, available from EEA. It is assembled to a uniform dataset, which makes handling it in production easier.

Recommendation:

- The EU-DEM shall be used in EGMS production.

#### 3.7.9.2. GNSS data

For the generation of the L2b product, external information that currently can only be provided by GNSS is necessary. Mainly, we need to be able to eliminate crustal motion phenomena from influencing the InSAR analysis, including

- Tectonic plate motion [EUREF89 datum]
- Dynamic earth effects, such as earth tides [IERS], tidal loading etc.
- Steady vertical motion, including postglacial uplift in Fennoscandia and surrounding effects.

For the first two, there are well established models. However, while some regional models exist, there is no unified model for vertical motion in Europe. Sources of vertical rates for single locations are available from

- Nevada Geodetic Lab [<http://geodesy.unr.edu>]
- EUREF [<http://epncc.oma.be>]

Minimum requirements for vertical motion data:

- < 2 mm/yr residuals for the vertical rate difference between any two stations in the applied GNSS network.

Recommended long-term requirements:

- High enough accuracy to avoid GNSS input being the dominant (spatially relative) error source of the L2b product.

- High enough density in the GNSS network to allow the L2b/L3 product requirements to be fulfilled. The exact impact of GNSS station density on InSAR products is not currently studied in detail in the context of large-scale applications, but the recent paper [Parizzi2020] indicates that a reliable station every 25-40 km is sufficient to reach 1 mm/yr per 100 km accuracy, which is a similar requirement as the recommendations for EGMS in Section 3.7.6.2. However, more work is needed to quantify this properly.

Recommendation:

- First production cycle:
  - Build a minimum viable product version of a pan-European vertical model from freely available sources. This may limit the accuracy of the L2b product in areas with a low density of GNSS stations or low-quality data.
  - Start a cooperation process with relevant umbrella organisations within the GNSS community with the goal of jointly producing a reliable unified vertical model for EEA39. The process has to begin on the GNSS side, while EGMS can contribute to densification of the model over time due to higher (but relative) vertical precision and much higher resolution.
- Service evolution:
  - Goal: a unified vertical model for Europe that does not dominate the error budget of EGMS L2b and L3 products.

### 3.7.9.3. Numerical weather data

Operational numerical weather can be used to mitigate large- and medium-scale atmospheric effects. When successful, this approach is much less demanding than corresponding data-driven methods that usually require spatial unwrapping of a large number of interferograms. Currently, numerical weather prediction (NWP) data are only available in uniform quality with a latency of 2-3 months, which imposes a corresponding latency on the production. ECMWF launched a preliminary product in December 2019, with 7 days latency. However, this product is not guaranteed to be processed in a uniform way, and its use still needs to be demonstrated. In general, there is limited operational experience in InSAR community, with few exceptions. However, NWP models are improving. Once the ECMWF 7 day product is fully operational, NWP will be much more attractive for operational use.

Recommendation

- The use of NWP data in production should be left as a choice for bidders to consider, but if chosen, its use should be demonstrated to have a positive impact in almost all cases.

### 3.7.10. Ionospheric modelling from GNSS

Ionospheric phase screens are typically low-pass only and smaller than tropospheric ones in C-band. Available ionospheric models have low resolution (200-500 km), and will only be of limited use in case of larger ionospheric disturbances, e.g. aurora in northern latitudes. Such ionospheric events are not frequent, and it has been demonstrated to have negligible impact on operational ground motion products (e.g. the Norwegian ground motion).

**Recommendation:** Do not consider external data for ionospheric mitigation. The effect is expected to be insignificant for almost all interferograms.

### 3.7.11. Validation

There are two separate topics with respect to validation (see section 0.1.1 and 3.5.1.2).

- Internal validation within the production system.
- External validation of products using ancillary data.

#### Recommendations

- Internal validation:
  - Internal product validation procedures should, as far as possible, be automated, including anomaly flagging. The overall production is far too large for manual quality control to be realistic.
  - In the case of multiple partners involved in the production team, it is recommended to include some redundancy (i.e., geographical overlap) in the production plan to ensure harmonised quality between different providers.
- External validation:
  - It should follow robust geodetic principles, using data with comparable accuracy with the EGMS products. Potential procedures:
    - Direct cross-validation in a controlled environment - networks of Corner Reflector (CRs) collocated with (preferably continuous) GNSS or semi-continuous levelling.
    - Validation of deformation parameters, e.g. linear velocity, by utilising a collection of reliable permanent GNSS stations and assessment of variation of ground motion of nearby measurement points around there.

### 3.7.12. References

[IERS] G. Petit and B. Luzum (eds.) IERS Conventions (2010), IERS Technical Note No. 36. Available at <http://iers-conventions.obspm.fr/content/tn36.pdf>

[EUGMS\_WhitePaper] <https://land.copernicus.eu/user-corner/technical-library/egms-white-paper>

[EUREF89 datum] "EUREF Technical Note 1: Relationship and Transformation between the International and the European Terrestrial Reference Systems" Available at <http://etrs89.ensg.ign.fr/pub/EUREF-TN-1.pdf>

[Parizzi2020] A. Parizzi, F. Rodriguez Gonzalez, R. Brcic, "A Covariance-Based Approach to Merging InSAR and GNSS Displacement Rate Measurements," Remote Sensing, 2020, 12(2), 300, Jan 2020. <https://doi.org/10.3390/rs12020300>

### 3.8. Service evolution

To ensure that EGMS evolves from its initial state toward a mature operational ground motion service, the long term EGMS evolution Strategy has to be defined. The Strategy is intended to guide change over the period of 5-10 years after the service initialisation. It identifies the highest priority lines of action to achieve that change and articulates the expected benefits.

Service Evolution will build on the following Principles:

- Users are explicitly and transparently involved: user's needs drive service evolution, with work to translate user requirements into achievable service evolution objectives.
- Scientific (observations, modelling, data assimilation) and technological (e.g. computing capabilities, information systems) advances relevant for EGMS shall be fully taken into account.
- Lessons and knowledge derived during the initial phases of the service are used to drive the service change and/or service upgrade.
- Delineation with downstream activities: the core service focuses on activities best performed at a pan-European scale.
- Transparency about EGMS evolution with respect to downstream sectors in order to foster European industrial growth.

Potential directions for service evolution:

- Better algorithms become available, resulting in backwards incompatible products in terms of quality and information content. How should this be handled?
- Improvements in available hardware make more complicated algorithms feasible, either everywhere, or in a limited set land cover classes.
- New user requirements lead to new potential products or adaption of existing ones, e.g. increased update rate for the service.
- Include a medium to large-scale test production using the cross-polarisation channel in order to assess its added value, and whether the doubled storage and processing capacity requirements is an acceptable trade-off. The test should include study of which land cover classes benefit most from the additional information.
- SAR data from new operational missions become available, e.g. a potential L-band SAR in the Copernicus mission.
- For the first few production cycles, it is recommended to reprocess everything from scratch for each processing cycle, or in moving windows of 5-6 years. However, over time, many scatterers will appear and disappear, typically due to anthropogenic activities. This brings new challenges:
  - How to detect that measurement points have appeared/disappeared?
  - What latency is acceptable for the user when it comes to detecting new/lost measurement points? This impacts the length of the processing window, so a tradeoff must be made between having enough data within the processing window for reliable estimation, but not so long that it takes 5-10 years to update the spatial measurement point distribution.
  - How to format a product where points have different durations.
  - Can a simplified, and less computationally demanding, procedure be used to update existing products instead of starting from scratch?
  - Or a simplified procedure for N years, and a full update every M years?
  - Should date older than M years be rolled out, or be available in the dissemination system indefinitely?
  - All such questions must be carefully studied in a parallel evolution activity.

## 3.9. Risk register

This section provides a non-exhaustive list of potential risks connected with the development, deployment, long term maintenance and evolution of the EGMS service. For the risks, there are also possible mitigation suggestions. Any service carries risks, even more so if the objective is as ambitious as for the EGMS service.

### 3.9.1. Satellites and other services

EGMS is part of the services being offered in the context of the Copernicus programme. This creates possible dependencies on the Sentinel satellites and potential incompatibility or redundancy with the other Copernicus Services.

#### Dependency on Sentinel-1A and 1B satellites

Sentinel-1A and 1B are currently the foreseen satellites providing the bulk of data for the EGMS service. However, a number of circumstances could affect the functioning of the satellites and endanger the continuous and stable stream of data.

The worst-case scenario is that both satellites fail within time span too short to launch one of the replacement satellites Sentinel-1C/ID (S1C and S1D). In this case, the service could potentially still draw from other sources of data (e.g. other contributing missions). However, data continuity will be lost for existing time series until a replacement is in orbit. Where only one satellite would fail, then revisit time would increase to 12 days (i.e. making use of only one satellite) instead of 6 days. This longer revisit time would make the service still relevant for most use cases. Currently, S1C/S1D are already being designed in order to provide data continuity for the coming decade.

#### Incompatibility with other Copernicus Services

The availability of the right data for the EGMS service due to future changes in the acquisition plan of the Sentinel-1A/B is a remote, though worth to mention, risk. The High-Level Acquisition Plan for the satellites is frequently revisited to accommodate requests from other services, from governments and/or from companies. A change in acquisition mode, for instance over a certain area to support needs from a specific service, could result in a gap in data. Once the EGMS service is operational, the prioritisation of other services over EGMS would be extremely unlikely. However, during the development and early deployment phases would be crucial to follow the evolutions of the High-Level Operations Plan (HLOP).

### 3.9.2. Challenging user uptake

User uptake for a new service can be a challenge. The risks for the EGMS service could be summarised in the following three scenarios:

- User requirements were not captured properly, leading to dissatisfaction with the service and lack of uptake.
- Deployment of the service results in a wider awareness about the possibilities of the technique leading to new and initially unforeseen requests (e.g. connected to use cases not foreseen at the beginning of drafting user requirements).
- The initial estimates of the target, were not accurate enough, leading to under- or overuse of the service.

- Uptake varies from country to country due to lack of local knowledge and local institutions to help with user education.

Possible mitigation measures (non-exhaustive list) for these risks are to ensure early awareness about the service by advertising it, and involve a pool of end-users during the development and deployment of the service.

### **3.9.3. Insufficient knowledge and experience of the service providers**

The development, deployment, maintenance and evolution of the EGMS service require an experienced team able to handle a large-scale project with many layers of complexity. An example is, for instance, the dependency of the algorithms from certain local geographical features such as snow cover, disturbances connected to varying levels of soil moisture. This results in an algorithmic complexity that is justifiable and realistic for a pan-European service.

The EGMS service will potentially be handled by a consortium of several parties (e.g. private-public partnerships or group of industries). To impose requirements on the completeness of the production consortium will be the most important way to mitigate risks related to inferior of the production team.

An example of such a requirement, besides having a number of experts with several years of experience and a well-established track record in the field, could be the request of a proof of concept production over a large Area of Interest, with redundant processing in case of multiple providers in the same consortium. The area chosen should be a minimum of two overlapping slices (e.g. ascending+descending 250 x 250 km). Ideally more than one area should be required, with variable land use and topographic relief. This could ensure that the team bidding is able to deliver the service while conforming to quality requirements.

### **3.9.4. Vendor lock-in**

The EGMS service will require some form of cloud-based platform on which the service should be deployed. The potentially risky choice with a long running service would be to select a specific platform early in the development phase and tailor the service to that platform. This could result in a lack of flexibility of the service, in terms of how easy it is to move the service to a different platform in case of insurmountable technical problems or overpricing of the service or indeed contractual change during service evolution where data continuity would still be required. The mitigation strategy would be to choose generic solutions that could be more easily adapted and migrated from one platform to another.

### **3.9.5. Service Production Risks**

Given the challenging nature of the EGMS service, several risks can be identified for the development and initial deployment of the service.

#### **3.9.5.1. Timing and scalability of service production**

Given the scale of the service it is possible to identify several reasons that could lead to delays in the production of the service and a lack of scalability of the service. The most critical ones are connected to the choices of algorithms, methodologies and input data sources. The mitigation strategy would be to apply continuous monitoring during development phases, identify potential bottlenecks timely and have alternatives ready. For instance, a strategy would be to create a development plan layered in complexity with conservative fall-backs in algorithmic complexity and methodology. Such fall-backs, though simpler

and offering compromise on information content, would ensure the delivery of basic functionality and increase in scalability of the service.

### **3.9.5.2. Harmonisation of product quality across team members**

It is extremely likely that a consortium of several parties will develop and deploy the EGMS service. This could potentially result in a team of parties with inhomogeneous approaches to quality control. This could result in a lengthy process and create potential inconsistency in the final product. The mitigation strategy would be for the consortium to agree upfront on the quality measures and monitor them along the development phases. Another possible mitigation strategy would be to request consortia to present the quality control plan as part of the requirements being used in the bidding phase for the service.

### **3.9.5.3. Quality of auxiliary data**

The service requires utilisation of auxiliary data. The quality of this data is a potentially limiting factor. The current network of auxiliary data (e.g. GNSS data via EUREF) is not sufficient for the reliable transition from Level 2a to Level 2b.

Possible mitigation strategies would be:

- Cooperate with the responsible authority in order to improve the EUREF network, while applying a data driven InSAR solution as temporary approach.
- Deploy a network of corner reflectors collocated with GNSS, primarily as datum connection of InSAR results, that could also serve as densification of the EUREF network. This solution would be considerably more expensive, and the resolution of the network would have to be first extensively validated before being fully adopted.

### **3.9.5.4. Sentinel 1 data availability**

Currently, through the Scientific Data Hub dissemination channel, Sentinel-1 data from years before the 10th of September 2018, are rolled out from the data access points forcing the community working with the data to download them from lower-level data nodes such as NASA's Alaska Satellite Facility (based on Amazon Web Services) or some of the DIAS platforms. The other alternative is to request data via Scientific Data Hub with significant access latency as per the Long-Term Archive policy of the various Copernicus data hubs.

In the case of Scientific Data Hub, data are backed up on tapes, and are not continuously available and have to be specifically requested. In the future, this may happen to other providers as well, including the DIAS platforms. This might impose restrictions on the service availability, especially in the initial production cycle. The mitigation strategies are, in the short term, to have a separate archive of data potentially managed by EGMS service provider, while in the long-term it would be to adopt a different (dynamic) update strategy.

### 3.9.5.5. Scalability of the processing system, including storage limits

The volumes of data that will be involved and the computational power required for the EGMS are such that deployed production systems might incur the risk of hitting limits in terms of storage and computational power for Sentinel-1A/B data. In addition, evolving requirements might pose an extra burden on the processing system. For instance, all S1 data over Europe are acquired in dual-polarised mode. This means that there is a cross-polarised channel that potentially can be exploited. It has been shown in several independent studies that cross polarised PS analysis can result in about 30% more scatterers than using the co- or dual-polarised channel only. For DS processing, no gain is expected. While this is currently considered too little gain to justify close to doubling the storage requirements (as well as the necessary processing capacity), this might change over time.

The mitigation strategy for this risk is, in the short term, to increase performance of the processing system by acquiring more hardware. In the long term, it would be to consider, as part of service evolution, different and “more sophisticated” algorithms for updating of EGMS ground motion maps (See section 3.8).

## 4. PRODUCT SPECIFICATION DOCUMENT (PSD)

### 4.1. Introduction

Sentinel-1 SAR data are delivered by ESA. Raw SAR images are designated Level 0, while single look complex (SLC) are designated Level 1. For this reason, the product level numbering begins at Level 2, which is derived from Level 1 data. In the EGMS service, the main products are Level 2a, 2b and 3, as outlined in Section 1.3.



Figure 4-1. Illustration of EGMS product levels and their interdependence.

### 4.2. Level 2a

Level 2a is a necessary first step to produce other levels. It contains sufficient information to detect and interpret local movements. Level 2a data is produced for individual processing units (see section 3.4.3.3.1). It provides basic displacement information provided in the satellite line-of-sight (LOS) in the radar geometry grid, with annotated geolocalisation and quality measures per measurement point. As each processing unit has its own local reference point, differential movements between points in different units cannot be measured.

Depending on the chosen processing system, individual Level 2a datasets may be as small as 10 km by 10 km. For some end-users, this may be sufficient to cover their area/object of interest, and thus provide useful information, provided the data were distributed as individual datasets. In order to serve the most end-users, however, EGMS data is meant to be accessed within a web GUI. Level 2a data would not be suitable for such a system as it would lead to confusion. Thus, this product is not expected to be delivered to end-users within the web GUI, but should be made available for download to serve the needs of expert users.

### 4.3. Level 2b

Level 2b data is considered the main deliverable of EGMS because it meets the needs of most users. This product is based on Level 2a products, harmonised and integrated into a standardised reference frame using external information such as GNSS network measurements (see 11.5). It is produced at the highest possible spatial resolution and contains the full line-of-sight deformation history of each measurement point. No assumptions are made about the true direction of the ground motion that is measured.

Note that some isolated islands may not have available GNSS stations. For these areas, L2b products will be produced by harmonizing L2a products with respect to each other, and adjust the mean velocity to zero. Information about actual motion w.r.t. the datum cannot be retrieved.

Level 2b data will be available within the web GUI. LOS displacement and velocities given will be with respect to a standardised reference frame, rather than a local reference point. The data should appear to be seamless within the GUI.

#### 4.4. Level 3

Level 3 data is derived from Level 2b data. It contains east-west and up-down deformation rates produced by combining Level 2b data from ascending and descending orbits (see 11.6).

A benefit of Level 3 data to the end-users may be that it is easier to understand than LOS data. The LOS (and thus the measured component of the true velocity) of Level 2b data points is variable between satellite tracks and from near range to far range. Thus the same true ground motion will have different LOS velocities for different points. Level 3 data will be consistent across the tracks. In addition, the east-west and up-down velocities can be recombined to produce a true movement direction vector within an east-west vertical plane. This can be very useful to understand specific types of deformation.

However, there are significant limitations to the data. The first is the coverage. As it requires Level 2b results from both ascending and descending geometry, it can only be produced where both datasets exist. This excludes many areas where topographic relief is high. The second is the necessary assumption within the decomposition that there is no north-south component of motion. This will, of course, not always be the case, leading to incorrect vertical and east-west estimates, as well as underestimation of the real component of motion. Finally, to ensure that both input datasets represent the same area on the ground, the data must be produced on an interpolated grid, with significantly coarser spacing than the input Level 2b data.

#### 4.5. Common Technical specifications

##### 4.5.1. Standardised framing

Sentinel-1 scenes are not delivered using standardised framing. However, each scene is composed of individual TOPS bursts. Due to the requirements of maintaining interferometric capability, the S1 TOPS bursts are unique, and stable over time. This makes S1 TOPS bursts natural units for data management for Levels 2a and 2b.

The S1 mission does not provide a system of ids for each individual burst. Such a system is needed, and one way of defining a burst id for any S1 TOPS burst is the following:

**ttt-bbbb-mmn-pp**

where:

<b>ttt</b>	<b>Satellite track number (001-175)</b>
<b>bbbb</b>	Burst cycle number counting within track from equator ( <b>0001-</b> )
<b>mmn</b>	Mode + subswath number ( <b>IW1 to IW3, EW1 to EW5</b> )
<b>pp</b>	Polarisation ( <b>VV, HH, VH, HV</b> )

Due to the width of Sentinel-1 tracks, Level 2a and 2b data produced from adjacent orbits will overlap. Within the web GUI, all available data points should be visible for a given orbit direction. However, the

acquisition dates of the individual scenes used in each dataset will vary. Thus it is logical to keep data from different tracks separate, both in the underlying database and for distributed data.

Level 3 products will be generated from ascending and descending Level 2b products, which do not align. Thus Level 3 products will be managed as standard tiles, e.g. 100x100 km, defined by projected ground coordinates . See also Section 4.5.5.

#### 4.5.2. Geographical coverage

See section 3.3.

#### 4.5.3. Spatial and temporal resolution

Levels 2a and 2b are to be produced at the highest possible spatial and temporal resolutions. Level 3 should be produced with 100 x 100 meter pixels, with full temporal resolution.

- Full resolution PS: ~5m x 20 m pixels
- Low resolution DS: <100 m pixels

#### 4.5.4. Update rate and timeliness

Datasets should be produced annually. Timeliness must vary by product, due to dependencies. Level 2b can only be produced once Level 2a is complete. Similarly, Level 3 production relies upon the completion of Level 3. No recommendation on timeliness can be made at this time.

#### 4.5.5. Projection and datum

Level 2a and 2b products are point databases. As such, the choice of projection and datum do not affect the products themselves. They can be reprojected on-the-fly without any geometric distortion of the data. Modern GIS platforms can due such reprojections rapidly, so the choice of projection for storage and delivery of these products is not critical.

A uniform projection should be used for the end products. This excludes UTM and other projections that are not accurate over the full continent without using multiple zones. Data should be delivered using the European Grid (ETRS89-LAEA), a standard based upon the ETRS89 Lambert Azimuthal Equal-Area projection coordinate reference system, with the centre of the projection at the point 52° N, 10° E. In addition, non-projected (geographic) coordinates using WGS-84 datum shall be annotated for each point in the L2a/L2b products.

Level 3 products are based upon a grid, where each cell is dependant on the chosen projection and datum. When such data are reprojected they must be resamples, and thus are susceptible to distortion. The choice of projection should be made carefully during the production of these products, and maintained for delivery. The projection should be equal area, and thus the European Grid would again be a suitable choice.

#### 4.5.6. Quality/accuracy

The product quality requirements stated in this section are based on experience from existing national-scale products (see APPENDIX H: LARGE SCALE CAPACITY EXAMPLES).

Level 2a are to be produced with less than 5 mm standard deviation for any constant velocity point, with respect to a local reference point (up to 10 km apart) and a temporal reference.

Level 2b are to be produced with a minimum of less than 10 mm accuracy between any two constant velocity points within a single scene up to 50 km apart. Geolocation accuracy for individual points should be 15 m in 3D.

Level 3 are to be produced with a minimum of 10 mm accuracy for any points up to 50 km apart. This requirement is valid for 100 m x 100 m resolution cells with space-homogeneous and time-constant velocities, and zero north-south motion.

See section 3.7.6.2. Note in particular that:

- The quality of L2b products depend strongly on the available GNSS network, and may presently not be possible to fulfil in areas with sparse or low-quality GNSS coverage. See Section 3.7.9.2. On the other hand, areas with dense GNSS coverage, the currently achievable accuracy will be better than the requirement.
- The quality of L3 products depend directly on the quality of the L2b products.

## 4.6. Ancillary datasets

The following ancillary datasets will be needed in the production and validation phases:

- Production:
  - Sentinel-1 precise orbit information
    - Precise orbit information is essential for high-quality InSAR analysis. Precision orbits are distributed by ESA, currently with a latency of about 3 weeks.
    - [https://qc.sentinel1.eo.esa.int/aux\\_poeorb/](https://qc.sentinel1.eo.esa.int/aux_poeorb/)
  - Digital Elevation Model: EU-DEM v1.1
    - The standard unified elevation model used in the Copernicus Land Services
    - 30m posting
    - <https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem>
  - Land cover: CLC 2018
    - CORINE land cover maps from another Copernicus Land Service Element
    - <https://land.copernicus.eu/pan-european/corine-land-cover/clc2018>
  - Snow cover: SCE
    - Snow cover extent maps from another Copernicus Land Service Element
    - <https://land.copernicus.eu/global/products/sce>
  - External datum reference: GNSS
    - For the reference frame harmonisation, the basis will be data from the EUREF network, and models derived from them, where available.
      - <http://www.epnccb.oma.be/>
    - An independent source of processed GNSS is the following service from Nevada Geodetic Laboratory. The data are conveniently delivered on a unified format.
      - <http://geodesy.unr.edu/>
  - External weather data for InSAR corrections
    - Atmospheric correction from Numerical Weather Prediction may be considered.
      - Operational reanalysis data from ECMWF (ERA5) is available with 3-month latency. It is expected that preliminary data will be available with a week latency in 2020.

- <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>

- Validation:
  - Indirect validation data
    - Levelling
    - Data from available permanent GNSS stations
  - Direct validation data
    - Corner reflectors, with associated GNSS and/or levelling data

## 4.7. Product format & dissemination

### 4.7.1. File format

Ground motion data does not require a complicated file format. Each measurement point has a set of coordinates, a number of attributes summarising the average displacement and quality measures, as well as a set of cumulative displacement measurements, each with a specified date and time. All of this can be represented in a simple, two-dimensional table, with metadata attached. The simplest format is an ASCII text file, with delimiters, such as a csv file, along with a file containing metadata. The download server and API should offer a choice of download formats, such as shapefile, GeoJSON, and kmz. The conversion can be done on the fly from the underlying database.

As the total number of data points in the EGMS product portfolio will be in the tens to hundreds of billions range, there will be a standard geographic tiling of the data. The size of this tiling should be chosen to produce reasonably sized files for download.

### 4.7.2. Metadata

Copernicus products must be INSPIRE compliant (<https://inspire.ec.europa.eu/>) and follow standards developed by the Open Source Geospatial Foundations (OGC; (<http://www.opengeospatial.org/>).

Ground motion metadata standards are being developed by the European Plate Observation System (EPOS) satellite data thematic core service. The metadata schema follows the ISO 19115 standard. A general description of metadata for a Level 2a or 2b product is provided in Table 4-1.

Table 4-1. Example of metadata for a Level 2a product.

Tag	Example	Notes
Data_Type	LOS_DISPLACEMENT_TIMESERIES	Type of data (according to the EPOS categories)
Product_ID	DTSLOS_CNRIREA_20170106_20171120_ME7G.csv	Product Identifier (can correspond to the file name)
Product_format	ASCII	Format of the product (geoTiff or CSV)
Product_size	23249970	In byte
Product_url		The url to locate the file
Bounding_box		The polygon relevant to the processed area

License	<a href="https://creativecommons.org/licenses/by/4.0">https://creativecommons.org/licenses/by/4.0</a>	Applicable license for the product
User_ID	CNRIREA	User that generated the product
Software_version	CNR-IREA P-SBAS 25	
Applied_algorithm_description	Parallel SBAS Interferometry Chain	Short description of the algorithm used to generate the product
Main_reference	10.1109/TGRS.2002.803792 10.1109/JSTARS.2014.232267	DOIs of the main publications describing the used algorithms
Date_of_measurement_start	2017-11-07T02:53:48.378740Z	
Date_of_measurement_end	2017-11-19T02:53:48.215234Z	
Date_of_production	2017-12-01T23:51:09Z	
Date_of_publication	2017-12-01T23:51:09Z	
Service_used_for_generation	EPOSAR	
Geographic_CS_type_code	EPSG4326	
Used DEM	SRTM_3arcsec	DEM used within the interferometric processing
Super_master_SAR_image_ID	S1A_IW_SLC_1SDV_20171107T025348_20171107T025415_019153_02069A_D2C6.SAFE	Reference SAR geometry
Spatial_resolution*	73	Ground resolution, in meters
Sensor	S1	Used sensor
Mode	IW	Acquisition mode
Antenna_side	Right	Right/Left
Relative_orbit_number	6	Satellite Track
Wavelength	0.055465760	In meters
Number_of_looks_azimuth *	5	Applied multilook along azimuth
Number_of_looks_range *	20	Applied multilook along range
List_of_dates	2017-01-06T05:11:09Z, 2017-11-19T02:53:48.21Z	List of used acquisitions
Reference_date	2017-01-06T05:11:09Z	Acquisition used as temporal reference in the time

		series
Reference_point**	14.323914 40.862183	Lon Lat format.
Applied_corrections	No_Corrections, local DEM error, stratified APS, residual orbital plane	Description of possible correction applied to the interferograms or time series
Applied_filter	Goldstein_0.5, GACOS	Possible spatial filter applied to the interferogram
Inputs_IDs	S1A_IW_SLC_1SDV_20171107T025348_20171107T025415_019153_02069A_D2C6.SAFE	Comma-separated list of input products IDs
Interferogram_used	20170101S1A_20170106S1B, 20170106S1B_20170112S1A	Comma-separated list of references to interferograms in the form of <start_date><3_char_sensor>_<end_date><3_char_sensor>

\* relevant to multilooked DS products

\*\* relevant to Level 2a only

#### 4.7.3. Distribution

Section 3.6.1 describes the need for a visualisation and dissemination system. Most user needs are expected to be met by the web-GIS visualisation system. However, some end-users will need to integrate data into their own tools and workflows. To this end, an API for data download and/or dissemination must be provided. This API should be based upon the standards set by the OpenSearch Community (<http://github.com/dewitt/opensearch>), as already used by the Copernicus Open Access hub as well as numerous Collaborative Ground Segment hubs.

## 4.8. Summary of product technical specifications

Table 4-2. Level 2a summary

Level 2a product level
<b>Description</b> <p>Basic displacement information provided in the satellite line-of-sight (LOS) in the original radar geometry grid, with annotated geolocalisation and quality measures per measurement point. The product will be delivered for individual and consistent data blocks of a size suitable for storage in a single file. This product is mainly suitable for expert users, and will not be distributed in the graphical user interface.</p>
<b>Compliance with user needs</b> <p>This product is a necessary first step to produce other product levels. It contains sufficient information to discover and interpret local movements. However, differential movements between points in different datasets cannot be measured directly.</p>
<b>Input data sources (EO &amp; ancillary)</b> <p>EO data used in the production:</p> <ul style="list-style-type: none"><li>• All available Sentinel-1A and -1B data for a given relative orbit, in SLC format.</li></ul> <p>Ancillary data used in the production:</p> <ul style="list-style-type: none"><li>• Digital Elevation Model:<ul style="list-style-type: none"><li>◦ The currently available version of EUDEM is uniform and of sufficient quality and resolution</li><li>◦ <a href="https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem">https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem</a></li></ul></li><li>• Land cover data:<ul style="list-style-type: none"><li>◦ The currently available version of CORINE land cover data will be used</li><li>◦ <a href="https://land.copernicus.eu/pan-european/corine-land-cover">https://land.copernicus.eu/pan-european/corine-land-cover</a></li></ul></li></ul> <p>Additional data sources: see section 4.6</p>
<b>Methodology &amp; assumptions</b> <p>The deformation map is derived using the methodology outlined in APPENDIX F: BEST PRACTICES FOR TIME SERIES INSAR.</p>
<b>Geometric resolution</b> <p>Ground motion estimates will be made at the full resolution of Sentinel-1 images (approximately 5 x 20 m), wherever it is possible to make such estimates. The product is augmented with lower resolution data where applicable, with a ground resolution of up to 100 m.</p> <p>See section 3.7.6.2 for details.</p>
<b>Geographic Projection / Geodetic reference system</b> <p>ETRS89 Lambert Azimuthal Equal-Area</p> <ul style="list-style-type: none"><li>• (EPSG: 3035, <a href="http://spatialreference.org/ref/epsg/etrs89-laea/">http://spatialreference.org/ref/epsg/etrs89-laea/</a>)</li></ul> <p>WGS-84</p> <ul style="list-style-type: none"><li>• (EPSG: 4326, <a href="http://spatialreference.org/ref/epsg/wgs-84/">http://spatialreference.org/ref/epsg/wgs-84/</a>)</li></ul> <p>See section 4.5.5 for details.</p>
<b>Geographical coverage</b> <p>For details, see Section 3.3</p>

- |  |
|--|
| <ul style="list-style-type: none"><li>• Baseline service: Copernicus participating countries, with some exceptions.</li><li>• Service evolution: Full EEA39 area</li></ul> |
|--|

**Accuracy**

- Geometric:
  - ~15m 3D geolocalisation accuracy for full-resolution measurement points
- Time series:
  - precision of 3-5 mm for each temporal sample, relative to reference time
- Velocity / trend:
  - relative accuracy of ~1mm/year between any two constant velocity points up to 50 km apart

See sections 3.7.6.2 and 12.2

**Time span:**

- Start of estimation: Oct-2014 [variable]
- Stop of estimation: all data up to a month before production start. This ensures that precise orbits, and potentially other ancillary data, are available.

**Update frequency**

- Annual update

**Delivery format / type:**

- Level 2a: Point cloud, with associated parameters and deformation time series per point.
- Format: TBD (INSPIRE compliant)

**Delivery time**

Within four months after production start

Table 4-3. Level 2b summary

<b>Level 2b product level</b>
<p><b>Description</b>                      Basic displacement information integrated into a standardised reference frame using external information such as GNSS network measurements or models. The product will be delivered for individual and consistent frames (i.e., same relative orbit) of image stacks, as well as through a dedicated graphical web interface.</p>
<p><b>Compliance with user needs</b>                      This product is considered the main deliverable of EGMS because it meets the needs of most users. It is produced at the highest possible spatial resolution and contains the full line-of-sight deformation history of each measurement point. No assumptions are made about the true direction of the ground motion that is measured.</p>
<p><b>Input data sources (EO &amp; ancillary)</b>                      EO data used in the production:                     <ul style="list-style-type: none"> <li>• All available Level-2a results</li> </ul>                     Ancillary data used in the production:                     <ul style="list-style-type: none"> <li>• GNSS data and/or models</li> </ul>                       Additional data sources: see section 4.6                 </p>
<p><b>Methodology &amp; assumptions</b>                      The deformation map is derived using the methodology outlined APPENDIX F: BEST PRACTICES FOR TIME SERIES INSAR.</p>
<p><b>Geometric resolution</b>                      Ground motion estimates will be made at the full resolution of Sentinel-1 images (approximately 5 x 20 m), wherever it is possible to make such estimates. The product is augmented with lower resolution data where applicable.</p>
<p><b>Geographic Projection / Geodetic reference system</b>                      ETRS89 Lambert Azimuthal Equal-Area                     <ul style="list-style-type: none"> <li>• (EPSG: 3035, <a href="http://spatialreference.org/ref/epsg/etrs89- etrs-laea/">http://spatialreference.org/ref/epsg/etrs89- etrs-laea/</a>)</li> </ul>                     WGS-84                     <ul style="list-style-type: none"> <li>• (EPSG: 4326, <a href="http://spatialreference.org/ref/epsg/wgs-84/">http://spatialreference.org/ref/epsg/wgs-84/</a>)</li> </ul>                       See section 4.5.5 for details.                 </p>
<p><b>Geographical coverage</b>                      For details, see Section 3.3                     <ul style="list-style-type: none"> <li>• Baseline service: Copernicus participating countries, with some exceptions.</li> <li>• Service evolution: Full EEA39 area</li> </ul> </p>
<p><b>Accuracy</b> <ul style="list-style-type: none"> <li>• Geometric:                             <ul style="list-style-type: none"> <li>○ &lt;15 m 3D geolocalisation accuracy for full-resolution measurement points</li> </ul> </li> <li>• Time series                             <ul style="list-style-type: none"> <li>○ &lt;10 mm for any two constant velocity points up to 50 km apart.</li> </ul> </li> </ul> </p>
<p><b>Time span:</b> <ul style="list-style-type: none"> <li>• Start of estimation: Oct-2014 [variable]</li> </ul> </p>

- Stop of estimation: all data up to a month before production start. This ensures that precise orbits, and potentially other ancillary data, are available.

**Update frequency**

- Annual update

**Delivery format / type:**

- Level 2b: Point cloud, with associated parameters and deformation time series per point.
- Format: INSPIRE compliant, see section 4.7

**Delivery time**

Within four months after production start.

Table 4-4. Level 3 summary

<b>Level 3 product level</b>
<p><b>Description</b> East-West and Up-Down deformation rates produced by combining Level 2b data stemming from all available ascending and descending geometries covering the same area;</p>
<p><b>Compliance with user needs</b> This product is useful for characterisation of ground motion with a (differential) horizontal component, including e.g. landslides and tectonic faults. The resolution is reduced, so the product will not contain information about individual buildings.</p>
<p><b>Input data sources (EO &amp; ancillary)</b> EO data used in the production:<ul style="list-style-type: none"><li>● All available Level 2b results</li></ul>Ancillary data used in the production:<ul style="list-style-type: none"><li>● Additional data sources: [TBD]</li></ul></p>
<p><b>Methodology &amp; assumptions</b> The deformation map is derived using the methodology outlined in APPENDIX F: BEST PRACTICES FOR TIME SERIES INSAR.</p>
<p><b>Geometric resolution</b> Level 3 data is derived from Level 2b, ascending and descending data. To ensure that both input datasets represent the same area on the ground, the data must be produced on an interpolated grid, with significantly coarser spacing than the input Level 2b data. Typical grid sizes to be considered may be in the range 100-300m [TBD].</p>
<p><b>Geographic Projection / Geodetic reference system</b> ETRS89 Lambert Azimuthal Equal-Area<ul style="list-style-type: none"><li>● EPSG: 3035, <a href="http://spatialreference.org/ref/epsg/etrs89-laea/">http://spatialreference.org/ref/epsg/etrs89-laea/</a></li></ul>WGS-84<ul style="list-style-type: none"><li>● EPSG: 4326, <a href="http://spatialreference.org/ref/epsg/wgs-84/">http://spatialreference.org/ref/epsg/wgs-84/</a></li></ul>See section 4.5.5 for details.</p>
<p><b>Geographical coverage</b> Level 3 data is derived from Level 2b data. As it requires Level 2b results from both ascending and descending geometry, it can only be produced where both datasets exist. This excludes many areas where topographic relief is high.</p>
<p><b>Accuracy</b> The accuracy depends on the quality of the input Level 2b data. Due to spatial averaging, the precision of this product is higher than the input Level 2b products.<ul style="list-style-type: none"><li>● Geometric:<ul style="list-style-type: none"><li>○ 100 m grid spacing</li></ul></li><li>● Time series of East/West and Vertical components:<ul style="list-style-type: none"><li>○ ~ 10 mm per temporal sample per component between any two points with constant velocity and zero north-south component, up to 50 km apart</li></ul></li></ul></p>
<p><b>Time span:</b><ul style="list-style-type: none"><li>● Start of estimation: Oct-2014 [variable]</li></ul></p>

- Stop of estimation: all data up to a month before production start. This ensures that precise orbits, and potentially other ancillary data, are available.

**Update frequency**

- Annual update

**Delivery format / type:**

- Map projected grid.
- Format:
  - INSPIRE compliant (see section 4.7)
  - Standard image format with support for geographical metadata (e.g. GeoTIFF)

**Delivery time**

Within four months after production start.

## 5. SUMMARY

This document has presented a contextual overview of the different inputs and considerations required for a ground motion service on a European scale, in support of the Copernicus program. It has focused on all major considerations related to the implementation of such a service, with detailed justifications and reasoning to support recommendations. These include, but are not limited to, user needs, product specification, processing type, coverage area and repeat cycle. In addition, product dissemination, focusing on file formats, projection, quality, metadata and distribution, is a critical component for consideration.

It is important to learn lessons from the InSAR community, which includes experience from national services, research and commercial experience. The Aurora consortium brings together key players within the commercial InSAR community along with InSAR research and value-added service providers. This combination of partners has provided a range of inputs, experience and knowledge that is truly complementary while also allowing all parties to consider the most suitable approach for this EGMS service. EGMS will be complementary to these existing (and upcoming) services, while also providing a baseline for more focused national or commercial analysis.

At the heart of this service is the user. The user is critical to the success of a European Ground Motion Service, and the service must be applicable to as many users as possible. With that in mind, consideration has been provided with respect to the different types of users, their use cases and, where possible, their different requirements and how EGMS can meet their needs. EGMS must provide as much benefit as possible to as wide a group as possible. Therefore, understanding the needs of the users is critical to the success of EGMS.

It is also well understood that these users may change over time, evolve their needs and may themselves have varying levels of technical expertise with respect to InSAR and ground motion data. EGMS is expected to be dynamic and evolve over time, both with respect to the users, as the understanding of this data increases into a wider breadth of use cases, and through future development and growth of the Copernicus program. The success, therefore, lies in EGMS ability to also be responsive to the community, within realistic bounds.

The roadmap proposed considers both a ramp up and development phase to build momentum in the service while focusing on the elements of most interest to the users as its starting point. As usability and knowledge increases, so can the wider roll-out and increased scale of the activities.

As with any project, there are considerations with respect to risk and potential challenges with a service of this nature and scale. The risk register outlines what are considered, at this stage, to be the primary risk considerations for this project. The importance of these factors will vary but consideration to the potential impact and likely mitigation is, of course, important when preparing for a service at a European level.

In conclusion, this is a 'Living Document' that is as reflective as possible on the current, and expected future position, drawing together information, feedback and resources from a range of collaborators to present a comprehensive assessment of considerations and recommendations with associated justifications. It allows for, and importantly, expects adaptations as part of a long term and future service.

## 6. APPENDIX A: SAR/INSAR IN A NUTSHELL

In this section, we outline briefly the concepts needed for a detailed discussion of EGMS concepts.

### 6.1. Synthetic Aperture Radar (SAR)

Synthetic Aperture Radars (SAR) are imaging radars that use the sensor motion to increase the effective antenna size artificially. This translates into an improvement of the resolution in the direction of motion (azimuth direction) of several orders of magnitude with respect to the resolution provided by a real size antenna. The improvement of the resolution in the perpendicular (range) direction is achieved by pulse compression methods. See [Cumming2005, Moreira2013] for a general discussion on the subject.

SAR is unique in its imaging capability: It provides high-resolution two-dimensional images independent from daylight, cloud coverage and weather conditions, see [Moreira2013] and references therein.

### 6.2. Geometry of SAR system

Spaceborne SAR systems have a *side looking* imaging geometry and are based on a pulsed radar installed on a platform usually deployed in a circular orbit around the earth, typically a sun synchronous, polar orbit. The radar system transmits electromagnetic pulses with high power and receives the echoes of the backscattered signal in a sequential way. Typical values for the pulse repetition frequency range from a few hundred to a few thousand Hertz for airborne and spaceborne systems, respectively. The swath width varies in the spaceborne case typically from 30 to 500 km.

The transmitted pulse interacts with Earth's surface and only a portion of it is backscattered to the receiving antenna which can be the same as the transmit antenna (for a monostatic radar) or a different one (for a bi- or multi-static radar). The amplitude and phase of the backscattered signal depends on the physical (i.e., geometry, roughness) and electrical (i.e., permittivity) properties of the imaged object.

For a graphical representation of a typical SAR system, see Figure A-1.

### 6.3. SAR Products

SAR systems provide a 2-D reflectivity map of the imaged area, i.e., targets with high backscattered signal are identified as bright spots in the radar images and flat smooth surfaces as dark areas. The flight direction is denoted as azimuth and the line-of-sight as slant range direction.

SAR images are composed of a regular grid of pixels that store both real and imaginary parts of received echoes, from which amplitude and phase can be calculated, see Figure A-1. The recorded raw data (RAW), with annotations, is in general referred to as a *Level-0* product [NASA1986]

The basic product for SAR is the single-look-complex (SLC) product, which in context of EGMS and ESA production system in general is referred to as *Level-1* product. This product has been processed to full resolution as outlined briefly above.

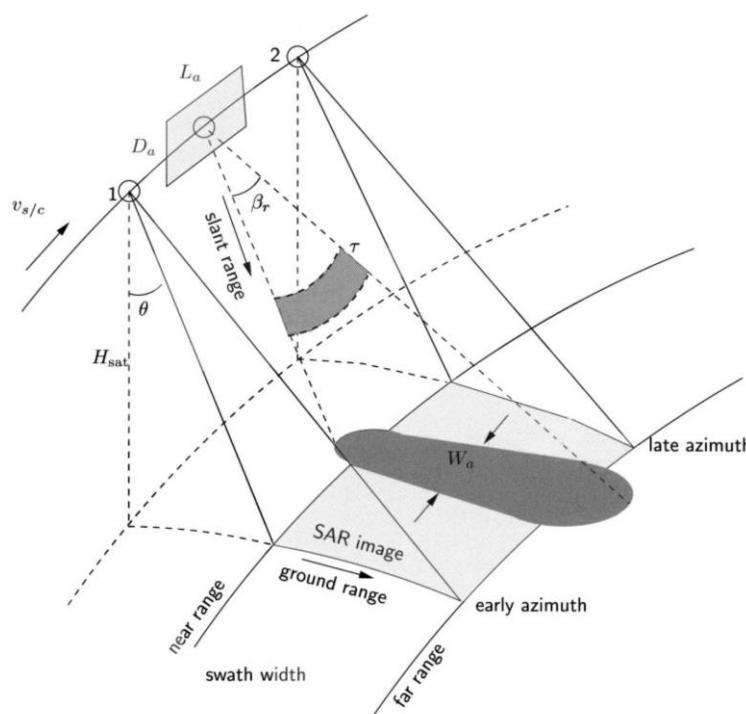


Figure A-1. Side-looking image geometry of a spaceborne SAR acquisition. The satellite velocity  $v_s$  is approximately 7 km/s. The dark gray area indicates the footprint of a single pulse. The total coverage of a SAR scene, between early and late azimuth direction, and near and far range, is depicted in light gray.

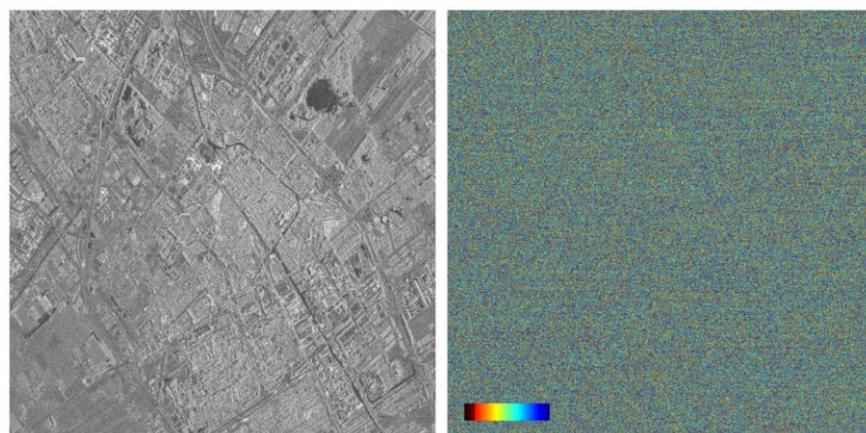


Figure A-2. (Left) Amplitude of a SAR image. Strong reflections are visualised in white, whereas areas with limited reflection towards the satellite (such as water bodies) are represented in black. (Right) Phase of a SAR image. Only the fractional phase of the received signal is recorded, resulting in phase values between  $-\pi$  and  $+\pi$ . The phase in a SAR image cannot be interpreted directly.

## 6.4. Ascending and descending orbits

Most earth observation satellites are polar orbiting, which means that the satellite passes above or nearly above both poles. This means that for half their trajectory, they are travelling from the south towards the north, which is referred to as an *ascending* orbit. Conversely, for the other half of the orbit where the travel direction is from the north towards the south, it is said to be in *descending* orbit, See Figure A-3.

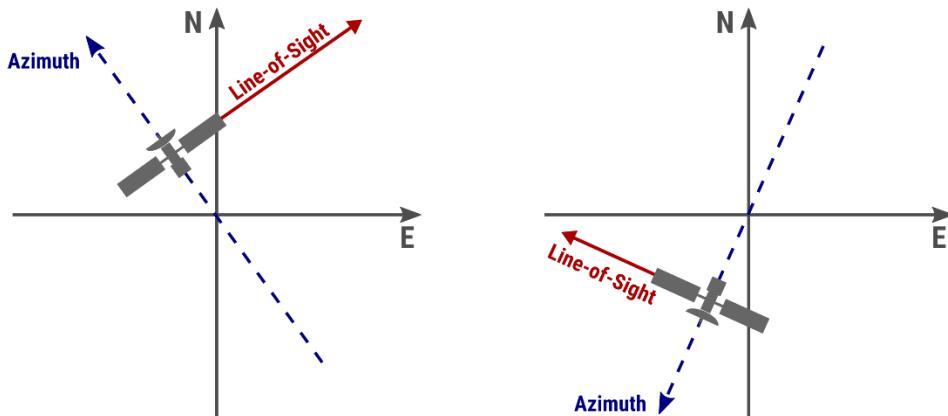


Figure A-3. SAR acquisition modes: (left) ascending orbit direction; (right) descending orbit direction

## 6.5. Radar Interferometry

Synthetic Aperture Radar Interferometry (InSAR) techniques use the phase differences between two radar images acquired over the same area to generate maps of, e.g., surface displacements or topography, [Massonnet1994, Bamler1998]. The phase difference image is called *interferogram*.

Although it contains several nuisance terms, the phase difference largely reflects the surface deformation in the radar line of sight during the period between the two acquisition dates. To form the interferograms, the images must be in the same SAR geometry, i.e. cover the same area on the ground and with the same incidence angle. This is achieved by resample one of the images to the other and calculating the phase difference.

### 6.5.1. Geometry of Differential InSAR

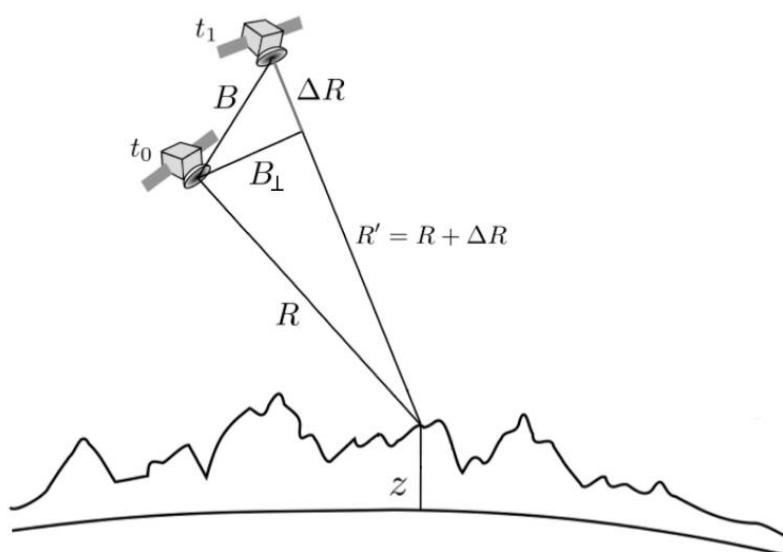


Figure A-4. Geometry of differential InSAR, adapted from [Lauknes2011a]

Figure A-4 shows a sketch of the acquisition geometry for repeat pass interferometric acquisition. The vector between the two orbital positions at times  $t_0$  and  $t_1$ , respectively, is called the *baseline*. The components of the baseline along ( $\Delta R$ ) and across ( $B_{\perp}$ ) the direction from satellite to target influence the range difference  $\Delta R$  between the two acquisitions, and hence the interferometric phase.

### 6.5.2. Surface displacement observed by InSAR

The InSAR technique has many potential applications. In this document, we limit the discussion to observation of surface displacement.

This section gives an overview of the components of the interferometric phase, and general principles and challenges for application of InSAR for ground motion mapping and monitoring, with more details given in later sections.

### 6.5.3. SAR phase components

SAR data contain information on the strength of the radar signal reflected from the Earth's surface (amplitude) as well as the travel time of the radar signal in the physical path to and from the Earth's surface (phase).

The strength of these reflections depends on the physical properties (e.g., size, orientation, roughness, dielectric characteristics) of the individual scatterers. SAR system characteristics such as radar wavelength and incidence angle govern the interaction of the signal with the scatterers, [Hanssen2001].

Each complex pixel in an SLC image consists of several contributions, which can be summarised as:

$$\phi = -2\pi a + \phi_{\text{range}} + \phi_{\text{atmo}} + \phi_{\text{scat}} + \phi_{\text{noise}}$$

where  $a$  is an unknown integer number of phase cycles,  $\phi_{\text{range}}$  the range-dependent phase,  $\phi_{\text{atmo}}$  the signal delay caused by the atmosphere,  $\phi_{\text{scat}}$  the scattering phase related to the additional path length travelled due to the presence of multiple scattering objects within a resolution cell, and  $\phi_{\text{noise}}$  the thermal noise [Hanssen2001].

## 6.6. Interferometric phase components

An interferogram is the phase difference between two SLC images. It has phase contributions that can be grouped as follows:

- Geometric term
- Propagation term
- Scattering term
- Thermal noise term

In the following subsections, these terms are briefly outlined. They will be discussed in more detail, in the context of estimation of parameters of interest (eg. ground motion), and mitigation of noise sources in later sections.

### 6.6.1. Geometric term

The geometric contributions to the interferometric phase are related to the change in range from satellite to a given target between two acquisitions.

- Ground motion
  - Local motion (our signal of interest)
  - Tectonic motion (motion of tectonic plates)
- Orbital positions (baseline):
- Topography

## 6.6.2. Propagation term

The propagation contributions to the interferometric phase are related to the change in propagation time through the atmosphere between the two acquisitions.

## 6.6.3. Scattering term

This term arises due to changes in the electromagnetic scattering properties within a resolution cell over time, e.g. due to changes in soil moisture.

## 6.6.4. Thermal noise term

This term is mainly caused thermal noise processes in the SAR instrument. Note: other noise terms arise later during processing due to inaccurate compensation of the various non-deformation terms.

## 6.7. Notion of double differences

Interferograms are created using pairs of SLC images, with contributions as discussed above (Figure A-5).

The phase value  $\phi_i^{01}$  of a pixel  $i$  in an interferogram is the phase difference between the corresponding pixels in the SLC images acquired at times  $t_0$  and  $t_1$ . However, the total atmospheric delay adds up to several meters, orbit inaccuracies are usually on the (sub)-decimeter level, and the total number of integer phase cycles is unknown, making a deformation measurement using a single interferogram pixel with millimeter-level precision impossible [Massonnet1994].

The InSAR double difference is the phase difference between two interferometric resolution cells, in time between  $t_0$  and  $t_1$ , and in space between pixels  $i$  and  $j$ .

$$\phi_{ij}^{01} = (\phi_j^1 - \phi_j^0) - (\phi_i^1 - \phi_i^0) \quad (2.2)$$

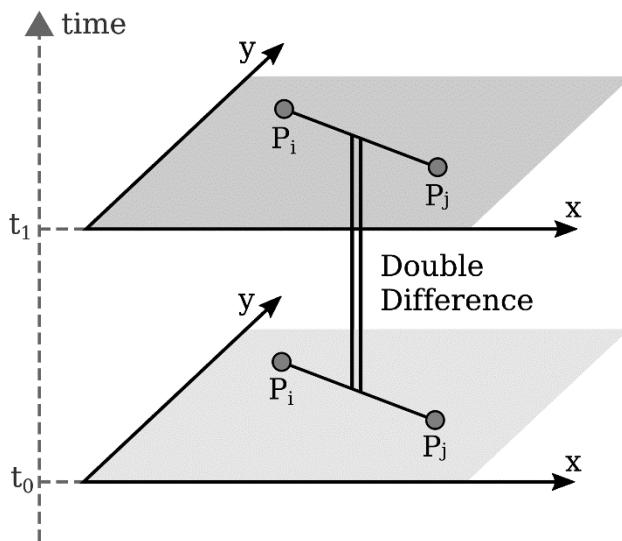


Figure A-5. Graphical representation of InSAR double-differences. Importantly in interferometry double-difference are computed by differencing “first in time then in space”, in contrast to conventional geodetic techniques (e.g. leveling) where differentiation is performed “first in space then in time”.

## 6.8. Relative nature of technique

As for any geodetic technique (e.g., leveling, GNSS), in order to achieve an "interpretable" InSAR phase observation, a *double difference* in space and time has to be formed. All InSAR phase measurements should be considered relative with respect to a reference pixel, which is exactly a double difference. Thus, InSAR is a relative technique, unless a-priori knowledge on the reference point, or without assumption.

## 6.9. Radar line-of-sight

Radar is only capable of measuring path length differences in its line-of-sight or slant range direction, see Figure A-4. A three-dimensional ground motion vector, with components in North, East, and Up direction respectively, will be projected to one slant-range component in the radar line-of-sight (LoS), see Figure A-6. Thus, a ground motion estimate derived from InSAR is non-unique and needs to be interpreted with care.

For a satellite orbit with heading (azimuth), see Figure A-6-7 and Figure A-6, we find the total displacement to be given as:

$$d_r = d_u \cos(\theta_{\text{inc}}) - \sin(\theta_{\text{inc}})[d_n \cos(\alpha_h - 3\pi/2) + d_e \sin(\alpha_h) - 3\pi/2]$$

where  $(\alpha_h - 3\pi/2)$  corresponds to the angle to the azimuth look direction, which is perpendicular to the satellite heading  $\alpha_h$ , for a right-looking satellite. The incidence angle is denoted by  $\theta_{\text{inc}}$ .

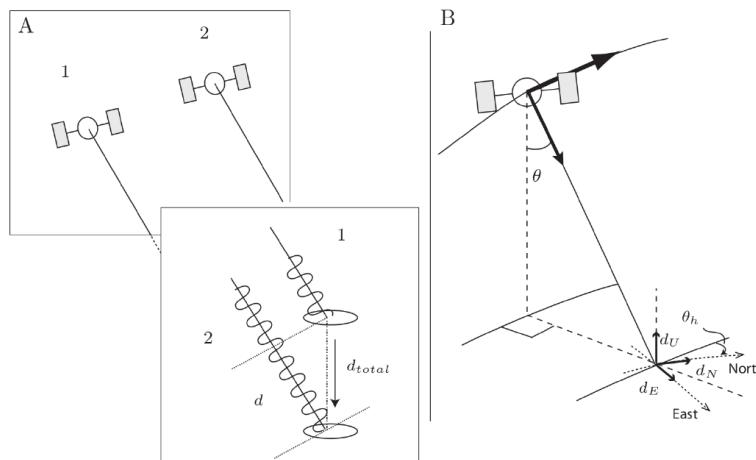


Figure A-6. (A) Surface displacements as observed by the satellite sensor;  $d$  is the projection on the satellite LoS of the total displacement  $d_{total}$ , having only an Up component, i.e. vertical. (Satellite flying direction is perpendicular to the paper plane.) (B) 3-D view of a displacement vector in the satellite geometry. The heading direction is represented with  $\theta_h$  measured clockwise. The displacement vector between acquisitions 1 and 2 is represented with three components  $d_U$ ,  $d_N$  and  $d_E$  in Up, North and East directions, respectively. Figure taken from [Hanssen2001].

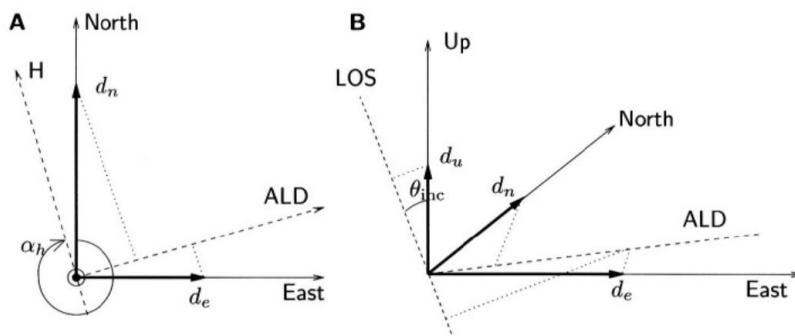


Figure A-6-7. Projection of the three components of the deformation vector onto the satellite line-of-sight (LoS). (A) Showing the North and East components projection on the azimuth look direction (ALD), which is perpendicular to the satellite's heading ( $H$ ). The heading is indicated by  $\alpha_h$ . (B) 3D sketch including the projection of the Up-component to the LoS via incidence angle  $\theta_{inc}$ .

## 7. APPENDIX B: SCATTERING MECHANISMS

### 7.1. Phase stability

SAR interferometry exploits the fact that several kinds of scattering mechanisms have a stable phase response over time, which we will refer to as coherent scattering. There are two main classes of phase stable scatterers, which we will refer to as Point-like Scatterers (PS) and Distributed scatterers (DS), discussed further below. Both of these types of scattering can also be temporally coherent or incoherent, depending on the change experienced by the scatterer in the period between the SAR acquisitions, see Figure B-1 Examples depicting point and distributed scattering for coherent and incoherent cases. Top: Scattering objects within a resolution cell during two SAR acquisition epochs, indicated respectively by black and gray scatterers. Larger scatterers correspond to stronger reflections. Middle: Phasor diagrams for the two acquisitions, also respectively in black and gray. Bottom: Examples of scattering objects. Figure taken from [vanLeijen2014].Figure B-1.

The signal scattered back toward the satellite by every resolution element is the result of the coherent summation of many individual scatterers. If the scattering properties of these individual scatterers change, or if the viewing geometry between acquisitions changes, the coherent summation changes as well. This introduces noise into the phase of the signal, known as decorrelation [Zebker1992], along with a quantitative measure for decorrelation, called coherence.

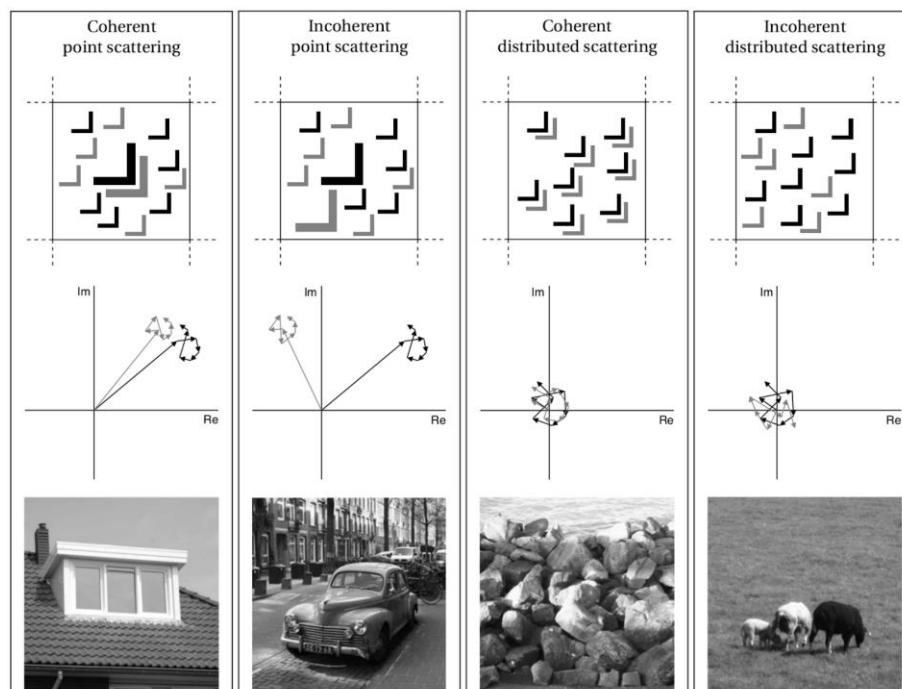


Figure B-1 Examples depicting point and distributed scattering for coherent and incoherent cases. Top: Scattering objects within a resolution cell during two SAR acquisition epochs, indicated respectively by black and gray scatterers. Larger scatterers correspond to stronger reflections. Middle: Phasor diagrams for the two acquisitions, also respectively in black and gray. Bottom: Examples of scattering objects. Figure taken from [vanLeijen2014].

## 7.2. Pointlike coherent scattering

If the backscattered signal from a single SAR resolution cell is dominated by a single scatterer, the signal may have a very stable phase over time, relative to a nearby reference point. We call this a pointlike scatterer, [Hooper2006].

Note that this definition depends on the resolution of the SAR system, meaning that a given scatterer may be pointlike in a high-resolution SAR system, but not in a medium-resolution SAR system.

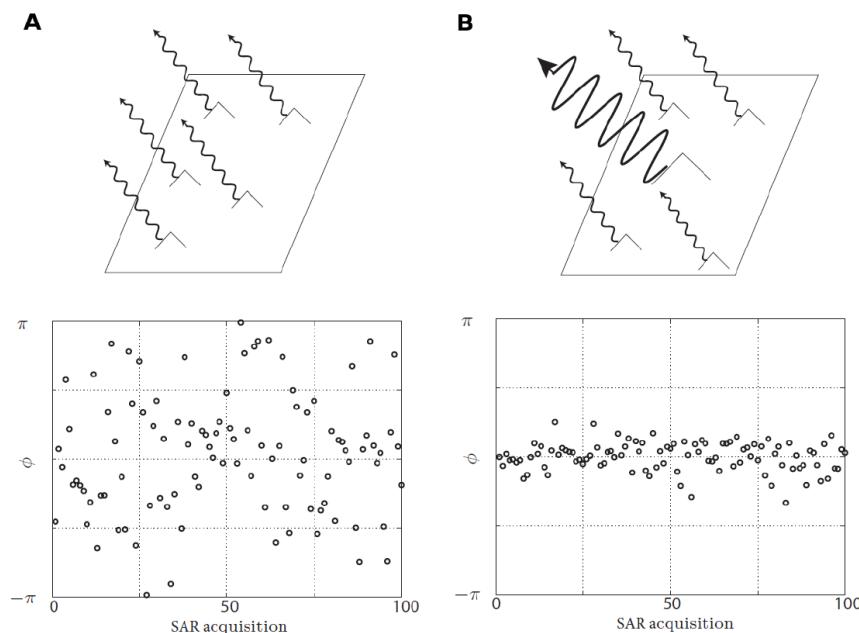


Figure B-2 Phase simulations for (A) a distributed scatterer (DS) pixel and (B) a stable scatterer, i.e. a Persistent Scatterer (PS) pixel. The cartoons above represent the scatterers contributing to the phase of one pixel in an image and the plots below show simulations of the phase for 100 iterations, e.g., SAR acquisitions, with the smaller scatterers moving randomly between each iteration. Figure taken from [Hooper2006].

## 7.3. Distributed coherent scattering

In the case where the backscattered signal from a single SAR resolution cell consists of a larger number of small scatterers, but with no single dominant scatterer. It may still have a relatively stable phase over time, typically for land cover classes without significant vegetation. We call such a resolution cell, or a group of adjacent resolution cells with similar statistical properties, a *distributed scatterer*. Due to statistical variations, it is typically necessary to average a number of adjacent cells to achieve high enough phase stability for subsequent time series analysis.

## 7.4. Coherence and decorrelation

Coherence is a normalised measure of the phase stability of a scatterer over time, where coherence = 0 means statistically independent statistics in time, i.e. pure noise, while coherence = 1 means a noise free

stable phase. Note that if the scatterer is displaced over time, the coherence is usually defined as the phase stability after subtracting the effect of the motion and other non-random phase components.

For distributed scatterers, it is common to estimate the coherence by looking at the phase variation in a group of nearby pixels of a given interferogram, in its simplest form a complex spatial average of  $M \times N$  pixels. Note that the estimated coherence is a measure of the phase change during the time period between the two acquisitions forming the specific interferogram, not an overall measure of phase stability for an entire time series.

For a full time series, a large number of such pairwise coherence estimates can be calculated. These coherences may be organised in a matrix that is the basis of several recent algorithms for time series analysis of distributed scatterers.

For pointlike scatterers, estimation of coherence must be carried out in the temporal domain to avoid loss of resolution. If the coherence is to remain a meaningful quality measure, this requires a model for the deformation, either in the form of a parametric model, or a smoothness criterion.

Various kinds of coherence based quality measures will be discussed for two purposes below: for use in identification of coherent scatterers during processing, and for use in post-analysis and quality control.

## 7.5. Polarimetric data

Some SAR systems collect data in multiple polarisations. Most common:

- *Dual polarimetry*: Transmit a single linear polarisation, receive on two orthogonal polarisations
- *Full polarimetry*: Transmit two orthogonal polarisations, receive on two orthogonal polarisations.
- *Compact polarimetry*: Transmit a circular polarisation, receive on two orthogonal linear polarisations.

In the context of InSAR time series analysis, polarimetric data can potentially be exploited to increase the number of phase stable pixels since more scattering mechanisms are captured.

## 8. APPENDIX C: FROM PHASE OBSERVATIONS TO DEFORMATION ESTIMATES

### 8.1. Limitations of conventional InSAR for deformation monitoring

The InSAR deformation signal is generally superimposed by geometric, atmospheric, and scattering terms, as well as thermal noise. Furthermore, in order to estimate the parameters of interest from a single interferogram, the phase signal has to be spatially unwrapped, which in itself is a challenging problem. Even in an ideal situation where the interferogram is perfectly unwrapped, the estimation model is rank deficient: the number of unknowns is higher than the number of observations. Thus, certain assumptions about the signal to be estimated are required in order to constrain the estimation problem.

In order to fully exploit the potential of the InSAR technique, the various phase components must be separated. This is possible by either including apriori information (e.g., ground truth, meteorological data, etc), or considering the correlation properties of InSAR phase contributions. In particular, the interferometric phase term due to atmospheric propagation delay change, usually called the atmospheric phase screen (APS), is inherently impossible to estimate from a single interferogram.

The strategy for how to deal with rank deficiency and un-observability of the APS contribution is further discussed in the following.

### 8.2. The atmospheric phase screen: APS

The propagation term represents the changes in delay through the atmosphere, commonly referred to as *atmospheric phase screen (APS)* in the InSAR community, see Figure C-1.

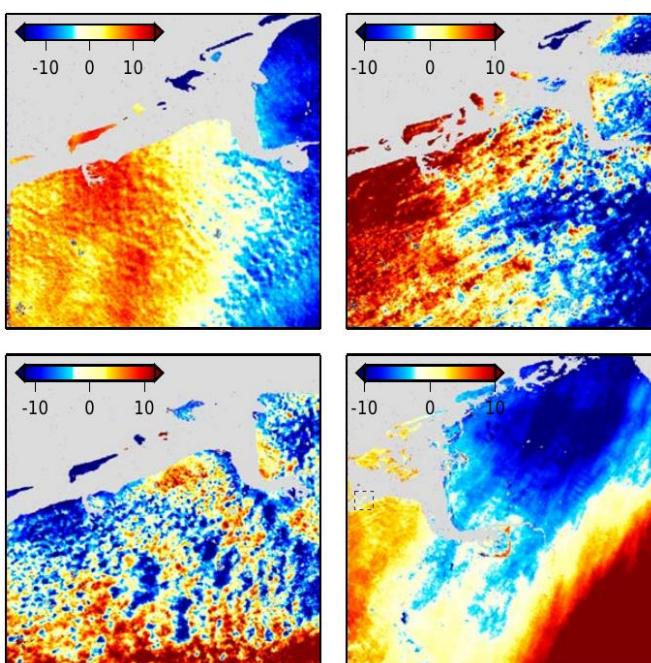


Figure C-1 Four differential ERS-1/2 tandem interferograms over the northern part of the Netherlands (area of approximately 100 x 100 km), showing only atmospheric signal, expressed in millimeters zenith delays. Note the different ranges in the color scale. Figure adapted from [Hanssen2001].

The APS consists of the following main contributions.

### 8.2.1. Long wavelength troposphere

This phase component consists of spatially correlated structures in the troposphere with a scale length of tens to hundreds of kilometers. This component tends to decorrelate completely between acquisitions but may be correlated over a few hours. In addition, it has a seasonally correlated component.

### 8.2.2. Turbulent troposphere

This phase component arises due to turbulent variations in temperature, humidity and pressure in the troposphere. These physical properties influence the propagation time. This component is correlated in space, with correlation length limited to a few km. In time however, we may reach complete decorrelation in a few minutes.

### 8.2.3. Stratified troposphere

This phase component is caused by different path length through the atmosphere depending on the topographic height of the measurement point. Typically, the non-turbulent part of the troposphere has a layered structure with slow spatial and relatively slow temporal variations. This component can be estimated from data by looking at the correlation with the DEM, or potentially from NWP. Usually, a linear term is sufficient, but in areas with very high topographic relief, or areas prone to inversion phenomena, a higher order correction may be needed.



Figure C-2 Interferometric map of the Mount Etna, from [Massonnet1995]. It was initially believed that the observed deformation signal was due to a deflation at the end of eruption, However, further studies shown that most of the observed fringes (i.e., deformation) result from the uncompensated stratified component of the atmosphere.

### 8.2.4. Ionosphere

In the ionosphere, highly energetic solar radiation leads to the ionisation of some atmospheric molecules and creates a mixture of free electrons, ions, and neutral gases. Thus, electromagnetic signals traversing

through the ionosphere are dispersively delayed along their path, depending on the number of free electrons.

Variations in the propagation time through the ionosphere can give severe phase artefacts, in particular in the Arctic and Antarctic areas, but also sometimes at other latitudes. Sun synchronous satellite missions are usually deployed in a dawn-dusk or dusk-dawn orbit, which are less prone to ionospheric effects. The presence of electron can vary strongly depending on the latitude the time of the day and the solar activity, see Figure C-3, and [Gomba2016].

### 8.3. Unwrapping

Phase unwrapping is the process of restoring a spatially consistent multiple of  $2\pi$  to each point of the interferometric phase image. Successful unwrapping of the phase in space, and in case of time-series methods also in time, is an inherently ill posed problem [Ghiglia1998, Constantini1998]. There are several ways of handling this, depending on algorithm and scattering properties.

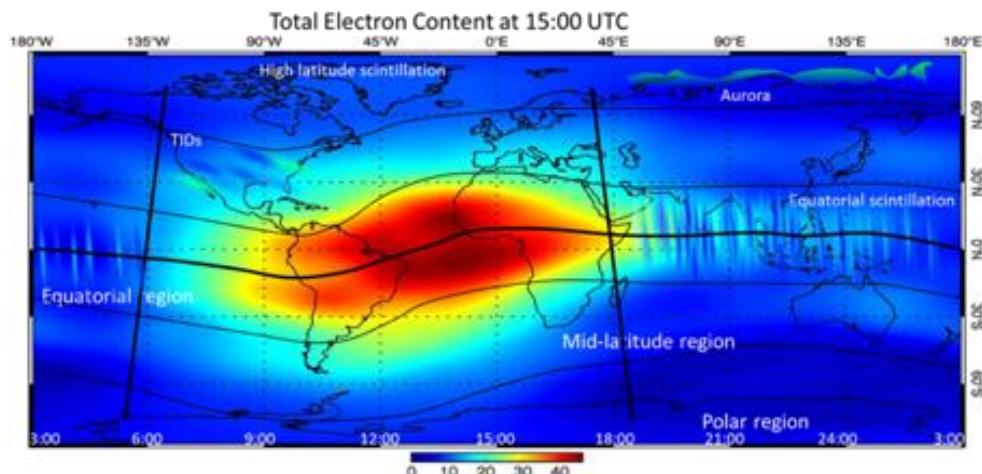


Figure C-3 A World Map of Total Electron Content (TEC) at 15:00 UTC [NASA CDDIS]. This typical situation shows that a dusk/dawn orbit configuration with satellite passes around 06:00 and 18:00 local solar time avoids much of the sun influenced ionospheric disturbances.

### 8.4. Mitigation of noise components

#### 8.4.1. Geometric contribution

The satellite geometry is usually known with high precision from Auxiliary data, [ESA S1]. The available satellite orbit data are typically known within <10 cm, and uniform DEMs of sufficient quality are generally available, e.g. [EU-DEM, SRTM]. In addition, reliable models for the reference frame motion exist, [Frame Motion]. Furthermore, there are reliable models for other geometric effects, like dynamic motion of the tectonic plates (earth tides, etc.), [Agnew2005]. Thus, the main geometric contributions to the interferometric phase can be directly compensated.

However, due to imperfection of auxiliary data, some residual phase effects will still be present, mainly:

- Baseline error: Resulting in phase ramp in range and azimuth direction, per interferogram;
- Height of scatterer relative to reference DEM: Resulting in an extra signal component that is essential to estimate correctly in order to achieve accurate geopositioning of the scatterer.

**Note:** For detailed treatment of auxiliary data in context of EGMS see dedicated section 3.7.9. The purpose of this section is to itemise geometric contributions on the interferometric phase, and how they are parameterised by a-priori information via auxiliary data.

#### 8.4.2. Tropospheric disturbances

Estimation of APS from a single interferogram only is inherently impossible due to rank deficiency. This means that single interferograms are only useful for deformation estimation in cases with very high deformation between acquisitions, such as earthquakes, where the signal dominates the APS contribution.

For precise ground motion mapping and monitoring, we need to use a stack of interferograms from a large number of SAR acquisitions (15+). For such time series, we may exploit spatiotemporal statistical properties of the APS. The various components of the APS are all spatially correlated, but slightly correlated between acquisitions (depending on interferometric revisit time frequency). The deformation signal is in most cases smooth in time, meaning that it is possible to separate APS from deformation by filtering. This can be done in a mostly data driven way by first subtracting initial estimates of other terms, then applying a spatial lowpass filter to the residuals, followed by a temporal high-pass filter. There are multiple ways of implementing such filters, with large variations in accuracy and computational complexity.

Some components of the APS still have a certain correlation over short time periods (< 1 day), and can to a certain degree be derived from numerical weather prediction (NWP) models. In particular, the long-wavelength and the stratification components can potentially be mitigated using NWP. Note also that despite the lack of short-term correlation, there is a strong seasonal component, directly influencing both the stratification component, and the incidence angle dependent part of the long-wavelength component. The turbulent term, however, decorrelates too fast and typically has too much spatial variation to be captured by NWP, where typical operational models have a resolution of 10+ km in space and 1+ hours in time, see Figure C-4. Thus, turbulent troposphere must be estimated from data.

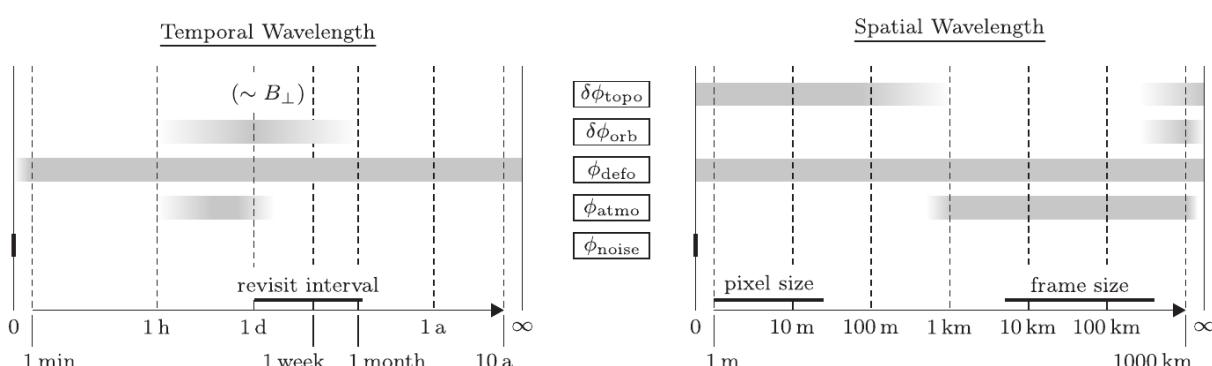


Figure C-4 Spatio-temporal correlation properties of the individual phase components. Ground deformation may occur at all temporal and spatial scales; the atmospheric contribution can completely change within a few hours, whereas variations are insignificant at spatial distances below 500 m.

### 8.4.3. Ionospheric disturbances

The ionospheric phase contribution is different from the tropospheric contributions due to electrically charged particles. In addition, the troposphere is mainly from ground level up to about 10-12 km above ground, while the ionosphere starts at 50 km from ground level, see Figure C-5.

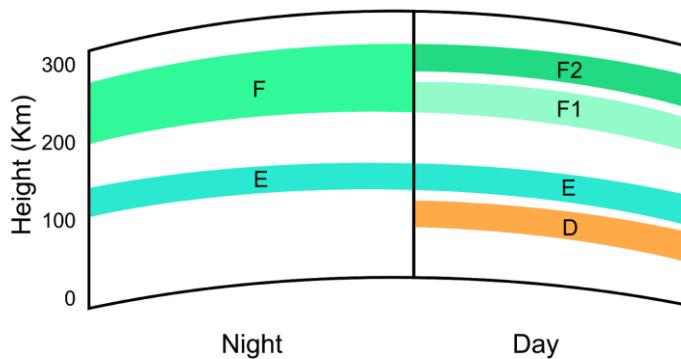


Figure C-5 Sketch of ionospheric layers with contributions to the electronic content. More details, and figure taken from [Wikilono].

The path delay caused by the ionosphere is dependent on the Total Electron Content (TEC), see Figure C-3, and [Gomba2016]. The effect on the interferometric phase is the following.

$$\phi_{\text{iono}} = \frac{4\pi}{\lambda} \frac{K}{f_c^2} \Delta TEC \quad (4)$$

Note that this effect is non-linearly dependent on the carrier frequency  $f_c$  of the SAR system. This is illustrated in Figure C-6.

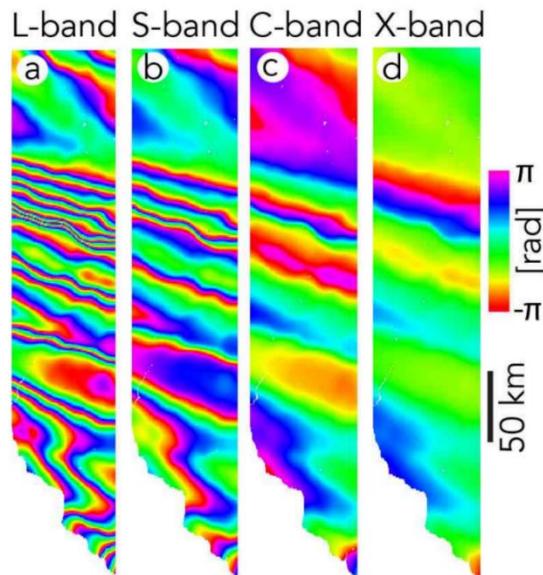


Figure C-6 Ionospheric delay at different frequencies shown as wrapped phase for the corresponding wavelength. Source [Fattah 2017a].

In general, ionospheric disturbances at C-Band in mid latitudes have a lower impact than the troposphere. Strategies for mitigation of ionospheric disturbances are outlined in the following sections.

#### 8.4.3.1. Data driven approaches

In order to estimate the ionospheric contribution to the interferometric phase, it is necessary to separate this contribution from the other components.

#### 8.4.3.2. Estimation of azimuth shifts by incoherent cross-correlation (or spectral diversity)

The azimuth shift method exploits the proportional relation between differential azimuth shift and the azimuth derivative of the differential ionosphere [Meyer2006]. An estimation of  $d \Delta TEC/dx$  is possible with high spatial resolution by using cross-correlation procedures.

#### 8.4.3.3. Model based compensation

GNSS satellites operate at L-band and need to compensate for the ionospheric delays from the different satellites in order to reach the required positioning accuracy. This is achieved by a similar approach to the “split band” data driven technique outlined above: Two or more narrow bandwidth signals with spectral separation are used to measure and mitigate the ionosphere [NASA CDDIS]. From these measurements, operational models of TEC in the ionosphere can be realised, see Table C-1.

Table C-1. The availability of the Global Ionospheric Maps (VTEC) that can be used for the interferogram corrections. TECU is a unit of measure for TEC, defined as TECU= 1016 electrons/m<sup>2</sup>. [WikiTECU]

Type	Accuracy	Latency	Updates	Temporal Res.	Spatial Res.
Rapid Ionospheric TEC Grid	2-9 TECU	< 24 hrs	daily	2 hrs	5deg (Ion) x 2.5deg (lat)
Final Ionospheric TEC Grid	2-8 TECU	< 11 days	weekly	2 hrs	5deg (Ion) x 2.5deg (lat)

#### 8.4.3.4. Soil moisture

The dependence of radar backscattering coefficient on soil moisture has long been recognised, as have effects on phase and phase coherence that are thought to be due to a combination of swelling and buckling of the surface and changes in the relative strength of SAR scattering centres distributed within each pixel. These effects are closely linked to variations in the dielectric properties of the soil – in drier soils the radar interacts with a larger depth range and there is more contribution to the backscattered signal from scatterers at larger depths below the surface than there is in soils with higher moisture content. Because the strength of individual scatterers within a resolution element changes, interferograms between dates with different moisture levels are less coherent than those with similar moisture content, [Scott2017].

For bare soils, expected variable contributions to the delay are 2 - 4 cm for a typical soil type when observed in L-band [Zwieback2015]. A model developed in [deZan2014] predicts a magnitude proportional to the wavelength for bare soils: in C-band the effects are expected to be 4 times smaller. The temporal behaviour (e.g. seasonality) of soil moisture may bias the estimation of deformation if it is ignored. Furthermore, it is currently unknown how moisture variations influence the interferometric phase in moderately vegetated land cover classes, e.g. grassland or agricultural areas, where we still have a coherent signal.

Qualitative assessment of the impact of soil moisture on the estimation of deformation is still under investigation. From an operational perspective, it is still mandatory to interpret the interferometric signal with great care for these land cover classes.

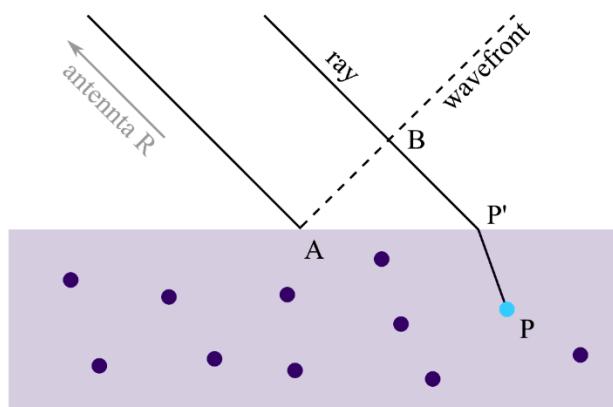


Figure C-7 Visualisation of the effect of soil moisture on the SAR phase, that consequently results in a phase center offset. Multiple scatterers (dark dots) within a dielectric medium (in purple). The rays undergo refraction where the refractive index  $n$  changes ( $P'$ ). Figure source [Zwieback2015]

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## 9. APPENDIX D: TIME SERIES INSAR - OVERVIEW OF METHODOLOGIES

### 9.1. Common processing strategies

Simplified, ground motion estimation from interferometric observations consists of the following steps, not necessarily in order:

- Remove apriori known contributions to the interferometric phase;
- Estimate and remove APS;
- Identify targets that are potentially phase stable/coherent;
- Estimate the height of each scatterer above the reference DEM;
- Unwrap the desired phase signal in space and time

The order that these steps are executed varies between algorithms.

### 9.2. Operational challenge: resolving nonlinear motion

The objective of EGMS is the reliable estimation of deformation of as many non-linear phenomena as possible, see section 3.2.6.1. However, there may be a major limitation on availability of unlimited computational resources (and time) considering the continental scale of the interest area.

#### Problem statement:

- Fundamental limitations: No spatio-temporal regions can be separated from all other regions by more than quarter-wavelength over the interferometric sampling period (e.g. for Sentinel-1 6 or 12 days). If this happens, external information is needed in order to correctly resolve the signal.
  - Note: If a PS/DS exhibiting a nonlinear motion “survives” the point selection, but with unwrapping errors, and if external information about its deformation is available, correction of PS/DS unwrapping can also be performed in post processing, see e.g. [Chang2016].
- Limitations in the presence of noise:
  - The presence of noise components limits the ability to reliably unwrap in space and time. Before APS and the PS height contributions are removed, the 3D unwrapping problem is fundamentally ill-posed.
  - There will always be a certain amount of unwrapping errors since there are virtually infinite variations within the class of non-linear deformation, and many of those will not follow assumptions made.

#### Assumption about signal components necessary for robust workflows:

- Deformation signal: Assume that the fundamental limitation apply
  - Less than a quarter wavelength change on any spatio-temporal arc used in the unwrapping;
  - All spatio-temporal points needs to be reachable by at least one arc fulfilling the previous assumption.
- APS component: Before analysis of all pixels can be done, error contributions must be mitigated. Typically, the first applied simplification is done by exploiting that APS is slowly varying in space.

This means that the phase difference over short spatial arcs can be assumed to be small. This assumption is applied in virtually all InSAR workflows.

EGMS context:

- Operational considerations (an example): For a reliable 3D unwrapping an estimation network of arcs between points in space and time are exploited. There are  $O(Ns^2 * Nt^2)$  possible spatiotemporal arcs for  $Ns$  spatial points measured at  $Nt$  time samples, where  $Ns \sim$  millions and  $Nt \sim$  hundreds.
  - Numerical example:
    - A small patch of 100x100 pixels has  $\sim 10000^2 / 2 \sim$  possible spatial arcs. This implies that direct analysis of *all* spatial arcs is impossible, even if the temporal dimension is already completely resolved.
- Achieving computational scalability:
  - Recognizing the fact that important phase components are slowly varying in time, one can reduce the computational complexity considerably by exploiting a network only short spatial arcs of high quality. E.g. the number of arcs in a Delaunay triangulation is  $O(N)$ , which renders the complexity completely scalable in space.
  - However, even with a scalable approach in space, the complexity is still quadratic in time without further simplifications: there are  $O(Nt^2)$  possible interferogram pairs for  $Nt$  scenes.
    - *Discussion:* For a stack of 200 scenes, we have already tens of thousands of combinations. It is in principle possible to reduce this to  $O(Nt)$  combinations by using only short temporal arcs. However, exploiting only short temporal arcs may lead to high bias due to the non-triangularity phenomenon, in particular in the DS case as demonstrated by [deZan2014, Ansari2018]. Thus, a certain number of long temporal arcs are needed to robustify the analysis. Care must be taken in order to not end up with a non-scalable approach.
  - A simple and robust way of ensuring computational scalability, is to assume quasilinear motion (section 3.2.6.1), where temporal analysis can be done with  $O(Nt \log Nt)$  complexity. For full-resolution analysis, where the number of spatial measurement points  $Ns$  is very large, it is paramount to not increase the complexity further. This means that care must be taken in any attempt to detect and resolve strong nonlinearities. Any  $O(Ns^2)$  algorithm will be practically impossible to apply at full resolution, in particular on a continental scale. However, on small identified hotspots, typically in urban areas, a second step can be considered, where more time consuming algorithms can be considered, either in terms of exploiting more spatial and temporal arcs, or by using higher-order deformation models.
  - For many points exhibiting non-linear behaviour, the deviation from linear deformation is large enough to cause unwrapping errors in time, but small enough to survive the point selection process. In such cases post-processing using parametric deformation models can successfully correct the unwrapping errors [Chang2016].

## 9.3. Processing methodologies

We will in this section outline the main classes of processing methodologies for time series InSAR processing.

### 9.3.1. Persistent Scatterer Interferometry (PSI)

One important class of algorithms focuses on identification and analysis of pointlike scatterers (PS). Most of these inherit from the seminal papers [Ferretti2000, Ferretti2001]. We will refer to this class of algorithms in general as *PSI* and distinguish the original algorithm explicitly where needed. The following general algorithm was presented in the original papers:

- Amplitude stability is a good proxy for phase stability up to a certain noise level, meaning that the initial analysis can be limited to pixels with very low amplitude dispersion.
- If atmospheric contributions are ignored, a maximum likelihood estimator for the linear velocity and height of a scatterer with respect to a reference point is the argument of a periodogram peak. The value of the interferogram peak is a measure of the temporal coherence, that can be used as a test statistic for identification of coherent arcs.
- Atmosphere is spatially correlated, such that two nearby scatterers will exhibit very similar disturbance. This means that relative velocity and height between pairs of scatterers in a sparse network can be estimated. After subtracting the corresponding double difference phase terms, the residuals in network can be integrated to yield the APS contribution for each acquisition. The sparse APS estimate can then be interpolated to the full grid for each acquisition, lowpass filtered in sparse and highpass filtered in time. The resulting APS estimate is subsequently removed from the data.
- After the APS has been removed, a high quality point in the initial PS network is chosen as a reference point, typically one where all incoming arcs have high temporal coherence which indicates that the point is stable or has completely linear deformation with low noise level. The remaining PS candidates, e.g. selected using a higher amplitude dispersion threshold, are analysed for relative velocity and height with respect to the reference point, using the coherence as selection criterion.
- Finally, the accepted PS deformation time series is formed by using the estimated relative velocity to unwrap the time series.

Many variations of this algorithm have later been published, see [Crosetto2016] for an extensive summary. Different kinds of selection criteria for the initial network have been applied, or different sparse phase unwrapping algorithms [Kampes2005, Costantini1998].

This original algorithm has a potential limitation in areas where no good scatterers can be found for inclusion in the initial network, typically resulting in large holes in the network, or even separation into subnetworks. Both of these results in suboptimal estimation of APS. One later important variation of this algorithm is a generalisation of the first order network selection by testing many pairs of nearby PS candidates for coherence, and successively building a network of PS connected by coherent arcs [Costantini2008].

### 9.3.2. Small Baseline Subset (SBAS)

A second class of algorithms focus on analysis of distributed scatterers (DS). Most of these algorithms build on the algorithm published in [Berardino2002], which is based on the fact that the coherence of distributed scatterers is higher for small baselines [Gatelli1994]. We will refer to this class of algorithms in general as SBAS, and distinguish the original algorithm explicitly where needed. The basic algorithmic flow as originally presented is:

- A connected temporal network of spatially averaged interferogram pairs with short baselines are formed, and the topographic phase subtracted using a reference DEM.
- The interferograms are spatially unwrapped and a reference point selected.
- Low pass deformation signal together with the unknown DEM error are estimated.
- The lowpass deformation model and the DEM error contributions are subtracted from the wrapped interferograms, and finally the double difference residuals are unwrapped and are inverted to a time series, e.g. using a singular value decomposition.
- The residual time series are lowpass filtered in space, and highpass filtered in time. The result is an estimate of the APS.
- The APS is finally subtracted from the residual time series, and the lowpass deformation signal is added back to obtain the final estimate.

A large number of variations of this algorithm exist in the literature.

- Different ways of choosing the baselines in the temporal network [Yang2013, Pepe2006];
- Different spatial phase unwrapping methods [Pepe2006];
- Different inversion methods [Pepe2016, Lauknes2011];
- Different filtering methods [Pepe2015];

### 9.3.3. Hybrid methods

The two main classes of algorithms both consider a single scattering mechanism only:

- PSI methodology: pointlike scatterers, typical for urban environments
- SBAS methodology: distributed scatterers, typical for natural environments

However, in a typical area of interest, one may have both urban and non-urban land cover classes. Thus, several hybrid approaches have been proposed. The concept behind hybrid methods can be seen from two different perspectives: either extending SBAS methodology by integrating phase information of full resolution PS pixels into multi-baseline filtered interferograms or extending PSI methodology by transforming filtered multi-baseline DS into equivalent single-master stacks. Some well-known approaches include (in chronological order)

#### 9.3.3.1. Full resolution extension of SBAS [Lanari2004]

SBAS yields deformation estimates also in urban areas. Due to the resolution it may be hard to interpret what this signal means. To mitigate this, it is possible to upsample and then subtract the SBAS low-resolution estimates from the full resolution interferograms. Each pixel in these residual interferograms is analyzed at full spatial resolution scale and can be related to PS or DS behaviours. The retrieved phase residual signals are then temporally integrated and added to the earlier removed low-resolution deformation components.

### 9.3.3.2. A hybrid PS/DS approach [Hooper2006, Hooper2008]

In addition to identifying initial PS candidates, this algorithm increases the number of candidates for the formation of initial network by lowering the threshold on amplitude statistics, and then analysing the phase stability of each candidate with respect to other points in a small radius around it. An accepted candidate is effectively a DS. The identified pixels are then processed using a 3D unwrapping approach. This hybrid PS/DS approach typically allows identification of more phase stable targets in natural terrain than PSI while retaining full resolution for pointlike targets.

### 9.3.3.3. Homogeneous distributed scatterers [Ferretti2011]

Several ideas in the InSAR community at the time were combined in this hybrid approach. First, the coherent spatial correlation method of [Hooper,2008] was adapted to a non-coherent one, using amplitude statistics only. Statistically homogeneous local areas, called *homogeneous distributed scatterers (HDS)*, are identified by successively applying two-sample similarity tests known from mathematical statistics to nearby pixels. The second important step is to generate all possible interferogram combinations, estimating phase and coherence over each of the identified HDS clusters by spatial averaging. The full interferogram stack is then transformed to an equivalent single master stack using a procedure called *phase linking* [MontiGuarnieri2008]. From this point, one can combine the identified HDS candidates with the PS candidates and proceed with the standard PS algorithm.

There are several variations to the HDS approach:

- Different two-sample tests [Parizzi2011]
- Sequential estimator for long time series [Ansari2017]
- Different phase linking algorithm [Ansari2019]

### 9.3.3.4. Persistent scatterer pair (PSP) enhanced method [Costantini2014]

The PSP method, introduced in [Costantini2008] and further developed in [Costantini2013] and [Costantini2014], is characterised by exploiting only the relative properties of neighboring pairs of points for both detection and analysis of scatterers. The pair-of-point approach makes for reducing the processing problems coming from effects slowly variable in space, like those depending on atmosphere or orbits. Moreover, by exploiting a very redundant set of pair-of-point connections, the PSP approach guarantees dense and accurate displacement and elevation measurements, both in correspondence of structures and when the backscattering is weak or distributed as in the case of natural terrains. In all cases, the measurements keep the full resolution of the input SAR images. The redundant set of arcs is exploited also in the 3D phase unwrapping [Costantini2012] to guarantee a more reliable solution.

### 9.3.3.5. Quantitative assessment of Hybrid PS/DS approach

Analytical or numerical assessment of the level of improvement when replacing a pure PS approach with a more sophisticated hybrid PS/DS approach, is non-trivial task. The number of measurement points depends heavily on land cover class, the threshold on phase noise considered acceptable. However, a number of general considerations can be made for different general classes of land cover.

For C-band Sentinel-1 like data, typical improvement range for a PS/DS hybrid approach in terms of coverage increase with respect to a PS only solution are reported in Table D-1.

Table D-1. Level of improvement in terms of MP coverage for PS/DS hybrid approach with respect to PS only solution. Note dependency on specific AOI.

Terrain	Increase in MP coverage	Comments
Urban	Modest (<20%)	Since most of the targets correspond to deterministic, point-wise, scattering centers, DS do not usually improve significantly the density of the measurement points.
Semi-urban	Fairly high (20% - up to 100%)	The increase depends on land cover type and the density of man-made structures.
Non-urban (Bare soil)	High (100% or more)	Clear improvements are visible over rocky areas or mountain slopes covered by short vegetation.
Non-urban (Vegetated or agricultural)	Limited	Heavily vegetated areas and areas with significant soil moisture variations remain unsuitable for InSAR analysis with or without a PS/DS approach at C-band.

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## 10. APPENDIX E: COPERNICUS SENTINEL-1 MISSION

### 10.1. Copernicus Sentinels

The Copernicus Sentinels are a fleet of dedicated EU-owned satellites, designed to deliver the wealth of data and imagery that are central to the European Union's Copernicus environmental programme. The European Commission leads and coordinates this programme, to improve the management of the environment, safeguarding lives every day. ESA is in charge of the space component, responsible for developing the family of Copernicus Sentinel satellites on behalf of the European Union and ensuring the flow of data for the Copernicus services, while the operations of the Copernicus Sentinels have been entrusted to ESA and EUMETSAT.

The mission has an open-ended lifetime, planned in a similar way as EUMETSATs existing fleet of meteorological satellites, where new satellites are put into orbit at regular and planned intervals.

#### *New era in Earth Observation*

Data at the scale, frequency, and quality available with Copernicus programme via free and open data policy constitutes a fundamental paradigm change in earth observation [<https://www.geospatialworld.net/article/free-and-open-data-via-copernicus-makes-it-a-gamechanger-says-esas-josef-aschbacher/>].

### 10.2. TOPS: Terrain Observation by Progressive Scans

#### 10.2.1. Overview

Before the Copernicus Sentinel-1 mission, essentially three classic SAR acquisition modes have been in common use:

- *Stripmap* Simple and versatile continuous imaging of a relatively narrow swath, typically <150 km for C-band satellites with a traditional antenna
- *Spotlight* Very high resolution imaging of a restricted area, typically 10 x 10 km or smaller. Continuous long tracks are not possible.
- *ScanSAR* Bursted acquisition in multiple parallel swaths, with strongly reduced resolution compared to stripmap.

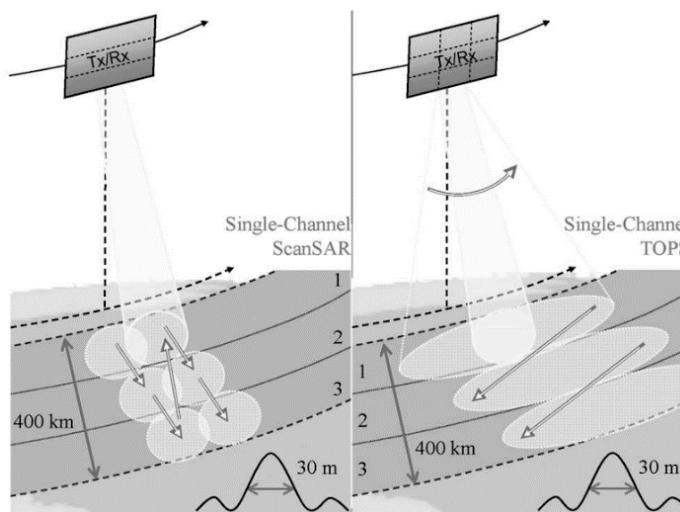


Figure E-1 Panel show the ultrawide swaths obtained by burst-mode systems as ScanSAR (left) and TOPS (right) with effectively a single Rx and Tx aperture. The shaded (yellow) area indicates the jointly steered Tx/Rx beam, while the dotted area represents the steering range.

A strict requirement for the Sentinel-1 mission was to be able to image all landmasses globally with a limited number of satellites [Torres2012], with medium resolution (~20 meter), stripmap like amplitude characteristics, and interferometric capabilities. This was not possible to achieve with the traditional acquisition modes.

Traditional ScanSAR suffers from azimuth-varying backscatter signal statistics. Due to the bursted acquisition mode, targets on ground in different along track locations will be illuminated by different parts of the antenna pattern, resulting in the so called scalloping effect, see Figure E-2 [Meta2008]. The TOPS mode was introduced [deZan2006] to overcome this problem, while still retaining a wide swath, which is essential to an operational SAR system.

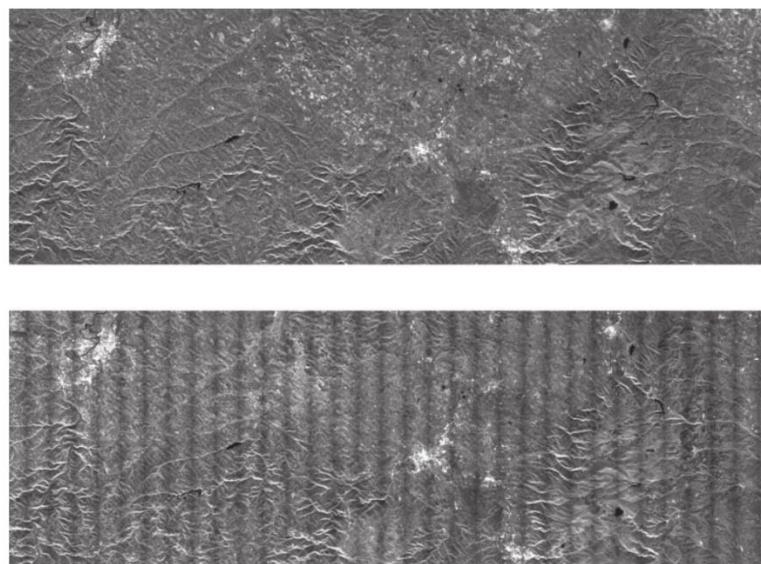


Figure E-2 Why TOPS? Reduction of scalloping and increase of resolution wrt ScanSAR. (Top) TerraSAR-X TOPS image, (Bottom) TerraSAR-X ScanSAR Image;

The TOPS mode operates by electronically steering the antenna beam in the azimuth direction. Thus, the scalloping effect is greatly reduced since all targets will be illuminated by the entire azimuth antenna pattern. This strategy allows scanning several other sub-swaths before returning to the first swath with only a minimal overlap.

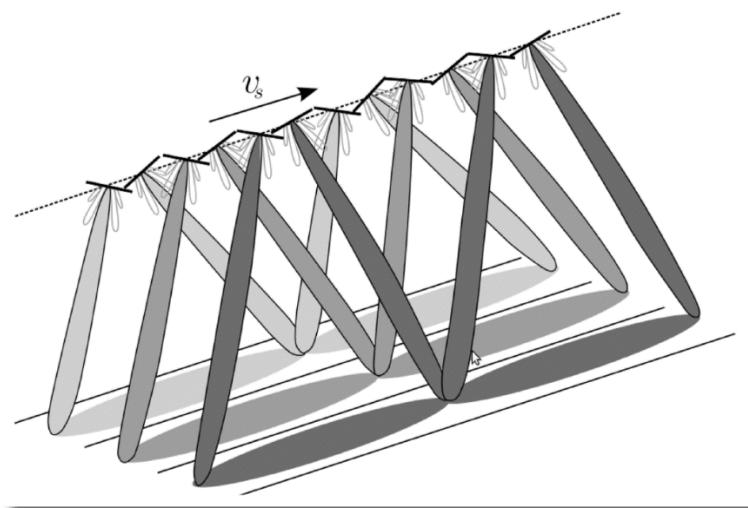


Figure E-3 Sketch of the acquisition geometry for a 3-swath TOPS system. TOPS is a wide swath mode that has comparable coverage and better resolution than the ScanSAR mode, but without the scalloping effect. Figure taken from [Engen2011]. For more information on the scalloping effect, see [Meta2008].

The TOPS mode of SAR acquisition introduces new challenges to space-borne SAR and InSAR signal processing:

- The steering of the antenna azimuth angle introduces a time-varying Doppler frequency,
- Bursted acquisition in multiple swaths results in multiple small images (bursts), see Figure E-9-4.

The time-varying Doppler property is shared both with the spotlight acquisition mode and the traditional ScanSAR mode, while the multi-swath burst acquisition is also similar to ScanSAR. Thus, the extensive prior knowledge from these modes can be leveraged.

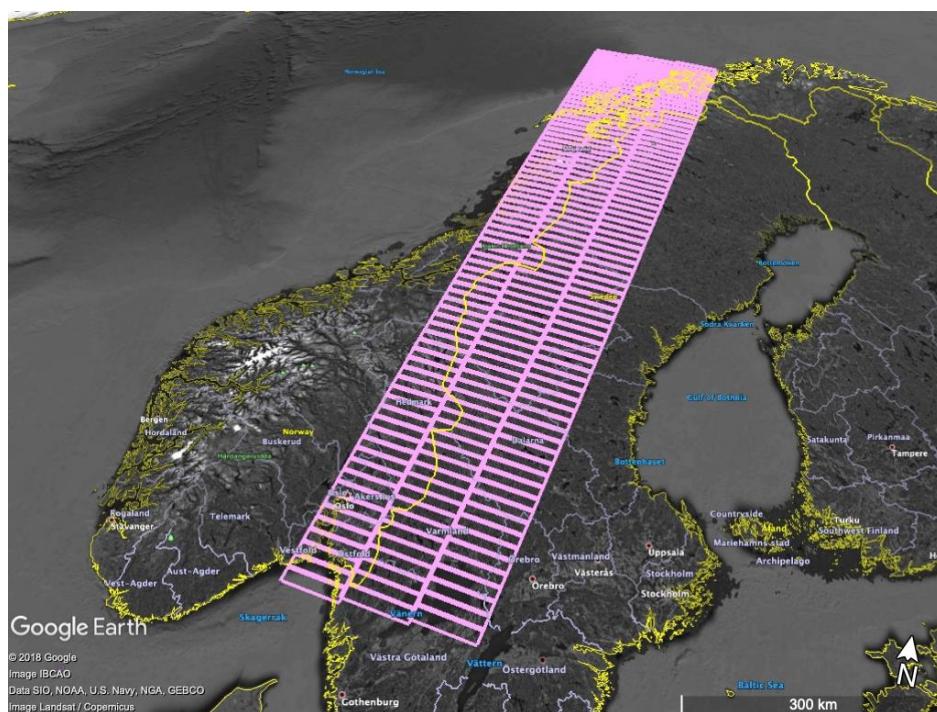


Figure E-4 Bursted acquisition with the S1 IW TOPS mode

### 10.2.2. Resolution tradeoff

The TOPS mode is a tradeoff between along-track resolution and swath width. For a TOPS mode with  $N$  subswaths and only small overlap between bursts, the loss of azimuth resolution is roughly a factor  $N+1$ .

### 10.2.3. Consequences of the time-varying doppler

#### 10.2.3.1. Burst synchronisation requirements

Another important requirement for the S1 mission is that it should support interferometric applications. The coverage in the TOPS mode was achieved by alongtrack antenna steering, which causes a linearly time varying doppler centroid, ie center frequency of the azimuth spectrum. For distributed scatterers to remain coherent, the azimuth spectrum must be overlapping as much as possible from acquisition to acquisition to avoid loss of coherence. That means that the burst acquisition pattern must repeat itself very precisely, typically accuracy in the millisecond range is required in order to keep >95% spectrum overlap.

#### 10.2.3.2. Azimuth coregistration accuracy requirements

Another effect of the time varying Doppler is that even a small error in the azimuth coregistration, will cause artificial phase ramps in azimuth direction within each burst [Prats2012]. This leads to phase jumps between subsequent bursts in azimuth direction, see Figure E-9-5. Typically, azimuth coregistration accuracy on the order of 1/1000 pixel is necessary, depending on the mode design.

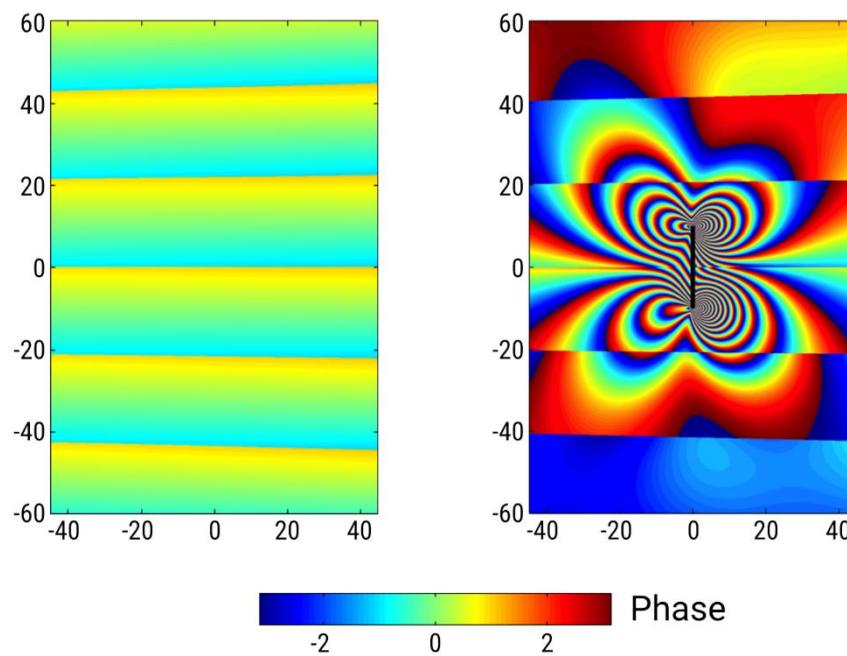


Figure E-5 Demonstration of an impact of the azimuth coregistration error on the TOPS interferograms. Simulated effect of a 1/20 of a pixel azimuth coregistration error, and its impact on a simulated interferogram capturing an earthquake event. (Left) Azimuth phase error due to the azimuth coregistration error, (Right) Effected interferogram. Note that the example is exaggerated to illustrate the effect. The accuracy obtained directly from orbital information is much better than 1/20 pixels. [Figure: Andy Hooper]

### 10.3. Copernicus Sentinel-1 Mission and the TOPS mode

Copernicus Sentinel-1 (S1), was the first mission to be launched as a part of the Copernicus programme. The first satellite, Sentinel-1A, was launched on 3 April 2014, while its twin Sentinel-1B was launched on 25 April 2016. Both satellites lifted off from the same location in Kourou, French Guiana, and each on a Soyuz rocket. Sentinel-1C and 1D are in development with launch dates to be determined.

#### 10.3.1. Key components of the S1 mission

Apart from a fixed and conflict free acquisition scenario, the key characteristics for the S1 mission are:

##### 10.3.1.1. Orbital characteristics:

- Repeat cycle: 12 days per satellite (6 days with two satellites)
- Baselines: 70m standard deviation, 300m maximum

##### 10.3.1.2. Mode characteristics:

- The main acquisition mode of Sentinel-1 over land is a TOPS mode, see Section 2.5.6.2, with three subswaths, called *interferometric wadeswath* (IW).

- Three subswaths: IW1-IW3
- Swath width: 250 km
- Incidence angle: ~30-45 degrees
- Resolution:
  - Along-track resolution: ~20 meter
  - Ground range resolution: ~5 meter
- Dual polarisation: VV+VH (default) or HH+HV

#### **10.3.1.3. Alternative interferometric SAR modes of S1:**

- Extended Wide Swath (EW) mode:
  - Five subswaths: EW1-EW5
  - Swath width: 400 km
  - Incidence angle: ~18-48 degrees
  - Resolution:
    - Along-track resolution: ~40 meter
    - Ground range resolution: ~20 meter
  - Dual polarisation: VV+VH or HH+HV (default)
  - Note: This mode is mainly meant for ocean applications and is not used over the EEA39 area, with the exception of areas where the Copernicus Maritime Environment Monitoring Service runs its sea ice services. This is limited to the Baltic Sea area during the sea ice season. While the EW mode is interferometrically capable, the resolution and temporal coverage is very limited. These data will not be exploited in the EGMS context.
- Stripmap mode:
  - 6 selectable beams: S1 - S6
  - Swath width: ~80 km
  - Incidence angles: 18 (S1) - 46 (S6)
  - Resolution:
    - Along-track resolution: ~5 meter
    - Ground range resolution: ~5 meter
  - Note: Stripmap is in operational use mainly for small remote volcanic islands where switching mode does not influence other areas. For the EEA39 countries, this includes some French overseas departments, e.g. the Réunion Island in the Indian Ocean.

#### **10.4. Golden age of SAR**

SAR systems are predestined to monitor dynamic processes on the Earth surface in a reliable, continuous and global way. With the operational characteristics of Copernicus Sentinel-1 mission, together with more than 15 spaceborne SAR sensors being operated today, and many new SAR systems being launched within the next years, it can be undeniably stated that SAR has entered into a golden age.

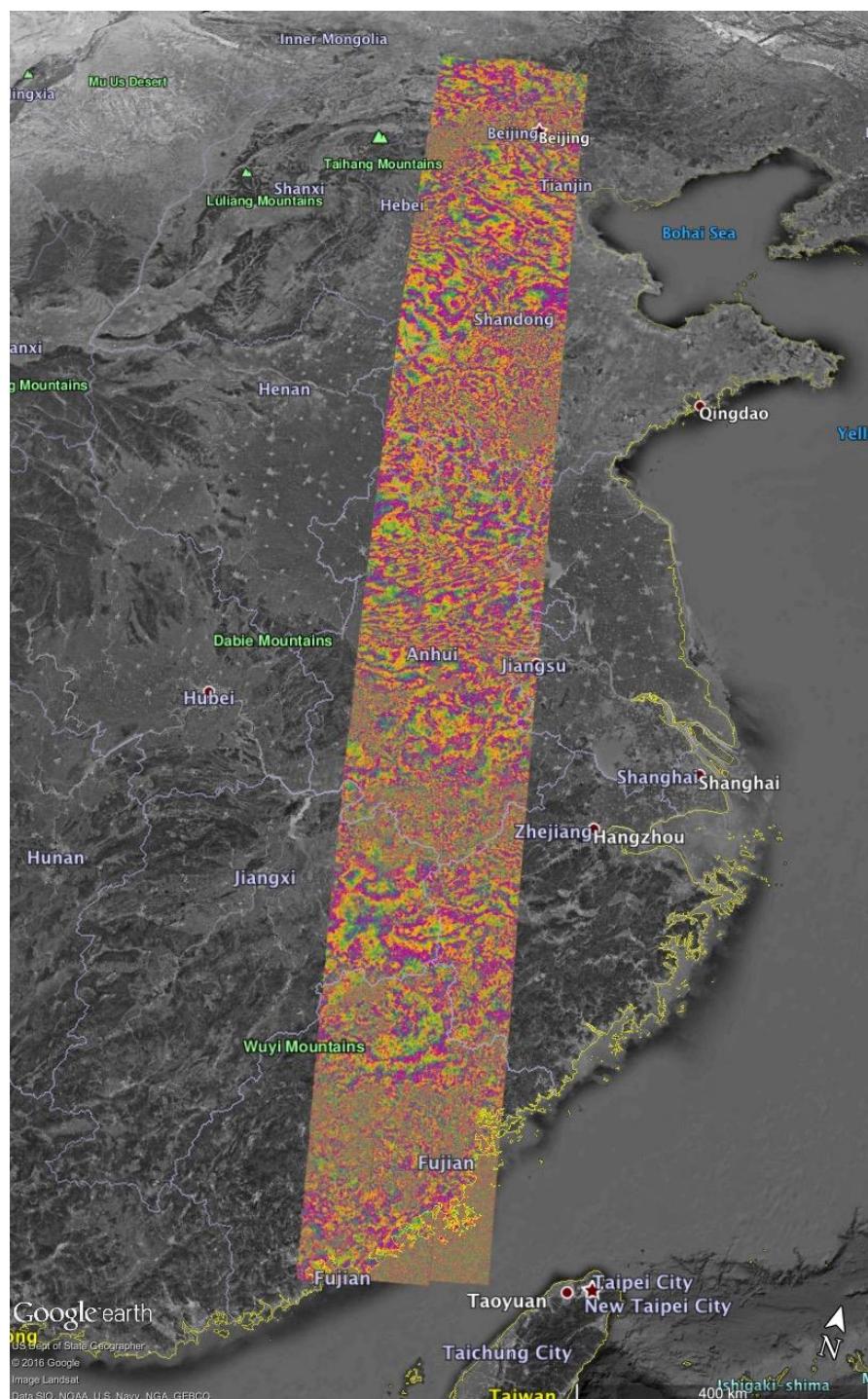


Figure E-6 Example of a 6-day Sentinel-1 A/B interferogram from ascending track 142 over Eastern China. The interferogram is 1900 km along-track, and 250 km across-track.

## 10.5. Operational opportunities and challenges

This section itemises a number of challenges and opportunities in the context of operational use of S1 data for EGMS. The purpose is to identify and group them in this dedicated section on the Sentinel-1 mission, for the sake of completeness, while each of the topics is addressed in more detail in dedicated sections.

### 10.5.1. Data availability, continuity and open policy

The operational characteristics of S1, coupled with an open data access policy are very favorable for the long-term operational use.

#### 10.5.1.1. General availability of Copernicus data:

- The Sentinel High Level Operations Plan (HLOP), the top-level operations plan of the S1 mission is predefined, and enables long-term planning of Earth Observation applications building on top of Copernicus data.
- Copernicus services are being first-priority users.

#### 10.5.1.2. Continuity:

- Due to HLOP of Sentinel Mission, S1 data continuity is already secured for the next decade(s).
  - pre-defined mission observation scenario
  - optimum use of the SAR duty cycle within the technical constraints of the overall system
  - minimising the number of potential conflicts during operation
- In terms of ground motion applications, until the availability of S1, InSAR have been limited to retrospective analysis of deformation episodes. The frequent revisits of S1 along with rapid delivery of data allows for operational ground motion mapping and monitoring applications.

#### 10.5.1.3. Open & free data policy:

- Benefits are diverse and range from improved efficiency of data collection, to stimulating innovation, and operationalisation of workflows for InSAR based ground motion applications.

**Sentinel-1 Constellation Observation Scenario:  
Revisit & Coverage Frequency**

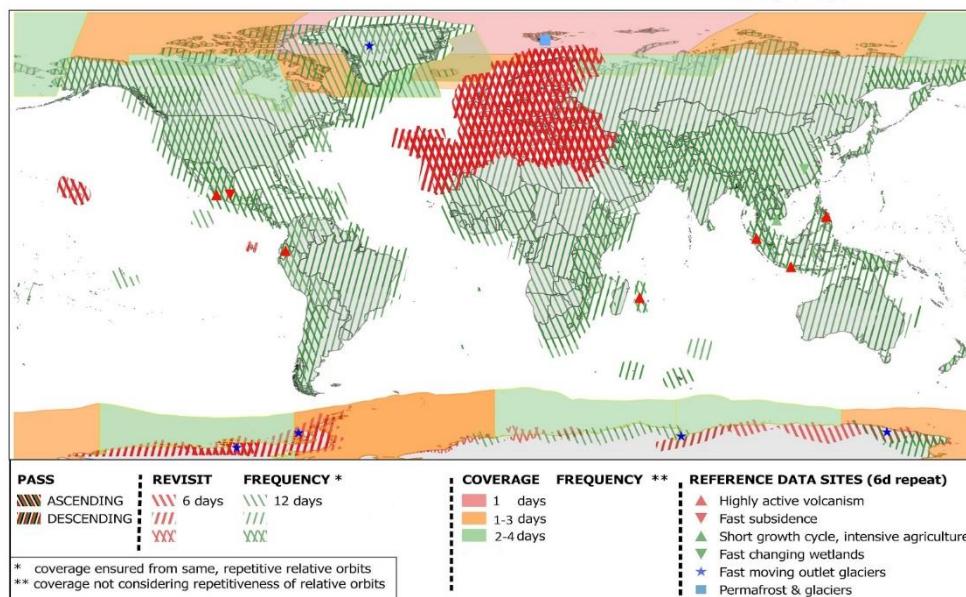
 sentinel-1  
validity start: 05/2019


Figure E-7 Visualisation of the pre-defined acquisition scenario for Sentinel-1 (Validity start: May 2019)

### 10.5.2. Algorithmic complexity

Due to the new TOPS mode, S1 brought new challenges to the InSAR community. As discussed, there is a very high accuracy requirement for the coregistration. For the first few years after launch of S1A, this was an important research topic. While the challenge remains, there is now a community consensus on how to handle this problem in an operational context.

Due to the unprecedented coverage of the S1 mission, it is now possible to perform nationwide, or even continental scale, ground motion analysis. The scope of such an analysis requires a scalable approach both in terms of hardware and software.

### 10.5.3. System Operations and Data Volume

The S1 mission delivers unprecedented data volumes. This has put a large challenge on the SAR/InSAR community in terms of data handling. Even smaller scientific case studies need tools and resources for large scale data handling.

Moving computation and processing closer to data is objective for efficient handling of Big Data. This is one of the biggest operational challenges for successful implementation and deployment of EGMS.

Example: Currently, the minimum data product size for interferometric applications is an 8GB SLC product. This product covers an area of 250 x 170 km, and no mechanism exists for downloading partial products. This means that in order to perform an InSAR time series analysis of even a very small AOI, a full time series of 200-250 products (2014-2019, areas with continuous coverage since launch) must be downloaded. This minimum data volume quickly adds up to almost 2TB for a single geometry.

### 10.5.3.1. Orbital tube

To keep the coherence of distributed scatterers as high as possible, S1 has been designed to restrict the maximum perpendicular baseline. On the other hand, restricting the perpendicular baseline will limit the sensitivity to the height of the scatterer above a reference DEM. This will lead to a loss of precision in localisation of each scatterer, with a negative impact on applications which require high geolocation accuracy (e.g., buildings and other localised man-made infrastructure objects). This can be partially mitigated in postprocessing using very high resolution building models.

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## 11. APPENDIX F: BEST PRACTICES FOR TIME SERIES INSAR

### 11.1. Concept of building blocks

In this Section, we will outline best practices for the major building blocks used in time series InSAR analysis.

#### Assumptions:

- We do have a big computer, but not infinite resources,
- We do have big storage, but there is a limit.

Each building block will be described in terms of the most well-known algorithms, and there is a separate reference list for each one.

It is worth noting that generating a ground motion time series from InSAR data is a complex task that requires heavy computation, sophisticated algorithms and implies the generation of a not negligible number of intermediate products.

## 11.2. Block #1: Data Management / S1 Database

### Requirements:

- Database System for SAR products and auxiliary data
- Flexible data access
  - Individual bursts with corresponding metadata, not slices

### Input/output:

- Input: Stream of Level1 S1 products
- Output: Database of S1 bursts, with corresponding metadata

### Algorithms:

- No particular algorithms are necessary per se
- Definition of an identification system for individual bursts necessary
  - Bursts are unique due to burst synchronisation
  - ESA does not provide a system for this

### Community best practice:

- The Sentinel-1 products, consisting of ~3x9 bursts, are *not* unique, and can start with any unique burst.
- A system for unique *virtual frames* is necessary
  - It is natural to align this concept with the specification of Level 2a products
  - The size of the frames is a design topic to be explored for the final report.
    - Tradeoff: data volume vs avoiding edge effects

### Measure of success:

- Production is not limited by data access time

## 11.3. Block #2: InSAR processing system

### Requirements:

- Efficient and reliable interferometric preprocessing of S1 IW mode data
- Automatic steps for each individual data product, continuously processed (ie. not in batches)
  - Coregistration:
    - Orbital correction vs chosen reference geometry
    - Reliable TOPS data resampling
  - Formation of single master full resolution differential interferograms
    - Topographic phase correction

### Input/output:

- Input: Stream of S1 Level 1 products (SLC bursts)
- Output: Datacube of S1 interferograms (full resolution and multilooked)

### Algorithmic baseline & Community best practice:

#### S1 TOPS Coregistration

- The community standard before the S1 mission was the geodetic approach using patch correlation, e.g. [Li1990]. A large number of patches were distributed across the data product, and the resulting offsets were fitted to coregistration polynomial that was used for image resampling. For Sentinel-1, however, this approach is not viable due to the very high accuracy requirement in the azimuth direction, see Section 2.5.6.2.2. The only viable option here is the combination of the following approaches:
  - Assume that the azimuth offset is a constant single number for all bursts in a given acquisition. Unless the acquisition is extremely long, this is a very good assumption. Otherwise, a linear component can be introduced, e.g. [Mancon2015]
  - Phase based estimation of this azimuth offset exploiting the overlap zones in azimuth direction. This algorithm is referred to as *Extended Spectral Diversity (ESD)* [Prats 2012]. This algorithm has been shown to reach the required accuracy of ~1/1000 azimuth pixel in a robust way, e.g. [Yague2017]
  - Optimisation for long data stacks: Note that ESD is a coherent technique, in principle requiring long-term coherence if always applied between a fixed reference dataset each new dataset (single master). To overcome this, one solution is to rely on a network of pairwise ESD estimates (multimaster) and invert the resulting equation system to arrive at the equivalent offsets with respect to a single reference [Yague2017, Fattahi2017].
  - Derivation of an offset model in range. This can be done with any of the traditional methods, like (range) Spectral Diversity [Scheiber2000] or incoherent cross correlation, e.g. [Li1990]. One simple offset model is to assume that the cross-track error is in the direction of the line-of-sight vector at a given range, e.g. in the middle of the S1 swath, and average a large number of patches at this range.

- Finally, the offset model is used for orbital corrections, and the data are subsequently resampled using a purely geometric approach [Sansosti2006]
- Note that during resampling, the aliased azimuth spectrum due to the Doppler variation needs to be taken into account [Miranda2017]. This can be done either by demodulating the spectrum, or modulating the resampling kernel.

### Interferogram formation

- Note: Most algorithmic steps unchanged from classic InSAR, except spectrum handling [Miranda2017], adapted from Spotlight mode processing [Eineder2009].
- Removal topographic correction using external DEM, e.g. [Eineder2003], yielding single master full resolution interferograms.
- Multilooking to low-resolution interferograms
  - [Optional]: Common band filtering in case of multilooked interferograms [Gatelli1994] . For Sentinel-1 specifically, the baselines are all relatively small compared to the critical baseline, meaning that this step is not very critical.
  - [Optional]: Adaptive interferogram filtering [Goldstein1998, Baran2003]
  - [Optional]: Spatial phase unwrapping, e.g. [Costantini1998, Chen2000, Pepe2006, Hooper2007] . Some algorithms that exploit the full stack of interferograms in the unwrapping, typically defer this step to a later stage in the processing.

### **Measure of success:**

- Automatic background processing system in continuous operation

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## 11.4. Block #3: Time-series processing

### Requirements:

- Selection of candidates for reliable, phase stable targets
- APS correction
- Estimation of deformation time series per Measurement Point (MP)
- Estimation of the location of each MP

### Input/output:

- Input: Datacube of S1 interferograms (output from Block #2)
- Output: EGMS Level2a product

### Algorithmic baseline & Community best practice:

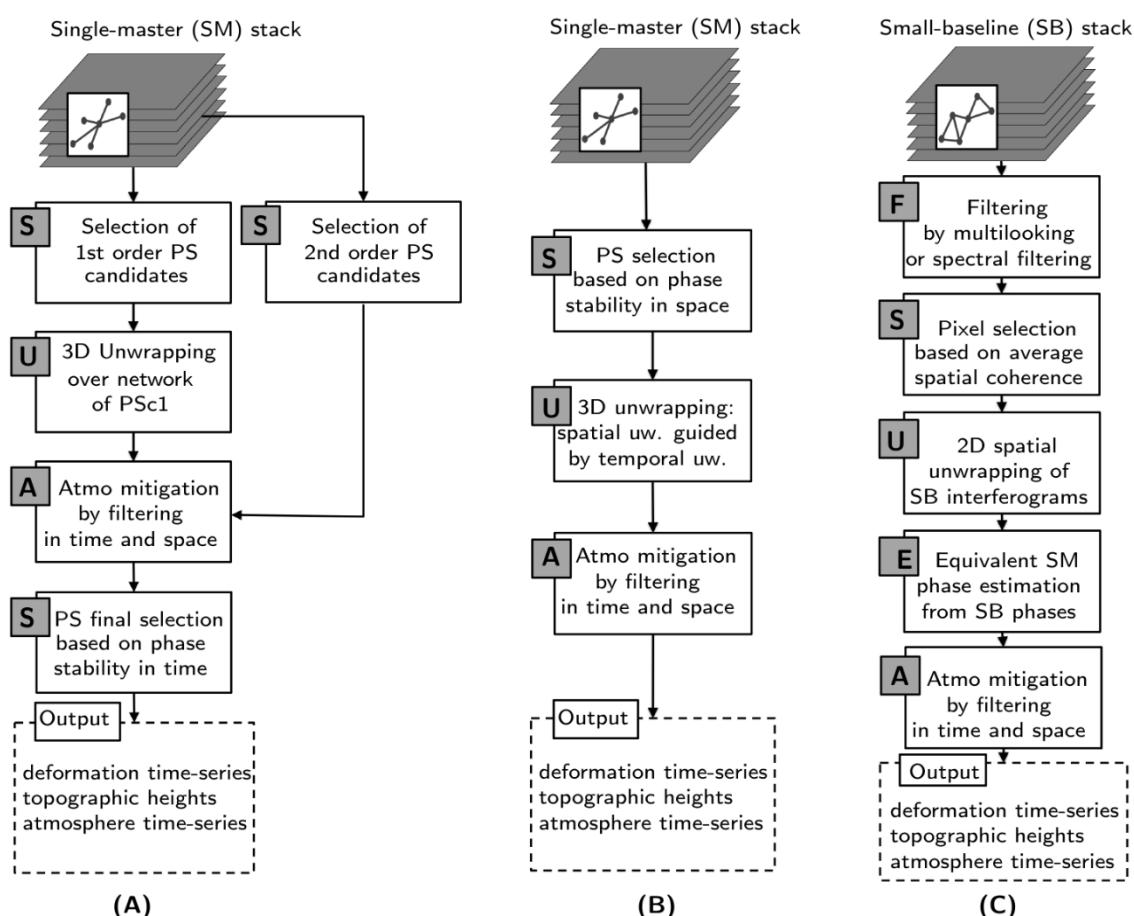


Figure F-1 Generic flowchart of (A) PSI processing (B) Hybrid PSI/SBAS, and (C) SBAS method. The steps are classified into five basic time-series InSAR processing blocks (expressed in the gray boxes) as [S]: pixel selection, [U]: unwrapping, [A]: atmospheric-signal mitigation, [F]: filtering, and [E]: equivalent single master phase estimation from multi-master phases. Processing-blocks F and E are specific to distributed scatterers and are hence applied only in SBAS processing. Figure taken from [SamieiEsfahany2017].

### Filtering, [F] in Figure F-1

- Treated in Block #2.

### Initialisation - Subdivision of data set in suitable processing units

- Full resolution methods: A burst, or even a smaller tile of e.g. 10x10 km, is a flexible processing unit.
- Low resolution methods: burst interferograms should be mosaicked to larger units, e.g. 250x250km = 3x13 mosaicked bursts, or larger depending on multilook factor. Larger units are favourable to avoid edge effects, while smaller units are less demanding for certain processing steps, in particular phase unwrapping.
- It is natural to define the EGMS Level-2a products to be the output from one processing unit. The precise definition is a tradeoff and will be discussed in more detail in the product specification document (Chapter 4).

### Selection of candidate MP for interferometric analysis, [S]:

- PSI
  - Amplitude dispersion [Ferretti2001]
  - Amplitude difference dispersion [Hooper2008]
  - Temporal coherence between pairs of points [Costantini2008]
- SBAS
  - Temporal stability of spatial coherence [Berardino2002]
  - Triangular Coherence [Manunta2019]
- Hybrid methods
  - Homogeneous distributed scatterers
    - Phase [Hooper2008]
    - Amplitude [Ferretti2011, Parizzi2011]
  - Full resolution extension of SBAS [Lanari2004]
    - Generalized temporal coherence measure
  - A hybrid PS/DS approach [Hooper2006, Hooper2008]
    - Amplitude and phase stability
  - Persistent Scatterer Pair [Costantini2014]
  - Analysis of temporal coherence in a highly redundant network of point pairs.

### Unwrapping, [U]:

- Spatial
  - SBAS
    - 2D spatial unwrapping per interferogram, see Building block #2 above.
  - PSI/PSP
    - Formation of robust network of high quality MPs

- Estimation of parameters of relative motion for all arcs forming the network. Usually, a quasilinear model is used since nearby points often experience similar motion, such that the differential motion is limited [Ferretti2001, Costantini2008]
- Sparse network unwrapping, e.g. [Costantini2012]
- Temporal unwrapping of initial network
  - Single master scenario
    - 3D unwrapping (integrated in the spatial unwrapping) [Hooper2007]
    - Model based temporal unwrapping [Ferretti2000, Costantini2014]
      - Spatial integration of pairwise motion parameters in a network
  - SBAS scenario
    - 3D unwrapping (spatial unwrapping guided by temporal unwrapping) [Pepe2006].

Equivalent single master phase estimation, [E]:

- SBAS scenario (unwrapped phases)
  - SVD based reconstruction of time series based on unwrapped interferograms [Berardino2002, Pepe2006]
- HDS scenario (wrapped phases)
  - Phase linking [MontiGuarnieri2008, Ansari2019]

APS correction, [A]:

- [Optional] Estimate long wavelength atmospheric phase components
  - Data driven approach:
    - Estimate long wavelength components from low resolution, short temporal baseline interferograms, e.g. [Tymofyeyeva, 2015]
    - Estimate stratification using correlation with DEM, e.g. [Beauducel2000, Lauknes2011]
  - Model approach:
    - Use operational numerical weather prediction (NWP) products [Jolivet2014, Bekaert2015, Cong2018]
- [Optional] Estimate ionospheric phase component
  - Data driven approach:
    - Exploit the fact that the ionospheric contribution is frequency dependent [Gomba2016], see also Section 2.5.4.6.
  - Model approach:
    - Estimate a low resolution ionospheric phase contribution from available models, eg. IGS products  
[\[https://cddis.nasa.gov/Data\\_and\\_Derived\\_Products/GNSS/atmospheric\\_products.html#iono\]](https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/atmospheric_products.html#iono)

- Note: At C-band, a model based approach is expected to be of sufficient resolution, and significantly less computationally intensive than the data driven approach.
- Estimate turbulent part of APS from data:
  - Apply the following steps :
    - Estimate apriori deformation model and DEM error
    - Invert to to equivalent single master stack [multimaster only]
      - SBAS: Singular Value Decomposition (SVD) [Berardino2002]
      - HDS: Phase linking [MontiGuarnieri2008, Ansari2019]
    - Lowpass filter residuals in space, highpass filter in time to estimate APS [Ferretti2000, Berardino2002]
  - Note: the order of these steps may vary depending on algorithm

#### Ground motion time series estimation

- After APS mitigation, it is possible to select a single reference point, and analyse double difference phase time series for a much bigger set of measurement points.

#### **Measure of Success**

- Time series of ground motion satisfying the product specification for EGMS Level-2a products, as defined from a combination of user requirements and theoretically derived quality bounds, see Section 4.2.

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## 11.5. Block #4: Harmonisation

### Requirements:

- Harmonised Level 2b product, Section 4.3.

### Input/output:

- Input: EGMS Level2a product (Block #3)
- Output: Level 2b product

### Algorithmic baseline & Community best practice:

We have discussed the estimation of Level 2a products for a relatively limited area, restricted by algorithmic complexity, and hardware limitations. In this Section, we elaborate on how to merge a large number of Level 2a products from the same radar geometry to a harmonised product, and reference it to a well-defined datum.

Note that there is still limited available literature on this topic. One reason for this could be that only recently the S1 mission had time series long enough for very large InSAR ground motion products of high accuracy. Earlier missions only had sporadic data coverage in space and time, meaning that ad hoc procedures were needed to harmonise products successfully.

- Data driven (relative) tile harmonisation
  - Two overlapping processed tiles from the same S1 burst:
    - Typically, tiles are generated with enough overlap that it is straightforward to harmonise them relative to each other.
    - Common measurement points in the overlap zone are compared, and the resulting difference due to separate reference points eliminated.
  - Two overlapping processed tiles from different bursts:
    - The same pixel will be observed slightly different view angle in two overlapping tiles. This means that the selection of quality MP are slightly different. However, in most cases there are enough common pixels to apply the same procedure as for tiles from the same burst.
  - All pairwise corrections between processing tiles can then be integrated, e.g. [Adam2011, Costantini2012, Manunta2019].
- Datum connection:
  - InSAR measurements are inherently relative, see Section 2.5.2.5.
  - In order to reference harmonised InSAR measurements to a well-defined datum, we are dependent on crustal motion models derived from GNSS.
    - Reference frame (horizontal) motion and dynamic earth effects have standardised models.
      - Reference frame motion [Bähr2011]
      - Dynamic earth effects [Cong2012]
        - Earth tides and other tidal effects [IERS Conventions 2010]
        - Ocean loading [Lyard2006]
    - Currently, there is no unified vertical model for Europe. Thus, in this document, we must limit our discussion to the requirements EGMS will have for such a model in order to reach the desired quality level. This will include a discussion on

available regional vertical trend models, e.g. postglacial uplift in Fennoscandia and the Baltic [Vestøl2019].

- Note: This topic will be further elaborated on in the final report.

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## 11.6. Block #5: Multigeometry / Decomposition

The EGMS Level-3 product is formed by gridding all available satellite geometries to the same regular grid on the ground, and identifying grid cells with sufficient number of geometries for reliable decomposition. The data are then decomposed to motion components in East-West and vertical.

A fundamental challenge for the Level-3 generation is that the InSAR measurement is blind to displacements perpendicular to the Line of Sight (LoS). For polar orbiting satellites, all available geometries have their LoS approximately in the East-Up plane. This implies that the north-south direction is difficult to estimate. This makes the inversion problem ill-conditioned and constraints based on some a-priori knowledge are required. Several different constraints are possible including

- In moderate topography: Assume zero North-South motion
- In steep terrain: Assume slope parallel motion, or equivalently, assume no lateral motion.

For a generic service, a uniform constraint is recommended, so EGMS L3 products should be derived assuming a zero North-South component. In this case, we have 3 or more properly conditioned equations, meaning that motion components in the EW and vertical directions can be reliably estimated.

Note that the presence of a north-south motion component will bias the results. This is a fundamental limitation of any SAR system in polar orbit.

## 12. APPENDIX G: EMPIRICAL BASIS FOR EGMS PRODUCT REQUIREMENTS

This Appendix outlines experimental evidence used as a basis for specific EGMS product requirement recommendations.

### 12.1. Tropospheric Correction of InSAR data using NWP

Spatial variations of the atmospheric conditions drive to changes in the refractive index of the troposphere varying consequently also the delays of the radar echoes travelling through it. The value of the refractive index can be computed in function of a relative restricted set of physical parameters:

$$N = (n - 1) \times 10^6 = k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

where  $P_d$  is the partial pressure of dry air [Pa],  $e$  is the partial pressure of water vapor [Pa],  $T$  is the absolute temperature [K] and  $k_1, k_2, k_3$  are coefficients. Knowing these parameters even on a coarse grid permits a spatial reconstruction of the refractive indexes for the master and the slave acquisitions allowing a mitigation of the additional phase delays present in the interferometric measurements.

Knowing the acquisition geometry it is possible for every point of the image to reconstruct the path travelled by the radar echo. Using the physical parameters mentioned in the Equation above the extra delays related to the troposphere can be calculated and removed from the SAR interferograms.

The knowledge of the atmospheric parameters can be obtained by using external data. ECMWF provides a wide range of data describing the weather conditions. For the reconstruction of the refraction index changes only four layers are needed. The calculation of the refractive indexes on a three-dimensional grid and the estimation of the delay is computed properly interpolating the weather data and re-constructing the additive delay [Cong2014, Cong2018].

The available parameters are grouped in different products having different characteristics temporal and spatial resolutions, Table G-1.

The products can be Operational or Re-Analysis (ERA5 currently). Operational Products are available almost in real time but are processed with most recent processor. Re-Analysis products have three months delay but are all processed with the same processor.

Table G-1 ECMWF Products

ECMWF Products	Horizontal resolution	Vertical resolution	Time Resolution	Date Start	Latency
<b>Operational</b>	16 → 9 km (8-Mar-2016)	NL = 91 → 137 (2013-06-25)	6 hours	1982	Real Time
	31 km	NL = 137	1 hour	1979	2-3 months
	31 km	NL = 137	1 hour	before 2-3 months (last ERA5 data)	5 days

Re-analysis data are suggested since they guarantee a processor consistency. The use of different processor (Operational uses the processor version in use at the moment of the data assimilation) can lead to different product characteristic making the derived corrections not consistent on a large interferograms' stack. This is a very important issue that should be considered in the use of such data in

an operational framework. In December 2019, a preliminary ERA5 product (ERA-5T) was released. The product should deliver a preliminary result of the ERA5 re-analysis to reduce the latency from 2-3 months to 5 days. At the moment no consistency/accuracy assessments for an operational interferometric use of such products are known.

The impact of the ECMWF correction on the final performance of the interferometric processing has been however evaluated (Figure G-1) for the ERA5 data. The evaluation has been carried out comparing the variograms of the interferometric phase before and after the corrections [Rodriguez2018].

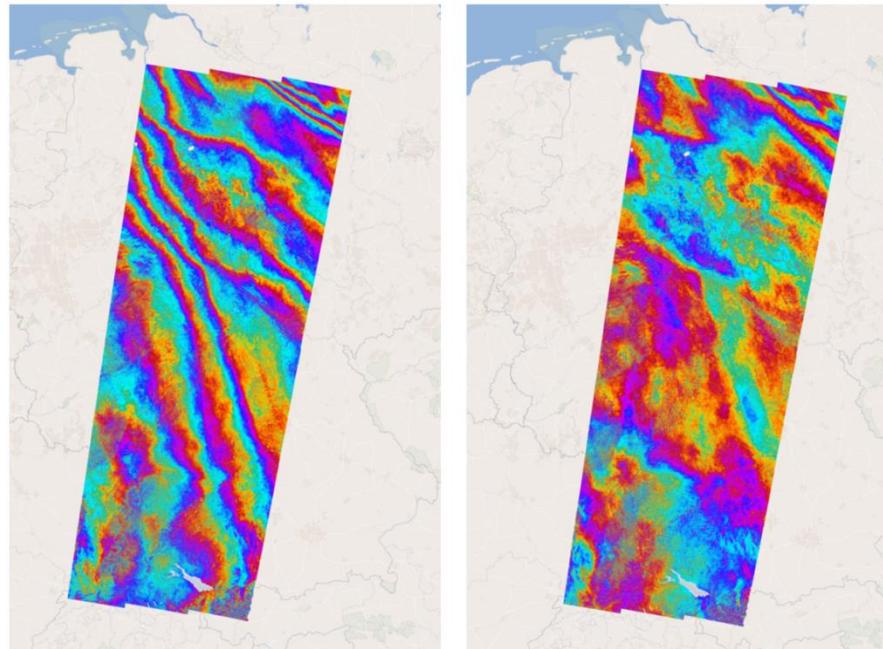


Figure G-1 Example of interferogram correction on a long Sentinel-1 stripe covering almost the whole Germany using ECMWF ERA-5 products. On the left the original interferogram on the right the corrected one

Large stacks of Sentinel-1 interferograms (> 100) have been considered for the analysis. Short temporal baselines have been computed in order to avoid the effects of ground deformations. Figure G-2 shows the variograms before and after the corrections of a large Sentinel-1 A/B interferogram stack over Germany. The achieved improvement depends on the distance; since the ECMWF data have a much lower resolution than the radar data the effect of the corrections is visible starting from 30-40 km distance. At 200 km can reach even a factor 10 in power. The mean behaviour is highlighted in red in Figure G-2.

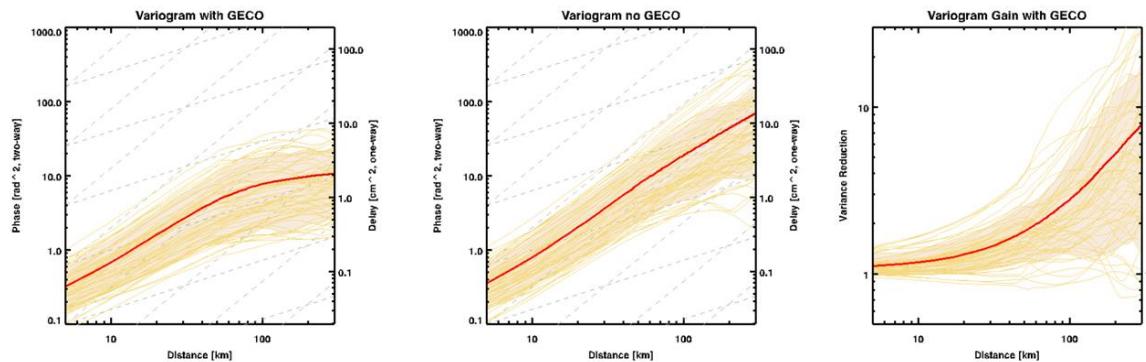


Figure G-2 Example of variograms after, before corrections and the scale dependent Gain (from left to right). In yellow the variograms of every single interferogram of the stack, in red the mean behaviour.

## 12.2. Accuracy of the EGMS Level 2A Products

Exploiting the numbers extracted from the analysis it is possible to extrapolate the impact on the final performance. The estimation of the deformation rate is essentially a line fit and the performance, for a regular acquisition scenario, can be derived scaling the mean variogram considering the accuracy of a linear regression:

$$\sigma^2_v(\mathbf{d}) = \frac{1}{2} \frac{N}{N \sum_k t_k^2 - (\sum_k t_k)^2} \sigma^2_r(\mathbf{d})$$

Where  $N$  is the number of acquisitions,  $\sigma_r(\mathbf{d})$  represents the tropospheric contributions to the line-of-sight error in function of the distance  $\mathbf{d}$  [Rodriguez2018]. The time of the acquisitions w.r.t. the reference (master) are given by  $t_k$ . The factor  $\frac{1}{2}$  takes in account that all the phases are related to a reference (master).

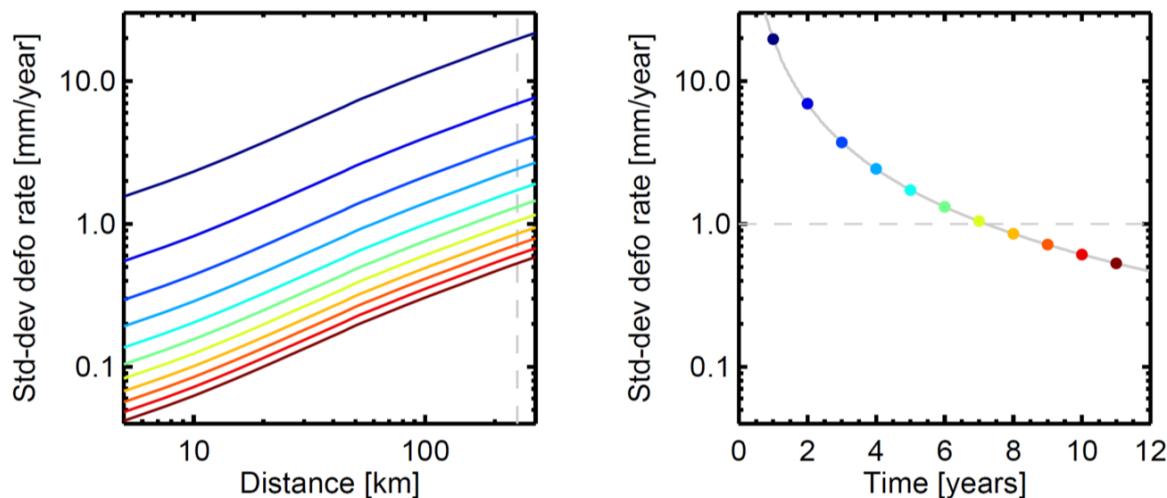


Figure G-3 Deformation Rate error variograms without tropospheric corrections. On the left the error variograms of the deformation rate estimation varying the observation time. On the right the accuracy at 250 km varying the observation time

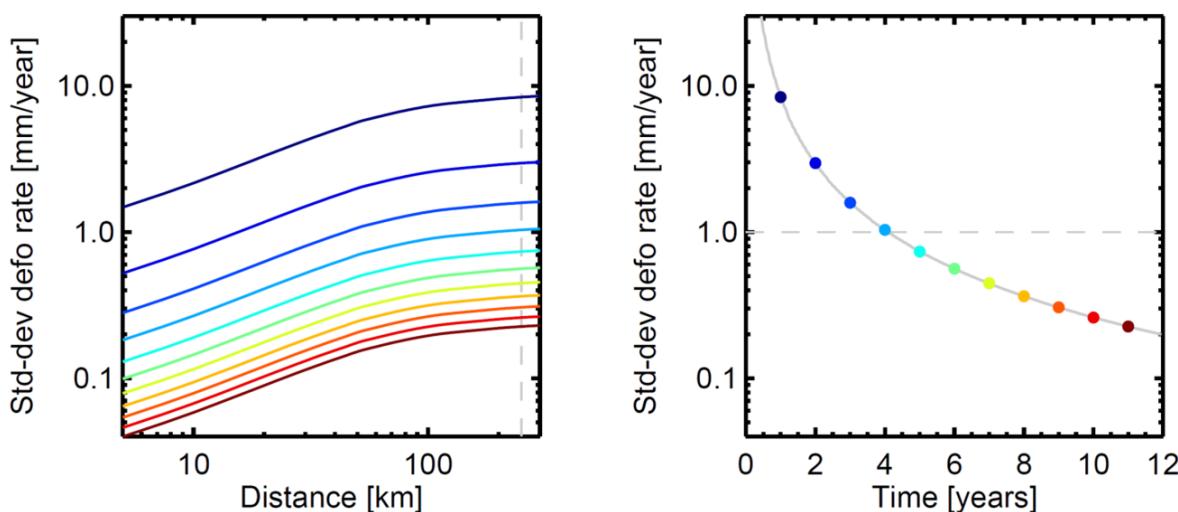


Figure G-4 Deformation Rate error variograms performing tropospheric corrections. On the left the error variograms of the deformation rate estimation varying the observation time. On the right the accuracy at 250 km varying the observation time

In Figure G-3 and Figure the performance improvement is shown in terms of how many years of regular Sentinel acquisitions are needed in order to achieve 1 mm/y accuracy at 250 km distance assuming 12 days regular revisit.

The required time span drops from 7 years to 4 years. In order to summarise the results of Figure G-3 and Figure , Table G-2 has been compiled showing the derived accuracy for medium and large scale.

A possible description of the requirements for Level 2A can be provided in terms of:

- Minimum: derived from the expected performance of DInSAR without any corrections.
- Goal: derived from the expected performance of DInSAR after tropospheric (NWP) Solid Earth Tides (model) and Ionospheric (model) corrections.

Table G-2 Resume of possible accuracy requirements for the Level 2A products

$T_{obs}$ [y]	MEDIUM SCALE <i>50 km</i>		LARGE SCALE <i>250 km</i>	
	MINIMUM [mm/y]	GOAL [mm/y]	MINIMUM [mm/y]	GOAL [mm/y]
1	8	6	20	8
2	3	2	7	3
4	<1	<1	3	1
5	<1	<1	2	<1
7	<1	<1	1	<1

### 12.3. Geolocalisation

The geolocation procedure involves projection of the selected PS/DS in a geographic or cartographic system. The geolocation step needs the following input data:

- Orbital data of the coregistration master image;
- Digital elevation model (DEM) used for flattening procedure in the differential interferograms generation;
- PS/DS height correction estimated during the PSI/DSI procedure;
- [Optional]: PS range and azimuth sub-pixel position;
- [Optional]: external data for “absolute” localisation (i.e. optical image, ground control points or similar cartography).

The use of the height correction measurements for the geolocation of the PS/DS allows to better identify them on the corresponding structures on the ground (Figure G-5).



Figure G-5: Comparison between the PSs geolocated by using the input DEM, SRTM in this example (red dots) and the PSs geolocated by using the height corrections (green dots), over two urban areas in Naples city. Sentinel-1 data were the input for the PS analysis.

Several error sources affect the geolocation:

- The orbital data precision;
- Timing (range and azimuth);
- PS/DS estimated height correction (elevation accuracy);
- PS range and azimuth sub-pixel determination;

Usually, PSI/DSI processing is able to recover systematic large-scale errors due to orbital data accuracy and timing errors. In addition, absolute localisation can be obtained exploiting external ortho-rectified VHR optical data. In the following, only the two last points are considered.

From a theoretical point of view, by considering the error source contributions as independent, with zero-mean value and not affected by systematic errors (estimated and removed during the PSI/DSI processing), the elevation error can be evaluated as the sum of contributions from:

- the interferometric phase noise;
- point to point timing accuracy (sampling jitter, etc.);
- sub-pixel residual error.

The contribution to the geolocation error due to the interferometric phase noise can be obtained considering a physical model of the interferometric phase. As a first-order approximation, the interferometric phase can be expressed as a function of the displacement mean velocity  $v$  and of the correction of the target height (with respect to an input reference DEM)  $h$  as follows:

$$\phi_k = \frac{4\pi}{\lambda} \left( \frac{1}{r \sin(\theta)} B_k h + t_k v \right) \quad k = 0, \dots, N-1$$

where  $B_k$  is the k-th spatial orthogonal baseline,  $t_k$  is the k-th acquisition time,  $r$  is the sensor-target distance,  $\vartheta$  is the incidence angle and  $N$  is the number of acquisitions. The values of  $v$  and  $h$  can be obtained through a linear regression and therefore, the corresponding height correction estimation error is given by:

$$\sigma_{h,phase}^2 = \frac{1}{(1-\rho^2)} \left( \frac{\lambda}{4\pi} r \sin \theta \right)^2 \frac{1}{\sum_k \frac{B_k^2}{\sigma_{\phi_k}^2}}$$

where  $\rho$  is the correlation coefficient of the times and baselines vectors and  $\sigma_{(\phi_k)}$  is the phase noise associated to the k-th acquisition date. Assuming baseline vector uniformly distributed and independent from time vector ( $\rho=0$ ), the phase noise constant for each acquisition date ( $\sigma_{(\phi_k)}=\sigma_\phi$ ) and  $N \gg 1$  the previous equation can be simplified in the following expression:

$$\sigma_{h,phase}^2 = \left( \frac{\lambda}{4\pi} r \sin \theta \right)^2 \frac{12}{N} \frac{\sigma_\phi^2}{B_{\max}^2} \quad [1]$$

The second contribution to the elevation error is due to the timing accuracy and is given by the following expression:

$$\sigma_{h,timing}^2 = \cos^2 \theta \left( \frac{c}{2} \right)^2 \sigma_t^2$$

where  $\sigma_t$  is the standard deviation of the sampling jitter and  $\vartheta$  is the incidence angle.

The last contribution is due to the fact that the position of the main scatterer inside the image resolution cell is not known and is given by:

$$\sigma_{h,resolution}^2 = \cos^2 \theta \left( \frac{\delta r^2}{12} \right)$$

where  $\delta r$  is the slant range residual error estimation.

The complete formula of the elevation error variance is given by:

$$\sigma_h^2 = \frac{12}{N} \left( \frac{\lambda r \sin \theta}{B_{\max} 4\pi} \right)^2 \sigma_{\phi_k}^2 + \cos^2 \theta \left( \frac{c^2}{4} \sigma_t^2 + \frac{1}{12} \delta r^2 \right) \quad [2]$$

In the following, a qualitative and quantitative analyses of the elevation error will be performed using the results of the PSI analysis of Sentinel-1 SAR data, acquired over the Campi Flegrei area. The results obtained by the quantitative analysis will be successively compared with those ones obtained by using the theoretical expression of the elevation error standard deviation for deriving the preliminary specification for the geolocation accuracy of PS/DS derived from Sentinel-1 data.

As shown in Figure G-5, the selected PS geolocated using only a low-resolution DEM (red dots) is less accurate with respect to the same PSs geolocated after the DEM height correction obtained through the

PSI analysis of 28 images acquired over the Campi Flegrei area. The PSs 3D position is very inaccurate when only the DEM height values are used: it is not clearly identifiable the correspondence between structures and PSs. The 3D position accuracy improves using the estimated height corrections; the PSs in the pictures on the right side of Figure G-5 are better positioned over the corresponding buildings.

The same interferometric PSI results have been used to quantitatively evaluate the Sentinel-1 PS elevation error by estimating the  $\sigma_h$  value from the real data. Some flat roofs have been identified and the standard deviation of the heights of the PS selected over these roofs has been calculated. Since the height of the PSs located over these flat structures should be constant, the measured elevation standard deviation can be used as a reliable estimation of the PS elevation error. The following images show two examples of the structures used for the elevation error estimation. The measured elevation standard deviation ranges from a minimum of about 4.3 meters to a maximum of about 6.0 meters.

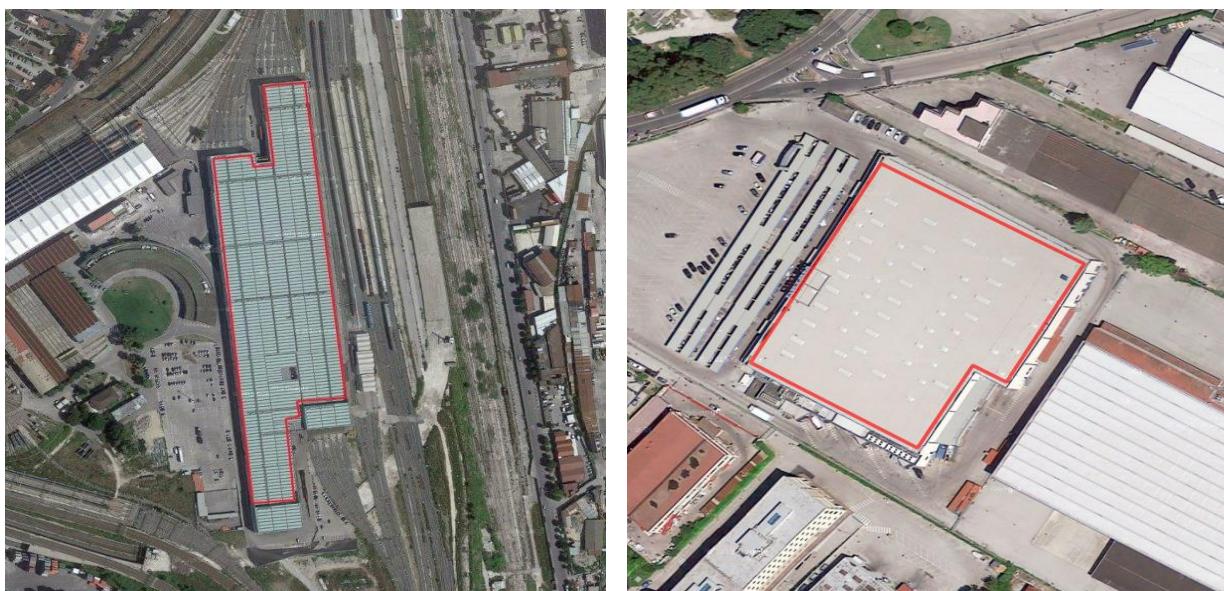


Figure G-6: Two examples of the structures used for the elevation error estimation.

The following table summarizes the performed statistical analysis results and shows that the theoretical and measured elevation error values are comparable.

Table G-3. Statistical analysis of theoretical and measured elevation error.

Satellite	Theoretical Elevation error [m]	Measured elevation error [m]
Sentinel-1	4.6	4.3 – 6.0

As shown in the formula [ 1 ], the height correction error is inversely proportional to the maximum spatial baseline of the interferometric SAR data stack. In addition, the baseline value affects the interferometric phase error because of the spatial decorrelation: the higher spatial baseline the higher is the phase error, even if the lower is the height correction error. When the baseline value reaches a critical value (critical baseline) the interferometric phase signal is not correlated. A parameter that is linked to the signal

decorrelation is the spatial coherence associated to a differential interferogram. Considering only the spatial decorrelation, the coherence  $\gamma$  can be derived from:

$$\gamma = \gamma_0 \cdot \gamma_{bas} \cdot \gamma_{volume} = \gamma_0 \cdot \left(1 - \frac{B}{B_c}\right)$$

where  $B_c$  is the critical baseline and  $B$  is the spatial baseline of the interferometric SAR image pair. The critical baseline is given by:

$$B_c = \frac{\lambda \cdot r \cdot \tan \theta}{2 \cdot (\delta r + \delta p)}$$

where  $\delta r$  is the size of the scattering surface in the slant range direction and  $\delta p$  is the penetration (volume scattering) in the slant range direction. A point-like scatterer has not spatial decorrelation. The link existing between coherence and interferometric phase noise is shown in the following figure.

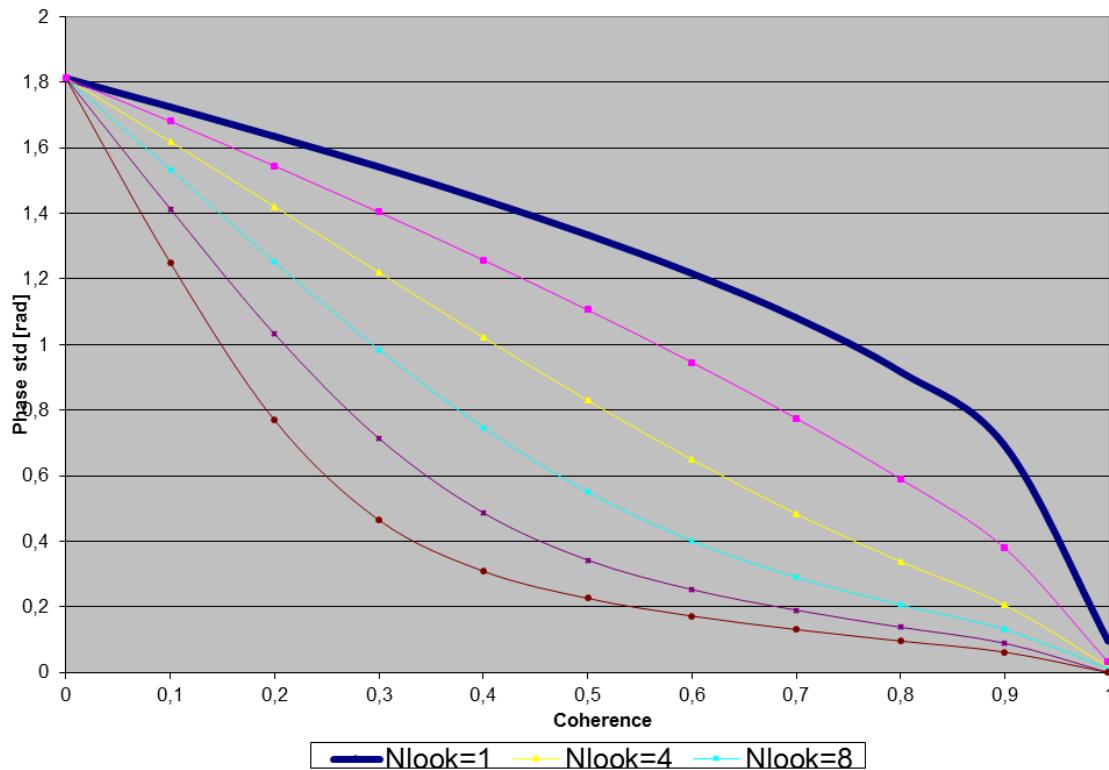


Figure G-7: Phase noise in function of the coherence and for different values of look number.

From the previous consideration and relations, it is possible to evaluate the deformation and elevation error variation in function of the baseline value (see the three following graphs: Figure G-8, Figure G-9 and Figure G-10). These variations (of elevation and deformation errors) had been evaluated using three different values of  $\gamma_0$ . In particular, the value of  $\gamma_0$  equal to 0.92 (corresponding to the green lines) is that one that better agrees with the results obtained by the previously presented analyses on the

elevation and deformation errors. The first graph shows the elevation and deformation error sensitivity to the baseline in the case of point-like scattering. Of course, the phase noise in this case does not depend on the baseline, and a larger baseline would improve the 3D localisation capability without an increase of phase noise. The second graph shows the same relation in the case of fully distributed scattering. Even for fully distributed scattering (5 m ground resolution), a larger baseline can improve the 3D localisation capability. Finally, the third graph shows the deformation and elevation error variation in function of the baseline value, in the case of distributed (5 m ground resolution) scattering with a slant range penetration of about 0.5 meter. This graph shows that also when the volumetric scattering is considered, the sensitivity of the phase noise to the baseline values does not increase in a significant way.

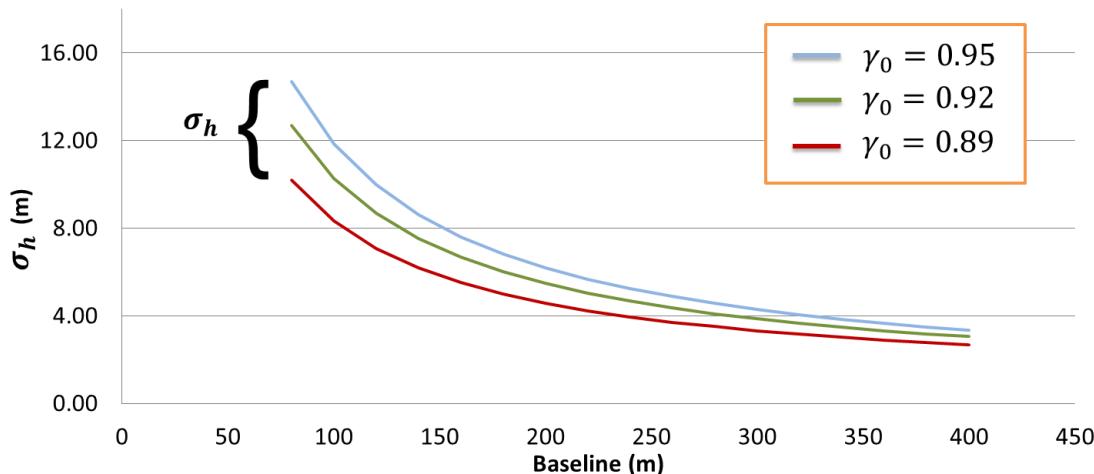


Figure G-8: Elevation error sensitivity to the baseline: point like scattering.

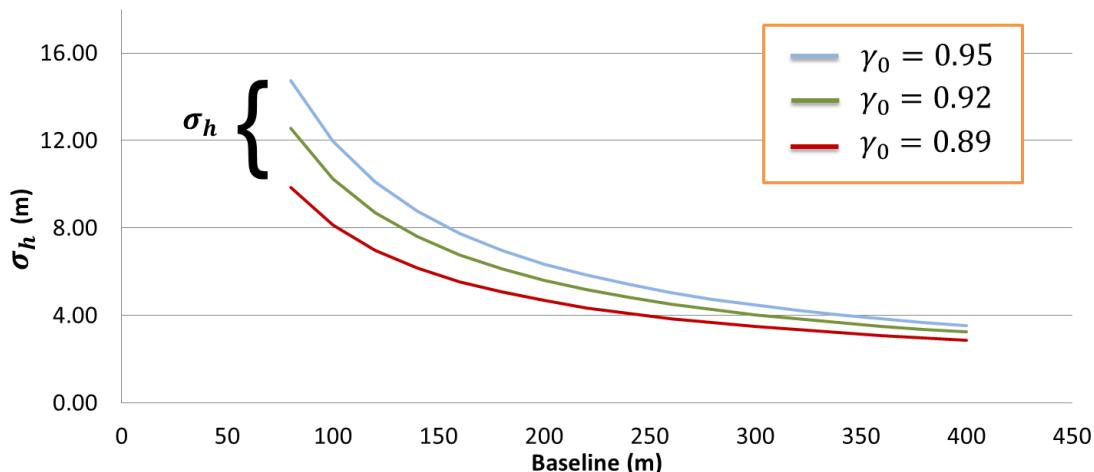


Figure G-9: Elevation error sensitivity to baseline: fully distributed scattering (5 m ground resolution).

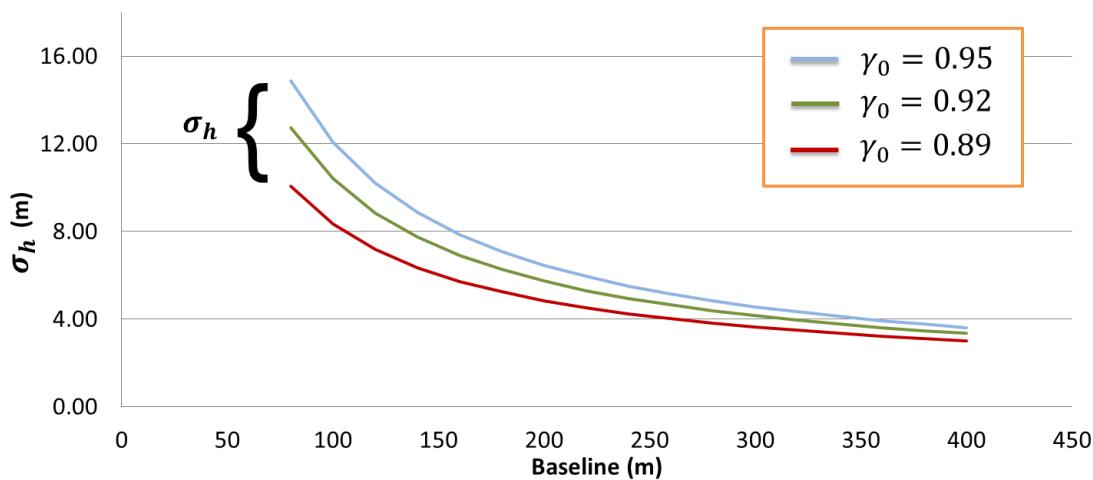


Figure G-10: Elevation error sensitivity to the baseline: distributed (5 m ground resolution) and volumetric (0.5 m of slant range penetration) scattering.

The previous analysis was carried out with a relatively short data stack ( $N=28$ ). Note from equation [2] that the first (and dominant) error term depends on  $1/N$ , such that the standard deviation of the overall height estimate slowly decreases. Table G-4 shows the best-case height estimation error for Sentinel-1 for different PS quality (temporal coherence) and number of images in stack.

Table G-4. Localisation error of Sentinel-1 PS as a function of PS temporal coherence and number of available images.

PS quality (temporal coherence)	PS height standard deviation [m]			
	N=100	N=160	N=220	N=280
0.60	4.7	3.7	3.1	2.8
0.80	3.1	2.4	2.1	1.8
0.95	1.5	1.2	1.0	0.9

### 12.3.1. Azimuth localisation error

Note that the azimuth PS localisation error due to subpixel position is not possible to estimate from the phase data in the Sentinel-1 case due to the very precise burst synchronisation, which implies almost no doppler differences from pass to pass. Thus, unless there is a clear amplitude peak within the pixel that can be found by oversampling, the standard deviation of the localisation error in azimuth is about  $1/\sqrt{12}$  of the azimuth pixel spacing, assuming uniform distribution of the azimuth position of the scattering phase center within the pixel. For Sentinel-1 IW mode, this corresponds to about 4 meters.

### 12.3.2. Ground range localisation error

The ground range localisation error has two terms; the first is due to PS height error, already discussed in depth above. The second term is due to unknown PS phase center position within the pixel. As for the azimuth localisation error, this can be mitigated by oversampling only for point-like targets of dimension less than the pixel dimension. In this case, this error term is negligible ( $<0.2\text{m}$ ), while in the opposite case, the error term is  $1/\sqrt{12}$  of the ground range pixel spacing. For Sentinel-1, this corresponds to about 1.5 meter standard deviation.

### 12.3.3. Geolocalisation requirement for EGMS products

The overall 3D geolocalisation depends on the quality of the PS and the length of the interferometric stack. As a worst-case scenario, we consider the following

- We have available a 5-year long stack (2015-2019).
- The stack has only  $N=200$  available images due to various issues in the S1 observation scenario, in particular the first couple of years.
- At northern latitudes and high altitude, only half of these images may be snow free.
- We assume a PS with temporal coherence = 0.7, a typical threshold for PS selection.
- The pixel containing the PS does not have a clear amplitude peak

In this case the standard deviation of the localisation error in 3D is about **7-8 m**.

As a best-case scenario, we consider the following

- We have available a 5-year long stack (2015-2019).
- The stack has almost all acquisitions available ( $N=300$ ), under snow free conditions.
- We assume a PS with temporal coherence = 0.9, a typical quality found in urban environments.
- The PS is pointlike with small dimension, thus the pixel containing the PS has a clear amplitude peak that can be found by oversampling

In this case, the standard deviation of the localisation error in 3D is about **1.5 m**.

The presence of non-linear motion will tend to increase the achievable accuracy. Thus, for EGMS products, it is thus useful to put a worst-case requirement for the standard deviation of the 3D localisation error at about 10 m.

## 12.4. References

[Cong2014] Cong, Xiaoying. *SAR interferometry for volcano monitoring: 3D-PSI analysis and mitigation of atmospheric refractivity*. Diss. Technische Universität München, 2014.

[Cong2018] Cong, Xiaoying, et al. "Mitigation of Tropospheric Delay in SAR and InSAR Using NWP Data: Its Validation and Application Examples." *Remote Sensing* 10.10 (2018): 1515.

[Rodriguez2018] F. Rodriguez Gonzalez, A. Parizzi and R. Brcic, "Evaluating the impact of geodetic corrections on interferometric deformation measurements," EUSAR 2018; 12th European Conference on Synthetic Aperture Radar, Aachen, Germany, 2018, pp. 1-5

## 13. APPENDIX H: LARGE SCALE CAPACITY EXAMPLES

This Appendix includes production capacity calculations for specific large-scale production experiments. The production capacity recommendations for the EGMS (section 3.4.3) are partially based on numbers from these examples.

### 13.1. Full resolution PS analysis: the Norwegian ground motion service

The Norwegian ground motion service ([insar.ngu.no](http://insar.ngu.no)) is currently based on a PS only workflow for Sentinel-1 data, updated every 12 months. The production is run on a dedicated cluster consisting of 19 high-performance processing nodes with the following characteristics:

- 14 physical CPUs (=28 vCPUs)
- 512 GB RAM
- Fast access to large storage system (2 PB)

The following preprocessing steps are applied continuously:

- Data retrieval
- Coregistration to master scene
- Full-resolution single master interferogram generation

Apart from storage, the resources needed to do this are relatively small, and is handled by a single processing node as a nightly routine job that typically finishes in a couple of hours or less for the entire Norwegian territory.

The production cycle is currently run once per year after the snow free season ends (~Nov 1). Assuming that full-resolution single-master interferogram stacks are already available, the production cycle has the following average performance characteristics per processing unit per vCPU:

- InSAR data ingestion: 5 min (given full utilisation of system I/O)
- Primary network identification: 5 min
- APS estimation and removal based on primary network: 10 min
- Deformation mode estimation for all pixels, except apriori mask (low SNR, layover, shadow, water bodies): 50 min
- Time series analysis and L2a product generation: 10 min
- Total: 80 min per processing unit per vCPU

The main production had the following characteristics for L2a production using all data covering mainland Norway:

- ~25,000 processing units including some redundancy in the form of overlap
- 6 processing nodes used = 168 parallel jobs
- Total production time: 6.5 days
- Total number input SLC products (excluding winter scenes): ~8,000

- Total number of PS candidates processed: 50 billion
- Total number of identified PS points: 3.5 billion

## 13.2. Low-resolution DS analysis

This section is aimed at describing the performance, in terms of elapsed computing time, of the Cloud Computing (CC) implementation of an SBAS-based processing chain [Manunta2019].

### 13.2.1. Full Italian territory, processed using Amazon Web Services

This section reports on the tests carried out within the Amazon Web Services (AWS) to process the Italian territory. No specific characteristics of the exploited CC environment (i.e., vendor-specific solutions) have been used, apart the Simple Storage Service (S3) use, making the proposed experiment valid in general.

In order to exploit the AWS resources for the SBAS processing, the following setup was used:

- S1 IW data archive located on the S3 of AWS, which is a long-term storage having a theoretically infinite network bandwidth in connection to the computing nodes of the AWS Elastic Compute Cloud (EC2). This archive consists of S1 IW SLC images over Italy, and is maintained and updated. The main constraint is to exploit a catalogue of data that is close (i.e., accessible with dedicated/fast connection) to the computing nodes. The S3 solution of AWS, is similar to the one offered by DIAS, and in principle to any other network storage;
- An automatic processing chain for all SBAS steps, including upload of interferometric results to the long-term storage for preservation.
- As a reference for the evaluation of the elapsed processing times we selected a S1 IW frame, covering the Bay of Naples and the area up to the city of Rome:
  - The mapped area extends for approximately 250 x 250 km<sup>2</sup>, dataset consists of 160 S1 IW SLC products, from March 2015 and April 2017 for a total of 67 scenes. The total number of bursts to be processed is 2624, and the number of generated interferograms is 381. As a consequence, the size of the input dataset is of about 1.2 TB, whereas the storage required for the entire processing (including the intermediate and final products generation) is 3.7 TB.

The elapsed time needed to transfer the S1 IW input data from the S3 AWS archive to the EC2 instance was of approximately 1 hour. Time for the overall SBAS processing was approximately 24.9 hours. The upload of the final SBAS results to the S3 storage took just a few minutes. The overall processing took less than 30 hours to run.

For further details, please refer to [Zinno2018, Manunta2019].

### 13.2.2. Full coverage of Europe using Onda DIAS

In order to test the performances and capabilities offered by the DIAS infrastructures, a processing experiment at European scale has been carried out by ONDA-DIAS using the SBAS technique. The processing exploited the entire available Sentinel-1 data set collected between March 2015 and September 2018 from descending orbits over large part of the continental Europe. The infrastructure used

to perform the processing was composed by 6 nodes, each one equipped with 64 virtual CPUs, 512 GB RAM and 20 TB internal storage.

The S1 Input data are archived on a storage connected to the computing nodes via NFS with an actual average transfer speed of 2Gb/s for data query and download the specific API made available by ONDA was used. The S1 input data are accessed and unpacked in parallel, then the entire input dataset is transferred to the computing nodes internal disks and processed. For archiving and long-term storage, ONDA makes available an object storage with enough archiving capacity directly connected to the computing nodes on which the data upload is managed through python-based commands.

The experiment lasted 24 weeks. The main characteristics were:

- Number SBAS processing flows: 180
- Exploited S1 data: ~85,000
- Average S1 data per single stack: 150
- Covered Area: ~5.700.000 km<sup>2</sup>
- Observed multilook pixels: ~120,000,000
- Final product pixel size: ~80 m
- Time elapsed: ~6 months

Accordingly, the final experiment assessment can be summarized as follows:

- Data availability: all requested data available
- SLC download speed (average): 2 Gb/s
- Average single stack elapsed processing time: 2.5 days

DIAS experiment was slower than the corresponding AWS experiment, due to the different amount of exploited data per stack and partially to network and disk speed restrictions.

### 13.3. References

[Manunta2019] Manunta, M., De Luca, C., Zinno, I., Casu, F., Manzo, M., Bonano, M., Fusco, A., Pepe, A., Onorato, G., Berardino, P., De Martino, P., and Lanari, R., The Parallel SBAS Approach for Sentinel-1 Interferometric Wide Swath Deformation Time-Series Generation: Algorithm Description and Products Quality Assessment. IEEE Transactions on Geoscience and Remote Sensing, 2019, 57, 6259-6281

[Zinno2018] I. Zinno et al., “National scale surface deformation time series generation through advanced DInSAR processing of sentinel-1 data within a cloud computing environment,” IEEE Trans. Big Data, doi: 10.1109/TB DATA.2018.2863558.