DEFORMATION MONITORING AT EUROPEAN SCALE: THE COPERNICUS GROUND MOTION SERVICE

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ABSTRACT:

The Advanced Differential Interferometric SAR (A-DInSAR) technique is a class of powerful techniques to monitor ground motion. In the last two decades, the A-DInSAR technique has undergone an important development in terms of processing algorithms and the capability to monitor wide areas. This has been accompanied by an important increase of the Synthetic Aperture Radar (SAR) data acquisition capability by spaceborne sensors. An important step forward was the launch of the Copernicus Sentinel-1 constellation. The development of A-DInSAR based ground deformation services is now technically feasible. This paper describes some of the most important features of A-DInSAR. Then, it describes the European Ground Motion Service (EGMS), part of the Copernicus Land Monitoring Service, which represents a unique initiative for performing ground deformation monitoring on a European scale.

1. INTRODUCTION

This paper is focused on deformation monitoring at European scale, and in particular the development of a new service part of the Copernicus Land Monitoring Service: the European Ground Motion Service (EGMS), see EGMS (2021). The technique used to derive the EGMS is the Advanced Differential Interferometric Synthetic Aperture Radar (A-DInSAR) technique, see for a review Crosetto et al. (2016), which is an advanced version of the DInSAR technique.

The DInSAR technique makes use of at least two Synthetic Aperture Radar (SAR) images acquired over the same area in different times, exploiting the interferometric phase, i.e. the difference of the phases contained in the two SAR images. The interferometric phase is related to the topography of the observed scene and to the ground deformation occurred in the period between two image acquisition times. The topographic component is usually removed using a Digital Elevation Model (DEM) of the scene. DInSAR has been successfully used in several fields, e.g. seismology (Peltzer and Rosen, 1995), volcanology (Massonnet and Sigmundsson, 2000; Antonielli et al. 2014), glaciology (Rignot et al., 1997), landslides (García-Davalillo et al., 2014), ground subsidence and uplift (Amelung et al., 1999), etc. Several examples of DInSAR applications are reviewed in Massonnet and Feigl (1998) and Hanssen (2001).

Compared to classical DInSAR techniques, the A-DInSAR techniques provide advanced monitoring capabilities. This is basically due to the exploitation of large stacks of SAR images acquired over the same area, and the use of advanced data processing, modelling and analysis tools.

Several radar satellites provide SAR observations at global scale, e.g. Sentinel-1, TerraSAR-X, CosmoSkyMed, etc. That is to say, the primary data acquisition potentially covers the entire globe. However, especially in the first decade after the introduction of the A-DInSAR technique, the deformation monitoring has been mainly focused on localized areas. As described in the following section, the A-DInSAR techniques have undergone important development in the last years, and now the monitoring over wide areas is technically feasible.

This paper briefly outlines the most important factors that have made possible the A-DInSAR deformation monitoring over wide areas (Section 2). This is followed by a discussion of the key characteristics of A-DInSAR (Section 3). The Section 4 describes the key features of the European Ground Motion Service. A more in-depth description of the EGMS can be found in Crosetto et al. (2020).

2. ADVANCED DINSAR

The A-DInSAR technique was proposed for the first time by Ferretti et al. (2000), with the name of Permanent Scatterer Interferometry. Since then, the technique has undergone a huge development. The result is that now A-DInSAR data processing and analysis over very wide areas, and using large stacks of images, is technically feasible. This is due to three key factors.

The first key factor is the availability of satellite-based SAR data. There are currently several active spaceborne SAR systems working at medium and very high resolution. The most important system, from the viewpoint of this paper, is certainly

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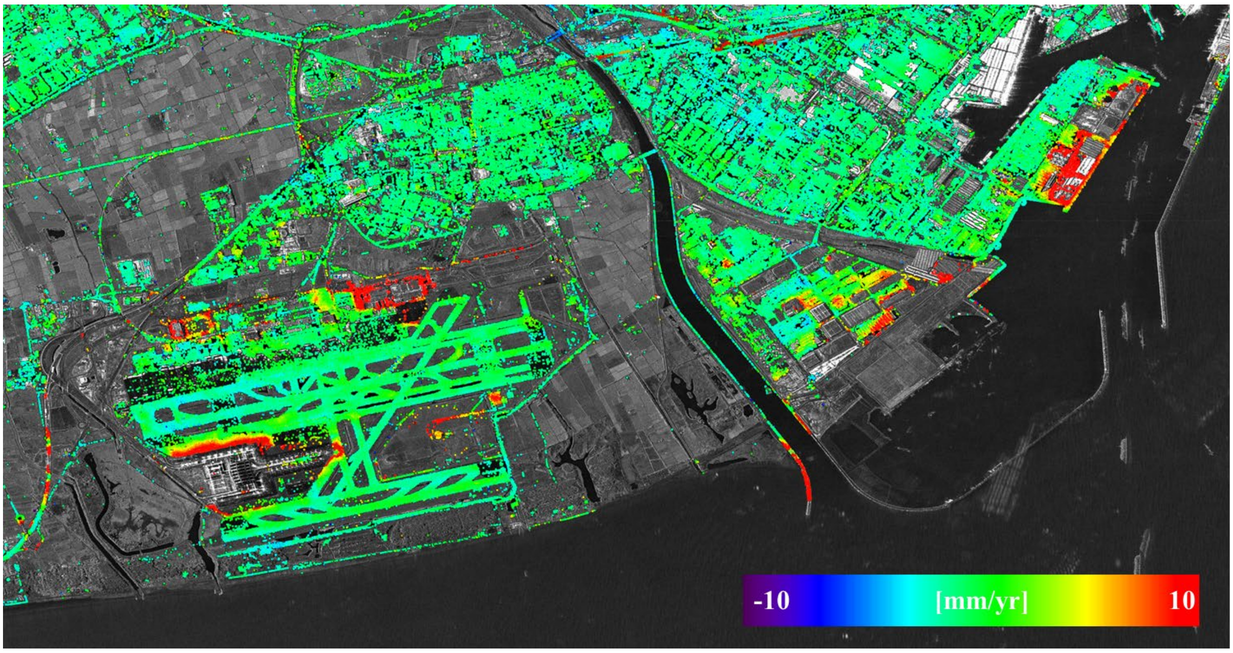

Figure 1: Example of A-DInSAR result (deformation velocity). The measurement points are mainly concentrated over structures and infrastructures, while over the vegetated area the coverage is very limited.

the European Commission's Sentinel-1 constellation part of the Copernicus Programme, which includes two operational SAR sensors: Sentinel-1A and Sentinel-1B. This constellation offers a wide area coverage (an Interferometric Wide Single Look Complex Sentinel-1 scene covers approximately 250 x 180 km) and a frequent revisiting time (6 days for any spot in Europe). In addition, Sentinel-1 data, like the entire Copernicus Programme, is supported by an open data policy. Since the launch of Sentinel-1A, in April 2014, Sentinel-1 is building up a valuable stack of SAR observations. In addition to the existing SAR systems, it is worth mentioning that there are huge historical archives of SAR images that cover more than thirty years (ERS-1 started its acquisition in 1991). This enables the study of past deformation phenomena.

The second key factor is given by the advances and improvements of the A-DInSAR data processing and analysis techniques. All the aspects of the A-DInSAR processing have been investigated and improved, see for a review Crosetto et al. (2016). Just to mention the most relevant, advances have concerned the selection of the measurement points (persistent scatterers vs. distributed scatterers), the phase unwrapping, the separation of the deformation and the atmospheric components, the modelling of the time evolution of the deformation, etc.

The third key factor is the huge increase of the computation capacity. Note that this capability has been always a major limitation for the exploitation of the SAR imagery acquired by the spaceborne systems. In fact, the data acquisition capability has always largely exceeded the data processing capacity: only a fraction of the acquired data is usually exploited. This is going to change. From one side, the available computational resources have notably increased in the last decade, and their cost has drastically reduced. From the other side, in the last years, several groups have focused their attention on advanced computational resources, like A-DInSAR parallel computing, cloud computing, and the use of distributed computing architectures, e.g. see Zinno et al. (2015) and De Luca et al. (2017).

3. A-DINSAR: KEY TECHNICAL ASPECTS

In this section we briefly discuss some technical aspects of the A-DInSAR techniques.

The first aspect is the spatial sampling of measurements. The SAR systems perform a 2D regular sampling of the terrain and the SAR imagery has a raster structure with azimuth and slant range coordinates. By contrast, the spatial sampling performed by A-DInSAR is spatially uneven: instead of having a raster structure it has a vector structure. This is because A-DInSAR can only estimate the deformation over the pixels that have sufficiently small phase noise. It is worth noting that such pixels are usually not known before performing the A-DInSAR analysis. The measurement density is typically low over vegetated and forest areas, and over smooth surfaces, etc.

The original Permanent Scatterer technique (Ferretti et al., 2000 and 2001) is based on the Persistent Scatterers (PS) that are point-like targets that dominate the response of a given pixel and that maintain a stable response to the SAR signal over time. The PSs are usually concentrated in urban and industrial areas, over structures, antennas, poles, etc., and over exposed rocks. There is another class of measurement points: Distributed Scatterers (DS). The DSs correspond to a set of scatterers that belong to the same pixels. Each of these scatterers has a rather weak response to the microwaves. However, if they are exploited collectively, they can provide a sufficient phase quality to estimate the deformation (Ferretti et al., 2011). The DSs can be found for instance in non-cultivated lands, desert areas, scattered outcrops, debris-covered areas, etc. The first A-DInSAR techniques were only focused on PSs or DSs. Now there are several approaches that exploit both PSs and DSs, thus providing and enhanced spatial density of deformation measurements.

The second aspect concerns the deformation measurement products. The A-DInSAR analysis produces two main types of products. As mentioned above, both are vector products. They contain deformation information that it is typically referred to a given reference point. That is to say, the deformation is not provided in absolute terms: it is relative information. The first product is the deformation velocity. It contains, for each measurement point (PS or DS), the deformation velocity estimated over the observed period, i.e. the period included between the first and the last SAR image acquisition. The A-DInSAR techniques usually employ N images to sample the observation period: usually N is at least equal or greater than 15 or 20 images. Each image corresponds to an observation. The deformation velocity is a single parameter that is estimated using N observations. For this reason, it is more precise and robust than the deformation contained in the second product. This second product contains, for each measurement point, the entire history of the deformation over the observed period. The time series contain N temporal samples, with one deformation estimate in correspondence to each SAR acquisition date. The deformation time series provide a rich information, which is useful to study the time history of the observed targets.

The third aspect concerns the product 3D location. For any deformation measurement system, it is fundamental to know the 3D position of the measured targets. In the A-DInSAR technique the 3D positioning is achieved using the 2D information contained in the SAR imagery, plus the so-called topographic error, which is estimated for each measurement point. The topographic error is the height of a given measurement point with respect to the Digital Elevation Model that is employed in the A-DInSAR processing. For Sentinel-1, the achieved 3D position has typically an uncertainty of several meters (Larsen et al., 2020). This is directly related to the so-called orbital tube that characterizes each SAR system. It is interesting to know that the uncertainty associated with the 3D positioning is approximately three orders of magnitude larger than the uncertainty of the deformation estimates, which is a small fraction of the SAR wavelength (55.4 mm in the case of Sentinel-1).

The fourth aspect concerns the observable deformation rates. The quality of the A-DInSAR product is directly influenced by the ambiguous nature of the A-DInSAR observations, i.e. the interferometric phases. For instance, this influences the maximum (differential) observable deformation rate. In case of Sentinel-1, this rate corresponds to $\lambda/4$ every 6 days, where λ is the SAR wavelength; this corresponds to a rate of 85.2 cm/yr. It is important to underline that the above limit concerns differential rates, i.e. the difference of rates between pairs of measurement points. This means that the capability to measure a given deformation phenomenon mainly depends on its spatial extent and pattern, and on the available density of measurement points. In any case, it is worth noting that A-DInSAR suffers limitations in the capability to measure fast deformation phenomena, e.g. over different types of active mines.

The fifth aspect is related to the adopted deformation modelling. Due to the ambiguous nature of the interferometric phases, in the A-DInSAR processing it is necessary to make assumptions regarding the temporal evolution of the deformation of a given measurement point. Many A-DInSAR approaches simply assume a linear deformation model. This aspect has a direct impact on the quality of the deformation time series. In fact, the linear model assumption can negatively impact the estimation of deformation phenomena that have a "non-linear" behaviour. A consequence of this fact is the lack of measurement points in the non-linear motion areas, where there a misfit between the assumed model and the actual deformation. It is worth observing that one of the most popular quality indices of A-DInSAR, the temporal coherence, is referred to the linear deformation model. To conclude, it is important to mention that some A-DInSAR approaches are model-free, i.e. they do not use a linear deformation model, e.g. see (Berardino et al., 2002; Devanthéry et al., 2014).

A sixth aspect concerns the 1D nature of deformation measurements. The A-DInSAR technique measures the deformations along the radar line-of-sight (LOS), that is the line that connects the SAR sensor and the target at hand. This is an important limitation of the technique. In fact, given a generic 3D deformation, the A-DInSAR detects and measures only a 1D component of such deformation. This component is obtained by projecting the given 3D deformation into the LOS direction. This limitation can be partially overcome by using two opposite views of the same area. This occurs when ascending (an acquisition taken when the sensor moves from the South pole towards the North pole) and descending (an acquisition taken when the sensor moves from the North pole towards the South pole) SAR data are available. Using these data, it is possible to retrieve a 2D deformation estimation described by a vertical component and an East-West horizontal one, e.g. see Notti et al. (2014). This requires an independent processing of the ascending and descending datasets.

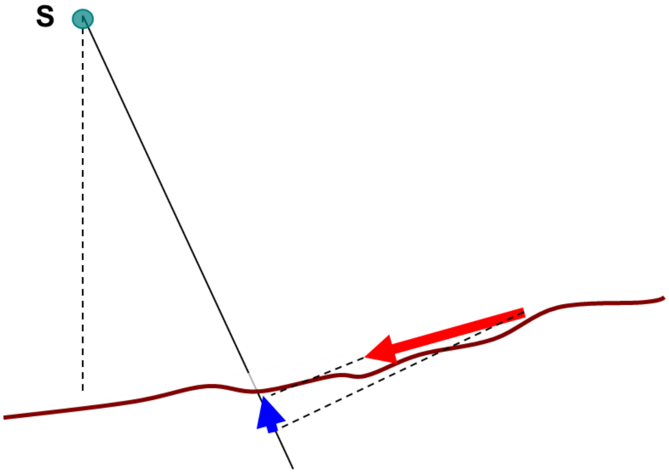

Figure 2: Scheme to illustrate the LOS geometry. The slope displacement (red arrow) is seen in the LOS direction as a displacement towards the satellite (blue arrow).

The seventh aspect concerns the low-frequency deformation signals. The A-DInSAR technique provides its best performances when measures localized deformation. By contrast, it is difficult to investigate low spatial frequency deformation signals. This typically occurs with phenomena whose extent exceeds several tens of kilometres. For instance, this occurs with deformation related to some tectonic motion or to the post-glacial rebound of Scandinavia. This is because the A-DInSAR low spatial frequency estimates are affected by uncompensated orbital errors or uncompensated low frequency atmospheric components that can mask the above signals. Any application focused on low spatial-frequency deformation signals should very carefully consider the above limitation. There are ways to overcome it: they require the fusion with external information, e.g. GNSS observations. Examples are described in Chen et al. (2010), Caro Cuenca et al. (2011) and Hanssen et al. (2012).

4. EUROPEAN GROUND MOTION SERVICE

As already mentioned earlier, the wide area A-DInSAR deformation monitoring is technically feasible. At national and regional level, this has been already demonstrated in several cases. The first Ground Motion Service (GMS) covered Italy (Costantini et al., 2017). In 2018, this was followed by Norway, with a GMS based on Sentinel-1 data. Germany launched its GMS at the end of 2019, see Kalia et al. (2020). In Italy, three regions have already implemented a GMS focused on the early detection of abrupt motion changes (Raspini et al., 2018; Solari et al., 2019; Del Soldato et al., 2019). Other regions will follow soon (Comerci and Vittori, 2019). GMSs are operational in Denmark and The Netherlands as well. Other countries are discussing the need for such services.

In this section, we briefly describe the main characteristics of the EGMS. The EGMS is part of the Copernicus Land Monitoring Service, which is implemented by the European Environment Agency (EEA). The fundamental characteristics of the service were defined by the EGMS Task Force and are described in the EGMS White Paper (EGMS Task Force, 2017). A specific working group was then commissioned by EEA in 2019 to further detail the technical specifications of the service (Larsen et al., 2020). In the following, we summarize some of the most important aspects of the EGMS.

The EGMS aims to provide consistent, updated, standardized, harmonized across national borders and reliable information regarding natural and anthropogenic ground motion phenomena over Europe. The ground motion will be estimated using full resolution Sentinel-1 SAR data. The service will use all the available acquisitions, coming from both ascending and descending passes. The EGMS will cover most of Europe, including all the Copernicus Participating States, see Figure 3.

The service will produce two types of deliverables. The first one, which is called baseline product, will be based of all images acquired from 2015 up to 2020. The second type of products will be a series of update products, delivered every 12 months. The processing will involve approximately 750 scenes. For the baseline product, on average 260 scenes will be available for each stack. For the regions affected by seasonal snow cover, the processing will be limited to the snow-free scenes.

The EGMS production is carried out by a consortium, "ORIGINAL - OpeRatIonal Ground motion INsar Alliance" composed of four companies, e-GEOS, TRE Altamira, NORCE, GAF, and five subcontractors. The processing will be split between different companies that will operate their own processing chains. The overlaps between adjacent scenes will be used to ensure seamless harmonization between chains.

The production of the baseline product is expected to be complete in the first quarter of 2022. Then, the service will be updated on an annual basis to guarantee its continuity over time. The EGMS will produce three main levels of products. The relation between the three products is illustrated in Figure 3:

- The first product is the Basic Product (Level 2a), which includes deformation velocity and deformation time series measured in the LOS direction. This product will be delivered by frames of the original 750 scenes. Each frame will have an independent reference point for the deformation measurements. This product will be suitable to study local deformation phenomena. This product will be generated using the Sentinel-1 imagery at full resolution.
- The second product is the Calibrated Product (Level 2b). This represents a more advanced product, where the frames of the previous product will be mosaicked and anchored to a reference network of GNSS stations. Like in the Level 2a, the deformation measurements will be in the LOS. This product relies on two key sources of information: A-DInSAR and GNSS data. The production will have to cope with the not homogeneous distribution over Europe of the available GNSS stations.
- The third product is the Ortho Product (Level 3). It offers a more advanced information: 2D deformation components, while the previous products only contain a 1D component. The two components are the horizontal East-West and Up-Down vertical ones. The input deformation map is Level 2b, using and fusing, for each location, the information coming from ascending and descending data. The drawback is that Level 3 will be obtained at a coarser resolution (100 by 100 m) with respect to the resolution of the Level 2a and 2b.

The production phase will include appropriate internal quality control and verification procedures. In addition, an external validation team will perform the independent validation of the products. The products will be disseminated using a dedicated web platform. The data will be free and open, following the Copernicus data policy. The service will provide tools for the visualization, the interactive data exploration, and the preliminary analysis of the products. There will be specific tools for expert and non-experts and a dedicated application programming interface (API). Different types of guidelines will be published. The user uptake will be facilitated through the organization of workshops and training sessions. It is expected to have a wide spectrum of users, including research centres and universities; geological, geophysical, geodetic and topographic surveys; civil protection authorities; public authorities (European, national, regional and municipal levels); road and railway administrations; water management authorities; cultural heritage institutions; mining industry; oil and gas industry; engineering companies; insurance industry; and the citizens.

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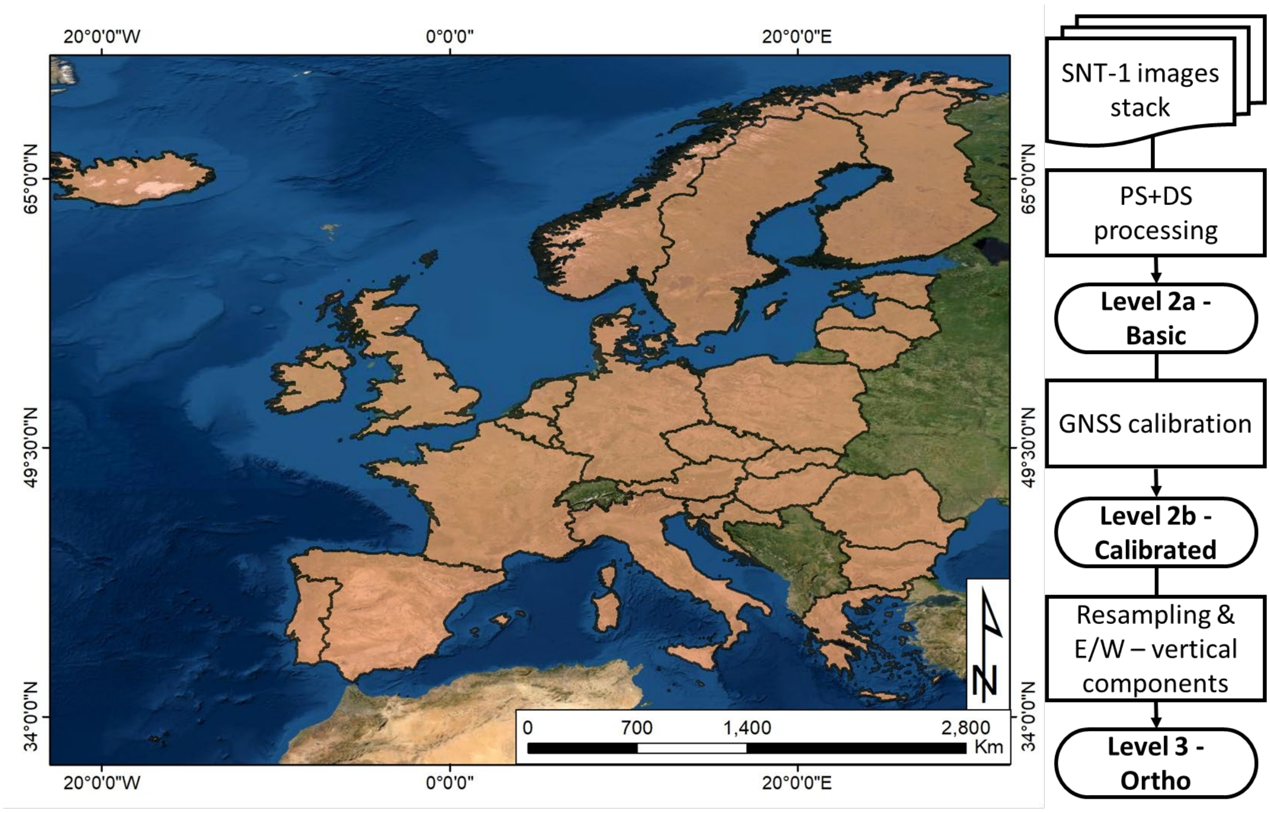

Figure 3: Left – EGMS coverage; the Azores and Madeira archipelagos, the Canary and Baleares islands, the French Overseas Departments and Regions are included. Right – Simplified flowchart of the EGMS production.

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