

Pan-European deformation monitoring: The European Ground Motion Service

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ABSTRACT

This paper describes the first results of the European Ground Motion Service (EGMS). The EGMS is part of the Copernicus Land Monitoring Service and represents a unique initiative for performing ground deformation monitoring at a European scale. This service makes use of Advanced Differential Interferometric SAR (A-DInSAR) techniques based on satellite Synthetic Aperture Radar (SAR) imagery. In particular, it exploits the Sentinel-1A/B SAR images of the Copernicus Programme, acquired over Europe. The paper briefly summarizes the main characteristics of the EGMS, describing different products of this Service. Then it presents some case studies extracted from the EGMS products. Examples of natural and human-induced geohazards are described.

I. INTRODUCTION

The Differential Interferometric SAR (DInSAR) technique exploits at least two SAR images acquired over the same area in different times to derive the interferometric phase, *i.e.* the difference of the phases contained in the two SAR images. The interferometric phase contains two components: one is related to the topography of the observed scene and the other one to the ground deformation occurred between the two image acquisition times. In DInSAR, the first component is usually removed using a Digital Elevation Model of the scene. In the last three decades DInSAR has been successfully used in several fields, especially in geophysics (seismology, volcanology, and glaciology) landslide, ground subsidence and uplift, 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 achieved by exploiting large stacks of SAR images acquired over the same area, and by using of advanced data processing, modelling and analysis tools (Crosetto *et al.*, 2016).

In the last decade, three different facts have remarkably increased the potential of the A-DInSAR techniques. The first fact is the improvement and reliability of the A-DInSAR data processing and analysis tools. The second fact is the availability of several SAR satellite missions. In the context of this paper, the most important SAR data sources are the twin satellites Sentinel-1A and Sentinel-1B. Finally, the third fact is the substantial boost in the data processing capabilities. Thanks to these facts, now the monitoring over wide

areas (*e.g.* country wise or beyond) is technically feasible.

This is exploited in the European Ground Motion Service, which is focused on deformation monitoring at European scale (Crosetto *et al.*, 2020). This is a new service, which is part of the Copernicus Land Monitoring Service managed by the European Environment Agency (EEA). The EGMS is based on A-DInSAR techniques.

This paper briefly describes the main characteristics of the European Ground Motion Service. A more in-depth description of the EGMS can be found in Crosetto *et al.* (2020). The second part of the paper presents some case studies based on the EGMS products. This includes examples of natural and human-induced geohazards.

II. THE EUROPEAN GROUND MOTION SERVICE

In the last years, the interest to implement wide area A-DInSAR deformation monitoring services over wide areas has increased. As mentioned earlier, the wide area monitoring is technically feasible. This has been already demonstrated in several international initiatives. Costantini *et al.* (2017) describe a Ground Motion Service (GMS) covering Italy; the service was based on ERS 1/2, ENVISAT and COSMO-SkyMed SAR images. In 2018, this was followed by Norway, with a GMS based on Sentinel-1 data. Germany launched its GMS at the end of 2019 (Kalia *et al.*, 2020). In Italy, the GMS have been implemented at regional level, *e.g.* see Del Soldato *et al.* (2019). Other initiatives are already operational, *e.g.* in Denmark and The Netherlands. Other countries are discussing the need for such services.

Taking advantage of the different GMS initiatives, a much more ambitious Service is now under implementations: the EGMS. It is part of the Copernicus Land Monitoring Service, and it is implemented by the European Environment Agency. The main features of EGMS are stated in the EGMS White Paper (EGMS Task Force, 2017). A more detailed definition of the Service is described in Larsen *et al.* (2020).

According to the White Paper, the EGMS must provide consistent, updated, standardized, harmonized across national borders and reliable information regarding natural and anthropogenic ground motion phenomena over Europe.

The products will be disseminated using a dedicated web platform. It is important to underline that the EGMS products will be free and open for everybody, following the Copernicus data policy. There will be a dedicated viewer and download interface for experienced and inexperienced users.

The ground motion is estimated using full resolution Sentinel-1 SAR and exploiting both ascending and descending passes. The EGMS covers most of Europe, including all the Copernicus Participating States. The Service includes two types of monitoring. The first one covers the period from 2015 up to the end of 2020. This is the so-called baseline product. The baseline product will be published in Q1 of 2022. For this product, on average 260 SAR scenes will be available. However, for the regions affected by seasonal snow cover, the processing will be limited to the snow-free scenes. Especially in North Europe this represents an important reduction of the available scenes. The baseline product will be followed by a series of updates, which will be delivered yearly.

The production of the baseline product is ongoing. It is carried out by a consortium ORIGINAL, "OpeRational Ground motion INsar ALLiance". This consortium includes four companies specialized in A-DInSAR (e-GEOS, TRE Altamira, NORCE, and GAF). Europe has been divided in four main areas. Each company processes one of these areas making use of its own A-DInSAR processing chain. There will be overlaps between the different areas that will be used to ensure seamless harmonization between the products.

The Service will deliver three types of products, which are briefly outlined below.

The first product type is called *Basic Product* or Level 2a. It is the classical A-DInSAR product, which includes deformation velocity and deformation time series. This will be delivered following the geometry of the frames of the Sentinel-1 scenes. All Europe is covered by approximately 750 Sentinel-1 scenes. The Basic Product will be generated using the Sentinel-1 imagery at full SAR resolution (approximately 4 by 14 m). The deformation estimates will be provided in the so-called Line-of-Sight direction (LoS), which is the line that connects the satellite and the given point on the ground. The deformations of the Basic Product will be

relative measurements that are referred to a reference point for each scene.

The second product is the so-called *Calibrated Product* or Level 2b. This is a more elaborated product, which requires as input the A-DInSAR data and data from a wide network of GNSS stations that cover the entire area of interest. In this case, the frames of the Basic Product are mosaicked to generate a seamless product, and then are adjusted to the GNSS data. In this way, the high spatial frequency deformation components come from A-DInSAR and the low spatial frequencies from GNSS. The deformation velocities and deformation time series of the Calibrated Product will be in the LoS direction. It is worth noting that the density of GNSS stations over Europe is not uniform. A 50 km grid velocity model, derived from GNSS information, is used to calibrate the LoS velocities.

The third product is the so-called *Ortho Product* or Level 3. This is the most elaborated product of the Service. The previous two products provide a mono-dimensional deformation, which refer to the LoS direction. This product provides a more complete information of the deformation: 2D deformation components. These are the horizontal East-West component, and the Up-Down vertical component. In order to derive the two components of the deformation, each location (*i.e.* grid cell) on the ground is required to have two deformation measurements, one coming from the so-called ascending dataset, and the other one coming from the descending dataset. The Ortho Product is generated at a coarser resolution: 100 by 100 m. It is worth noting that for all locations where only one observation is available, this product will not provide information.

Quality is an important aspect of the Service. This is key to guarantee an acceptability of the deformation products, especially to open new application fields, and to ensure a good product exploitation. Appropriate internal quality control procedures are implemented in the production process. In addition, an independent validation team will perform a comprehensive validation of the EGMS products.

The EGMS aims at expanding the current range of ground motion-based applications. A non-exhaustive list of possible users includes the academic centres; the geological, geophysical, and geodetic surveys; civil protection authorities; public authorities (at European, national, regional, and municipal levels); road and railway administrations; water management authorities; mining industry; oil and gas industry; engineering companies; cultural heritage institutions; insurance industry; and the citizens in general. This implies that the EGMS results must be easily accessed. In order to facilitate the exploitation of the products, the Service will provide tools for visualization and interactive data exploration. In addition, different types of guidelines and other supporting material will be published. The user uptake will be supported by

organizing workshops, webinars and user training sessions.

III. EXAMPLES FROM EGMS

This section presents some case studies extracted from the EGMS products. Natural and human-induced geohazards are presented below.

Note that the interferometric data shown in this section are to be considered as demonstrational. At the moment of writing this paper, the production of the EGMS is still ongoing. For this reason, only the Basic products are shown below.

A. Subsidence (water exploitation)

Subsidence in urban areas where water is exploited for agricultural and industrial purposes is one of the most classical targets for satellite interferometry.

Figure 1 shows the EGMS Basic product in the Firenze-Prato-Pistoia Basin (Tuscany, Italy). This is an intermontane sedimentary basin with an extension of approx. 824 km². The Basin hosts a complex and multi-layered aquifer system which is constantly stressed by the high demand of water for industrial and, mainly, agricultural activities (Ceccatelli *et al.*, 2021). In addition to water resource depletion, ground subsidence is a direct consequence.

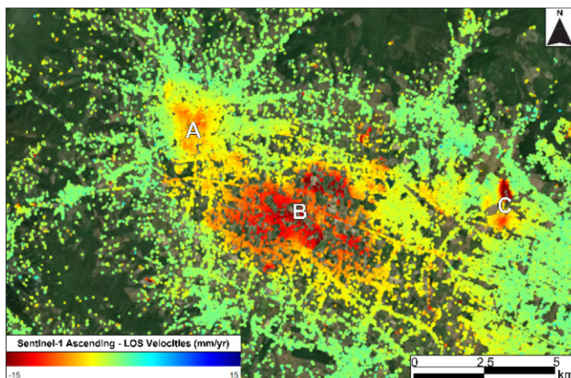


Figure 1. Subsidence in the Firenze-Prato-Pistoia Basin (Tuscany, Italy). A, Pistoia historic city centre; B, Bottegone area; C, Montemurlo. EGMS Basic product.

Because of the high population density, there is a high demand for ground motion measurements to estimate the effect of water exploitation. The Basin has already been the target of satellite interferometric analyses in the early days of the technique (Colombo *et al.*, 2003). Nowadays, using different SAR datasets and the Sentinel-1 data allow us to build up an almost 30 years long time series.

The results shown in Figure 1 offer a recent snapshot of ground subsidence in the Firenze-Prato-Pistoia Basin. Sentinel-1 data are acquired in ascending orbit and cover the period February 2015 – December 2020. Two-hundred and ninety-four images compose the interferometric stack. Velocities are calculated along the LoS of the sensor. A general lowering in the order of 2-3 mm/yr is registered through the Basin, but 3 areas

show an evident increase of LoS velocities (letters A, B and C in Figure 1).

The first area is Pistoia (letter A in Figure 1) and its historic city centre. This area did not record any relevant ground motion in the last 20 years, whereas, from 2015, LoS velocities increased up to -10 mm/yr. Time series show a linear displacement increase until June 2018 when the motion stabilized. On average, subsidence in the city centre is estimated in -6 mm/yr. The real cause of this unexpected phenomenon is yet to be found, although a link to ground water extraction in the outer parts of the city has been hypothesized (Ceccatelli *et al.*, 2021).

Letter B in Figure 1 refers to the Bottegone area. Here, the effect of water exploitation for plant nursery activities is well known and has been investigated since the ERS 1/2 era (Colombo *et al.*, 2003). Although some efforts have been made in the last years to reduce the amount of water exploited, Sentinel-1 data confirm the presence of a wide subsidence bowl in this area. Subsidence rates are on average equal to -10 mm/yr and reach a minimum of -22 mm/yr in the northern part of the bowl. Time series show a constant displacement rate with variations related to the seasonal demand of water.

The third area is smaller in size, but the subsidence rates are the highest in the entire basin (letter C in Figure 1). In fact, this small subsidence bowl reaches maximum subsidence rates of ~-40 mm/yr and an average value of ~-20 mm/yr. Time series show an abrupt trend change in July 2017 when the time series passes from the pure stability to an exponential acceleration. The phenomenon was promptly investigated following a regional procedure (Del Soldato *et al.*, 2019). It was possible to link the ground motion acceleration with an unauthorized over-pumping of water for textile production.

B. Subsidence (mining)

Ground motion induced by subsurface or surface mining is another usual application of multi-temporal satellite interferometry.

Figure 2 presents the EMGS Basic product in the surroundings of the Hambach open pit mine (North Rhine-Westphalia, Germany). The lignite extraction begun in 1978 and created a depression of ~50 km², almost 500 m deep. The mine has an obvious environmental impact with deforestation and the destruction of biodiversity. Moreover, the groundwater circulation is altered by the presence of the mine. The water level must be maintained low enough to guarantee the excavation; thus, subsidence is triggered in the surroundings of the mine.

The EGMS data in Figure 2 allow delimitating the extension of the subsidence area (roughly 600 km²). The deformation map is derived from 286 Sentinel-1 images acquired in descending orbit. Velocities are referred to the LoS of the sensor. Two major cities (Düren and

Kerpen – few kilometres south of the mine) are located in the moving area. Subsidence rates can reach -60 to -70 mm/yr in the proximity of the mine. The first 10 km around the mine record an average subsidence rate of ~-20 mm/yr. Time series show a linear deformation without big seasonal variations.

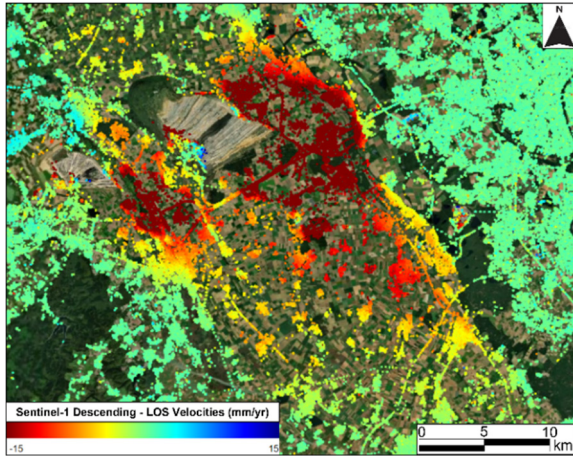


Figure 2. Subsidence in the surroundings of the Hambach mine (North Rhine-Westphalia, Germany). EGMS Basic product.

It is important to notice that the measurement point density falls off in the active mining area because of the decorrelation due to the frequent surface changes induced by the excavation of new coal levels (Crosetto *et al.*, 2020).

C. Landslides

The use of satellite interferometric dataset for monitoring and mapping landslides is nowadays an everyday practice for a lot of research groups and end users. These data are a huge support for landslide risk management, especially where the terrain conditions do not allow on site surveys and ground measurements.

Figure 3 shows the EGMS Basic product in one of the headlines that characterizes the coast of Granada, between Motril and Malaga. From a geological point of view, the headline of Punta de la Mona is located along a cataclastic zone with graphite schists, quartzites and blocks of marbles. Karstic processes affect the area. Thus, this is an area intrinsically unstable and commonly affected by rockfalls (Notti *et al.*, 2015).

Punta de la Mona, as the whole coast of Granada, went through a widespread and sometimes uncontrolled urban development in the 90 s. The whole Marina del Este resort (letter B in Figure 3) was built on top of a complex landslide (Notti *et al.*, 2015). The motion of this landslide, seasonally accelerated by heavy rainfalls, severely damaged some of the buildings part of the resort (Notti *et al.*, 2015).

The EGMS Basic product confirms the motion of the Marina del Este landslide (letter B in Figure 3), but also allow the detection of another phenomenon on the western side of the headline (letter A in Figure 3). The motion of this landslide was not detected by previous

authors that analysed ENVISAT images (Notti *et al.*, 2015; Galve *et al.*, 2017).

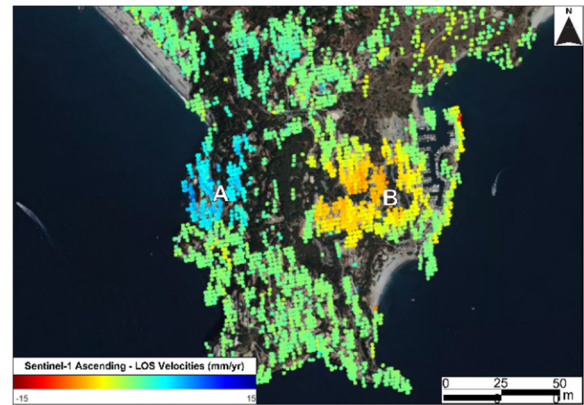


Figure 3. Landslides in the headland of Punta de la Mona in the municipality of Almuñécar (Granada, Spain). A, East landslide – Marina del Este; B, West landslide – Urbanización Punta de la Mona. EGMS Basic product.

The deformation map of Figure 3 is derived from 305 Sentinel-1 images acquired in ascending orbit. Velocities are calculated along the LoS of the sensor. Figure 3 is a self-explanatory representation of the role of LoS wrt slope orientation. The west landslide (letter A in Figure 2) records an average LoS velocity of 4 mm/yr, with a peak of 7 mm/yr in correspondence of the landslide foot. LoS velocities have a positive sign coherent with a motion towards the sensor, along the west-looking slope. The east landslide (letter B in Figure 3) records an average LoS velocity of -5 mm/yr, with a peak of -7.5 mm/yr in the central portion of the slope. LoS velocities have a negative sign coherent with a motion away from the sensor, along the east-looking slope. The dataset derived from descending orbit images will show the opposite situation, with negative velocities along the western flank and positive velocities registered along the eastern flank. Time series of deformation show a linear rate with only minor seasonal variations; the eastern landslides record a small deceleration after the second half of 2019.

Another example of EGMS Basic product used for landslide mapping is presented in Figure 4. The landslide is a deep-seated gravitational slope deformation (DSGSD), *i.e.* a flank scale landslide whose main sliding surface is hundred meters deep, located in the municipality of Emarese of the Valle d'Aosta Region (Italy). The landslide involves the entire mountain flank of the Tete de Comagne from an altitude of ~1800 m.a.s.l to the valley bottom. The boundary of the landslide, defined through photointerpretation aided by interferometric data, is known and it is part of the regional landslide catalogue (Solari *et al.*, 2020).

As many DSGSD, the Emarese DSGSD has a main large landslide body with several more superficial complex landslides. Thus, it is subdivided in sectors with different velocities and behaviours. This is confirmed by the distribution of LoS velocities in Figure 4. The deformation map is derived from Sentinel-1 images

acquired in descending orbit; 294 images compose the time series of deformation. The whole landslide body records an average LoS velocity of -6 mm/yr. High velocity sectors reach LoS velocities from -10 to -20 mm/yr. The velocity sign is coherent with a movement away from the sensor and along the slope direction. It is worth noting that the point density on the landslide body is uneven due to the vegetation coverage of the mountain flank. This is an unsolvable issue, especially using X- and C-band imagery. Nonetheless, more than 3500 moving points are found within the landslide area, making it possible to quantify the general motion of the landslide.

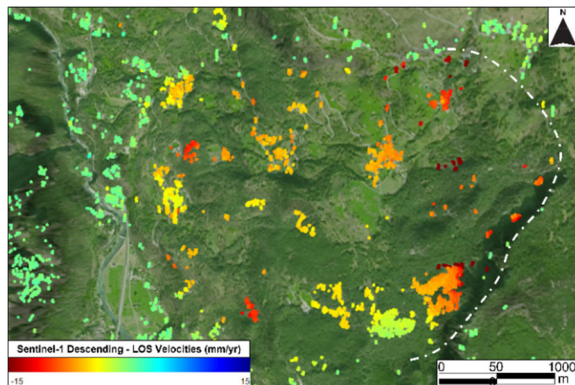


Figure 4. Deep seated gravitational slope deformation in the municipality of Emarese (Valle d'Aosta, Italy). EGMS Basic product.

D. Exploitation of geothermal reservoirs

The exploration and exploitation of geothermal reservoirs for power production has some environmental drawbacks such as air and water pollution, seismicity, and ground subsidence. The latter can be easily detected by satellite interferometry.

Figure 5 shows the EGMS Basic product in the Larderello geothermal field (Tuscany, Italy). Larderello is the oldest geothermal power plant in the world; the activity started in early 1900s. Nowadays, 34 power plants produce roughly 30% of the regional electricity demand. The geothermal reservoir reach temperatures of 200°C to 350°C at a depth between 400 and 3500 m and it is hosted by carbonate and metamorphic formations (Bertini *et al.*, 2005).

Previous investigations based on ERS 1/2 and Envisat data revealed the presence of a large subsidence bowl with maximum subsidence rates of ~ -30 mm/yr (Solari *et al.*, 2018). This is confirmed by the EGMS data in Figure 5. Sentinel-1 data acquired in ascending orbit (295 images) allow us to draw the contour of a subsidence area which extends for roughly 12 km in the NE-SW direction (Larderello-Lagoni Rossi axis) and for 10 km in the SE-NW direction (Sasso Pisano-Serrazzano axis). Subsidence rates are on average equal to -8 mm/yr with a maximum of -25 mm/yr in the centre of the valley.

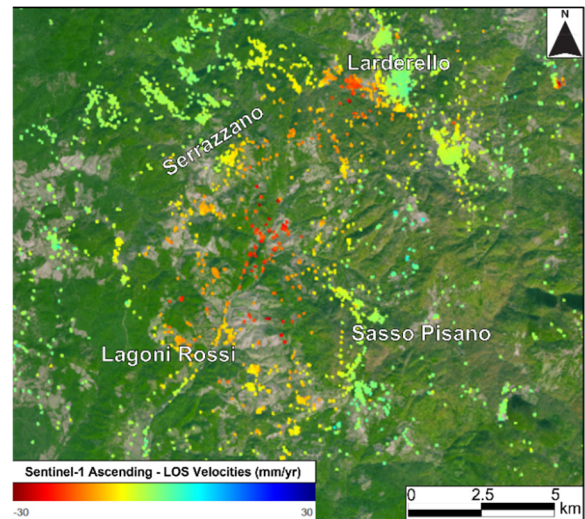


Figure 5. Ground motion in the Larderello geothermal field (Tuscany, Italy). EGMS Basic product.

E. Infrastructures

The EGMS is designed to target wide-area deformation; nonetheless, its data can also be used to detect localized motion affecting single infrastructures. Note that the EGMS is not intended for full structural analyses; rather, it provides a useful starting point for further studies, which can rely on *e.g.* X-band interferometric products or other types of in-situ data.

Figure 6 presents the EGMS Basic product in the fishing village of Thyborøn (Midtjylland, Denmark). The detection of ground motion in coastal areas of Denmark is particularly relevant due to the increasing impact of storm surges on the coastal communities. Thyborøn with a land elevation of 1 to 2.5 m is one of these highly vulnerable to flooding areas. By the geological point of view, the village is built on top of a sequence of marine sand and clay with landfill on top (Sørensen *et al.*, 2016).

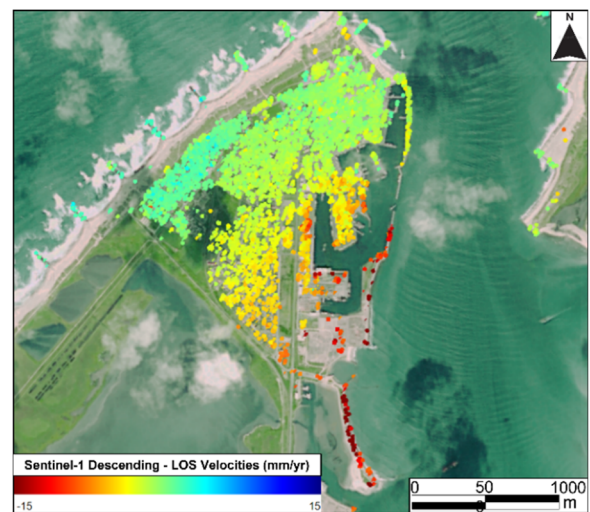


Figure 6. Ground motion in the Thyborøn harbour (Midtjylland, Denmark). EGMS Basic product.

Thanks to the EGMS data, it is possible to characterize the ongoing deformation in the Thyborøn harbour. The deformation map in Figure 6 is derived from 259 Sentinel-1 images in descending orbit. Velocities are referred to the LoS of the sensor. The deformation map depicts a clear pattern of velocity increase from west to the east. Maximum subsidence rates, up to -15 to -20 mm/yr, are recorded in correspondence of the harbour docks and of the internal breakwaters. EGMS data can capture the deformation of single buildings and of linear structures as the breakwaters.

The velocity pattern recorded in Thyborøn is connected to a geological factor, *i.e.* the increase of the landfill thickness in the harbour area, and to an anthropogenic factor, *i.e.* the age of the structures wrt consolidation processes (Sørensen *et al.*, 2016).

IV. CONCLUSIONS

In this paper, the main characteristics of the EGMS have been presented. The examples presented in the second part of the paper illustrate the potential of the EGMS. It is worth recalling that they only concern the first type of products, the Basic Product. Further examples will be published soon.

V. ACKNOWLEDGEMENTS

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