Nationwide deformation monitoring with SqueeSAR® using Sentinel-1 data

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Abstract

Subsidence and other surface deformation phenomena can now be routinely mapped on a national scale thanks to ESA's Sentinel-1 sensors and advanced InSAR algorithms. To be integrated into existing monitoring programmes, InSAR datasets should be calibrated with GNSS measurements. The dense spatial coverage of multi-temporal InSAR datasets captures local deformation phenomena and, with appropriate calibration, can advance the understanding of regional deformation trends. The regular and reliable SAR image acquisitions by Sentinel-1, as well as significant improvements in the scalability of InSAR processing chains allow regular updates of deformation maps on a national scale. Filtering the large amount of data for relevant information is achieved by using proper data screening tools, which have become extremely important for taking advantage of the unique amount of information provided by millions of measurement points.

Introduction

Despite the failure of Sentinel-1B in December 2021, which has immediately triggered a speed up of all project phases for the launch of Seninel-1C, the Sentinel-1 constellation, operated by the European Space Agency (ESA), has been acquiring SAR images all over the globe since late 2014. This constellation is the first of its kind, specifically designed for monitoring surface deformation over large areas, and it is creating a revolution in satellite geodesy.

The availability of a reliable satellite data source and the adoption of cloud computing solutions for data processing today allow regular updates of nationwide InSAR deformation maps with unprecedented accuracy. In fact, when calibrated with GNSS measurements, InSAR data provides a unique layer of information not only for scientists, but also for decision-makers and even the general public, as recently demonstrated - in the framework of the Copernicus program - by the European Ground Motion Service (EGMS, 2023).

In this paper, we report some results obtained by the SqueeSAR® processing chain, which has been lately updated to include specific algorithms for wide area processing (WAP).

Methodology

SqueeSAR® is a proprietary multi-interferogram technique (Ferretti et al., 2011; Ferretti, 2014), providing high precision measurements of ground displacement by processing multi-temporal satellite SAR images acquired over the same area, from the same acquisition geometry. By means of a statistical analysis of amplitude and phase data, the SqueeSAR® technique can select a sparse grid of image pixels, which can be used as a "natural geodetic network" to study and monitor slow surface deformation phenomena, with a precision of a few millimetres (Ferretti, 2014).

2-D Displacement Data

As any other InSAR analysis, the SqueeSAR® technique measures the projection of the displacement vector affecting each radar target along the satellite's line of sight (LOS) (Ferretti et al., 2011). However, a proper combination of SqueeSAR® results obtained from two different acquisition geometries (i.e. ascending and descending), acquired over the same area in the same temporal period, allows one to obtain an estimation of 2-D measurements, along vertical and east-west direction.

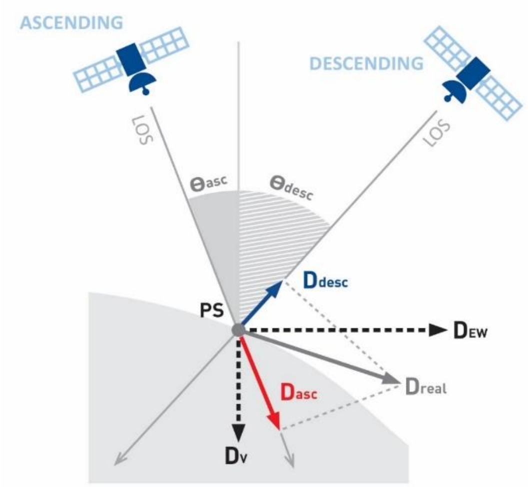

Figure 1 Decomposition of LOS displacements into vertical and horizontal components from images acquired in ascending and descending orbits.

This methodology requires the motion in north-south direction to be negligible or to be provided by other information sources (e.g. GNSS data). Whenever the (relative) motion of a measurement point in north-south direction is significant and no prior information is available, a bias will appear in the estimation of target motion, affecting mostly the vertical component of the displacement (Brouwer and Hanssen, 2021).

It should be noted that 2-D measurements are possible only whenever the same target is visible from both ascending and descending orbits: a condition not met very often in real-life scenarios. To overcome this limitation, the constraint of the radar target is relaxed: the area of interest is split into small patches of terrain and the measurements of all measurement points within the same cell are averaged, creating just one "pseudo-PS". The combination of the results and the estimation of the 2-D displacement time series is then performed for each cell containing data from both acquisition geometries (Ferretti, 2014; Teatini et al., 2011).

Since the acquisition dates usually differ from one dataset to another, the displacement measurements of each "pseudo-PS" are interpolated and re-sampled on a common temporal grid. For Sentinel-1 data, the spatial grid used for the estimation of 2-D displacement data is typically 100 x 100 m, while the sampling step in time is usually kept equal to 6 or 12 days.

Wide area monitoring with InSAR

Compared to InSAR analyses over areas of interest of hundreds or a few thousand square kilometres, Wide Area Processing (WAP) is characterized by three main challenges (Ferretti et al., 2019):

- Atmospheric effects – It is well known that the variance of atmospheric effects increases with the distance from a reference point (Ferretti, 2014; Hanssen, 2001). Moreover, ionospheric effects can become more significant. It is then extremely important, for the generation of high quality InSAR results over wide areas, to reduce the impact of this kind of disturbances, by using prior information (e.g. using GNSS data) or numerical weather models (Parizzi et al., 2020).

- Data mosaicking – in WAP, it is mandatory to deal with data mosaicking, to avoid introducing inconsistencies in combining results obtained from several independent “processing sites”. As a minimum, for Sentinel-1 data acquired in TOPS mode, the processing algorithm should not introduce any phase variations passing from one burst to another (Yague-Martinez et al., 2016).
- Computational burden – It is somewhat obvious that what is feasible when running a multi-interferogram approach on 30 images acquired over an area of interest of 100 km2 can become extremely challenging, if not impossible, when extended to 300,000 km2 covered by thousands of SAR images. Requirements on data storage, processing times, number of CPUs involved, and speed for data transfer can change by orders of magnitude. Although cloud computing can indeed be the solution, it is worth recalling that a proper and efficient use of the cloud requires bespoke software development, at least for complex processing chains, which can have major impact on processing costs.

All three points mentioned above, were carefully considered when developing the new processing chain for wide area processing used to generate the InSAR results presented in this paper, as well as the results provided by TRE ALTAMIRA in the framework of the European Ground Motion Service (EGMS, 2023).

InSAR data calibration using GNSS data

In order to validate and incorporate regional InSAR datasets into existing monitoring programs, it is crucial to calibrate using "absolute" measurements like GNSS data. To minimize the influence of possible misleading regional trends on the estimated displacement data (due, for instance, to atmospheric leakage or wrong satellite ephemerides), it is highly recommended to use GNSS data. An example of the calibrated SqueeSAR® results for the Denmark national deformation map is shown in Figure 2, with the GNSS stations marked in red. Even a limited number of stations can strongly improve the quality of InSAR measurements and mitigate the impact of low-wavenumber spurious signal components.

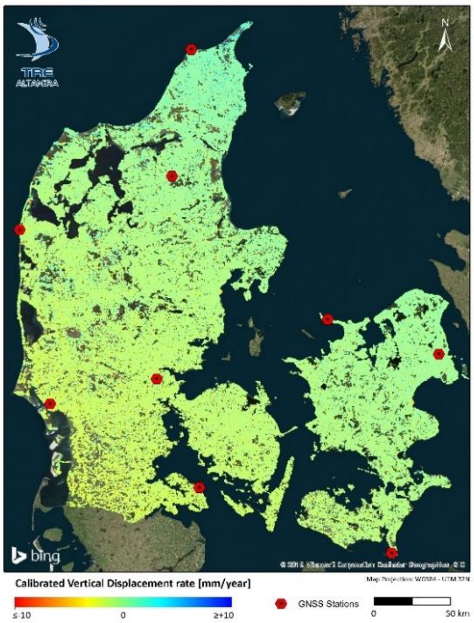

Figure 2   GNSS calibrated vertical deformation over Denmark. GNSS stations are shown in red.

The calibration methodology can be applied to both LOS measurements and the derived vertical and east-west components. The following outlines the main steps in the calibration procedure:

1) Time series filtering: GNSS time series are usually filtered using a moving average to reduce noise in the measurements. The time series of SqueeSAR® measurement points within a certain radius of each GNSS station (e.g. 200 m) are averaged.
2) Large-scale low frequency phase patterns are then removed from InSAR data, to avoid biases caused by uncompensated atmospheric components. To recover low frequency patterns due to real motion, first the difference in average velocity (linear trend) between each average SqueeSAR® time series and the corresponding filtered GNSS station time series is calculated. These differences are then used to estimate a first order surface (plane), which is subtracted from the SqueeSAR® data. This ensures that SqueeSAR® measurement points now also contain the low frequency component of the motion that was removed during the initial SqueeSAR® processing.
3) Absolute calibration: this step ties the two measurement techniques together and references the relative SqueeSAR® measurements to the absolute reference of the GNSS network. The procedure involves the generation of a time series of residuals, which is derived from comparing the averaged SqueeSAR® time series to the corresponding GNSS time series for each GNSS station. All the time series of residuals are then averaged to define a common time series of residuals (cRTS). This cRTS represents the movement of the local SqueeSAR® reference points with respect to the absolute GNSS reference frame. The cRTS was then removed from every SqueeSAR® measurement point time series.

The flow chart in Figure 3 is a summary of these steps is.

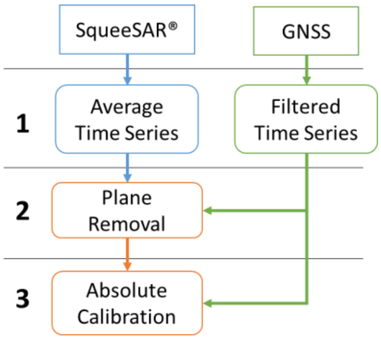

Figure 3 Overview of the steps in the calibration procedure.

Results

The following examples are taken from the national SqueeSAR® map for California (US), where InSAR data was calibrated and validated using GNSS measurements, from the national SqueeSAR® map for Japan (not calibrated with GNSS data, since the main focus was on local phenomena) and from the SqueeSAR® monitoring service provided to the region of Tuscany (Italy), where the main target of the service is landslide monitoring and where ascending and descending InSAR data are updated every 12 days all over the region (22,985 km2).

Aquifer related subsidence in California (US)

Nationwide ground deformation maps can deliver unique information by constraining the spatial extent of large-scale ground deformation phenomena, such as the subsidence in San Joaquin Valley, California, shown in Figure 4. This data was processed under contract with the California Department of Water Resources (DWR).

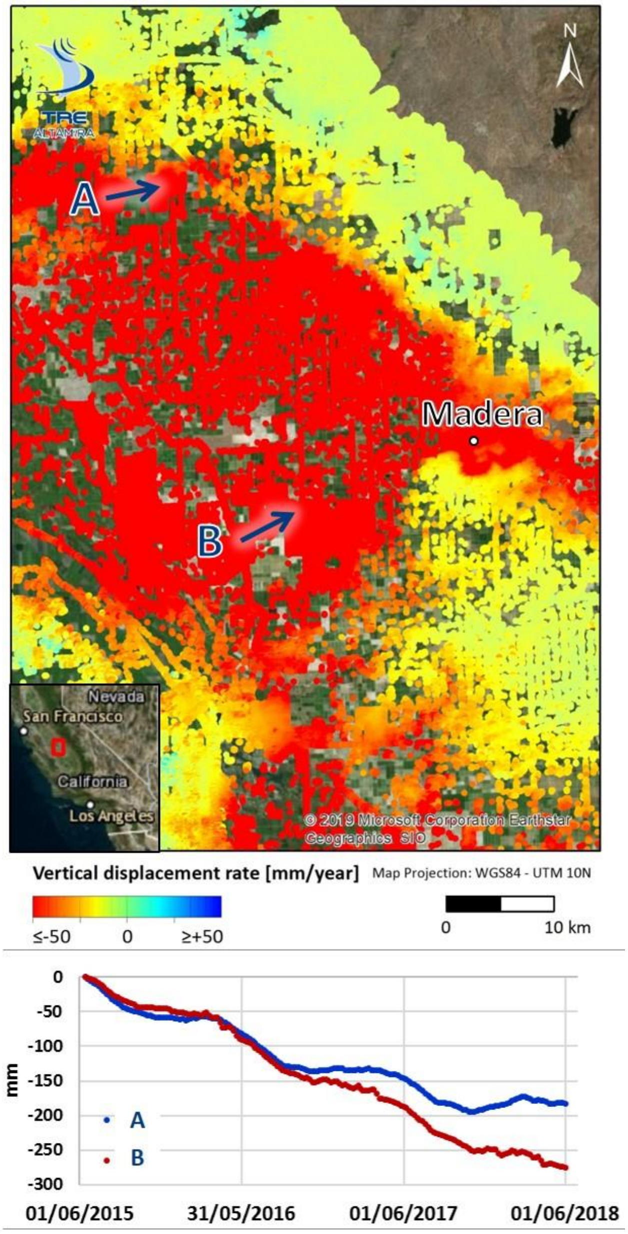

Figure 4 Map of the subsidence observed over California's St Joaquin Valley. Location is indicated on the overview map in the bottom left corner. Time series in the graph below show the difference in subsidence behaviour at location A compared to location B.

It is well established that land subsidence in San Joaquin valley is a danger to infrastructure, such as bridges, and that it has been caused by a combination of anthropic and natural factors, such as water pumping for agriculture and droughts (Faunt et al., 2016). In fact, water overdraft and the subsequent land subsidence over San Joaquin Valley already started in the 1920s, and became a widespread concern in the 1950s, when the water levels were lowered at unprecedented rates (Ireland et al., 1981). Since land use, surface-water availability and aquifer recharge vary, land subsidence across the valley is heterogenous, which makes monitoring crucial for managing the risk posed to infrastructures (Faunt et al., 2016).

The nationwide ground deformation map created with SqueeSAR®, based on Sentinel-1 SAR images, reveals these heterogenous patterns. The vertical displacement time series in Figure 4 demonstrate the different subsidence behaviours at two locations, which appear to be influenced by varying degrees of aquifer recharge.

Integration with data provided by 231 permanent GPS stations spread all over the state allowed the accurate estimation of vertical displacement components. The update of InSAR data over California is currently carried out every quarter over more than 100,000 km2. This data has become a timely, actionable, subsidence information that local, state, and federal agencies can use for decision making.

Post-seismic subsidence in Japan

As already mentioned, monitoring ground deformation on a large spatial scale using satellite SAR data can benefit from GNSS calibration, allowing one to better estimate low frequency spatial components of the motion. However, if no GNSS data are available, interesting patterns of motion can still be detected at medium scales, such as the deformation occurring in the aftermath of the earthquakes in April 2016 in Kumamoto, Japan, shown in Figure 5. This example was taken from the SqueeSAR® national deformation map for Japan, which is based on Sentinel -1 SAR images (Ferretti et al., 2019).

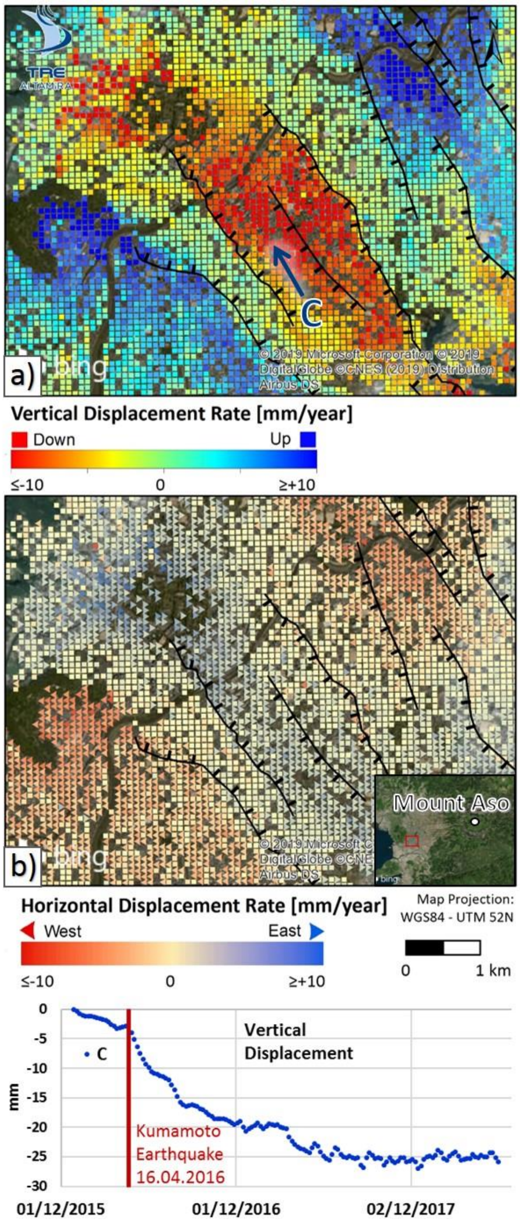

Figure 5 Maps showing a) vertical and b) east-west displacement rates between December 2015 – June 2018 over Kumamoto, Japan. The location is indicated on the overview map in bottom right corner. Black lines show faults inferred from ALOS-2 SAR interferometry by Fujiwara et al. (2016). The time series shows vertical displacement at location C, indicated in map a).

The ground displacement patterns shown in Figure 5 match well with the results of ALOS-2 interferometry published by Fujiwara et al. (2016). The structures shown in Figure 5 are secondary faults interpreted from the results of ALOS-2 interferograms. According to the authors, these faults form a graben group and are not directly related to the main faults on which the earthquakes occurred. The SqueeSAR® time series in Figure 5 shows that there is approximately −15 mm vertical displacement between April and December 2016. A second phase of relatively fast vertical displacement started in March 2017, however the cause for this is unknown (see time series in Figure 5). From June 2017 onwards, the area appears to stabilise.

Fujiwara et al. (2016) point out that there remains a question as to whether these secondary fault systems could become “primary” earthquake faults in the future.

While there is currently no concrete answer for this, Fujiwara et al. (2016) suggest that preparing for the possibility is important. Routinely monitoring displacement using InSAR may help to better understand and predict the behaviour of these structures.

Local subsidence in the region of Tuscany (Italy) automatically detected by a trend change algorithm

Despite the benefits of a dense spatial coverage of SqueeSAR® measurement points over wide areas, filtering the data for relevant information can become challenging. This is especially important if deformation maps are updated more regularly, such as for the service provided to the region of Tuscany (Italy), where SqueeSAR® deformation maps based on Sentinel-1 SAR images are updated every 12 days. This continuous monitoring generates a stream of data that needs to be filtered for significant changes in the displacement trends. This task is currently performed by an automatic trend change detection algorithm. Variables such as the magnitude of the trend change deemed significant, or the time period considered, can be changed depending on the phenomena of interest (Del Soldato et al., 2019).

The map in Figure 6 shows the displacement rate along ascending LOS, over an industrial area in the Montemurlo Municipality, Tuscany.

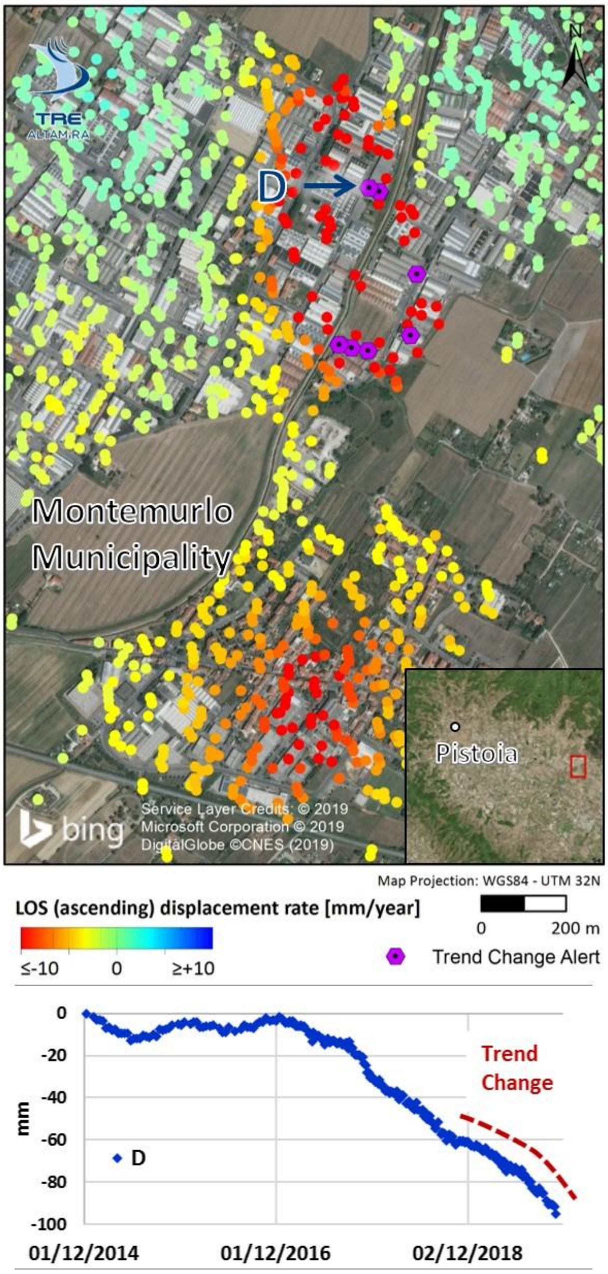

Figure 6 LOS deformation map from the continuous monitoring service provided to the region of Tuscany (Italy). The location is indicated on the overview map in bottom right corner. The violet markers highlight SqueeSAR® measurement points that display a significant recent trend change in their displacement. The time series is an example of a measurement point highlighted by the trend change algorithm.

The time series in the graph in Figure 6 shows that after negative displacement started in December 2016, there has been another trend change in 2018, which was highlighted by the trend change algorithm.

The negative displacement in LOS shown in Figure 6 is likely to be related to the over-pumping of water to meet the needs of local textile factories, which are numerous in the Montemurlo Municipality (Del Soldato et al., 2019). The displacement pattern observed in this industrial estate (see Figure 6) is discussed as a case study in more detail by Del Soldato et al. (2019).

Conclusions

Surface deformation phenomena can now be mapped routinely on a national scale with the frequent and reliable coverage provided by ESA's Sentinel-1 SAR sensors. Producing these maps is possible with bespoke cloud-based software using advanced InSAR algorithms, such as SqueeSAR®, which allows scalable processing of large SAR data stacks.

Recently, the publication of the results of the European Ground Motion Service (EGMS), in the framework of the Copernicus program, has shed new light on the potential of satellite radar data for detecting and monitoring surface deformation phenomena over wide areas. Radar images acquired by Sentinel-1 sensors can be used not only for nationwide analyses, but at continental scale. This can allow users to obtain synoptic views of subsidence phenomena, especially along coastal areas, over thousands of kilometres.

The availability of a growing number of InSAR datasets have also highlighted the importance of data calibration with GNSS measurements, especially for regional analyses and the estimation of vertical and east-west components. In fact, the bias of vertical displacement data estimated from ascending and descending satellite orbits, introduced by neglecting north-south displacement components, can be largely compensated for, at least whenever the spatial density of GNSS stations is high enough to capture the main components of the displacement field affecting the area of interest.

Recent InSAR analyses over wide areas, have emphasized the importance of data screening tools too, supporting users in the identification and selection of measurement points affected by a particular behaviour (e.g., acceleration, abrupt changes, etc.). To this end, machine learning algorithms are gaining momentum, due to their flexibility and their capacity to deal with big data. In general, due to the ever-increasing cardinality of InSAR datasets, anomaly detection algorithms will become a key element in any future monitoring program based on satellite radar data.

Finally, even if not presented in this paper, recent analyses based on Sentinel-1 data have shown the complementarity of large-scale InSAR results with what can be obtained using high-resolution (HR) radar imagery. In fact, HR data are much more suitable for monitoring individual assets, such as a building or a bridge, and can allow users to increase the temporal sampling of the phenomenon of interest.

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