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Mapping InSAR deformation of low and moderate earthquakes

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Abstract

Low-to-moderate magnitude earthquakes often induce small ground displacement. For such events, ground deformation fields detected by SAR interferometry can be masked or not clearly discernible from the fringes distribution because of the presence of error sources, such as atmospheric artifacts and topographic residuals. We show two examples of low-moderate magnitude earthquakes, for which we adopted a new automatic tool for calculating the fringe pattern stemming from seismological data. The tool estimates the extent and the geographic position of the deformation by running a forward model of the seismic source, thus identifying the best SAR frame to be collected and the expected surface effects to better figure-out the outcomes of InSAR processing. We present the Mw 5.7 occurred in Greece and the Mw 5.4 occurred in Zagreb on 21 and 22 March 2020, respectively. For the Greek earthquake, the tool predicted a deformation close to the InSAR product, and gave evidences of atmospheric disturbances, thus providing information for inverse source modelling. The tool in the Zagreb event was used to infer the extent and location of the ground motion, that were used to identify the best SAR pair to be processed, being the SAR frames edge very close to the epicenter.

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1. Introduction

Geodetic observational data, like Interferometric Synthetic Aperture Radar (InSAR) measurements, are by now regularly used to infer information concerning sources of surface displacements and to understand the underlying processes. InSAR is a well-consolidated technique, routinely used to measure ground deformation caused by many types of phenomena, from seismic events, to volcanic eruptions, passing through movements induced by human activities. InSAR products are often used as input for inversion algorithms with the goal of study volcanic systems, earthquake cycle, and many other geophysical phenomena. The outcomes from the inversion are the parameters values characterizing the source of the investigated phenomenon.

Even though InSAR is a very powerful instrument, sometimes it is not perfectly suitable for estimating the effects of low to moderate events, such as earthquakes characterized by magnitude ranging from 4.5 to < 6 magnitude. In this work, we propose a tool able to support the SAR data user as it provides an estimate of the expected ground displacement due to an earthquake starting from its location parameters. This tool becomes of great importance especially in case of events of low and moderate magnitude. In fact, in such cases the observed displacement will be very small, even less than an interferometric fringe, and the real signal can easily be misinterpreted as topographic and/or atmospheric residuals. In conclusion, in this way we can have an *a priori* information about the magnitude, position and extension of the expected deformation field on the surface.

In this work, we show the use of this supporting tool for two recent seismic events, of moderate magnitude. The first one is the Mw 5.4 earthquake occurred on 22 March 2020 in Zagreb and the second one is Mw 5.7 in Greece, on 21 March 2020.

2. Forward modelling of the earthquake source

As soon as an earthquake above a given threshold occurs, a semi-automatic system to predict the surface displacement is triggered. Based on the available focal mechanisms (from local or worldwide providers) we simulate a finite source using the Wells and Coppersmith [1] rules, deriving length, width and slip. These values, combined with the location, depth, strike, dip and rake angles coming with the focal mechanism, allow to generate the predicted East, North and Up components displacement maps using the Okada [2] solution for an elastic dislocation in a homogeneous and isotropic half-space.

When the predicted displacement exceeds the InSAR ordinary noise, i.e. about 2 cm, displacement maps are projected into the satellite line-of-sight (LoS), adopting reasonable azimuth and incidence angles for ascending and descending orbits, respectively. The line-of-sight displacement is provided in a wrapped and unwrapped form.

Goal of this tool is to provide a reliable estimate of the expected interferograms in terms of spatial extent, displacement (based on the fringes number), etc. in order to allocate the suitable resources (in terms of time and people) for the following analysis of InSAR data and subsequent modelling. All these tasks are performed using algorithms and tools provided with the SARscape® (Sarmap, CH) software.

3. Case studies and dataset

The case studies we present are two recent events occurred in March 2020. One investigated case is the earthquake that took place on 21 March 2020, in Greece. It is an Mw 5.7 event, and its focal mechanism is representative of an inverse type fault.

The second seismic event is the Mw 5.4 earthquake that occurred on 22 March 2020, in the proximity of the boundary between Slovenia and Croatia, close to Zagreb city.

Table 1. Events and seismic information used for run the direct modelling tool.

Case studies	UTC date and time	Mw	Epicentre *(lat; lon)*	Depth (km)	Mechanism	Provider
Greece	21/03/2020 00:49:53	5.7	39.30; 20.62	7	Inverse	EMSC
Slovenia	22/03/2020 05:24:03	5.4	45.85, 16.07	11.6	Inverse	INGV

As above explained, the output from the forward modelling drives the selection of the SAR frames and tracks for the following interferometric analysis. This is important because, even though some of the present SAR sensors (e.g. Sentinel-1) have a very large swath, it could happen that an earthquake occurs close to the borders of a frame, so that the spatial extent of the whole deformation field will be part of two adjacent tracks. Therefore, it is surely useful to immediately know how many SAR images we need and to which track they belong. At this point, it is possible to select the best SAR pairs, by also taking into account the temporal span between the earthquake occurrence and the temporally closer acquisition.

The considered SAR dataset is composed of eight images acquired by Sentinel-1A/B mission operated by the European Space Agency (ESA) and acquired in the TOPSAR mode. Both ascending and descending data have been collected and analyzed by means of the standard two-pass SAR interferometry (InSAR) technique [3].

Table 2. SAR Dataset used for InSAR processing.

Case studies	Master image	Slave image	Orbit direction
Greece	18/03/2020	24/03/2020	A
	19/03/2020	25/03/2020	D
Slovenia	17/03/2020	23/03/2020	A
	22/03/2020	28/03/2020	D

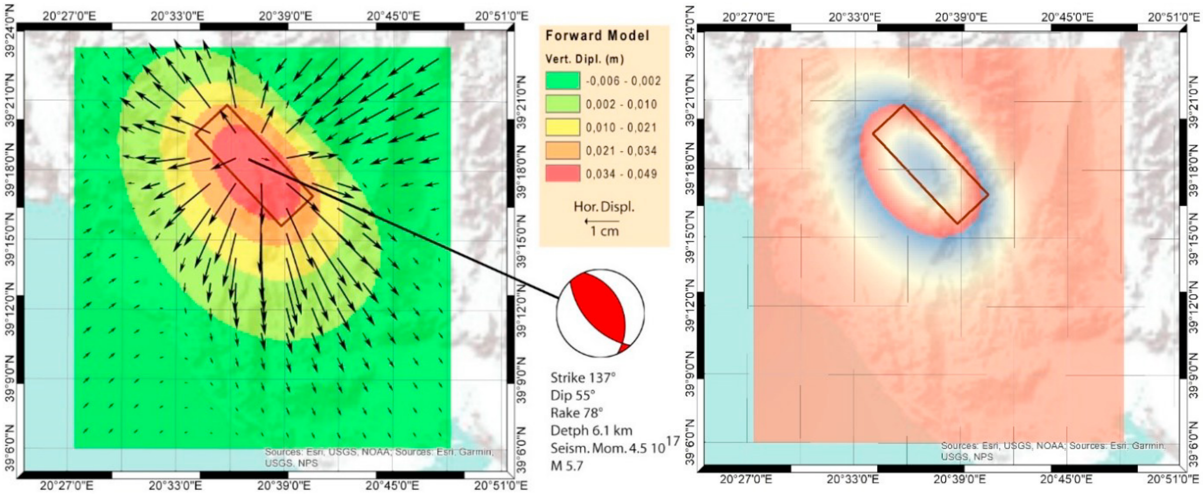
The selected interferograms have been multi-looked (8 in range and 2 in azimuth) and phase noise filtering [4] applied before performing phase unwrapping [5]. The topographic contribution has been removed from InSAR phase by using the SRTM-3 elevation model (90 meters ground resolution) [6]. Finally, the unwrapped phase has been converted in meters and geocoded according with the used DEM.

4. Results

4.1. The Greek seismic event

For the case of the March 21, 2020 event, we adopted a focal mechanism with the parameters of Strike/Dip/Rake=137°/55°/78° (plane1) and 337°/37°/106° (plane 2) for the generation of the forward model. Based on Wells and Coppersmith (1994), we assessed a uniform-slip fault of 10 x 6 km, with an average slip of 25 cm. This finite fault was used to predict a surface displacement reaching 5 cm in the vertical components (Fig. 1a), corresponding to about two fringes in the simulated C-band interferograms (Fig. 1b).

The retrieved InSAR displacement maps show a coseismic deformation associated to a little bit more than one interferometric fringe representing a positive LoS displacement peaking at about 4 cm for the ascending case and about 3.2 cm for the descending one.



(a) (b)

Fig. 1. (a) Predicted surface displacement; (b) simulated interferogram.

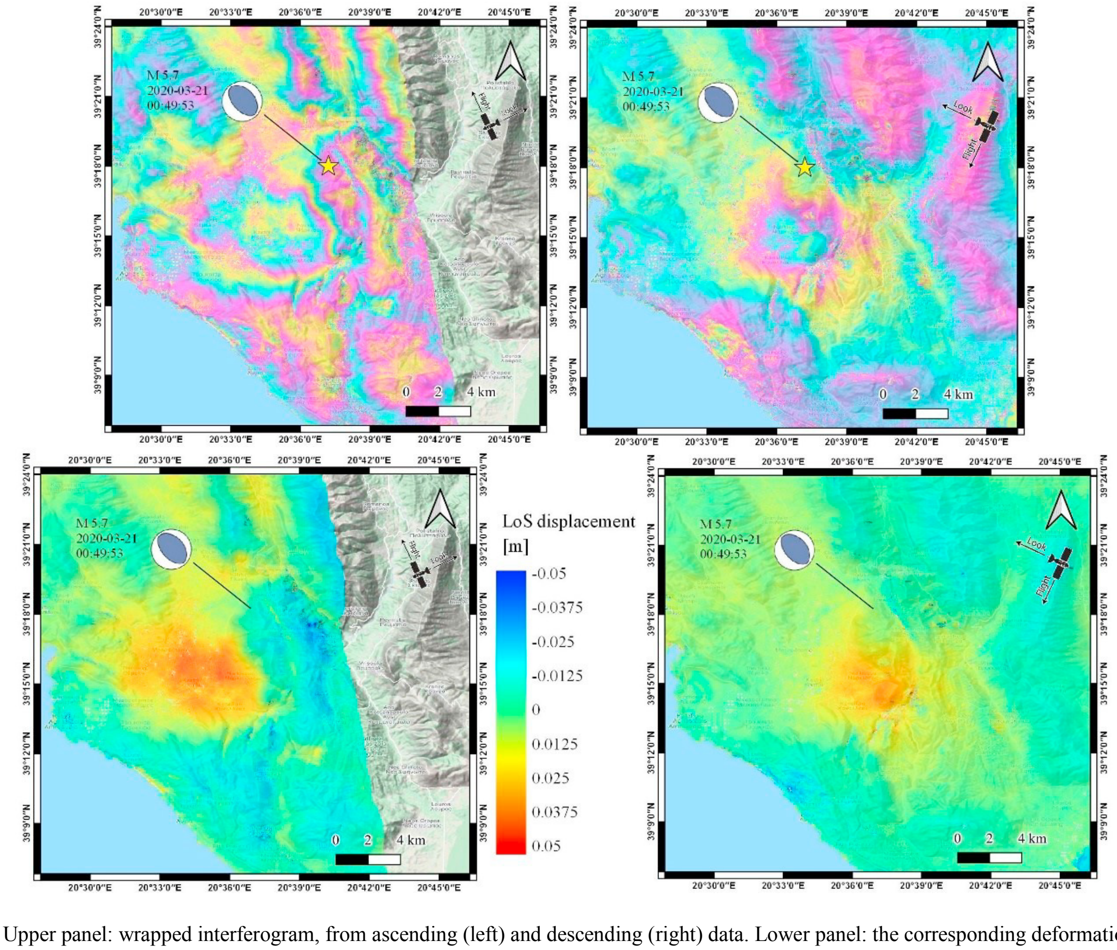


Fig. 2. Upper panel: wrapped interferogram, from ascending (left) and descending (right) data. Lower panel: the corresponding deformation maps for the two orbits.

4.2. The Slovenian seismic event

As for the Greek event, this earthquake was selected to run the forward modeling based on its focal mechanism, in this case provided by the INGV Quick Regional Moment Tensor (http://autorcmt.bo.ingv.it/quicks.html). Despite the event magnitude and the evident damages reported for the city of Zagreb, the expected surface deformation were found to be very small, and it did not reach one centimeter (Fig. 3). For this reason, we did not proceed with the calculation of the line-of-sight displacement, assuming that future interferograms were showing only background noise. We then verified that the outcome underestimated the measured deformation, small but visible. A modeling of the observed data revealed that this inconsistency was due to the different source depth between the one reported by of the focal mechanism (11.6 km) and the one derived from InSAR modeling (about 6 km).

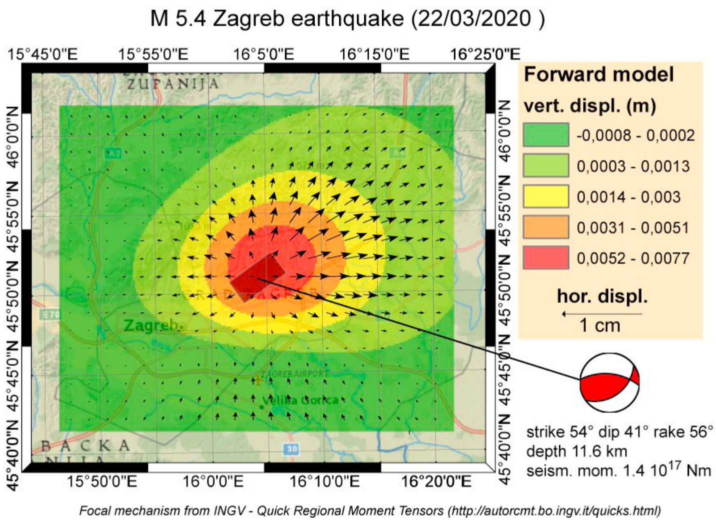
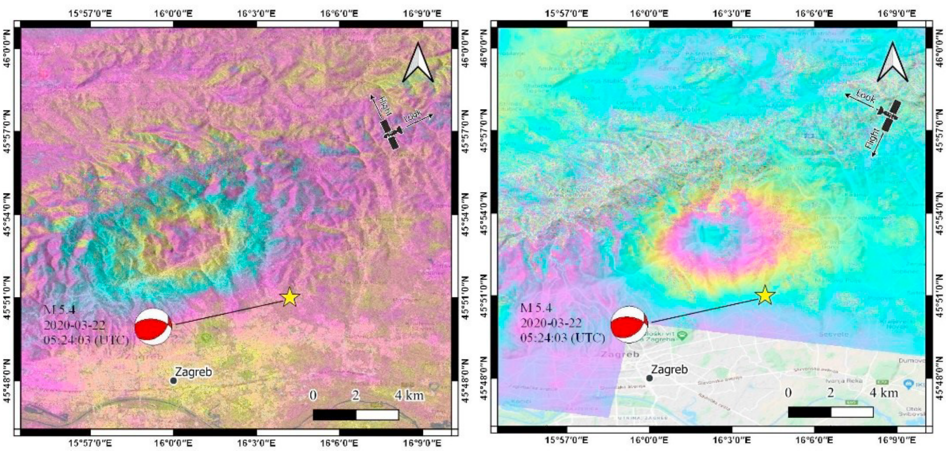


Fig. 3. Predicted surface displacement by the direct modelling tool.

The obtained products by processing the SAR data are showed in Fig. 4. The deformation fields, for both the ascending and descending dataset, are very similar, and about one fringe is present in each of the two maps. The maximum positive displacement value (movement towards the satellite) in the sensor LoS is about 3 cm and 2.5 cm on the ascending and descending maps, respectively, i.e. in agreement with the earthquake mechanism (thrust fault). Moreover, the two patters are slightly shifted relative to each other reflecting also the presence of a small horizontal component.



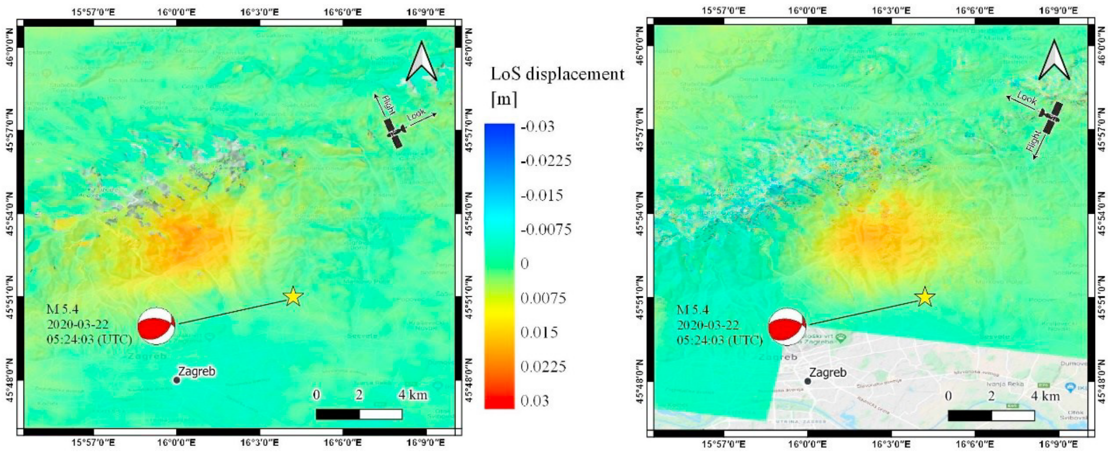


Fig. 4. Upper panel: the wrapped interferogram, from ascending (left) and descending (right) data. Lower panel: the corresponding deformation maps from the two orbits.

5. Discussion and conclusions

The adoption of the semi-automatic modelling tool has been here presented for two moderate magnitude earthquakes. The results we obtained are quite different for the two exercises. In the first considered event, the Greek earthquake, the automatic tool predicted a deformation very close, in terms of displacement values, to the amount estimated by InSAR data. Despite that, the fringe pattern from SAR processing is quite noisy, i.e. fringes are not clearly depicted and appear deformed probably because of atmospheric effects (see Fig 2), both dry and wet disturbances. The expected displacement provided by the forward model can give an alert by suggesting the use of additional, possibly better, SAR pair before attempting the estimation of the earthquake source from InSAR data. In this case, we can assume that the unwrapped maps can lead to an incorrect evaluation of the fault parameters. Differently, the Zagreb earthquake highlighted an underestimation of the displacement estimated by the forward model, even though we get information about the extent of the ground motion. This was used to identify the best SAR pair to be processed, especially for the descending orbit where the SAR frames border is very close to the epicenter. Such information allowed allocating the required resources, in terms of time, hardware and personnel, selecting a priority in the InSAR data analysis.

In conclusion, we think that this tool could be useful: it can give a first guess of the expected ground effects, that is also important when SAR data are not promptly available (i.e. few days of time lag between earthquake and first post-seimic SAR image). Moreover, it provides some indication on where and what the deformation will be, saving time and efforts, and enabling a better planning of the activities.

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