Surface Deformation Monitoring in the Republic of Croatia with MT-InSAR

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Abstract: The Multi-Temporal Synthetic Aperture Radar Interferometry (MT-InSAR) has proven to be a very useful tool in providing a high precise detailed characterization of surface deformation processes over wide areas. The first application in the Republic of Croatia was applied over the wider Zagreb area in the project "The Geodynamic GPS Network of the City of Zagreb". The project was established in 1997 with the aim to answer the need for a better understanding of an ongoing geodynamic processes in the area. The research was carried out with GPS campaigns, whereas the MT-InSAR technique was introduced into the project in 2015. The Persistent Scatterers MT-INSAR technique was applied on Envisat ASAR data in 2015 and on Sentinel-1 data in 2017. The paper provides a revisit of the research with Envisat-ASAR data and preliminary results of the Sentinel-1 data. Furthermore, we discuss other possible MT-InSAR applications in the area.

Keywords: Geodynamic GPS Network of the City of Zagreb, InSAR, surface deformation monitoring, geodynamic processes

Introduction

The first application of Multi-temporal Interferometric Synthetic Aperture Radar (MT-InSAR) technique in the Republic of Croatia was done through the project "The Geodynamic GPS Network of the City of Zagreb". The MT-InSAR was applied for surface deformation monitoring of the wider Zagreb area in order to fully characterize an ongoing geodynamical processes in the area. The latest significant earthquakes occurred in 1880(VIII MCS) and 1905(VII-VIII MCS) and left devastating effects on Zagreb and nearby settlements (Herak et al, 2009). The wider Zagreb area is located in the NW part of Croatia and it is considered as one of three most seismic active zones in the country.

The Geodynamic GPS Network of the City of Zagreb project was initiated in 1997 by GPS network establishment. The project's aim was to provide a better understanding of ongoing geodynamic processes with precise GPS observations of the network. Since then, nine GPS campaigns were conducted (1997, 2001, 2004, 2006, 2007, 2008, 2009, 2015 and 2017) on 43 specially stabilized GPS monuments. The results of the project are extensively documented in; Pribičević et al 2004, Medak & Pribičević 2004, Đapo 2005, Pribičević et al 2007, Đapo 2009, Pribičević et al 2011 and Pribičević et al 2012, Pribicevic et al. 2016. Moreover, the MT-InSAR technique was introduced in the project in 2015 (Pribicevic et al. 2017).

MT-InSAR is an advanced InSAR processing technique that provides ground deformation detection with an improved accuracy in the order of a few millimeters per year. (Hooper et al, 2012, and references therein). Moreover, it provides an unsurpassed spatial resolution and great coverage of surface deformations in the area. InSAR is the remote sensing technique that relies on the determination of a phase difference in the received electromagnetic signal (EM) acquired by spaceborne SAR imaging of the area at two distinct times. Taking into consideration the geometry of spaceborne SAR imaging and height of the imaging satellite, the phase difference can be connected with a change in the EM propagation length that can

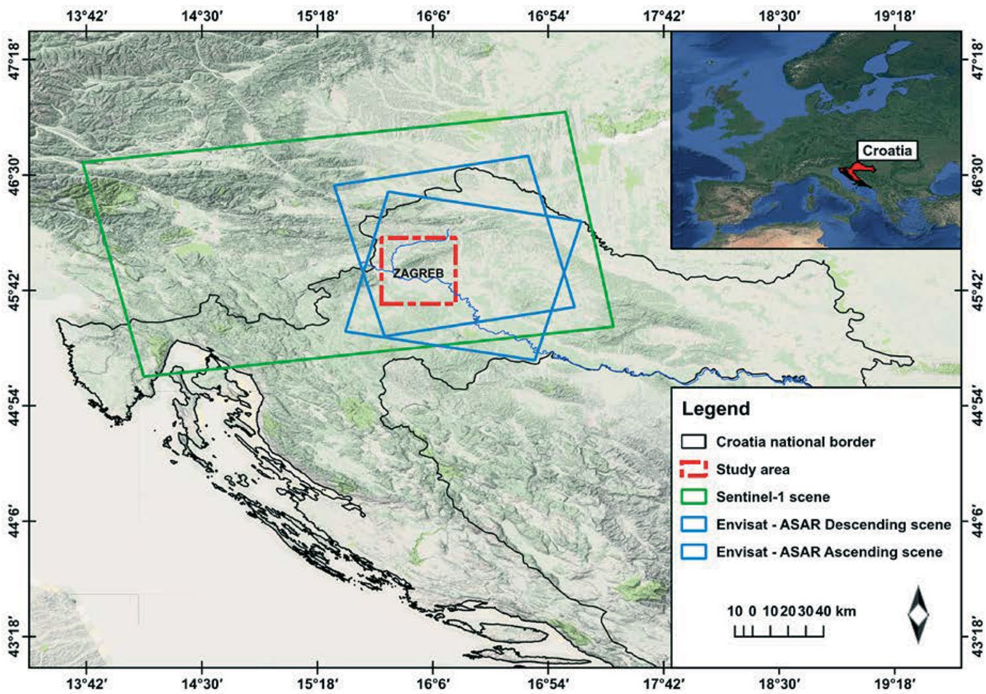

Fig. 1 – MT-InSAR application over the wider Zagreb area, Croatia

be afterwards connected with a ground displacement. The final InSAR result is a map of phase differences over the imaging area called interferogram. Furthermore, MT-InSAR methods work on the principle of stacking multiple interferograms that cover a certain time period. Based on the different approach of interferogram stack generation and an extraction of ground displacement information from interferograms, the methods can be generally divided on Persistent Scatterers, Small Baseline Subset or their combination. The comparison of different MT-InSAR approaches was discussed in Osmanoglu et al. 2016.

In this paper we present an overview of Persistent Scatterers MT-InSAR technique and its application in "The Geodynamic GPS Network of the City of Zagreb" project. The MT-InSAR Persistent Scatters technique was applied on ENVISAT satellite data in 2015 and on Sentinel1 data in 2017. We revisit the research on the Envisat data presented in Pribicevic et al. 2017 and also present for the first time preliminary results of the Sentinel1 data. Scene coverage of ever satellite mission is depicted in Fig. 1. Moreover, we discuss the future MT-InSAR research and its other possible applications in the area.

Interferometric Synthetic Aperture Radar (InSAR)

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique based on the Radio Detection and Ranging (radar) technology. The technique uses two Synthetic Aperture Radar (SAR) observations over the same area acquired at distinct times to measure ground displacements expressed as a phase change in received EM pulses. It can be used for continuous monitoring applications of various geophysical and surface processes occurring on the Earth's surface; such as earthquakes, volcanic eruptions, landslide, uprising and subsidence events, glacial movements and etc.

Today, the most common SAR platform are satellites that orbit the Earth in a near-polar orbits at altitudes ranging from 500 km to 800km above the Earth's surface. The SAR satellites orbit the Earth in two directions concerning the direction to the North Pole (ascending orbit) or to the South Pole (descending pole). The angle between satellite orbit and true North-South is called squint angle and it slightly varies depending on the satellite but is in the range up to 10 degrees. The SAR is an active imaging radar system that emits and receives an electromagnetic (EM) pulse with a wavelength in the microwave spectral domain. The imaging geometry is side-looking in order to ensure a precise discrimination of different received backscattered EM pulses. The system gathers spatial data stored in the form of an image where every pixel contains a piece of information concerning the received backscattered EM pulse. The stored information are amplitude and phase values of the each received backscattered EM pulse. The phase information is directly correlated with the emitted EM wavelength, thus, any change between the emitted and received signal's wavelength can be expressed as a phase shift. InSAR technique exploits the phase change information in order to determine surface displacements occurred in the area of interest between two spaceborne SAR acquisitions. The map of phase change values over the area of interest is called interferogram. The relationship between a ground displacement and corresponding phase change in two SAR signals acquired over the same area is depicted Fig. 2.

The relationship between a change in electromagnetic signal's phase and ground movement (URL1)

Phase change (Δφ) can be expressed with the following equation:

$$\Delta\varphi = \frac{4\pi}{\lambda}\Delta R + \alpha \tag{1}$$

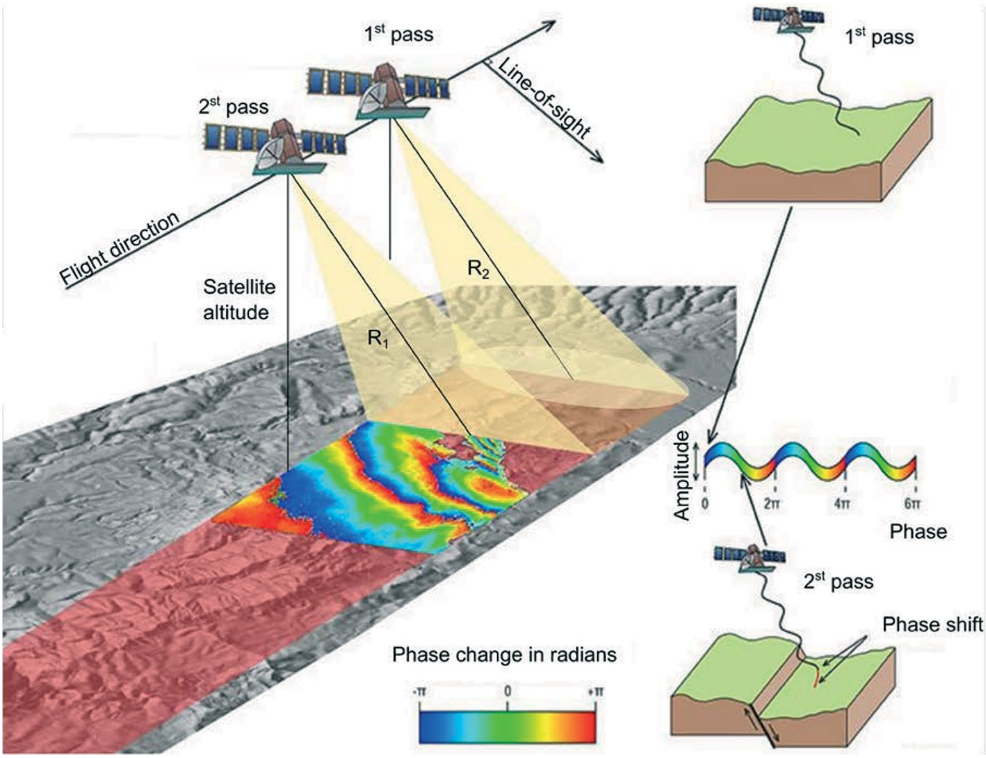

Fig. 2 – InSAR; imaging geometry and interferogram generation (URL2)

where λ is wavelength, ΔR is displacement and α is phase shift due to different atmospheric conditions at the time of two radar acquisitions. The determination of a true ground displacement is not a trivial task as a phase change is also affected by; topography distortions produced from slightly different viewing angles of two satellite acquisitions (t), atmospheric delay effects produced from interaction between EM signal with wet atmosphere layers (a) and other noise. Therefore, equation 1 can be extended to;

$$\Delta\varphi = \frac{4\pi}{\lambda}\Delta R + \alpha + t + noise. \qquad (2)$$

Phase change regarding topography can be removed from the total phase change information by stimulating the phase change related to the viewing geometry and topography provided by an external digital terrain model. The technique of topographic phase change removal is called Differential InSAR (DinSAR). Another significant noise contributor is atmosphere, which is completely random and hard to remove. The techniques to deal with this problem emerged in the late 1990'ies by stacking the multiple interferograms and removing the noise with a statistical analysis. The process was referred to as Interferogram Stacking or Multi-temporal InSAR (MT-InSAR). The two most used MT-InSAR techniques are Small Baseline Subset (SBAS) and Persistent Scatter (PS) technique.

Multi-temporal InSAR Persistent Scatter technique

Multi-temporal InSAR Persistent Scatterer is a part of the second generation of InSAR techniques. The base algorithm was developed at the Politecnico di Milano (Polimi) in 1999 (Ferretti et al. 2001). The algorithm determines a phase shift only on the stable backscatter ground points, so called permanent scatterers. Permanent scatterers (PS) are defined as a ground EM reflectors that maintain a stable amplitude and coherent phase properties in time. Thus, points with a good signal to noise ration can be considered as PS candidates. PS points are usually man-made objects but can also be natural objects like rock outcrops, un-vegetated earth surfaces and boulders. In most cases the best PS points are high objects, which are stable in time due to their best refractive capabilities. The main aim of MT-InSAR PS technique is to mitigate phase changes caused by the atmospheric delay in order to better determine the true ground displacement. This can be accomplished by using the spectral analysis of the interferogram stack in order to identify PS points. Further analysis is performed on the PS points in the spatial and time domain for determination of deformation trend model. After the initial removal of flat surface and topography phase contributors, other variations in the interferometric phase are considered to be produced by atmosphere as the other noise sources can be neglected.

Therefore, the PS technique is based on the statistical analysis of interferometric data where bigger input overall provides a more reliable model. The minimum recommended number of SAR scenes is 15. The precision of the surface deformation with the PS technique is around a few millimeters per year.

MT-InSAR PS results over the wider Zagreb area

MT- InSAR Persistent Scatterer technique was introduced for the first time in the project in 2015. The aim of MT-InSAR utilization was to condense the deformation results provided from GPS network. Moreover, the idea was to provide a detailed characterization of surface deformation with a special focus on urban areas in an area 50 by 50 km around the City of Zagreb. The PS MT-InSAR technique was applied to images acquired with Envisat – An Advanced Synthetic Aperture Radar (ASAR) on descending and ascending orbit. The images were stacked based on the orbit direction regarding their viewing geometry. The total number of satellite radar images used in processing were 23 of descending track and 17 of ascending track. Each stack covered the time period 2004-2009. The MT-InSAR processing was done with Stanford method for Persistent Scatterers / Multi Temporal InSAR (StaMPS/MTI). The MT-InSAR results were 121,490 PS points for descending track and 95,530 for ascending track. The velocity models of the area on both tracks show values in a range of -3 to 3 millimeters per year regarding the defined reference point. The research is described to a great extent in Pribicevic et al. 2017. The results are depicted in the figure

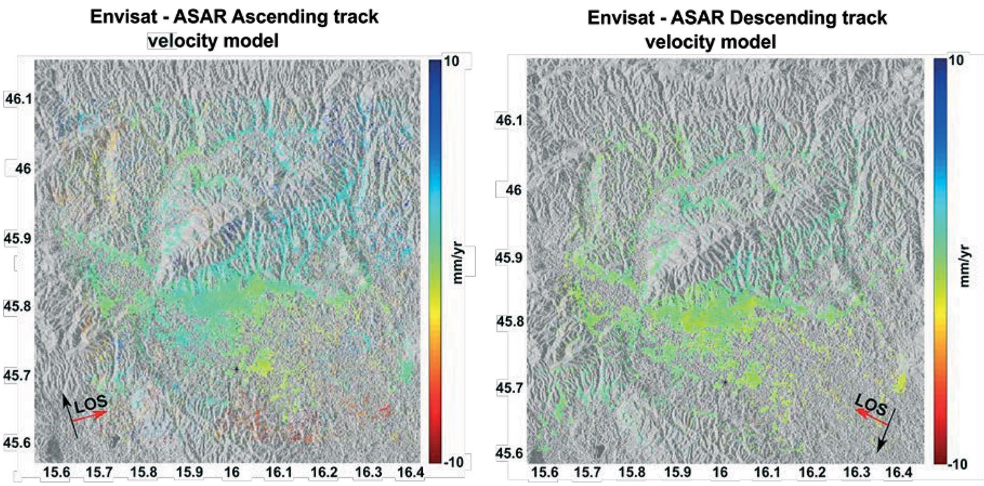

Fig. 3 – Envisat ASAR MT-InSAR results

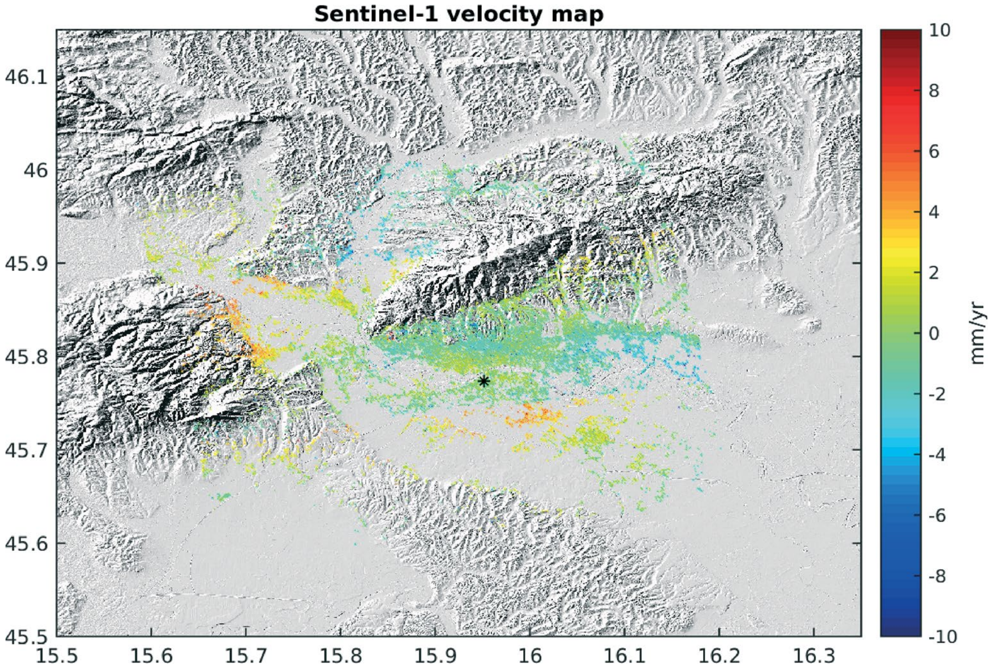

Fig. 4 – Sentinel1 MT-InSAR results

Envisat-ASAR data provided first PS results over the area of interest and revealed that the area is prone to a high level of temporal decorrelation due to a vegetation cover. The processing revealed that a high level of noise in the interferograms can be expected already with a temporal baseline above 30 days and a spatial baseline of 300 meters between two C-band spaceborne SAR acquisitions. The next MT-InSAR application was performed with Sentinel-1 data in 2017. Sentinel -1 is a part of European Space Agency program Copernicus comprised of two satellites carrying C-band SAR instrument. The first satellite Sentinel-1A was launched on April 2014 and the second Sentinel-1B on April 2016. Sentinel 1 is a state-of art space program that proved to have an excellent orbit and acquisition control keeping the spatial separation between acquisitions over the same area around 100m. Moreover, a temporal baseline of the mission was defined with revisit time of each satellite, which is 12 days with a 6 days difference between them. Therefore, it was expected to achieve an improved signal to noise ratio in interferogram stack with Sentinel-1 data, which would provide a more reliable velocity model of the area. The PS MT-InSAR processing was carried out with SarPROZ software on 41 Sentinel-1 images covering the period 2015-2017. Only swath 2 imaging mode was processed with a defined area of interest. The result was a velocity map with an average range of values between -2 and 2 millimeter per year on 33731 PS points. All MT-InSAR are one dimensional line-of-sight values that represent the movement towards to or away from the satellite under the viewing angle.

Discussion

The MT-InSAR results show overall small amplitudes of surface velocities in the area. The model reveals more or less no surface deformation in the urban parts of the area with an exception of a few possible locations of the landslide activity. The MT-InSAR research confirmed that the area experiences a very slow ground deformation processes with no significantly emphasized geodynamical activity. Nevertheless, it does not necessarily mean that there is no risk for future seismic hazard events, especially taking into account that the last series of strong earthquakes occurred ~120 years ago. We imply that future research needs to be considered with new satellite missions. The Sentinel-1 results are very promising and we expect to obtain more reliable results with a longer time span of investigations. Moreover, we detect several other possible applications for MT-InSAR that need to be considered. The first one concerns the monitoring of structure stability in the city. The results indicate a potential deformation activity on the bridges over the Sava River that needs to be further investigated. Second, according to the Croatian Geological survey in 2011, there are more than 700 registered landslide locations in the urbanized city area. MT-InSAR results correlated with some of the known landslide locations, especially with the largest one called Kostanjek. Nevertheless, further analysis needs to be done in landslide investigation with MT-InSAR technique in the area. Moreover, another possible MT-InSAR application in future could concern the ongoing Zagreb aquifer depletion. According to Nakić et. al. 2013 and references therein, groundwater levels are already on their minimum levels (defined as the upper elevations of the well screens) in some well, whereas the total annual abstraction from the well fields exceeds the annual renewable groundwater reserves. Depletion of groundwater reserves definitely presents a potential threat to the city as could eventually result in the following subsidence events.

Conclusions

MT-InSAR has proven to be a useful tool for surface deformation monitoring over wide areas. The MT-InSAR research over the wider Zagreb area has shown that the area exhibits a slow deformation processes that could eventually lead to a strong earthquake and it is necessary to continue with further research. Moreover, the MT-InSAR results show promising applications in other geological processes. The potential applications in the wider Zagreb area could be monitoring landslide activities, structure stability and potential aquifer depletion effects.

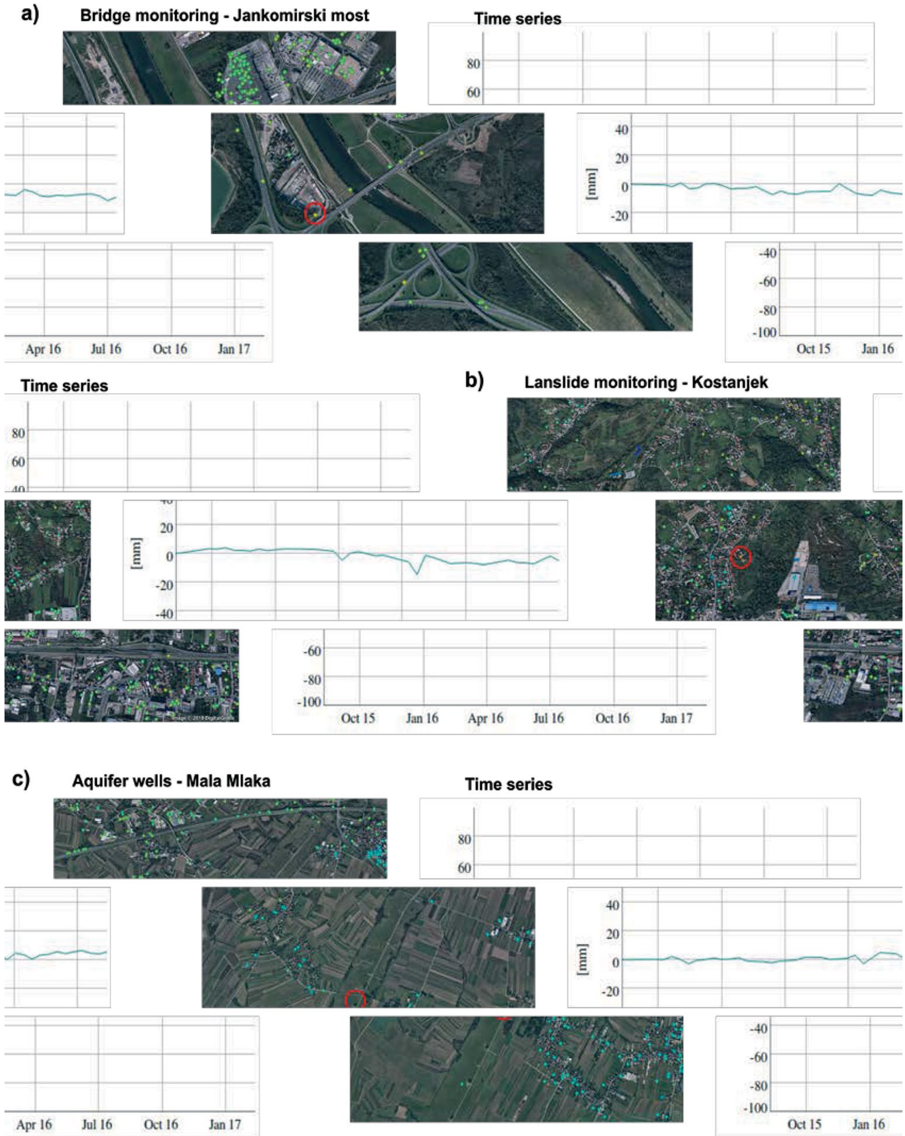

Fig. 5 – Other MT-InSAR applications over the wider Zagreb area: a) landslides b) structure stability and c) aquifer depletion monitoring **Fig. 5** – Other MT-InSAR applications over the wider Zagreb area: a) landslides b) structure stability and c) aquifer depletion monitoring

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URL2 InSAR figure Source: http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/geodetic-techniques/interferometric-synthetic-aperture-radar (last accessed: March 13, 2018)