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The Earth Surface Stability Observation by Satellite Radar Images

Yer Yüzeyi Kararlılığının Radar Uydu Görüntüleriyle Gözlenmesi

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Abstract

Remote sensing is the art of acquisition of information about any objects (such as the Earth) without making any physical/close contact. Remote sensing has many vital civilian and none-civilian applications. Interferometric Synthetic Aperture Radar (InSAR) is a radar technique used in geoscience and remote sensing to measure the Earth surface deformation from 800 km above the Earth. In particular, Permanent/persistent/point-like Scatterer Interferometry (PSI) is a powerful remote sensing technique, which is able to measure the deformation on the Earth's surface over temporal baselines. This technique was developed to estimate the temporal characteristics of the Earth's deformation rates from multiple radar images acquired over time (series). This paper reviews InSAR and PSI techniques, and explains the current state of the art and potentials of the available radar remote sensing techniques. One case study is examined, pertaining to well-known deformation problem in the Mexico City area.

Keywords: *Remote sensing, Mexico City, InSAR, PSI, ENVISAT-ASAR, GPS*

Özet

Uzaktan algılama, yeryüzündeki objeler hakkında herhangi bir fiziksel temas olmaksızın bilgi elde etme sanatıdır. Uzaktan algılamanın birçok sivil ve resmi uygulama alanları vardır. Interferometrik Sentetik Açıklıklı Radar tekniği (InSAR) yer yüzeyi deformasyonlarının ölçülmesi amacıyla yer bilimleri ve uzaktan algılama alanlarında kullanılmaktadır. Özellikle, Sabit saçıcılar (Persistent Scatterers Interferometry: PSI) interferometri tekniği ise, yer yüzeyindeki deformasyonları zamansal bazda ölçme yeteneğine sahiptir. Bu teknik, çok zamanlı radar görüntülerinden yer yüzeyine ilişkin deformasyon oranlarının zamansal karakteristiklerinin belirlenmesi amacıyla geliştirilmiştir. Bu makalede, InSAR ve PSI teknikleri açıklanmakta ve en son geliştirilen/kullanılan tekniklerin kullanılabilirliği analiz edilmektedir. Makale kapsamında, Mexico City'ye ilişkin örnek bir çalışma incelenmiştir.

Anahtar kelimeler: *Uzaktan algılama, Mexico City, InSAR, PSI, ENVISAT-ASAR, GPS*

1. Introduction

Radar ElectroMagnetic (EM) waves are barely influenced by clouds and/or atmosphere, except for very heavy rain and/or tornados, etc.; therefore, radar remote sensing is known as a unique tool for monitoring the Earth's surface deformations in almost all conditions. The word Radar, an acronym for "RAdio Detection And Ranging", refers to a specific band of EM waves as well as an engineering system. An engineering system has three functionalities: a transmitter, a receiver, and a processing system. In the radar system, antenna is a device for coupling energy between the outgoing and transmission lines. In remote sensing, different kinds of antennas exist such as disk like, spiral, or series of antennas etc. The Synthetic Aperture Radar (SAR) is a specific kind of side looking radars mounted on an aircraft, satellite, or even on the ground devices. EM signals are sent to the Earth's surface orthogonal to the orbit direction, and the backscattered EM waves are collected from the scatterers.

The SAR system was primarily tested for ocean studies on the Seasat satellite in June 1978. The SIR-A, SIR-B, Cosmos-1870, ALMAZ-1, ERS1&2, JERS, SIR-C/X-SAR, ENVISAT, RADARSAT1&2, ALOS, CosmoSktmed, TerraSAR-X, and Sentinel were the other SAR systems that launched one after another.

The launch of ERS-1 in July 1991 initiated a new era of Interferometric Synthetic Aperture Radar (InSAR) with which we are now acquainted. When the radar antenna moves forward in a specific trajectory, it allows to record the very high-resolution radar images with the help of advance signal processing. SAR interferometry has earned a considerable reputation in environmental science, oil and gas industries, engineering, and Earth surface deformation etc. Interferometry concepts, phase information, and tracking of transmitted and received EM waves are the fundamental concepts of the methodology. SAR data are acquired either by two antennas or by using repeated pass acquisition in the same orbit. Earth surface displacement monitoring with InSAR methodology is also possible with repeated pass arrangement. For deformation mapping of an area, two InSAR coherence images, one taken before and one taken after the deformation, would be suffice. It is enough to measure the phase attributes of the target during the time period. This approach works better for urban areas (man-made objects), as the backscattered EM signals are more stable during this period. Since the InSAR is a side-looking system, geometric distortion (such as layover, foreshortening, and shadows) of acquired images is one of the main limitations of the technique. The cost-effectiveness and availability of the InSAR data are two important advantages of these kinds of systems for monitoring the man-made targets.

Permanent Scatterer Interferometry (PSI) is one of the greatest inventions in the field of satellite remote sensing, which uses SAR image time series. This technique is a more advanced implementation of the well-known Differential Interferometric Synthetic Aperture Radar (DInSAR) approach, which has been employed for more than 20 years for monitoring the Earth's surface deformation and/or man-made structures. The InSAR time series methods work better on man-made structures or urban areas, where the radar backscatters are more abundant. In the original DInSAR approaches, radar coherency, geometrical decorrelation, and phase delay of the atmospheric effects on radar signals are three important limitations. Man-made targets such as, buildings, highways, railways, pipelines, etc. remain coherent for a long temporal baselines (Ferretti et al. 1999, 1999, 2000, 2001; Usai and Hanssen 1997). The PSI or PS (Permanent Scatterer) was developed to overcome the coherency problems of backscatterers in repeated pass (i.e. time series of) SAR interferometry.

The PSI technique was developed by some researchers in the university of Milan in Italy (Ferretti et al. 2000, 2001). A number of other similar methodologies have been developed as time passed. The Small BAseline Subset (SBAS) is another similar well-known time series radar interferometric approach (Berardino et al. 2004; Lanari et al. 2004; Pepe et al. 2005 and 2007). The difference between these two approaches is: in the PS approach, all InSAR coherence images are employed regardless of their spatial baseline variations; whereas in the SBAS methodology, some of them are ignored due to high spatial baseline arrangements. Geometric and temporal de-correlation errors of the InSAR approaches are more important in the SBAS, compared to the PS data analysis (Berardino et al. 2004; Lanari et al. 2004). The SBAS generates much more radar interferograms than the PS approaches. The SBAS and PS approaches also have different unwrapping procedures: the interferograms are unwrapped first spatially and then temporally in the SBAS, and the opposite is done in the PS data analysis. Disconnected clusters of generated interferograms may sometimes occur in the SBAS approaches. However, in the SBAS approaches, not only permanent scatterers can be used, but also distributed scatterers, with much moderate coherence, can be included in the analysis. For all of the abovementioned differences between SBAS and PSI techniques, a number of researches tried to proposed the innovative solutions in order to benefit from the advantages of both methods. The one great example for the minimization of the temporal baselines and employment of the InSAR coherence images with the SBAS approach was provided by Pepe et al. 2011. Mora et al. 2003 presents another similar approach. Hooper et al. 2004 gave a geophysical approach and Crosetto et al. 2005 discussed on a stepwise linear deformation with least square adjustment models. The Interferometric Point Target Analysis approach was given by Werner et al. 2003 and stable point networks approach was presented by Crosetto et al. 2008. In Ferretti et al. 2000, the PSI and small baseline analysis were combined heuristically: multiple imageries' pixels were employed within a certain radius to measure spatially correlated parameters. Ferretti et al. 2011 explained the SqueeSAR approach, which is capable of employing the PS and distributed scatterers approaches. This approach helped monitor rural areas where the coherency was limited. Contribution of fully polarimetric InSAR data was heuristically discussed by Navarro-Sanchez and Lopez-Sanchez 2013.

In PS technique, a large number of coherence images are used to estimate the changes on the Earth's surfaces in temporal domain. Historical deformation time series of the radar backscatterers, and the height of those scatterers are the results of PS techniques. In the PS approach, the pixels with high radar coherency during the temporal baseline are exploited. In general, more than 20 InSAR imageries are used to estimate and remove the atmospheric errors. In the PS data analysis, a master image is selected considering specific criteria (among K imageries), and $(K - 1)$ interferograms are produced with respect to the master image.

Then, with a number of different models, permanent scatterer candidates are selected. Final permanent scatterers can be produced through further refinements made on the selected permanent scatterer candidates (Kampes, 2005). Temporal changes in height for the Earth surface's, and the height of each PS with respect to a reference point, are the outputs. In man-made areas, the PS approaches can achieve an average of 100 PSs/ km^2 (points densities) with low resolution satellites such as ERS1/2 and ENVISAT-ASAR, and an average of a couple of thousands PSs/km^2with high resolution sensors like TerraSAR-X and Cosmo-SkyMed data. Since the permanent radar scatterers are limited, the rural/vegetated areas might not be explored properly with the PS techniques. The PS approaches need a minimum amount of InSAR coherence images for phase unwrapping steps, which could severely influence the degree of correctness of the selected PS candidates. PS (and SBAS too) is basically a relative approach, which means all of the calculated time series for InSAR time series points are measured with respect to a pre-defined reference point; Continuous Global Positioning Systems (CGPS) or leveling methodologies can help rectify this problem (Kampes, 2005). Another drawback of the PS is the observation geometry of the satellite: PS deformation measurements are given along the satellite line of sight direction; therefore, the measured deformation rates are just the projection of the deformation vector onto the SAR look direction, not absolute deformation in vertical or horiziontal directions.

2. Application of InSAR for the Earth surface monitoring review

In this section, we discuss some of the most essential applications of InSAR approaches in environmental science. Several important InSAR applications have been carried out by research communities, academic, and specialized companies; and have been reported in the scientific journals (see, for example www.npagroup.com, www.altamira-information.com, and www.gamma-rs.ch).

One of the most elegant and important applications of the radar monitoring is about man-made areas. Huge areas can be monitored through high-resolution InSAR coherence images with proper revisiting schedules. The estimation of the deformations on the Earth surface with InSAR data is currently done for several cites around the Earth. For example, in the PanGeo monitoring project (http://www.pangeoproject.eu/eng/project_overview), more than 52 european cities of the Europe in which 13% of these cities have a metropolitan population, were under this kind of monitoring continually.

PanGeo gives online deformation data based on the InSAR techniques for possible geohazard problems. However, PanGeo data are generated based on low-resolution InSAR coherence images, and no detail information in their area is given. For instance, these datasets might not be very helpful for studying a single building or a bridge. Dixon et al. 2006 presents a detailed study on a single target with InSAR coherence images of C-band. In Zerbini et al. (2007), the Bologna region and Po Plain (Italy) are the test sites for their InSAR work using the ERS and RADARSAT data. In Osmanoğlu et al. 2011, deformation in Mexico City metropolitan area due to water extraction was investigated with the C-band ENVISAT data. Telerilevamento Europa (www.treuropa.com) runs a big program for monitoring the deformation that occurs due to oil and gas extractions.

Tectonic/Fault deformation surveillance based on InSAR coherence images is also one of the prominent uses of the the InSAR remote sensing approaches. Lyons and Sandwell (2003) show that fault creeping measurements based on ERS InSAR data might be translated to the fault's future activities.

Landslide surveillance is one of the most important subjects of the InSAR remote sensing studies (see some examples in Colesanti and Wasowski, 2006, and Kimura and Yamaguchi, 2000).

In the Netherlands, InSAR remote sensing monitoring of dikes and dams is a common task for water defense systems evaluation (see Hanssen et al. 2008).

In Lazecky et al. 2017, the bridge deformation was found with the use of very high resolution X-band imageries. In Hanssen et al. 2015, RADARSAT-2 images were employed to monitor the railway deformations in the entire Netherlands, for a temporal baseline between 2010 and 2015.

Finally, in Poreh et al. 2016, the bridge movements in Campania (Italy) area were studied with high (spatial) resolution X-band Italian CosmoSkyMed imageries. They concluded that most of the movements on the railways were related to periodical/temporal changes of the temperature, and that the bridge was safe to run the trains.

3. A case study: monitoring the subsidence in the Mexico City

In this section, subsidence of Mexico City area due to excessive water withdrawal is discussed. This study focuses on this problem utilizing the InSAR and Continuous Global Positioning Systems (CGPS). Fifty-two ENVISAT and nine permanent GPS stations from Mexico City area were used to monitor the subsidence of Mexico City's area. The radar data covers a time span of 2002-2010, and the GPS data covers a time span from 1998 to 2012. Based on the InSAR data, a maximum of 352 mm/yr deformation in LOS direction is measured.

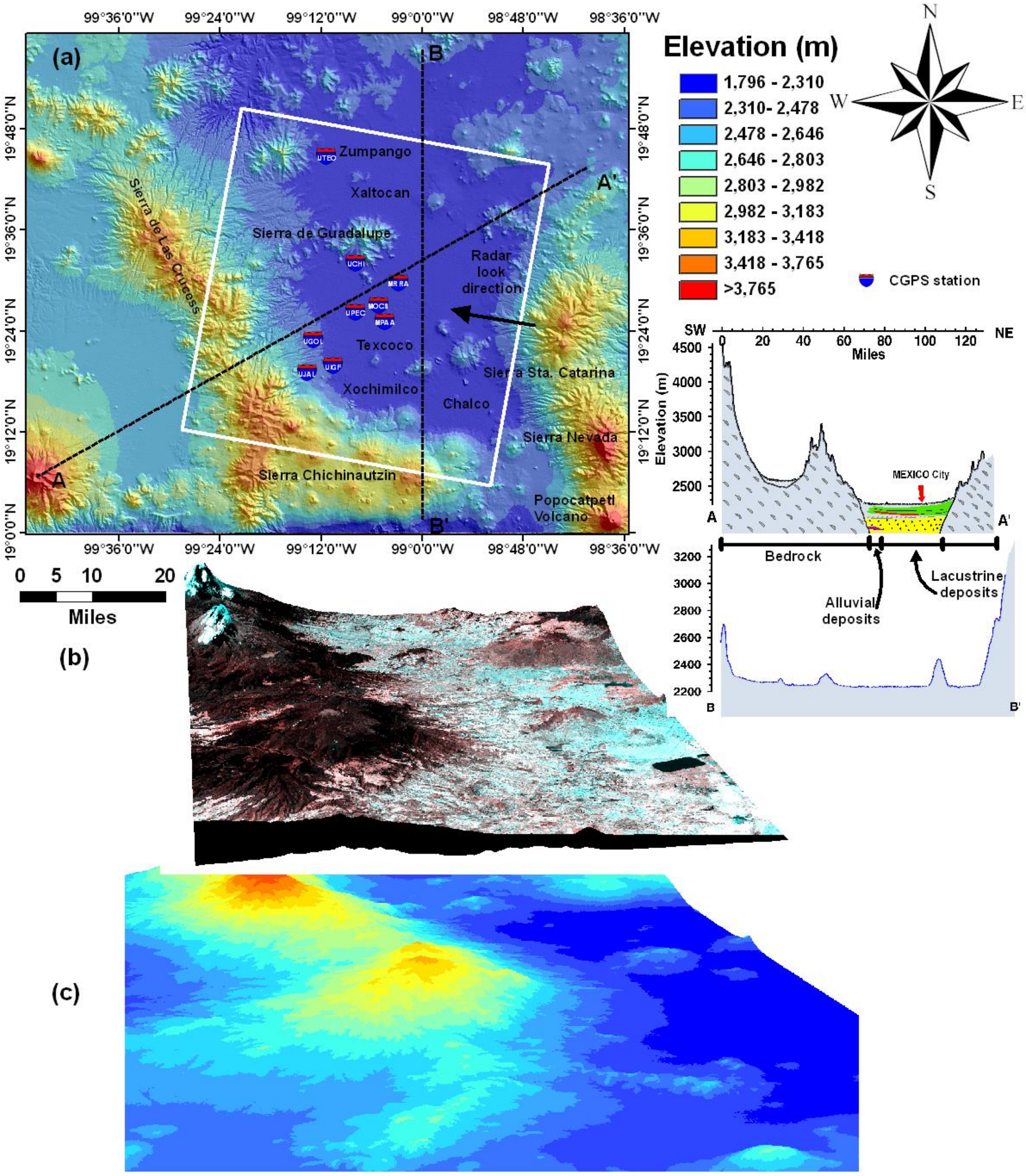

Figure 1. a) Mexico City topography map and installed CGPS stations in the metropolitan area. White rectangle shows the InSAR data coverage area in descending mode. b) 3D view of the study area with Landsat ETM+ imagery from 25/11/2005. c) 3D representation of Mexico City area (Poreh and Pirasteh, 2019)

Mexico City's (see Figure 1 and 2) subsidence began in the 1840s and expanded in the 1930s and 1950s. The Mexico City's soil comprise highly compressible clays, and the mechanism of the subsidence in Mexico City lacks enough natural water recharge, and consequently, compaction of the soil layers. The compaction of the overlying geological layers plays also a crucial role in the deformation mechanism.

Much of the deformation occurs in the irrecoverable, heavily pumped area, and results are loss of aquifer storage and damages on engineering structures. This subsidence accelerated since the 1950s, and several correlated structural damages were observed in the study area. More than 20 million (http://www.unesco.org) inhabitants in the Mexico City area are facing this extraordinary land subsidence problem (see Figure 2). For instance, in Mexico City's cathedral which took more than 250 years to build, one side is deformed nearly 2.44 meters deeper than the other side, and it is leaning to the left side.

Figure 2. Surface deformation in Mexico City area (The Geodesy Lab)

Figure 1 shows the study area with GPS station locations and InSAR data coverage. Nine GPS stations (Figure 4) and thousands of PSs form ENVISAT-ASAR imageries have been used. The GPS data are from the University of Mexico City, and employed as ground truth and/or calibration tool for the InSAR data. Given more than eight years of GPS and InSAR data overlap, the two independent methodologies provided a picture of deformation in the Mexico City and its surrounding area for the first decade of the 21st Century.

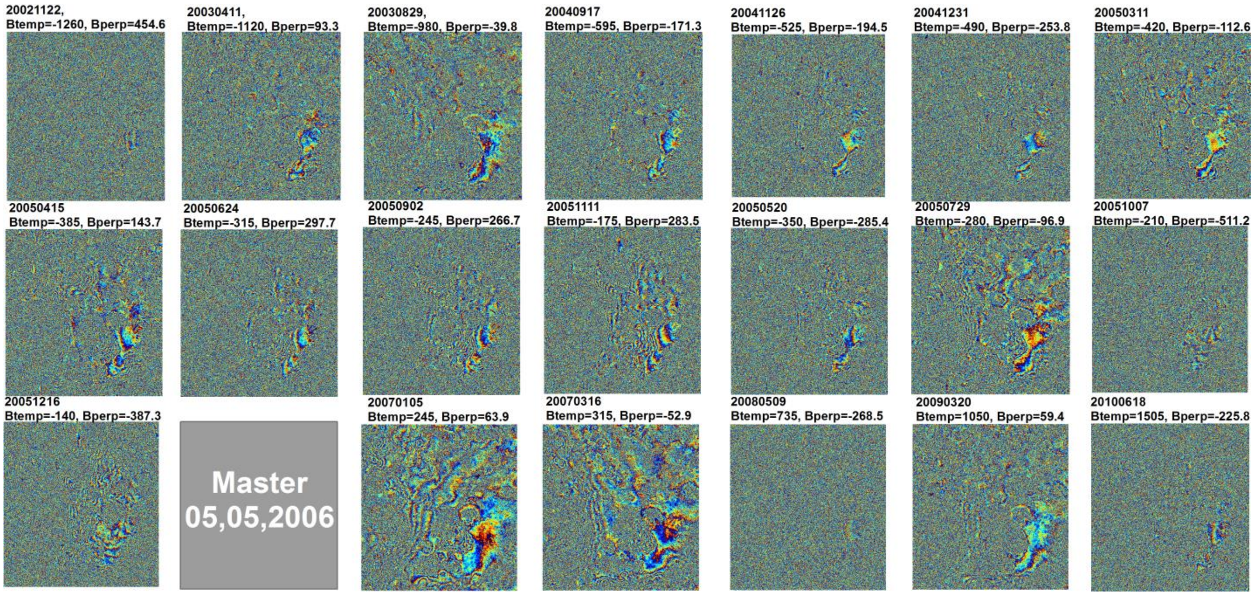

Figure 3. Some of the generated differential interferograms (from 51 interferograms) for Mexico City study area. Image 05.05.2006 is selected as the master image. Image acqusition time, temporal (Btemp), and perpendicular (Bperp) baselines are given on top of the interferograms

Image 05/05/2006 has been selected as the master image to minimize the effectiveness of the spatio-temporal baselines. The InSAR coherence images cover an area (Figure 1) of around 62 km×56 km and are centered over the Mexico City downtown. Some of the differential interferograms (from 51 interferograms) are given in Figure 3. Three well-known PSI/unwrapping approaches of ILS, bootstrapping, and periodogram results are given in Figure 5. As can be seen, there are not significant differences between the methodologies, and all of them presented similar results (sometimes the number of PSs (radar reflectors) are slightly different). Deformation rates and its extensions can be measured with the InSAR approaches. GPS data also can be used for calibration and InSAR data evaluation. If reference point of InSAR data is selected with the help of GPS measurements, then absolute deformation rates can be conducted over the study area.

Some of the widely used packages/softwares for InSAR and/or PSI processing are listed as: DORIS, ROI-PAC, ScatterersTM, GMTSAR, GAMMA, SARscape, PulSAR, DIAPASON, RAT (RAdar Tools), StaMPS, MintPy-Miami InSAR time-series software, and SNAP ESA's InSAR software.

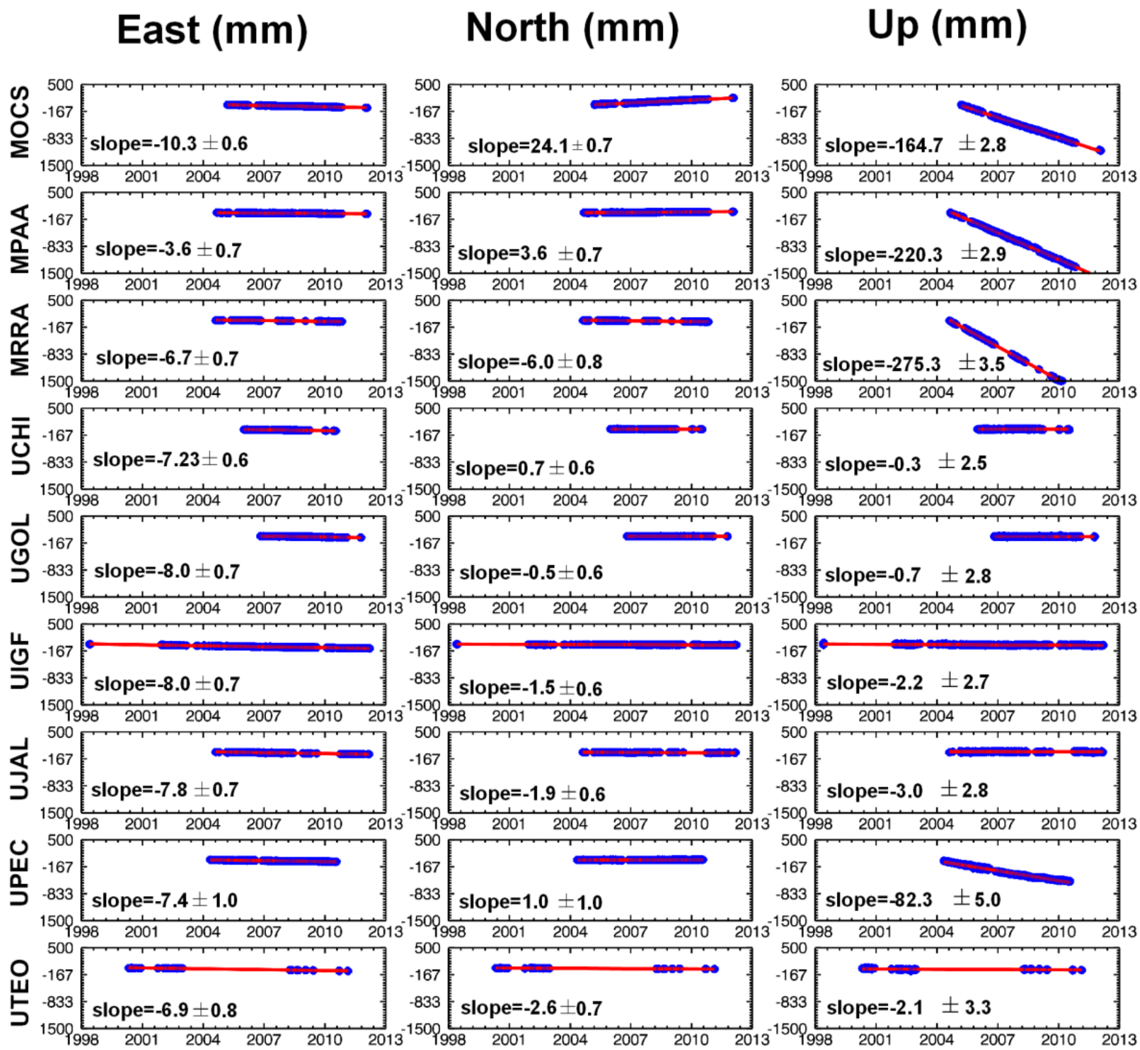

Figure 4. North, east, and vertical components of deformation based on GPS stations (Poreh and Pirasteh, 2019)

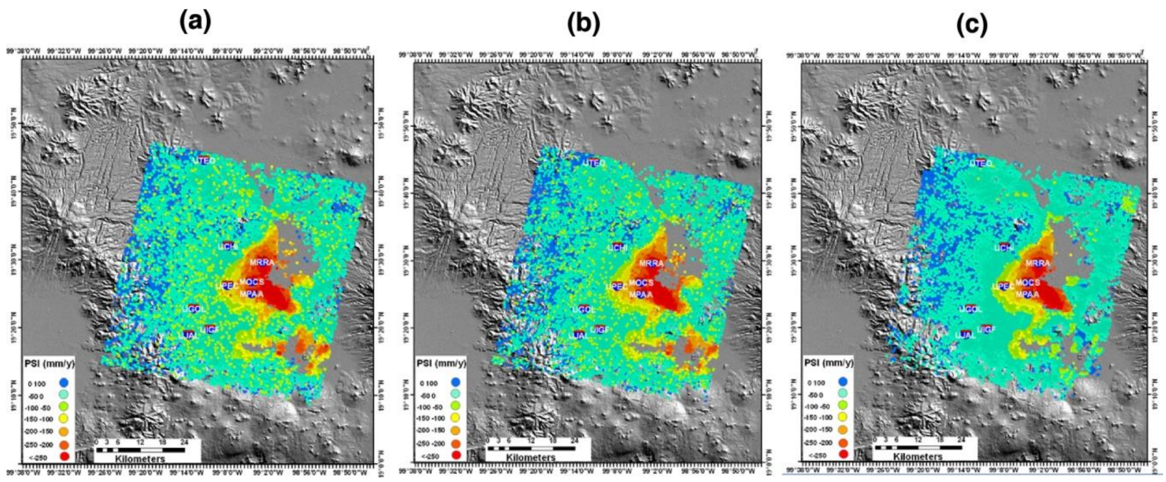

Figure 5. PSI deformation rates for Mexico City area for temporal baseline of 2002-2010 with a) Bootstrapping, b) ILS, and c) Periodogram approaches

4. Discussion and Conclusions

Monitoring the Earth surface based on radar remote sensing and InSAR time series is discussed in this study. The characteristics, benefits, and disadvantages of each InSAR time series techniques are highlighted. Since phase measurements are used in the InSAR systems, the wavelength characteristics of the radar systems are essential. L-band (24 cm), C-band (5.8 cm), and X-band (3 cm) are among the most common radar wavelengths. EM waves tend to interact with objects similar in size to the EM wavelengths. Meanwhile, surfaces appear rougher for shorter wavelengths. Compared to the shorter wavelengths (X-bands), longer EM waves (L-bands) are able to penetrate the vegetation, dry soils, and ice more deeply.

The most important practical point of InSAR data analysis is the availability of radar images for generation of interferograms. Given the limited re-visiting radar data and InSAR geometric problems, InSAR time series approach can not always be used for real-time monitoring porposes, and must be used parallel to the other surveillance methods.

In the case study, the deformation of Mexico City area is discussed. The extraction of groundwater from central part of Mexico City causes significant land deformation in the metropolitan area. We address the mechanism of this deformation based on GPS and InSAR coherence images. While several recent studies pointed out the potential of using InSAR data to assess the deformation rates in Mexico City area, we must stress that in some cases the unwrapping errors might cause significant errors in estimation of deformation rates; meanwhile, combination with other independent geodetic techniques such as GPS is essential. GPS stations were also used for calibration of InSAR time series. Three different InSAR unwrapping techniques show similarity on intensities and extension of the deformation rates. The combination of InSAR and GPS observations holds promise for high resolution mapping of Mexico City area deformation because of on groundwater depletion. GPS has a low resolution (only nine stations) data, but they measure the absolute deformation rates (i.e., absolute deformations in the north, east, and vertical); InSAR has high resolution, but not direct measurements: InSAR data is a relative method. The increasing coverage of the study area, high revisiting periods, and availability of InSAR data will encourage land subsidence/deformation mapping at InSAR scale of applications.

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