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TERRASAR-X DINSAR FOR LAND DEFORMATION DETECTION IN JAKARTA URBAN AREA, INDONESIA

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Abstract: The X-band synthetic aperture radar (SAR) on board the TerraSAR-X satellite is useful for land subsidence detection and monitoring, since the sensor provides high spatial resolution data with a relatively short repetition cycle of 11 days. Jakarta is one of the largest cities in the world with population more 10 million as of 2011. The area has been suffering from significant effects of land subsidence that causes damages to public facilities, buildings, and other public and private properties. In this work, we exploit the capability of TerraSAR-X for detecting land subsidence in Jakarta during a four year period between 2010 and 2013 using differential interferometry SAR (DInSAR) technique. Our analysis reveals that two northern areas in the city exhibit clear indications of land subsidence varying from 8.5 to 17.5 cm/year, mostly caused by intensive human activities in addition to the vulnerability due to geological structuresof these areas.

Keywords: Land deformation; urban area; TerraSAR-X; differential interferometry SAR

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INTRODUCTION

Jakarta is the largest city of Indonesia, inhabited by a population of 10 187 595 people in 2011 (Dinas Kependudukan dan Pencatatan Sipil Provinsi DKI Jakarta, 2011). As the capital city of Indonesia, Jakarta is a vital area for various government and economic activities. With urban development accompanied with the population growth in and around the city, however, concerns on various environmental problems have intensified during recent decades (Krank *et al*., 2009). Land subsidence is one of such problems of general public concern, and the problem is caused by several factors such as excessive extraction of ground water and natural consolidation of soil (Anisuzzaman *et al*., 2013). In addition, land subsidence can potentially be the cause of other problem such as change of topographic gradients, rupture of land surface, and reduction of aquifer capability of storing groundwater (Holzer *et al., 2005*). In Jakarta, land subsidence was one important cause of the disastrous flood that occurred in January 2013 (Geospasial Badan Nasional Penanggulangan Bencana, 2013). Hence, it is necessary to accurately detect and analyze land subsidence in the capital city for effective flood mitigation as well as for better planning of future urban development.

Differential Interferometry Synthetic Aperture Radar (DInSAR) has been known as a remote sensing technique to measure land displacement because of the resolution and accuracy provided by the technique (Bayuaji *et al*., 2010; Stramondo *et al*., 2006; Tralli *et al*., 2005). Another important advantage of DInSAR is that the method enables the study in large areas that are inaccessible by means of ground-based observation methods, such as the application of global positioning systems (GPSs) and leveling measurements (Raucoules *et al*., 2007).

The subsidence phenomena in Jakarta have been studied using ALOS PALSAR data with a spatial resolution of 10 m (Bayuaji *et al*., 2010; Abidin *et al*., 2007). In comparison, the TerraSAR-X data provides a much higher spatial resolution of 1 m owing to the use of X-band SAR based on active phased array antenna technology (Hermann *et al*., 2007; DLR Cluster Applied Remote Sensing, 2006). The ability of TerraSAR-X data to analyze subsidence in urban area has been proven in previous work (Bayuaji *et al*., 2012). In this study, even though the TerraSAR-X uses shortest wavelength (3.1 cm), it has one advantage, i.e. using the highest spatial resolution compared to other data. Since the launch in 2007, the TerraSAR-X data have been applied to several

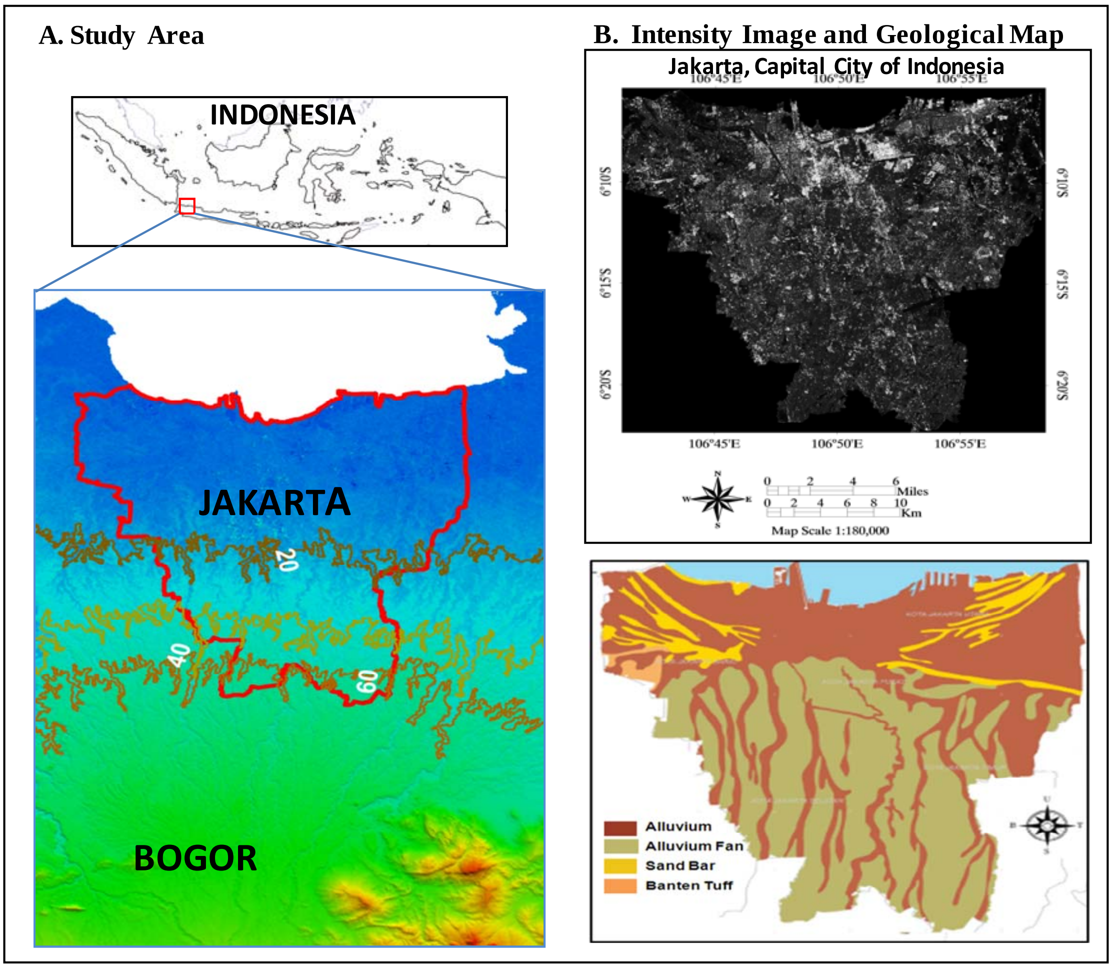


Fig. 1 (a) Map of Jakarta basin and (b) Intensity image and geological map of Jakarta urban area.

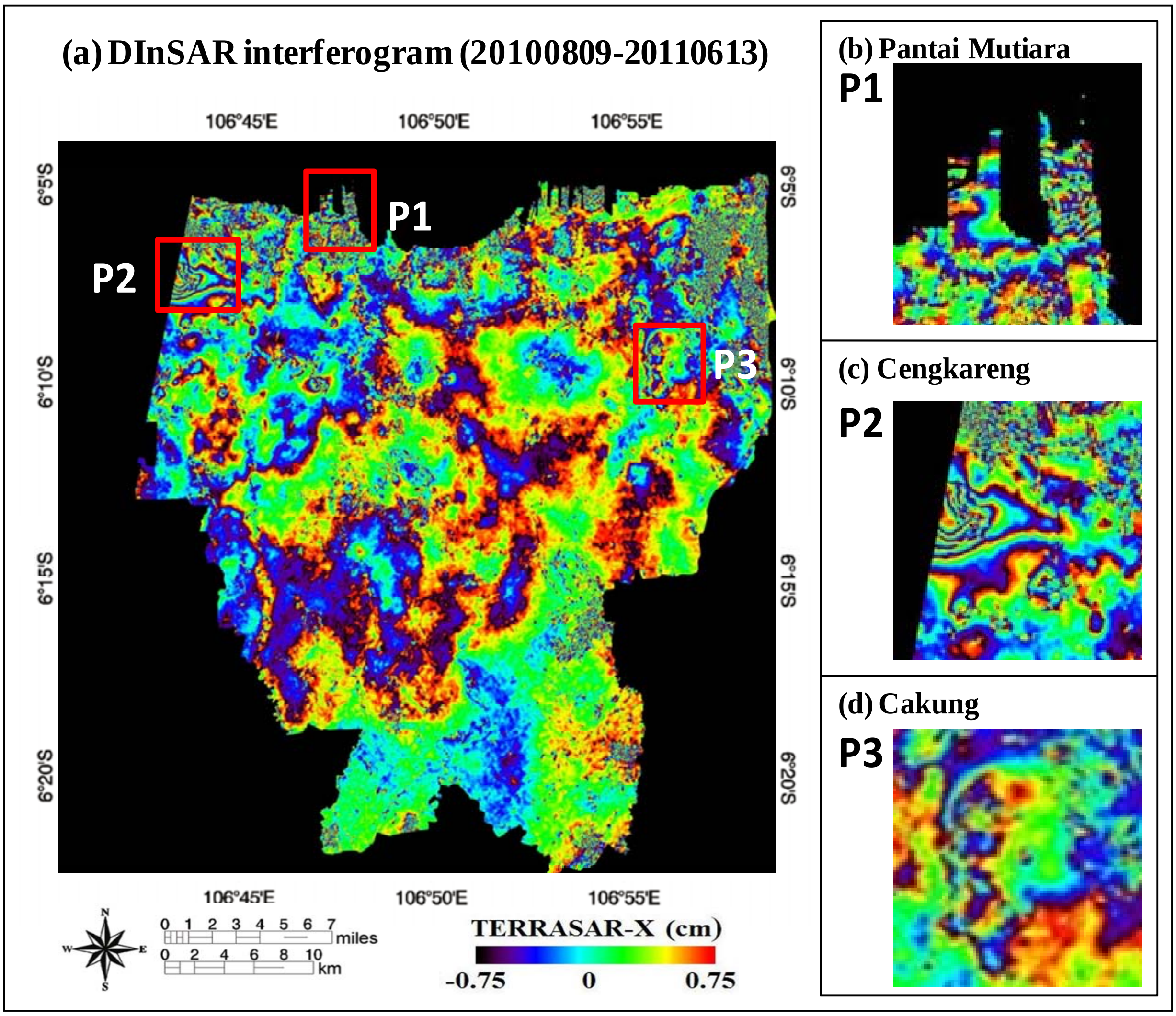


Fig. 2 The observation area of TerraSAR-X data using DInSAR: (a) Jakarta urban area, (b) Pantai Mutiara [P1], (c) Cengkareng [P2] and (d) Cakung [P3].

subsidence studies (Bayuaji *et al*., 2012; Monells *et al*., 2010; Herrera *et al*., 2010). However, to the best of the authors' knowledge, the usage of TerraSAR-X data to detect land subsidence in Jakarta has never been reported in previous literatures. In this research, the DInSAR analysis is implemented using the TerraSAR-X data from 2010 to 2013. The result of satellite analysis is compared with ground survey data taken by previous study in 1997–2005 to confirm the reliability of the proposed method.

Study Area

Jakarta is located on the northwest coast of West Java province with geographical location between 106º33′00″–107º00′00″E longitude and 5º48′30″–6º24′00″S latitude. Due to its topographical conditions, the area is relatively flat in both the northern and central parts with slopes ranging between 0 and 2º. The altitude of southernmost area, on the other hand, is about 60 m above sea level. The northernmost area has altitude below 20 m above sea level and the other areas are higher (**Fig. 1a**). The geological information of Jakarta urban area is shown in **Fig. 1b**, which is mostly dominated by alluvium fan sediment. This sediment type is young sediments derived from streams sedimentation that are generally composed of alluvium.

Jakarta urban area has 13 natural and artificial rivers for delivering public water. This area has humid tropical climate with annual precipitation condition about 1755 mm (69.1 in) or 146 mm (5.8 in) each month. The population of Jakarta has grown rapidly due to the urban development. Based on the census data taken in 2011, Jakarta has population density of 15 400 per km^2. The most resent population density data of six districts in 2011 was ranging from 2112 to 23 312 per km^2. Land subsidence is one of consequences of the urban development in Jakarta. In 1926, a Dutch surveyor made estimation about the existence of land subsidence in Jakarta city (Abidin *et al*., 2005). The leveling measurement was employed in the course of 1982–1999 by scientific surveyors (Djaja *et al*., 2004). The GPS measurement of land deformation was also conducted during 1997-2005 for some selected area in the city (Abidin *et al.*, 2008).

DATA AND METHODOLOGY

TerraSAR-X Data

TerraSAR-X is a German satellite program that was commercially launched on 15 June, 2007. With its active phased array X-Band SAR antenna, TerraSAR-X system is capable of acquiring data in three different imaging modes with different resolutions: Stripmap mode (SM), Spotlight mode (SL and HS) and ScanSAR mode. The cycle of its orbit repetition is 11 days and the platform's nominal orbit height at the equator is 514 km with 97.44^o of orbit inclination. The satellite's instrument can operate in dual polarization mode (HV, VH) or single polarization (HH, VV). The bandwidth range of this satellite for experimental mode is up to 300 MHz, while maximum value for the standard mode is up to 150 MHz. TerraSAR-X data provides high spatial resolution of about 3 m and its imagery has high geometric accuracy. Thus, TerraSAR-X is appropriate for detailed mapping of land deformation.

For the time being, the C-band and L-band of advanced SAR-satellite system are generally used in commercial remote sensing applications. The L-Band has long wavelength (i.e. 23.6 cm) which is appropriate for deeper penetration of vegetated areas and reducing temporal decorrelation while the C-band has shorter wavelength (i.e. 5.6 cm) that produces temporal decorrelation over vegetated areas. However, the usage of C-band and L-band for academic research is constrained by their availability since they are not available in public domain.

On the other side, there is X-band of advanced SAR-satellite system that is available for monitoring research. Compared with L-band and C-band, X-band has shorter wavelength (i.e. about 3.1 cm) and confers high sensitivity for land deformation. The effect of extremely short wavelength of X-band in TerraSAR-X improves the quality of the resulted data, i.e. the data has high sensitivity reaction from atmospheric substances like cloud and aerosol.

Data Processing and Software

We processed four TerraSAR-X images of Jakarta urban area recorded between 9 August 2010 and 1 March 2013. The information of temporal and spatial baselines for the six pairs analyzed here is summarized in **Table 1**. The SAR interferograms were computed from the data taken on four different acquisition dates (9 August 2010, 13 June 2013, 14 December 2012 and 1 March 2013). As seen from **Table 1**, each pair has different temporal and spatial baselines. Among the six pairs in **Table 1**, the 6th pair is the most reasonable one corresponding to the shortest temporal baseline of about 11 weeks and the 4th pair is the shortest spatial baseline of about 39.1 m. The DEM was acquired from the Shuttle Radar Topography Mission (SRTM) with a grid resolution of 90 m.

The DInSAR processing using remote sensing software was conducted to obtain the interferogram by utilizing the SRTM DEM of the Jakarta region. The conventional InSAR processing algorithms can not be used directly in TerraSAR-X interferometry. This is due to the fact that TerraSAR-X data has shorter wavelength and higher spatial resolution compared with conventional SAR data in the C-band or L-band. To handle a noisy interferogram, we used the Goldstein-Werner filtering approach (Goldstein & Werner, 1998). Each process was iterated to eliminate noise and produce smooth interferogram. The coefficient adopted in the filtering process was 0.2. The phase unwrapping was carried out to derive the subsidence depth from the interferogram. The resulting slant-range subsidence depth was converted to vertical subsidence depth using **Eq. (2)**. The DInSAR interferogram result was in the form of phase cycles, each cycle was affiliated to ground displacement along the slant-range direction. The TerraSAR-X wavelength is 3.1 cm (X-band) and hence, each cycle in the interferogram represents a ground displacement of 1.6 cm.

The coregistration procedure in TerraSAR-X data must be assisted with an extended DEM (with information on imaging geometry and topography) for the precise determination of the terrain heights by removing the topography phase. Precision ground-control points (GCPs) obtained using geodetic GPS during GPS campaign.

Table 1. TerraSAR-X pair and baseline information

Pair	Master	Slave	Temporal Baseline (week)	Spatial Baseline (meter)
1	20100809	20110613	44	110.5
2	20100809	20121214	122	149.3
3	20100809	20130301	133	138
4	20110613	20121214	78	39.1
5	20110613	20130301	89	248.1
6	20121214	20130301	11	286.3

Note: Date are given as year, month, and day (e.g., 20100809 denotes 9 August 2010)

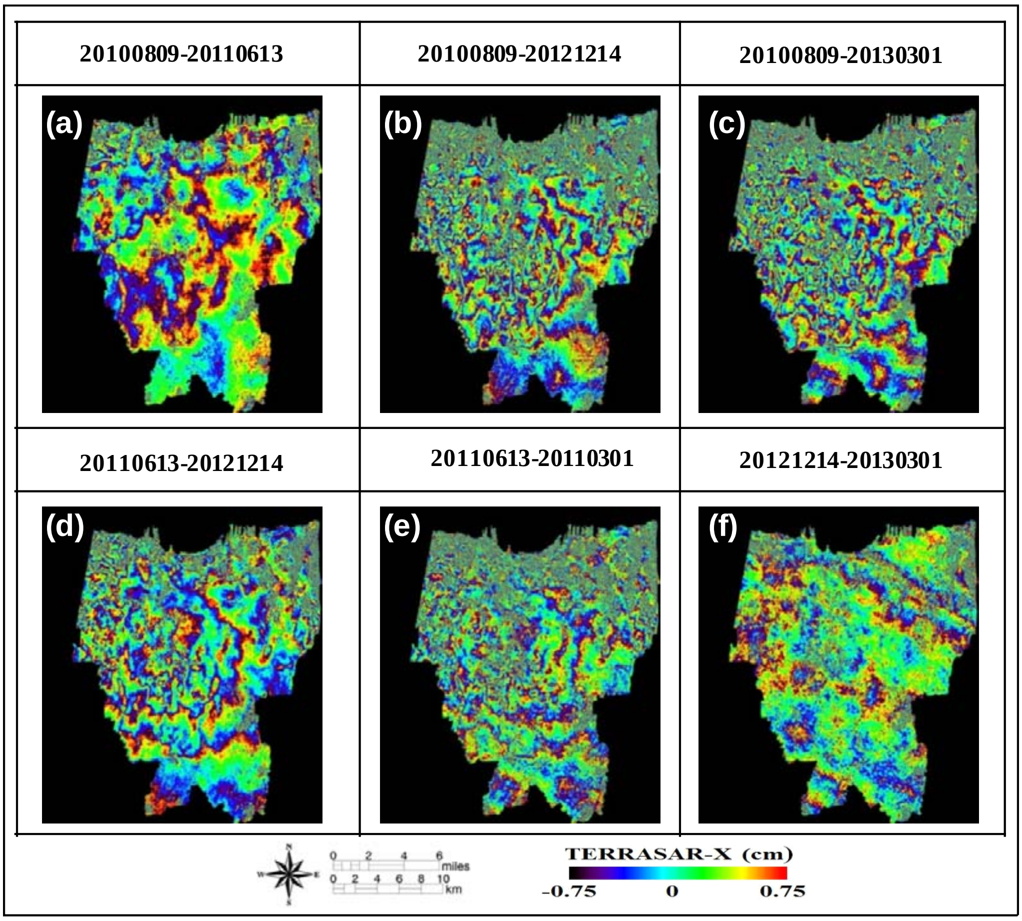


Fig. 3 DInSAR result of TerraSAR-X data pair all pairs mentioned in Table 1. (a) Data pair on 20100809-20110613, (b) Data pair on 20100809-20121214, (c) Data pair on 20100809-20130301, (d) Data pair on 20110613-20121214, (e) Data pair on 20110613-20130301 and (f) Data pair on 20121214-20130301.

DInSAR by Using TerraSAR-X

In the first stage of the DInSAR technique, the phase data of SAR images were analyzed to derive the local topography (original InSAR). Subsequently, the phase difference between the two SAR data obtained at different acquisition times were employed to detect and quantify the ground displacement that occurred in the slant-range direction between the two acquisitions (DInSAR) (Hay-Man, 2012). The two radar images were matched point by point to form the interferogram with the phase difference. The phase modification in the differential interferograms contained errors, such as the error in the digital elevation model (DEM) used for the analysis (DEM error), atmospheric error (or inhomogeneities if its effect is eliminated), residual orbital distortions and surface deformation. The phase difference between an InSAR data pair ($\Phi_{Int,\ P_1-P_2}$) can be derived as follows (Raucoules *et al.*, 2007):

$$\phi_{Int,P_1-P_2} = \phi_{disp,P_1-P_2} + \phi_{topo,P_1-P_2} + \phi_{atm,P_1-P_2} + \phi_{noise,P_1-P_2} + \phi_{flat,P_1-P_2} \quad (1)$$

where ϕ_{disp} is the phase due to the ground displacement, ϕ_{topo} is the phase because of topographical height change, ϕ_{atm} is the phase due to atmospheric effect, ϕ_{noisei} is the phase due to noise from the radar device, ϕ_{flat} is the phase due to error associated with the assumption of the ideally flat earth terrain. In the process of extracting the ground displacement, the topographic (ϕ_{topo}) and flat earth (ϕ_{flat}) phase differences should be eliminated using the DEM data coupled with accurate satellite orbital data. The result of DInSAR technique estimated the ground displacement in the slant-range direction. The ground displacement in the vertical direction, Δz, can be expressed as (Curlander & McDonough, 1991):

$$\Delta z = \Delta s \cos \theta \quad (2)$$

where Δs is the slant-range change caused by the ground displacement, and θ is the incidence angle. In the present study, the entire incidence angles for the target area were in a range of 20–45°.

RESULTS AND DISCUSSION

The DInSAR interferogram for the data pair of 20100809-20110613 are shown in **Fig. 2** for all the city area. In the following, more detailed analysis is made for three particular locations in the region, corresponding to Pantai Mutiara (P1), Cengkareng (P2) and Cakung (P3). All of these points are in the northern part of Jakarta, having mostly sand bar and alluvium geological formations. **Figure 2** indicates that all of these three regions are affected by land deformation that appears as fringe patterns in the DInSAR result.

Although the residential population density is lower than that in the southern part, the economic activity in the northern area is very high, with a large number of commuters and unregistered inhabitants. Harbors and an airport are located in this northern area, along with trading, settlement, industrial, and slum areas. The slum area covers an area of 662 km^2, approximately 35% of the total Jakarta urban area, and this high fraction causes many types of environmental problems in Jakarta (Suara Pembaruan, 2010).

The land usage of Pantai Mutiara (P1) is luxury residence area, trading, seaport, and tourism resort area. Cengkareng (P2) has land use such as settlement area with more than 300 hundred households, besides trading and office regions. Cakung (P3) is the biggest industrial area in Jakarta, covering a wide area of more than 10.33 km^2. **Figure 3** shows the enlarged differential interferogram patterns for each data pair listed in **Table 1**. The longest spatial baseline is 286.3 m for the data pair (f) 20121214-20130301 and the shortest is 39.1 m for the data pair (d) 20110613-20121214. Very similar fringe patterns are seen for the pairs of (b) 20100809-20121214 and (c) 20100809-20130301, characterized with longer temporal baselines of 122 and 133 weeks, respectively.

Generally, the estimation of land subsidence becomes more inaccurate as temporal baseline increases. It delivers the indication that the subsidence continually occurs in Jakarta urban area. Several pairs produced results with a lot of noise and many fringes that might come up from atmospheric disturbance, but the other pairs have clear and good fringes. The maximum subsidence for DInSAR result shows six fringes and corresponds to 17.5 cm/year in **Fig. 5(a)**. The following analysis focuses on the areas P1-P3, for which the fringe patterns in an expanded scale are shown in **Figs 4**, **5** and **6**, respectively. The subsidence occurrences in these areas are expected, since they are formed on alluvial geological structure as seen in **Fig. 1(b)**.

DInSAR results of Pantai Mutiara (P1) are shown in **Fig. 4**. The results in **Figs 4(c) and (d)** exhibit clear interference patterns in the northwestern part, though the number of fringes is somewhat different. **Table 2** summarizes the subsidence rate in Pantai Mutiara estimated from each result shown in **Figs 4(a)-(f)**. It is seen from **Table 2** and **Fig. 4(g)** that the result varies

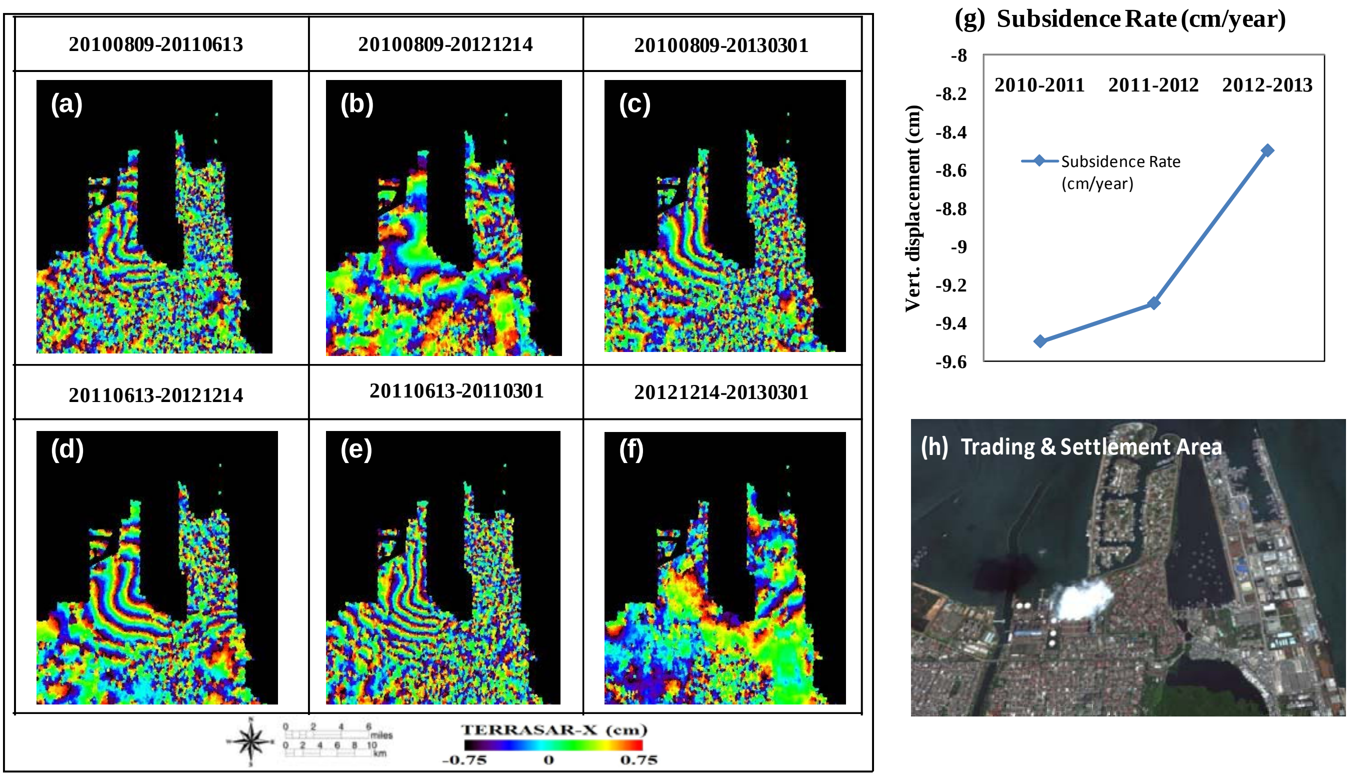


Fig. 4 Pantai Mutiara DInSAR result of TerraSAR-X data pair all pairs mentioned in Table 1. (a) Data pair on 20100809-20110613, (b) Data pair on 20100809-20121214, (c) Data pair on 20100809-20130301, (d) Data pair on 20110613-20121214, (e) Data pair on 20110613-20130301, (f) Data pair on 20121214-20130301, (g) Graphic of Subsidence Rate 2010-2013, and (h) Land Use.

between 8.5–10.9 cm/year. The largest value of 10.9 cm/year has been observed for the pair (f) 20121214-20130301, having the shortest temporal baseline of 11 weeks and the longest spatial baseline of 286.3 m. In 2010, the urban development scheme in the Pantai Mutiara region was a privately funded project comprising ten 30-story residential towers, a 40-story landmark hotel, two 5-story serviced apartment blocks and an 11 ha central waterpark. The development area is located on an island off the Jakarta coastline and the reclamation there started in September 2006, covering an area of about 0.11 km^2. **Figure 4(h)** shows the region of settlement area in reclamation area of Pantai Mutiara.

The effects of land subsidence in Cengkareng (P2) are more pronounced than other regions, as indicated in **Fig. 5**. Cengkareng is located in West Jakarta sub-district and covers a wide area about 27.9 km^2. The maximum land subsidence rate of Cengkareng is 17.5 cm/year, which has been detected for the interference pair of (a) 20100809-20110613. This subsidence can possibly be ascribed to the effects of human activities such as building construction and ground water extraction. According to the statistics in 2010, Cengkareng population density is 19,363 km^{-2}. The land use of Cengkareng area is shown in **Fig. 5(h)**. This area is characterized by landuse functions such as settlement (1.10 ha), industry (97.25 ha), trading area (328.92ha), agriculture (118.64 ha), park area (31.90 ha), unused land (619.12 ha) and others (715.57 ha). In addition, the construction of a new international airport was progressing during 2012 in the area next to Cengkareng. **Table 3** and **Fig. 5(g)** show that the estimate subsidence rate in Cengkareng area and the result vary between 10.0 - 17.5 cm/year.

The results of DInSAR analysis in Cakung (P4) are shown in **Fig. 6**. The subsidence rate varies between 7.5 – 9.5 cm/year as shown in **Table 4** and **Fig. 6(g)**. The area shown in each panel of **Fig. 6** is relatively wide (42.47 km^2), mostly used for industrial activities. The biggest industrial activity is found in Pulogadung area, which has approximately 24 000 small and middle sized factories inside a large area of 6.86 km^{-2} (Jakarta Timur, 2010). In the 2010 census data, Cakung population density is 11 919 km^{-2}. The major landuse is settlement (45.27%) followed by industrial area (24.33%). **Figure 6(f)** describes the settlement and industry area in Cakung.

The values of land subsidence rate derived from the GPS measurement (Abidin *et al.*, 2005) conducted between December 1997 and September 2005 are shown in **Fig. 7** in comparison with the present DInSAR result (201008-201303). The comparison can be carried out in two ways, namely, as a time series and the subsidence rate. All of the results of GPS measurement at the three points (P1-P3) indicated the occurrence of land subsidence (Abidin *et al.*, 2005). The maximum subsidence rates calculated from the DInSAR results, on the other hand, were in a range from 9.5 cm/year to 17.5

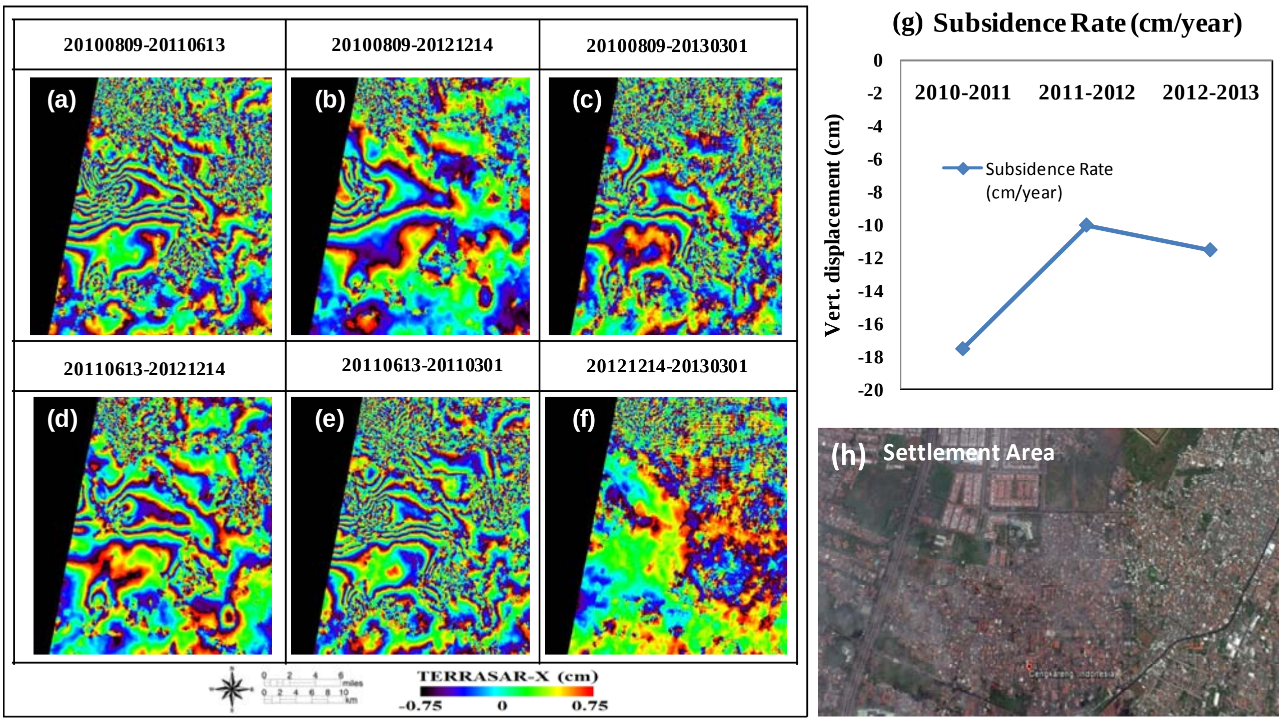


Fig. 5 Cengkareng DInSAR result of TerraSAR-X data pair all pairs mentioned in Table 1. (a) Data pair on 20100809-20110613, (b) Data pair on 20100809-20121214, (c) Data pair on 20100809-20130301, (d) Data pair on 20110613-20121214, (e) Data pair on 20110613-20130301, (f) Data pair on 20121214-20130301, (g) Graphic of Subsidence Rate 2010-2013, and (h) Land Use.

Table 2. Maximum subsidence rate estimation in Pantai Mutiara, Cengkareng and Cakung by using DInSAR

Pair Number	Acquisition Date		Pantai Mutiara Subsidence Rate (cm/year)	Cengkareng Subsidence Rate (cm/year)	Cakung Subsidence Rate (cm/year)
	Master	Slave			
1	20100809	20110613	9.5	17.5	8.8
2	20100809	20121214	8.5	11.5	9.2
3	20100809	20130301	10.5	11.7	8.3
4	20110613	20121214	9.3	10.0	7.7
5	20110613	20130301	9.9	10.5	7.5
6	20121214	20130301	10.9	11.8	9.5

cm/year. **Figure 7** shows that the highest land subsidence occurred in Cengkareng (P2) as indicated in both the GPS and DInSAR measurements. According to a report of the Ministry of Education and Culture Indonesia, land subsidence phenomenon in Jakarta is caused by several factors such as excessive groundwater extraction, land cover change, consolidation of alluvial soil and building construction (Ministry of Education and Culture Indonesia, 2013).

Figure 8 shows a comparison between the land subsidence information derived by using DInSAR technique from data pair 20121214-20130301 analysis and flood inundation areas in Jakarta area on January 2013. From this figure, a correlation can be seen between land subsidence and flooding inundation in the northern part of Jakarta urban area (Tempo, 2013). However, the dependency is quite weak for the other areas in Jakarta and, in this case, the flooding areas are mainly located along the flooded rivers.

At the ground level, land subsidence impacts in Jakarta can be seen in several forms. The subsidence damage appears as cracking in infrastructures such as buildings and streets, with considerable degradation in the environmental quality. Subsidence along coastal areas in northern part of Jakarta, in particular, is problematic since the degradation in infrastructures makes them more vulnerable to erosion associated with sea-level rise phenomena. Pictures in **Fig. 9** show degradation of various infrastructures in the consequence of land subsidence phenomena seen in the northern part of Jakarta observed during 1 September 2010 –15 December 2010.

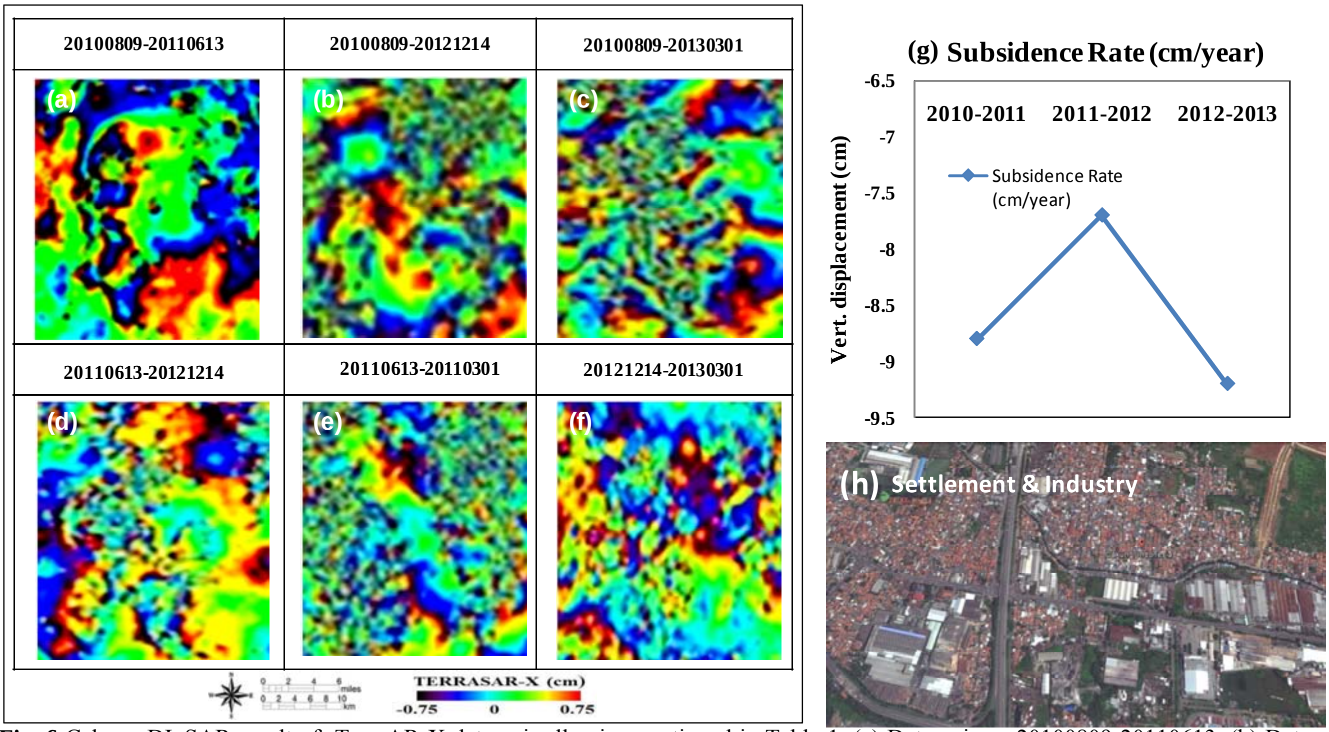
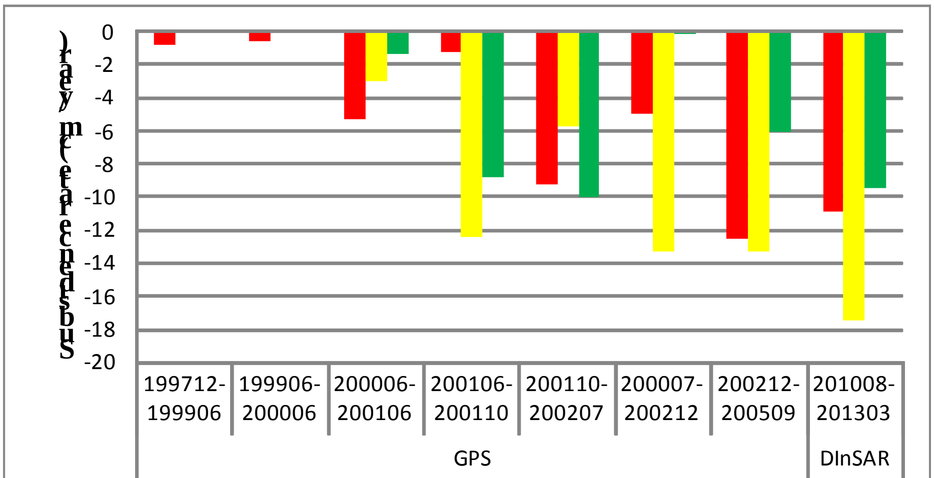


Fig. 6 Cakung DInSAR result of TerraAR-X data pair all pairs mentioned in Table 1. (a) Data pair on 20100809-20110613, (b) Data pair on 20100809-20121214, (c) Data pair on 20100809-20130301, (d) Data pair on 20110613-20121214, (e) Data pair on 20110613-20130301, (f) Data pair on 20121214-20130301, (g) Graphic of Subsidence Rate 2010-2013, and (h) Land Use.



	199712-199906	199906-200006	200006-200106	200106-200110	200110-200207	200007-200212	200212-200509	201008-201303
P1	-0.8	-0.5	-5.3	-1.2	-9.2	-4.9	-12.5	-10.9
P2			-3	-12.4	-5.7	-13.3	-13.3	-17.5
P3			-1.3	-8.8	-10	-0.1	-6	-9.5

Fig. 7 Chart of Land Subsidence rate taken from GPS measurement (199712-200509) and máximum lands ubsidence rate from the DInSAR result (201008-201303).

CONCLUSIONS AND FUTURE WORK

We have described the utilization of the differential synthetic aperture radar interferometry (DInSAR) analysis of TerraSAR-X data for detecting detailed conditions of land subsidence in the urban area of Jakarta. The center of subsidence has been successfully located, and estimations have been made of the land subsidence area. Most of the subsidence occurred in the northern part of the city during the time interval between 2010 and 2013. The maximum land subsidence rates detected for the three observation points are Pantai Mutiara (10.9 cm/year), Cengkareng (17.5 cm/year) and Cakung (9.5 cm/year). The deformation area occurred in separate regions with different types of land use. The local government planned several land use functions in northern part of Jakarta such as a seaport, reclamation areas, an international airport, trading centers, and industrial districts. The subsidence monitoring will be helpful for urban maintenance and development as one of influential factors that must be taken into consideration.

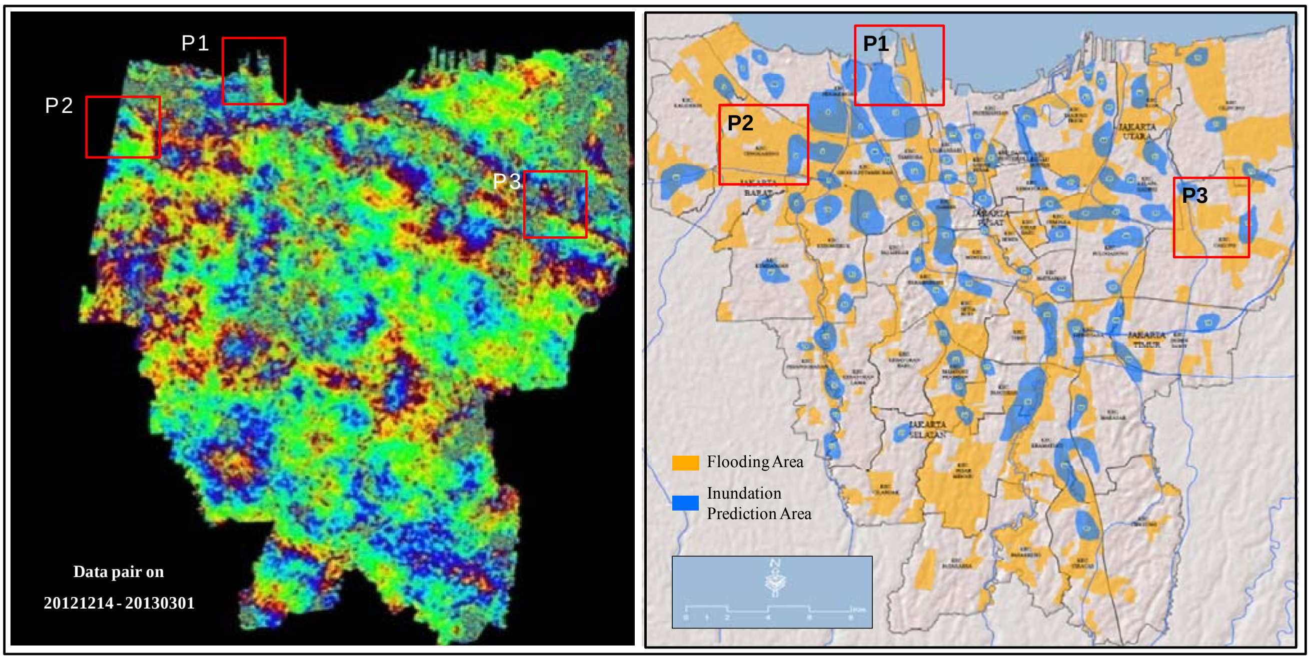


Fig. 8 Comparison phenomenon between Land Subsidence (DInSAR techniquef rom data pair 20121214 – 20130301 & Flooding Actual Map in 18 January 2013 [BNPB]).

Fig. 9 Land deformation impact areas in northernpart of Jakarta urban city: (a) Pantai Utara, (b) Cengkareng, (c) Cakung, (d) Flooding inundation area in northernpart of Jakarta urban area in January 2013 as one of land deformation impact and (e) Flooding area in Cakung (P3).

The applicability of TerraSAR-X data provides high spatial resolution and geometric accuracy imagery which supports well the land subsidence mapping. Thus, TerraSAR-X is very useful to build Digital Elevation Model (DEM) configuration with the detail elevation information. Jakarta represents urban characteristic city and has less canopy area population. Due to these reasons, TerraSAR-X with X-band wavelength is very suitable for land deformation measurement in urban area. In this study, the possibility of four different years TerraSAR-X data to detect monitor land subsidence over urban area has been investigated.

The TerraSAR-X imagery provides high spatial resolution and geometric accuracy which is well suited for land subsidence mapping. Most of the city area in Jakarta is covered with artificial constructions with limited vegetation coverage. This situation is favorable for X-band SAR observation, since the shorter wavelength does not work well if the target land is covered with dense vegetation canopy. In this context, the data is also useful to build DEM mapping with detailed land elevation information. The satellite data covers much wider area compared with ground-based observation using GPS. In the present work, the GPS data have been effectively utilized as validation data to examine the accuracy of DInSAR approach.

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