Title: Strong non-linear urban ground motion in Manila (Philippines) from 1993 to 2010 observed by InSAR

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Highlights:

- Differential SAR interferometry is applied to Manila (Philippines)
- Strong non-linear motion was observed for the periods 1993-1998 and 2003-2010
- Comparison with ground level measurement (GPS, DORIS and Tide Gauge) is carried out
- Consequences respect to the sea level evolution estimation by combining Tide Gauge and GPS are analysed
Strong non-linear urban ground motion in Manila (Philippines) from 1993 to 2010

observed by InSAR

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ABSTRACT:

In this letter we apply Differential SAR Interferometry (DInSAR) to monitor variable ground urban motion (uplift and subsidence) over long periods taking place in Manila (Philippines). Considering the high deformation rates we have to deal with (up to 15 cm/yr) and the fact that we work on an urbanized cover, we use conventional DInSAR with an adapted stacking procedure. The rationale of the processing is to produce surface deformation rate maps at different periods in order to represent the spatio-temporal evolution of the phenomena. Interpretation in terms of phenomena that originated the surface motion is proposed based on ground based observations. The ground motions are affecting several geodetic...
instruments, including a tide gauge with sea level records back to 1902, two permanent GPS stations and a DORIS station (Willis et al., 2010). A major implication of those large and locally variable ground motions is that they hamper the use of the nearby GPS and DORIS data for correcting the tide gauge records and deriving robust sea level trends associated with climate change.

1. Introduction

In addition to future sea level rise, subsidence is an immediate threat for coastal areas and particularly for several major coastal cities (e.g. Hanson et al., 2011). One difficulty arises from the fact that such vertical ground motions often reveal strong spatial and temporal variability, making their mapping a complex task. Complementary to in-situ monitoring (e.g. using GPS or levelling), space-borne synthetic aperture radar interferometry (InSAR) provides a means to provide comprehensive maps of surface deformations (e.g. Brooks et al., 2007; Raucoules et al., 2008; Bock et al., 2012; Chaussard et al., 2013). With means of InSAR processing and using data acquired by the ERS and Envisat satellites from 1993 to 2010 (Part 2), this letter reports on observations of highly variable ground surface deformation in Manila (Part 3). Beyond potential consequences for the urban environment (which will be addressed in further studies), this subsidence is affecting several permanent in-situ geodetic instruments (Part 4), altering the potential to use their long term time series for improving our understanding of the XXth century sea level rise.

2. Processing procedures and data

Previous studies suggest that the region of Manila is affected by strong ground motions (e.g. Siringan and Ringor, 1998; Jacinto et al., 2006; Rodolfo and Siringan, 2006; Daag et al., 2011). Therefore, we used Differential InSAR with an adapted stacking procedure instead of advanced techniques such as PSI (such as Persistent Scatterers techniques). Indeed, in certain cases, PSI appears as less efficient and difficult and for interpreting for monitoring of fast and irregular deformation (Raucoules et al., 2009). Using a series of ERS 1-2 images between 1993 and 2000 (Table 1) and ASAR/Envisat data between 2003 and 2010 (Table 2), we processed differential interferograms with perpendicular baselines shorter than 300m. Then, as suggested e.g. by Le Mouelic et al., (2005), we visually selected a subset of trustworthy interferograms
by rejecting noisy phase and data obviously affected by atmospheric effects. Finally, we stacked interferograms both on the whole data set acquisition periods [1993-1998 (ERS) and 2003-2010 (Envisat)] and for 3-years sub-periods. We focused on time-spans shorter than 400 days in order to firstly avoid using interferograms with deformation signatures corresponding to more than 5-6 fringes and then reducing the eventuality of unwrapping errors and secondly to limit temporal decorrelation. This processing was carried out using GAMMA interferometric software.

In addition, we used a principal components analysis (PCA) between the different produced deformation maps, in order to discriminate the areas affected by deformation during the whole period (1st component) from areas with important deformation rate variations. Finally, we applied a more specific processing on the Valley Fault area (East on Manila). By computing a directional filter on the 2003-2010 deformation maps, we aim at locating the sections of the fault affected by surface motion, whatever the causes: seismotectonics such as creeping or anthropogenic such as pumping related differential subsidence.

Table 1: ERS 1-2 acquisitions (track 418)

<table>
<thead>
<tr>
<th>Year</th>
<th>Acquisitions dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>25 July, 29 Aug, 3 Oct</td>
</tr>
<tr>
<td>1995</td>
<td>4 April, 13 June, 31 Oct, 5 Dec</td>
</tr>
<tr>
<td>1996</td>
<td>9 Jan, 19 March, 11 Sept</td>
</tr>
<tr>
<td>1997</td>
<td>1 Oct, 5 Nov</td>
</tr>
<tr>
<td>1998</td>
<td>14 Jan</td>
</tr>
<tr>
<td>2000</td>
<td>23 Feb</td>
</tr>
</tbody>
</table>

Mean incidence angle: about 23°
Table 2: EnviSat/ASAR acquisitions (track 418)

<table>
<thead>
<tr>
<th>Year</th>
<th>Acquisitions dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>8 Jan, 12 Feb, 19 March, 2 July, 10 Sept, 24 Dec</td>
</tr>
<tr>
<td>2005</td>
<td>12 Jan, 16 Feb, 23 March, 27 April, 1 June, 6 July, 10 Aug, 14 Sept, 28 Dec</td>
</tr>
<tr>
<td>2006</td>
<td>1 Feb, 8 March, 12 April, 17 May, 26 July, 17 Jan, 26 July</td>
</tr>
<tr>
<td>2007</td>
<td>17 Jan, 24 Oct, 28 Nov</td>
</tr>
<tr>
<td>2008</td>
<td>12 March, 25 June, 3 Sept, 12 Nov</td>
</tr>
<tr>
<td>2009</td>
<td>21 Jan, 2 Dec</td>
</tr>
<tr>
<td>2010</td>
<td>4 Aug</td>
</tr>
</tbody>
</table>

Mean incidence angle: about 23°

Figure 1: Location of the SAR data acquisition frames on Manila Bay. Plain lines correspond to the ASAR/ENVISAT acquisitions, dashed lines to ERS 1 and 2 data. Positions of the tide gauge and GPS considered for
sea level change estimation are shown. Noteworthy is the fact that the ASAR data covers part the Valley Fault whereas ERS data do not (slightly shifted toward West).

3. Results

3.1 deformation rate maps

We provide the resulting deformation maps in Figures 2 and 3. The scale corresponds to deformation estimates along the Line of Sight in rad/year (black contours). If we assume that the deformations are mostly vertical motions, 10 rad/year correspond to ~4.9 cm/year. In Manila, this hypothesis is realistic for anthropogenic subsidence. However, horizontal displacement could also occur in the Valley Fault since it is a partly strike-slip fault.

Pixels whose interferometric coherence is less than 0.3 were masked as considered as unreliable). Morphological operations (opening and closing) were carried out to the mask in order to make it connex.

Finally, we will point out that, because of the generalized surface motion on the area, it is difficult to state a reliable stable reference point. Although we tried to reduce the possible resulting bias by removing a global trend, the following maps have therefore to be considered as representing relative motions: i.e. defined with an arbitrary global constant shift. Such shifts can be observed between maps but do not affect differential displacements estimations.
Figure 2a: Line of Sight displacements in rad/yr for the whole 1993-1998 period (ERS 1-2 data). Black contour separation: 5 rad/yr. Negative values correspond to displacements towards the sensor (i.e. uplift).
Figure 2b: Deformation maps for 1993-1995 and 1995-1998. Subsidence rate in the Northern part of the urbanization clearly appears.
Figure 3a: Line of Sight displacement in rad/yr for the whole 2003-2010 period (EnviSat/ASAR data). Black contour separation: 5 rad/yr.

We observe in particular deformation up to 13 cm/yr in Valenzuela and Meycauayan and about 9 cm/yr North West from Guiguinto. On these sectors, deformation was much slower and spatially reduced on the 1993-1995 map. The higher deformation rates on Valenzuela and Meycauayan appear on the 1995-1998 and 2003-2005 maps (showing a decrease of the phenomenon) whereas maximum is obtained after 2005 near Guiguinto. Changes in the location and rates of groundwater extraction are a plausible explanation for this migration of the deformation maxima.

3.2 Principal Component Analysis

Since the interpretation of the results shows a strong temporal variability, we carried out a principal component analysis in order to highlight areas subject to deformation rate changes.
The idea is to separate areas with constant deformation rates from areas affected by non-linear components of the deformation. For this, we propose to apply Principal Component Analysis to the 5 deformation rate maps corresponding to different periods. We assume that the first PC is related to the linear deformation and the 2d and 3rd to non-linear deformation (we neglect upper order components as the 4th eigenvalue corresponds to about 1/20 of the first one – $\lambda_1=43$, $\lambda_2=11$, $\lambda_3=4.3$) as they reflect significant changes between deformation maps.

Figure 4: 3 first Principal Components. For 2d and 3rd components we showed the absolute values of the PC in order to better identify their location rather than the evolution (acceleration, slowing) of the displacement.

Figure 4 suggests that in addition to a strong spatial variability of the deformation subsidence phenomenon, deformation on Manila has a complex temporal evolution. In particular, it indicates that in addition to the Northern part of the city (e.g. the area between Valenzuela and Meycauayan) Malaboon, Mandaluyong and Muntinlupa cities were affected by non-linear deformation. In particular, small areas spotted on the 3rd component deserve deeper investigation as short spatial wavelengths of temporal regime changes have interest in terms of consequences on building (short wavelength of differential displacements are cause of damage) or phenomena (link with pumping locations should be investigated).
3.3 Directional filtering of the deformation maps on the Valley Fault area

In order to investigate the displacement along the Valley Fault, we applied an East-West directional filtering in order to highlight the differential motion each side of the Fault. Figure 5 shows an interpretation of the result. We located possible sections of the fault that moved during the 2007-2010 period. Noteworthy is the fact that the ERS frames do not cover the Fault. The observation is therefore only based on the ASAR data. Among ASAR derived maps, 2007-2010 was the one showing the more clearly differential displacement along the fault.

We divided the apparent fault in 3 segments based on their motion characteristics (A and C: West side goes towards sensor faster than East; B has the opposite behaviour). On the 3 segments the differential LOS displacement (identified on the deformation map) corresponds to about 2-3 rad/year. As the fault is practically oriented North-South, we can assume that strike-slip components have little influence on the produced deformation maps and that we mainly observe vertical motion. With this assumption, the observed motion can be interpreted as about 1-1.4 cm/year of vertical displacement between each side of the fault. The origin of the observed motion is difficult to state only on (the basis of these observations (1 component of the surface deformation). The mechanism of the deformation could be related to seismotectonics (e.g. surface creeping) but also differential subsidence related to water extraction (the fault being correlated with different subsurface characteristics each side and could be an hydrogeological barrier)
Figure 5: 2005-2010 deformation map after East-West directional filtering. The red line corresponds to possible parts of the fault affected by differential displacement between each side of the fault. 3 segments are identified with different displacement behaviours.

4. Discussion

4.1 Agreement with in-situ observations

Several geodetic instruments are located in Manila (Figure 2a). One permanent GPS provides too short time series (GPS MANL) to be analysed at the time of this study. Figure 6 shows that the DORIS instrument is stable in the 90’s (ERS acquisition period), while they were affected by an uplift in the 2000’s (Envisat acquisition). GPS PIMO station is also subject to slight uplift in the 2000’s. Consistently, the
differential movement between PIMO and DORIS is too small to be observed with InSAR. However, on the 2003-2010 period the differential displacement between PIMO and the Tide Gauge estimated from the InSAR result is about 10.7 mm/yr (± 2.1 mm/yr; based on the sum of the variances of the InSAR deformation rate measurements obtained on 200m windows around the PIMO and TG locations). Once corrected from the GPS absolute vertical motion, we can assume that the resulting TG motion respect to the reference ellipsoid is about 8 mm/yr subsidence (± 2.2 mm/yr). In order to validate this result, an alternative subsidence estimation based on the difference between the sea level evolution estimated from AVISO data and the TG is carried out (figure 7). The altimetric monthly sea level anomalies were obtained from AVISO data server (http://www.aviso.oceanobs.com/en/altimetry.html). This data is a multimission (Jason 1-2, Envisat, Cryosat) product with a spatial resolution of 1/4ºx1/4º, starting in 1992 and with all geophysical corrections applied. In particular, the dynamic atmospheric correction that accounts for the effects of atmospheric pressure and wind (Volkov et al, 2007) was removed. For the sake of comparison with the tide gauge this correction was added back to the altimetry observations. The most correlated grid point of altimetry observations was chosen for the comparison with in-situ observations (correlation was computed using deseasoned and detrended time series). Alternatives such as the closest grid point or an average among nearby grid points around 1º did not changed the results. The combination of the altimetric observation with the tide gauge data highlights a subsidence phenomenon that reaches 10.1 mm/yr ± 0.6 mm/yr. The discrepancy between the two observations is consistent with the expected respective precisions of the techniques. Nevertheless, it does not allow a correction in the perspective of sea level rise correction (for wich sub-millimetric accuracy is required) although 40 SAR acquisitions were used.

Finally, in addition to the inter-annual ground motion variability observed by InSAR, the GPS time series also reveals seasonal vertical deformations whose amplitude reaches about 5.5 mm.
Figure 6: DORIS and GPS PIMO station time series. Both points are affected by uplift phenomena with similar rates.

Figure 7: Estimation of the Tide Gauge subsidence based on the difference between sea level derived from altimetry (AVISO data) and tide gauge measurements.

4.2 Implications for solving the sea level enigma
Because sea level rise depicts significant regional variability (e.g. Meyssignac and Cazenave, 2012), one critical issue for better estimating past sea level prior to the altimetry era (1993) is the analysis of long term tide gauges time series. This question is particularly significant since there is a disagreement between sea level budgets as estimated (1) from tide gauges (2) through evaluations of thermosteric and continental ice melting contributions (Munk, 2002). A difficulty here arises because tide gauges measure sea level with respect to a terrestrial framework while global sea level refers to a geocentric framework. In other words, both the land and the sea can move with respect to a geocentric reference frame. In practice, vertical ground motions can be removed from the measurements of the tide gauge using a nearby GPS permanent station (e.g. Wöppelmann et al., 2007), provided two hypothesis are fulfilled: the tide gauge and GPS station (being close enough from the gauge) should follow the same vertical motion and the deformation should be linear, so that extrapolations of the linear trend of ~10 years GPS time series are valuable estimates of the past motion for at least 50 years. However, if the differential movements affecting the instruments remain linear, advanced techniques such as PSI could be utilized to reach the ~1 mm/yr or less required for estimating the global sea level change, estimated at 1.7 mm/yr over 1950/2010 a verifier (Wöppelmann et al., 2013).

Tide gauge measurements have been recorded in Manila since 1902, so that it is the longest time series in South East Asia (Santamaria Gomes et al. 2012). As a consequence, it belongs to the “Global Core Network” of the Global Sea Level Observing System (GLOSS). However, our results shows that none of the working hypothesis of the method for estimating geocentric sea level rise with GPS corrected tide gauge data is fulfilled. Therefore, this method cannot be implemented in Manila because the Tide Gauge and its surroundings are affected by highly variable ground motion in space and time. Secondly, the generalized surface motion affecting both the tide gauge and reference GPS locations and its observed temporal variability prevent any extrapolation from correcting gauge time series for the past 50 years: if the differential motion between GPS and tide gauge can be estimated for the period monitored by the space-borne radar sensor, the current motion is not representative of the past motion. In addition, if the subsidence whose maximum was initially located on Malabon city further migrates southward, the tide gauge area could be affected by increased subsidence, in the future. The current observations do not therefore allow anticipating the future evolution of the Tide Gauge values.
More generally, if for certain categories of surface deformation (with reduced spatio-temporal variability) such as isostatic rebound or aseismic tectonic motion the assumption is valid, subsidence (e.g. pumping or underground works) affecting urbanizations (e.g. Lagios et al. 2006, Raucoules et al. 2008) where tide gauges are installed could hamper the possibility to apply the method. As a first verification of the applicability of the method this study encourages InSAR monitoring at locations where long term tide gauge time series are corrected using a non-collocated permanent GPS.

5. Conclusion

In this letter, we presented observations of high rates of non-linear deformation on the Manila urbanization (Philippines) based on space-borne SAR interferometry during the 2 last decades. Displacements up to 15 cm/yr with variable rates and locations are observed. These ground motions are hypothesized to be related to ground water pumping and fault motion. In addition to local consequences for the urban environment and structures, these ground motions affect several geodetic instruments and alter the potential for using their time series for understanding past sea level.

It results in difficulties in using Manila's tide gauge time series for estimating the sea level rise because of the impossibility of correcting – on the basis of GPS data - the contribution of its proper motion that occurred for the whole time series duration (last century). However, InSAR products based on long SAR data archive (ERS 1-2 and EnviSAT/ASAR data) provide a way of improving the sea level estimation occurred since the 1990's. This approach could allow using a larger number of reliable tide gauges measurements (by correcting them or identifying and discarding unreliable data sets) for the estimation of sea level evolution.

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