

# MONITORING OF LAND DEFORMATION DUE TO OIL PRODUCTION BY INSAR TIME SERIES ANALYSIS USING PALSAR DATA IN BOLIVARIAN REPUBLIC OF VENEZUELA

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## ABSTRACT

The target area of this study is the Maracaibo sedimentary basin located in the western part of Bolivarian Republic of Venezuela. The full-scale exploration and development for oil resources in Venezuela which was the greatest oil-producing country in South America had begun at the Maracaibo sedimentary basin in the 1910s, and it was a center of the oil product in Venezuela until the 1980s. But, in most of oil fields in the Maracaibo sedimentary basin, there is concern over the drain on recoverable reserves due to deterioration, and the production amount of petroleum in Venezuela has been diminishing these days. Leveling and GPS surveying were carried out in the past, and they revealed that the large-scale subsidence phenomenon of which cumulative subsidence amount was approximately 5 meter had occurred.

The authors applied the vertical displacement measurement by InSAR time series analysis using PALSAR data obtained in the Fine-beam and ScanSAR observation mode. As a result, it could be confirmed clear ground deformation in the surrounding of three oil fields (Tia Juana, Lagunillas and Bachaquero) and easily recognized that the areas of phase anomalies detected by this analysis had expanded and the number of interference fringes had increased over time. The annual velocity of vertical ground surface displacement measured by InSAR time series analysis was -51 mm per year, -103 mm per year and -58 mm per year in Tia Juana, Lagunillas and Bachaquero oil field respectively. The tendency that an earth surface shifted towards the center of phase anomalies was detected from the result of the horizontal ground change measurement.

It was interpreted from Google Earth and Landsat images that oil-related facilities (mainly bowing stations) were built intensively over the areas where phase anomalies were detected. Therefore, it was inferred that there was a high association between the operation activity of the oil field and ground deformation. In addition, the deterioration is remarkable in the oil fields of the Maracaibo basin and oil production volume has been declining, on the other hand the spatial volume of the ground surface deformation also showed a clear decreasing trend.

## 1. STUDY AREA

A study area is the oil production zone around Lake Maracaibo in the western Venezuela shown in Figure 1. The surrounding area of Lake Maracaibo was the center of the oil production in Venezuela until the 1980s. Because there are many deteriorated oil fields, however, exhaustion of the oil resources approaches. The amount of oil production has been decreasing (Figure 2). The reservoir depth of the 3 oil fields (Tia Juana, Lagunillas and Bachaquero) is relatively shallow with around 300-1,000 m. As a result of levelling survey carried out from 1926 through 1986 (interval period; 60 years), accumulation subsidence quantity of approximately 5m was measured (Figure 3). Current ground height around these 3 oil fields becomes lower than a surface water of Lake Maracaibo, and the present situation about the serious subsidence disaster are pointed out.

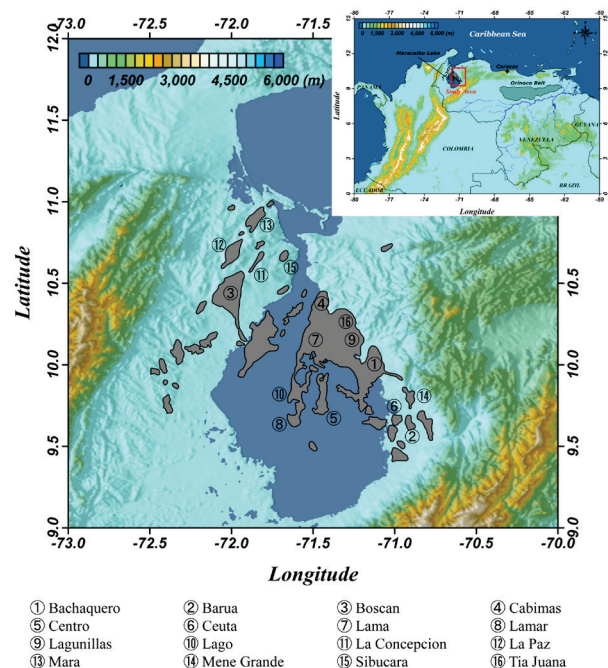


Figure 1. Location of this study area

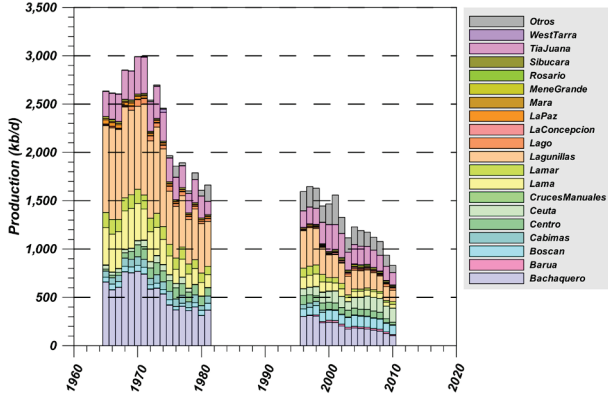


Figure 2. Daily production of oil fields in the Maracaibo Basin

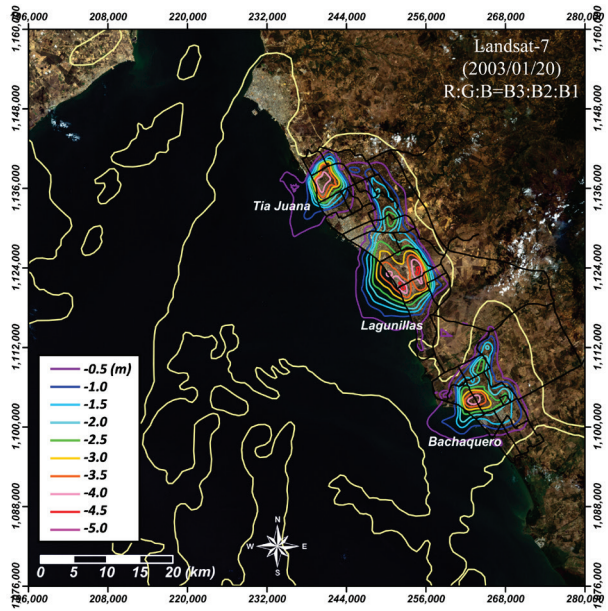


Figure 3. Isometric line of land subsidence in the eastern coast of the Maracaibo Lake (1926-1986)

## 2. METHODOLOGY

DInSAR is a unique methodology for measuring ground motions by analyzing phase differences on two SAR images taken at two different times. The phase difference  $\Delta\Phi$  after the removal of the orbit fringe ( $\Delta\phi_{orbit}$ ) and the topographical fringe ( $\Delta\phi_{topo}$ ) using orbit records and DEM includes not only the displacement component ( $\Delta\phi_{def}$ ) but also the noise component ( $\varepsilon$ ) due to atmospheric phase delay and ionospheric disturbance and the phase term due to elevation errors ( $\Delta h$ ) in the DEM data, where  $B_{perp}$  is the perpendicular component of the orbit distance between two observations,  $\lambda$  is the wavelength,  $\rho$  is the slant range length, and  $\alpha$  is the incidence angle.

$$\Delta\Phi = \Delta\phi_{def} + \varepsilon + \frac{4\pi B_{perp}}{\lambda\rho \sin \alpha} \Delta h \quad (1)$$

Consider a case where  $M$  pairs of interferograms are derived from  $N+1$  scenes of SAR imagery over a single area. Suppose that the land deformation from the first observation (0-th recurrence) is an unknown vector,  $t_n (n=1 \dots N)$ , and that the interferogram of the  $m$ -th pair ( $m=1 \dots M$ ) is obtained from the SAR images on the  $i$ -th and  $j$ -th recurrence ( $i=1 \dots N-1$ ,  $j=2 \dots N$ ,  $j>i$ ). A smoothness constraint is added to hypothesize that the time wavelength of land deformation is sufficiently longer than the satellite's revisit period. Specifically, a smoothness constraint condition represents the minimization of the second order difference for  $t_n$ . By rendering the phase difference of each interferogram, the optimal solutions to  $t_n$  and  $\Delta h$ , the variables used to provide the minimum value of  $S$ , can be estimated based on the least squares method.

$$S = \sum_{m=1}^M w \left\{ \Delta\Phi_m - \left( t_j - t_i \right) - \frac{4\pi B_{perp}}{\lambda\rho \sin \alpha} \Delta h \right\}^2 + \mu^2 \sum_{n=1}^N \left( t_n - 2t_{n-1} + t_{n-2} \right)^2 \quad (2)$$

The variable  $w$  in the first term on the right side of Eq. (2) is the weighting function from Tukey's biweight. The variable  $\mu^2$  in the second term is a parameter used to control the smoothness of land deformation, and is fixed to 1.0. The  $t_n$  finally obtained is regarded as a vector representing the land deformation in the line of sight after separating noise components. The value is output as a total of the long-term land deformation from the first observation.

## 3. DATA ANALYSIS

### 3.1. Fine-Beam Observation Mode

A total of 96 DInSAR combinations using the data of 21 images were processed in the analysis of the fine-beam observation mode. The largest displacement rate measured in line of sight was about -33mm/ year at P11 of the Bachaquero oil field, about -41mm/ year at P08 of the Lagunillas oil field and -74mm/year at P04 of the Tia Juana oil field.



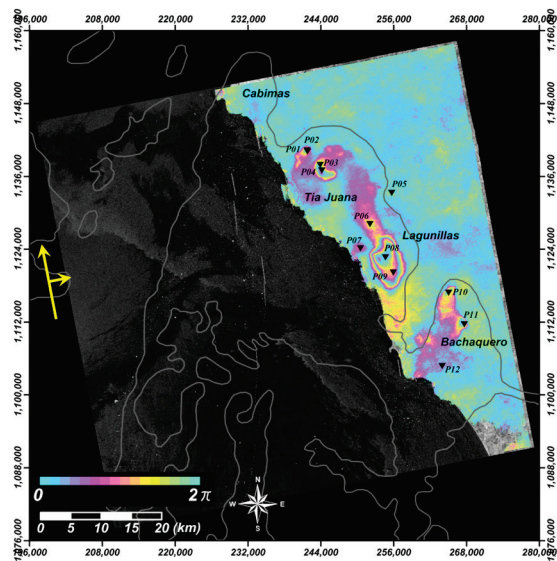


Figure 4. Result of InSAR time series analysis using PALSAR data in Fine-Beam observation mode.  
(July 11<sup>th</sup>, 2007 – March 6<sup>th</sup>, 2011)

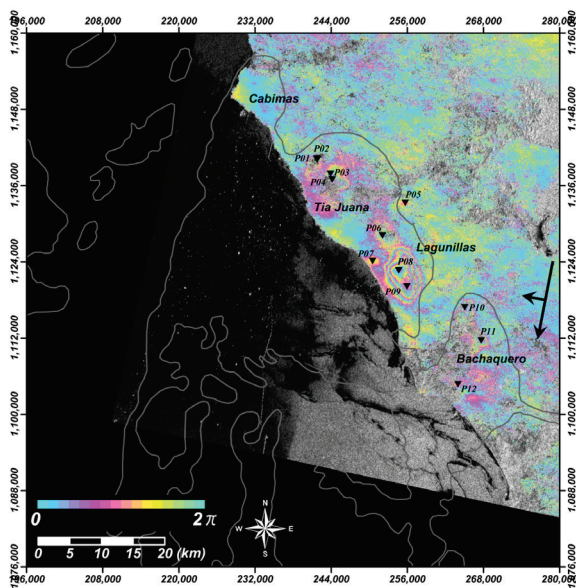


Figure 5. Result of InSAR time series analysis using PALSAR data in ScanSAR observation mode.  
(March 16<sup>th</sup>, 2007 – March 27<sup>th</sup>, 2011)

### 3.2. ScanSAR Observation Mode

The important condition in order to secure high coherence for DInSAR analysis is the perpendicular component of the spatial baseline between master and slave orbit. The shorter, the more continuous fringe in the interferogram can be acquired. In case of ScanSAR, however, because the irradiation of microwave in the range direction is switched in the 3 to 5 direction to

increase the observation width, the burst of the azimuth direction becomes intermittent and it is necessary for the timing of the burst of master and slave to be synchronized. When a burst overlap rate of master and slave decreases, it is impossible to get the continuous interferometric fringe even if the distance between master and slave orbit is 0 m.

A total of 39 DInSAR combinations using the data of 20 images were processed in the analysis of the ScanSAR observation mode. The largest displacement rate measured in line of sight was about -63mm/ year at P11 of the Bachaquero oil field, about -99mm/ year at P08 of the Lagunillas oil field and -48mm/year at P04 of the Tia Juana oil field.

### 3.3. Vertical and Horizontal Deformation

The 2.5 dimensional analysis using the results derived from InSAR time series analysis (the fine-beam and ScanSAR observation mode) was performed (Figure 6, 7, 8 and 9). Several deforming areas can be clearly identified around three oil fields (Tia Juana, Lagunillas and Bachaquero) in the vertical displacement map as well as the independent analysis results with fine-beam mode and ScanSAR mode. It is quite easy to understand that phase anomalies have spread out and the number of interferometric fringe have increased depending on time. The deformation rate in the vertical direction was measured about -58mm/ year at P11 of the Bachaquero oil field, about -103mm/ year at P08 of the Lagunillas oil field and -51mm/year at P01 of the Tia Juana oil field.

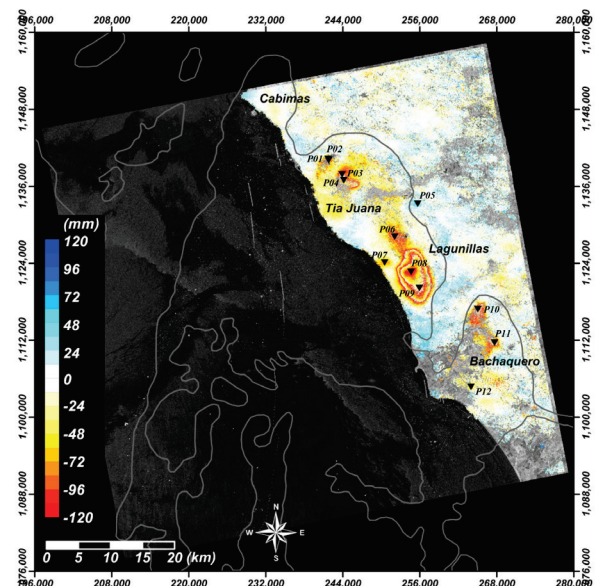


Figure 8. Result of 2.5 dimensional analysis (vertical deformation, July, 2007 – March, 2011)

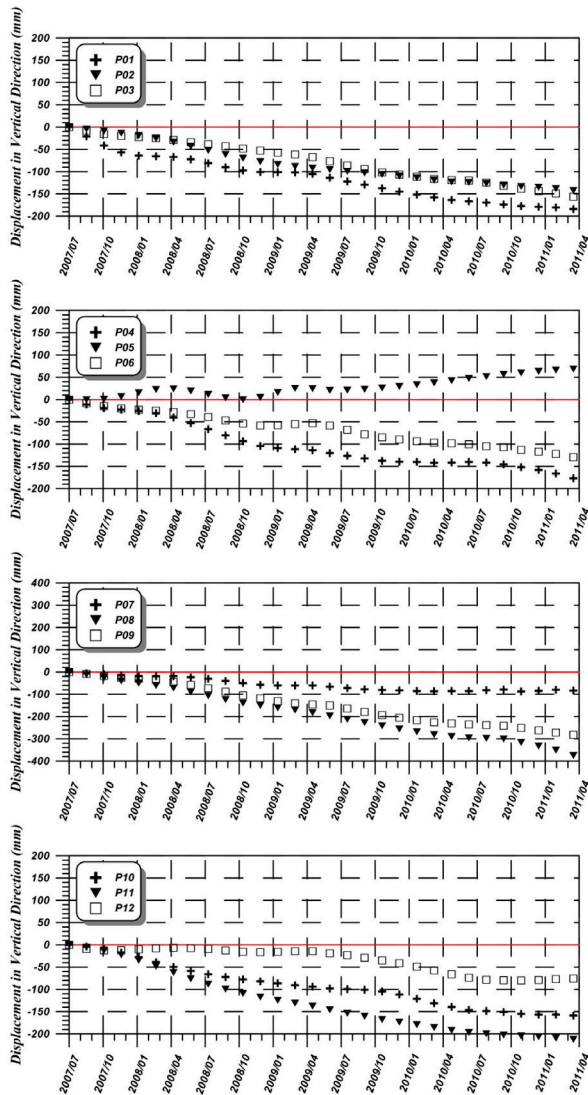


Figure 9. Temporal change of vertical deformation

In considering the horizontal displacement, let us focus in the surrounding area of Lagunillas and Bachaquero oil fields shown in Figure 10. In both oil fields, the motion to east (blue) and the motion to west (red) appeared symmetrically. It indicated that an earth surface have gathered toward the center between blue and red.

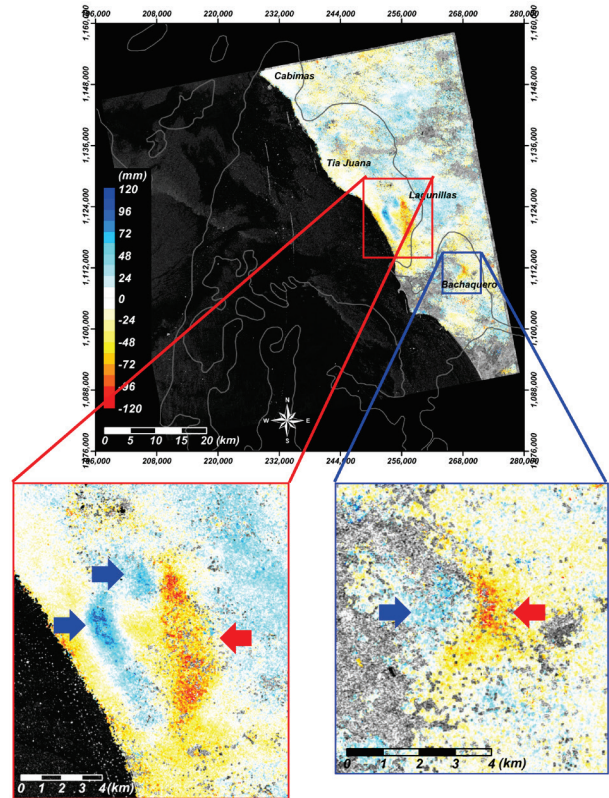


Figure 10. Enlarged image of horizontal deformation around Lagunillas and Bachaquero oil field

#### 4. DISCUSSION

As regarding the Maracaibo sedimentary basin, the oil production amount in individual oil fields is available to the public. Figure 11 shows the comparison between the annual oil production and the spatial volume of land deformation measured by InSAR time series analysis using fine-beam and ScanSAR observation mode of PALSAR.

As described above, deterioration is prominent and the oil amount of production shows a tendency to decrease in the oil field of the Maracaibo sedimentary basin. This tendency is remarkable after 2006 when the operation of ALOS satellite load PALSAR sensor had started.

The annual amount of oil production during three years from 2008 through 2010 was reported to be 59,720kb/yr. (2008), 53,331kb/yr. (2009), 46,297kb/yr. (2010) in Tia Juana, 58,216kb/yr. (2008), 52,517kb/yr. (2009), 42,775kb/yr. (2010) in Lagunillas and 55,180kb/yr. (2008), 45,419kb/yr. (2009), 37,534kb/yr. (2010) in Bachaquero. The oil production capability had decreased about 20 to 30 % even during three years at most. In contrast, the spatial volume of vertical deformation measured using PALSAR data shows also a clear tendency to decrease and the correlation with the change of the oil production amount is apparent.



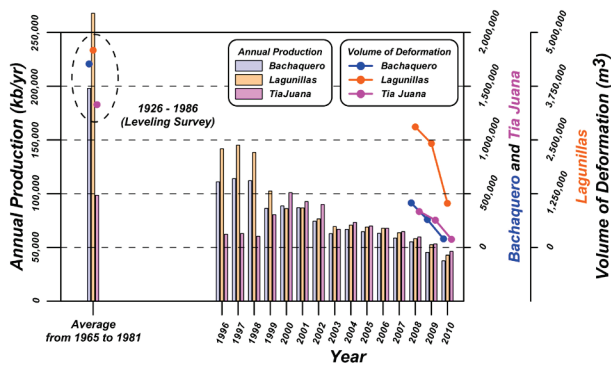


Figure 11. Comparison between annual oil production and volume of deformation

Subsidence monitoring by the levelling survey had been carried out since 1926 in this study area. The network of levelling survey had installed over the wide coverage of about 1,600 km<sup>2</sup> (total length of survey line; approximately 800 km and number of benchmark; approximately 1,600 points). Five survey crews had taken about three months to measure the whole network and been cost over US\$200,000 per campaign. It was reported by a survey result until 1986 that the accumulated quantity of land subsidence had reached approximately 5m and the maximum value of surface subsidence velocity had been about 20cm/ year. Figure 12 shows isometric lines of land subsidence measured from levelling survey overlaid on the vertical displacement map. The result of this comparison indicates good agreement between InSAR and levelling measurement.

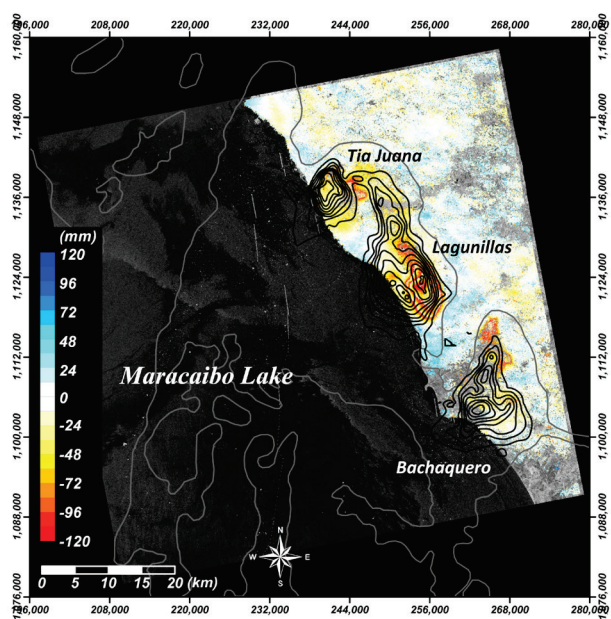


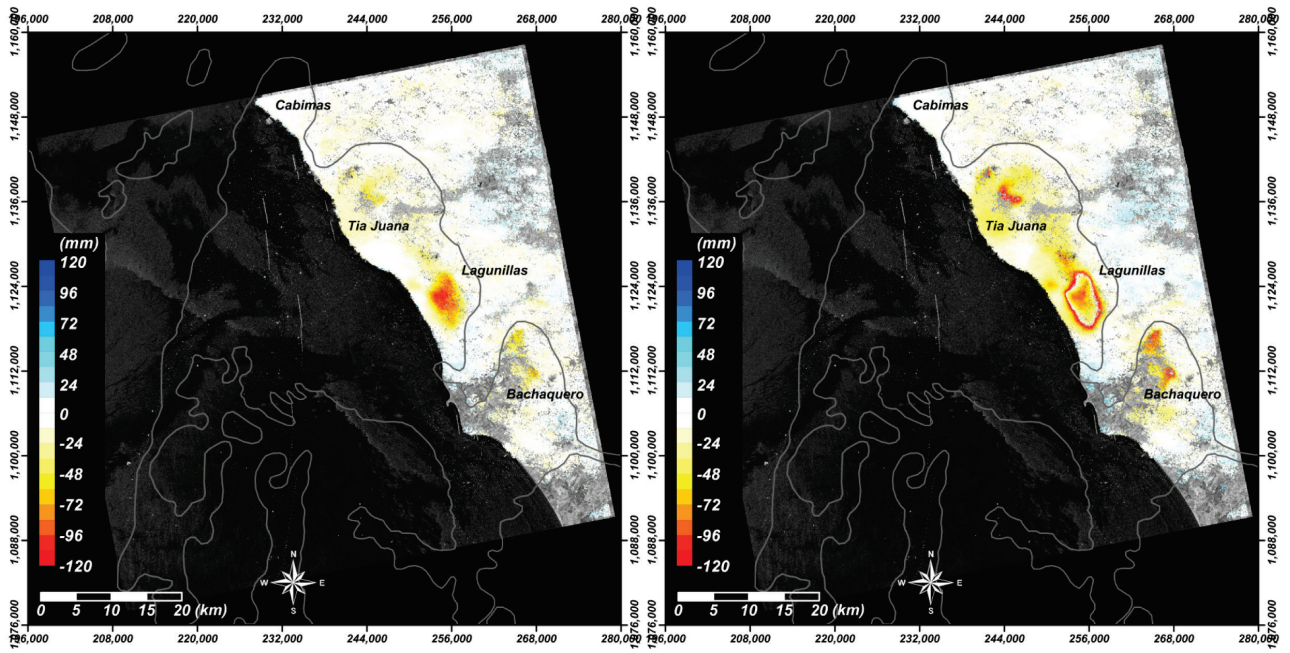
Figure 12. Comparison between the result of leveling survey and vertical deformation measurement

## 5. FUTURE WORKS

PALSAR-2 installed on ALOS-2 satellite was launched on 24th May, 2014, and data distribution has already be started. It would be expected to continue the observation and reservoir monitoring for the resource management.

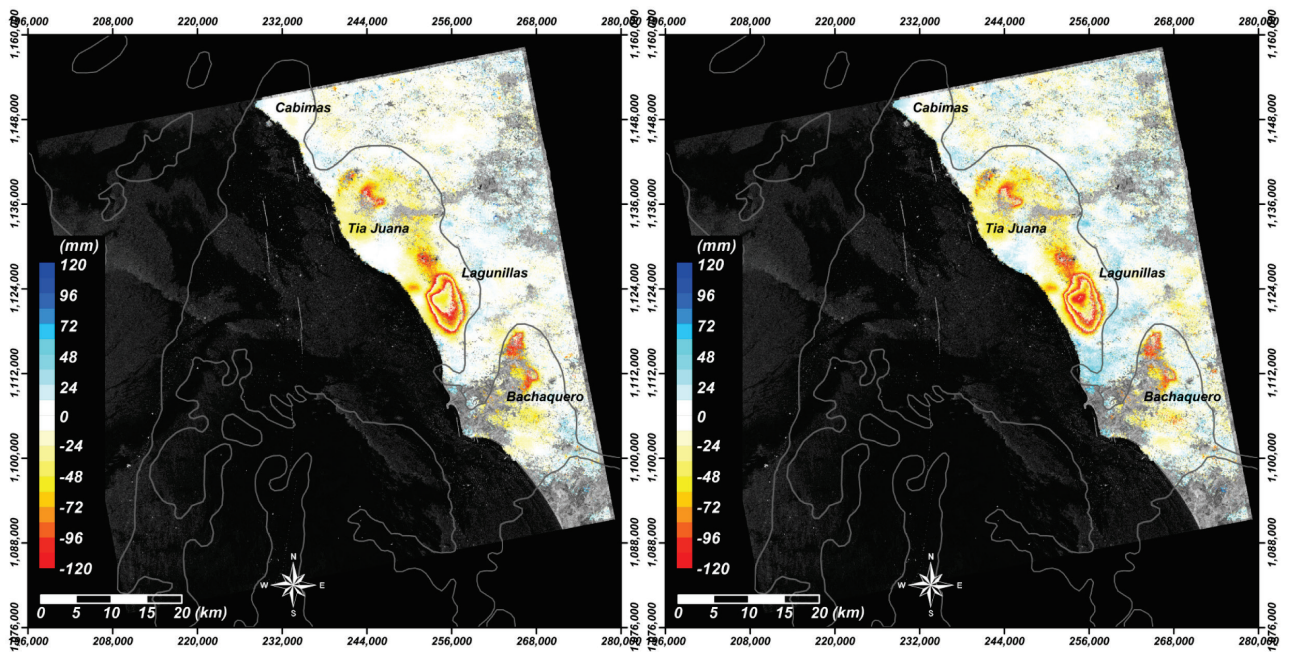
## 6. REFERENCES

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(a) July, 2007 – July, 2008 (1 year)

(b) July, 2007 – July, 2009 (2 years)

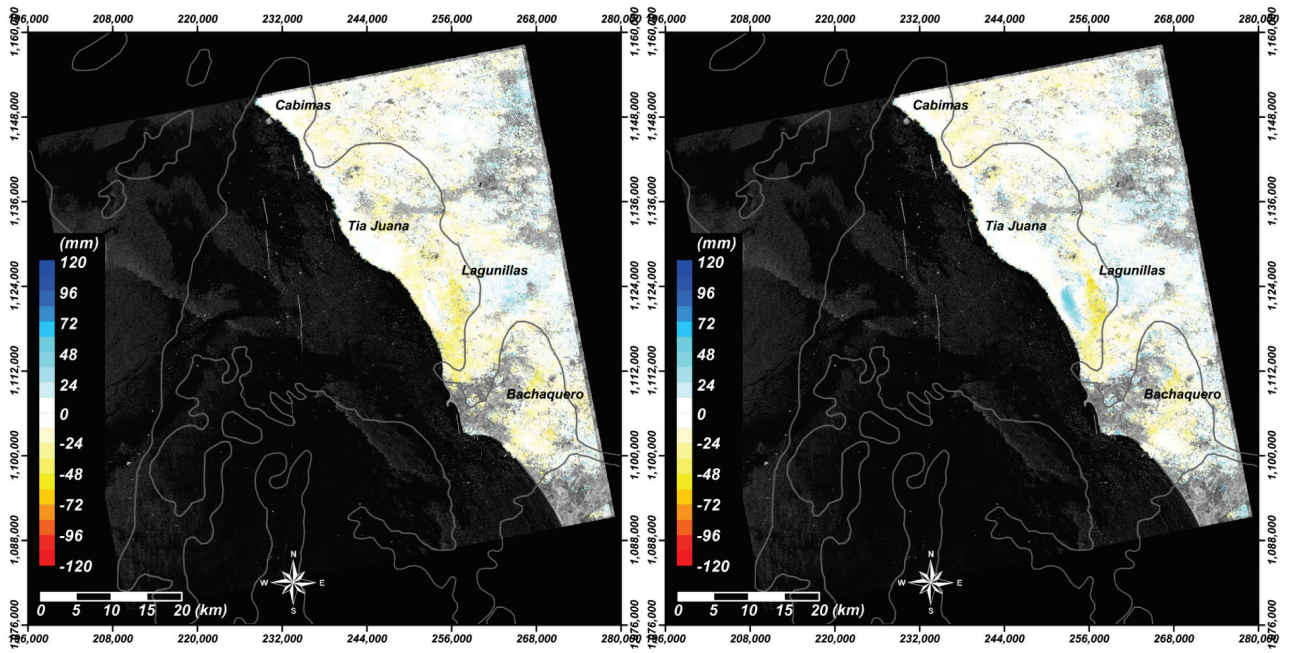


(c) July, 2007 – July, 2010 (3 years)

(d) July, 2007 – March, 2011 (3 years and 8 months)

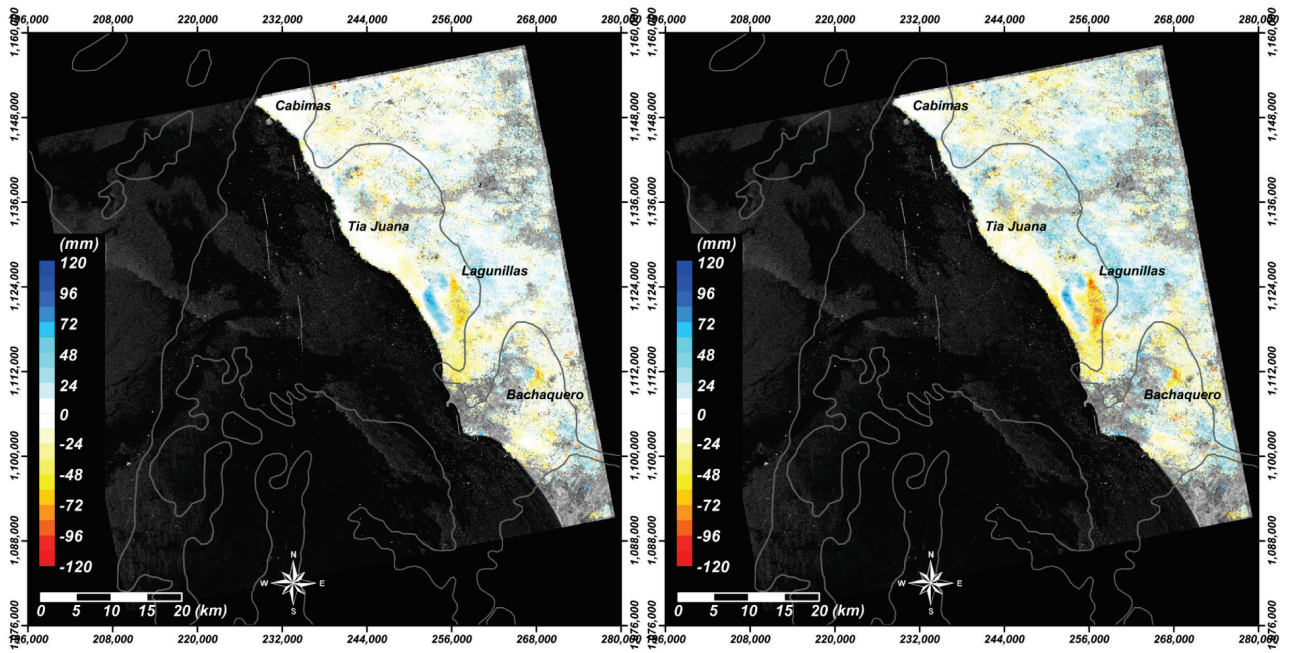
*Figure 6. Result of vertical deformation measurement*





(a) July, 2007 – July, 2008 (1 year)

(b) July, 2007 – July, 2009 (2 years)



(c) July, 2007 – July, 2010 (3 years)

(d) July, 2007 – March, 2011 (3 years and 8 months)

Figure 7. Result of horizontal deformation measurement