Interferometric Synthetic Aperture Radar (InSAR) Measurement and Its Inversion for Monitoring Steam Assisted Gravity Drainage (SAGD) Process

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ABSTRACT

Vertical displacements in bituminous oil sand field associated with steam chamber development undergoing SAGD (Steam Assisted Gravity Drainage) were estimated by using Synthetic Aperture Radar Interferometry (InSAR) technology which can take images of objects at a high spatial resolution under all weather conditions and at all time. To monitor the performance of the SAGD process, the reservoir deformations should be analyzed especially around injection and production wells in reservoir. Developed InSAR processing has been carried out to obtain accurate surface deformations. The unwrapped differential interferogram refinement, stacking technique, and trend removal are applied to attenuate some noises which inherently present in InSAR data. Poor offset estimation occured in geocoding look-up table creation; therefore the Landsat ETM+ was required to refine the look-up table. Maximum estimated vertical displacement rate is around 3.8 cm/year from 2007 to 2008.

Based on Okada's model, an inversion of the surface uplift using genetic algorithms can provide the location of displacement sources. While the least-square method was used to efficiently invert distribution of source opening in subsurface from the surface uplift data. From the genetic algorithms the depth of displacement sources is 297 meters. The maximum vertical displacement at the depth obtained from least-square inversion is 4.5 cm. The results show that the inversion results have a good agreement with that of real data. Moreover, surface deformations from forward modeling are comparable to real data estimated by InSAR. As conclusion, the InSAR technology combined with inversion techniques is powerful tools for monitoring reservoir deformations undergoing SAGD process.

KEY WORDS: InSAR, Genetic Algoritms, linear least-square inversion, surface uplift, source opening

INTRODUCTION

If a sufficient volume of fluid is withdrawn from or injected into a reservoir, the reservoir can deform (*Vasco, 2008*). For an example a reservoir undergoing steam injection, the reservoir pressure and temperatures will increase inducing reservoir deformations. The total of vertical displacement of the reservoir continued upwards through the overburden to ground surface, with little attenuation (*Patrrick, 2005*). The surface deformations have valuable information about the dynamic reservoirs under production.

There are some technologies used to monitor surface deformations such as GPS, tiltmeter, optical leveling and InSAR. GPS is one of the most suitable conventional techniques of surface deformation monitoring because it has not only high accuracy, but also provides three components of deformation. GPS surveys over a large area are labour intensive and very time consuming. Fortunately, InSAR technology provides its capability for imaging the ground surface deformations over large area (several 10s of km) with very small (1 cm or less) surface changes all weather conditions in daylight or at night.

Most of InSAR applications are in seismology, in natural disaster monitoring and assessment, in ground water hydrology, and in mining, but few in reservoir monitoring. All these applications that were already done in previous researches are almost the same processing flow to obtain ground surface deformations. In this study we developed the different processing flow to estimate accurate deformations associated with steam injection. From the surface deformations we inverted to estimate slip distributions as opening sources using a finite rectangular fault model which have not been applied in reservoir monitoring yet.

METHODS

2.1 Monitoring Ground Surface Deformations

In this study, we used 9 scenes acquired by Phase-Array type L-band (PALSAR) instrument on the Japanese Advanced Land Observation Satellite (ALOS) "Daichi" for the period from February 9, 2007 to December 30, 2008. Data modes are Fine Beam Single (FBS-HH) and Fine Beam Dual (FBD-HH+HV) acquired from ascending orbits with an off-nadir 34.3 deg. PALSAR has much higher successful rate for generating displacement maps than ENVISAT ASAR *(Ng et al. 2008*).

From nine SAR images we generated six interferograms. Interferogram is the phase difference measured based on two SAR images acquired from two slightly different positions at different times. Interferogram consisted of not only the topography and any displacements in the slant range direction between two acquisitions, but also the effects of atmospheric disturbances, orbit errors and decorrelation noises.

In order to estimate the ground deformations all the other components (e.g., atmospheric disturbances) in interferogram should be carefully removed. Using a 3 arc-second digital elevation model (DEM) we simulated the topographic phase in order to remove it from the interferogram to generate differential interferogram. Because DEM was in EQA projection, we needed look-up table to transform it from EQA projection to SAR coordinates. In this study a target area has moderate topography so that poor offset estimation occurs when co-registration between PALSAR image and simulated SAR image derived from DEM. Therefore, we used Landsat ETM+ image obtained from Global Land Cover Facility (GLCF) to refine look-up table. The obtained differential interferogram still exhibited a few fringes across the image because of small error in baseline model. To refine the differential interferogram, we improved the baseline estimate based on fringe rates and ground control point (GCP) (REFERENCE).

For ALOS PALSAR data a complete 2π phase change in differential interferogram is equivalent to a height displacement of 11.75 cm (half of the wavelength of the radar signal in the slant range direction). The measured phases in the differential interferogram are wrapped in modulo of 2π. Therefore, the interferogram had to be unwrapped to remove the modulo-2π using a minimum cost flow method (*Goldstein et al., 1988*) before estimating ground surface displacement. The flattened interferogram was filtered to reduce noise in the fringe before the phase unwrapping. Among some types of filters, we applied a modified Goldstein filter to reduce phase noises from interferogram (*Baran et al., 2003*; *Li et al., 2006*). This filter made the filter parameter alpha dependent on coherence, such that incoherent areas were filtered more than coherence areas. Therefore, this filter minimized loss of signal while still reducing the level of noise.

Squinted orbits affected large baseline changes along-track so that the differential still presented some residual phase components not yet compensated for after baseline improvement. Therefore, we needed to compensate unwrapped interferogram for residual quadratic phase components.

The atmospheric path delay has an effect in the accuracy limitation of the deformation estimated from individual differential interferograms. This error was reduced empirically by doing a local fit to the phase variations to measure a trend and then removing it. We also combined multiple observations into a single result, which is called as interferogram stacking, to reduce this error. The main assumption is that the deformation phase is higly correlated and the error terms are uncorrelated between the independent pairs. Vertical displacement rate was achieved from the stacked interferogram.

2.2. Opening Source

As a modern geodetic method SAR interferometry measurement has an ability to estimate a high spatial coverage of displacement maps. It provides an excellent opportunity to analyze physical processes by modeling the source of deformation especially steam chambers in our study case. Ground surface displacements do not exhibit a spherical shape and thus it does not seem to be the best approximation. As a more appropriate model, we used a rectangular dislocation in elastic, homogeneous, and isotropic half-space (*Okada, 1985*). Characterization of the deformation sources based on the SAR interferometry measurements has become major importance in related reservoir monitoring activity.

First step, we used an optimization technique of Genetic algorithm (GA) to invert for fault geometry from the ground surface deformations acquired by SAR interferometry processing in order to estimate the depth of a steam chamber. In this analysis, we used a Poisson ratio of 0.25 and a rigidity of 10 GPa. Second step, we used a linear least square method to model the distributed opening source and subdivided the fault plane into a 40 x 40 grid.

RESULTS

1. Ground Surface Deformation Estimation

In interferometry processing, the most important step is to co-registration between master SLC and slave SLC. For instance, data 2007/06/27-2008/09/29 the subset of the image used to generate interferogram is better than the full image. The maximum standard deviation of full image is 0.14. This value is higher than that of small image having a maximum standard deviation of 0.098. Therefore, an advantage of processing with co-registration in small image is more accurate than full image. It may be caused by involving a high decorrelation area across the images in full image co-registration.

The co-registration was also applied for geocoding to obtain a fine lookup table. In this study we used the external reference intensity image and compared it to the simulated SAR image for refinement of a lookup table. The number of estimate offsets is larger with the external reference intensity image than that of with the simulated SAR image. On the other hand, a maximum standard deviation is lower in this processing with the Landsat intensity image than with the simulated SAR image. In the case of SAR intensity image has many more features with the Landsat image than that of with the simulated SAR image.

The better co-registration in the generation of interferogram and in the geocoding were estimated, the better differential interferograms were obtained. The differential interferogram is much better with Landsat image than without it. Without the Landsat image some red strips are still present in differential interferogram. This affected the unwrapped-differential interferogram worse and then resulted in an inaccurate deformation map. On the other hand, the resulting differential interferogram with the Landsat intensity image does not present some red strips so that the unwrapped differential interferogram from this is smooth. Of course, it provided an accurate the deformation map.

The compensation of unwrapped differential interferogram for residual quadratic phase was applied for our case study because of some residual phase components. After the compensation the unwrapped differential interferogram is smoother and more homogeneous than before. Finally, the surface deformation rate was obtained by converting stacked-six unwrapped differential interferograms into vertical displacements. A maximum vertical displacement is 3.8 cm/year from 2007 to 2008. The result is in a good agreement with data estimated using conventional measurement by JACOS. Comparison between them is shown in Figure 1. Vertical displacement slopes across deformed area is shown in Figure 2. Information of the slopes is very important especially related to the safety of surface facilities.

2. Opening Source Estimation

For a geometry inversion using the genetic algorithm we constrained the lower and upper bounds of length, width, depth, source opening and strike of the fault to 4.2-5.0 km, 3.5-4.5 km, 280-300 m, 0-20 cm and 0^o-360^o, respectively in search space. We also considered the dip angle of zero as one of the inversion parameters and used the initial population of 500 individuals. The initial population were subjected to several changes by systematically approaches the best solution among many investigated solutions. Major genetic algorithm operators are evaluation, selection, cross-over and mutation to allow modification of the population to search the best solution. The searching process ended when a number of iterations or generations were achieved as a stopping criterion. In our case, a number of generations are 500. From the genetic algorithm we obtained the best-fit model predicted the rectangular fault with length, width and depth of 4.629 km, 3.767 km and 297 m, respectively with the root-mean-square error (RMSE) of 6.977E-005. The depth of opening source is in good agreement with real data related to the depth of injection wells.

For the estimation of the opening source distribution from observed-surface-deformation data from SAR interferometry measurement, we used a least square inversion. The best-fit-single fault model from the genetic algorithm inversion was enlarged to 4.6 x 4.0 km horizontal fault. The enlarged-fault plane was then discretized into 100 x 100 m patches for inversion of distributed-source opening. This opening is interpreted as steam-chamber growth under SAGD process. In this study, we used penalty function with smoothness factor of 0.1. From this inversion, the maximum of source opening rate was around 4.5 cm/year shown in Figure 3.

The observed and modeled surface displacement are comparable in which has root-mean-square error of 1.2498e-005 such as shown in Figure 4. The small residuals between observed and modeled displacements in Figure 4c may be related to some noises in InSAR data. The total of volume change rate was 148346.6692 m^3/year. This volume change rate is considered as steam chamber growth during SAGD process.

Conclusion

We presented a case study concerning the vertical surface deformation using DInSAR and used it to monitor SAGD process related to the growth of steam chamber. The maximum of vertical surface displacement rate is 3.8 cm/year from 2007 to 2008. Genetic algorithm inversion estimated the depth of opening source about 270 m. Based on least-square inversion, the maximum of source opening rate is about 4.5 cm/year. Finally, we estimated the total opening volume rate of 148346.6692 m^3/year considered as the growth of steam chamber.

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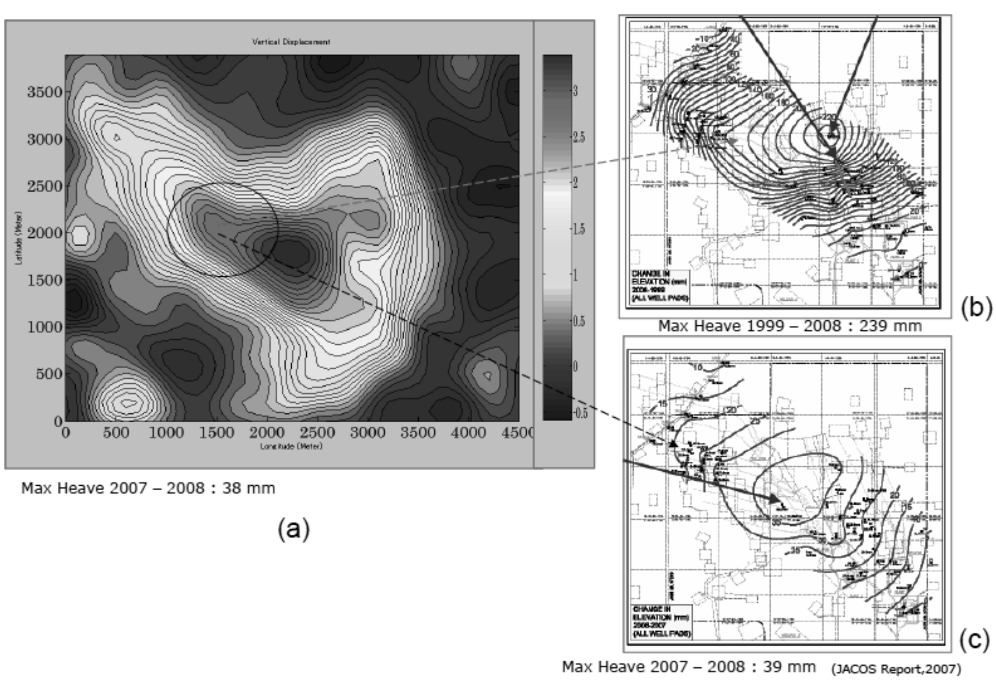

Figure 1. Comparison of vertical displacements between (a) our result and (b),(c) JACOS results (reference).

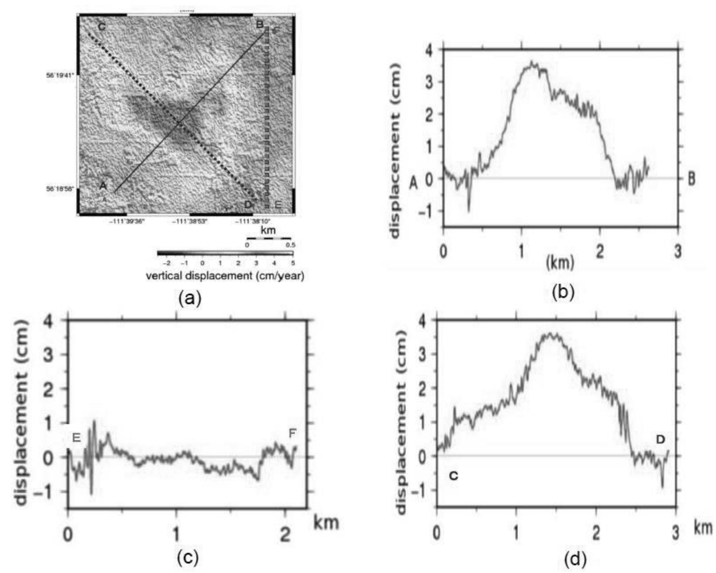

Figure 2. Vertical displacement rate slopes across deformed area of interest.

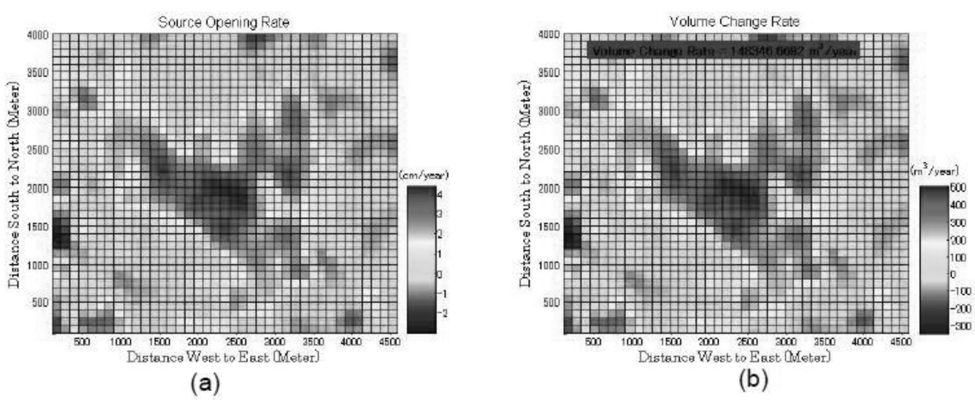

Figure 3. (a) Source opening rate. (b)volume change rate.

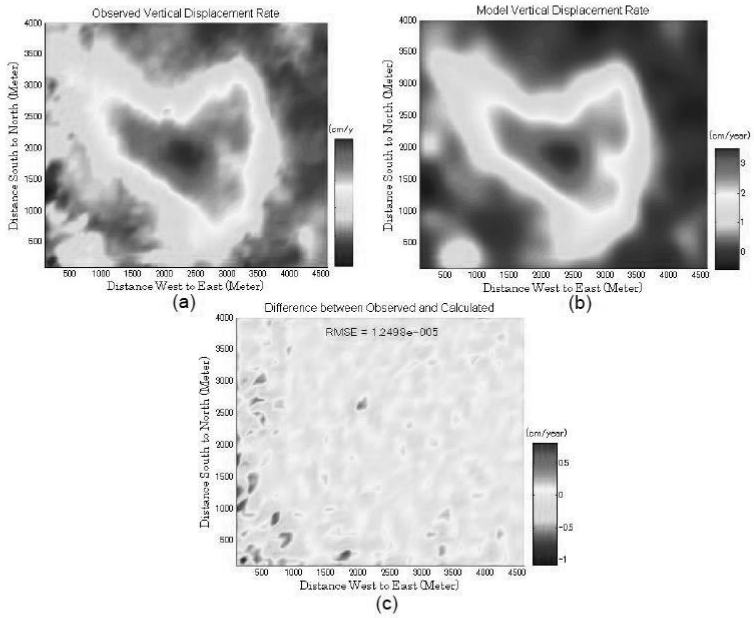

Figure 4. Comparison of (a) the observed and (b) the modeled vertical displacements, and (c) the residual between them.