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論文題目	Synthetic Aperture Radar Interferometry for Natural Disaster and Reservoir Monitoring （干渉 SAR 解析を用いた自然災害と貯留層のモニタリングに関する研究）		

（論 文 内 容 の 要 旨）

This study focuses on the capabilities of a SAR interferometry as a stand-alone technique to detect and quantify ground surface deformations. In order to achieve the accuracy of the deformation estimations from the technique comparable to traditional geodetic measurements, such as GPS and leveling surveys, careful data process in each step of the SAR interferometry is required with considerations of the qualities. In this dissertation, two methods presented in order to estimate the surface deformations are (1) two-pass differential SAR interferometry (DInSAR) and (2) interefrometric point target analysis (IPTA). Two case studies are investigated as (i) land subsidence in Bandung Basin, Indonesia and (ii) surface heave at oil-sand field at Hangingstone, Canada. This dissertation consists of 6 chapters.

In Chapter 1, general descriptions of this study is introduced including main topics related to excessive groundwater extraction in Bandung Basin, Indonesia and steam injection using SAGD technique for EOR at the Hangingstone field, Canada, along with this description of dissertation content and organization.

In Chapter 2, the history of SAR interferometry is described. In addition, overview of the principle of SAR interferometry is also introduced.

In Chapter 3, the differential SAR interferometry (DInSAR) technique is introduced. Since the subsidence has occurred in most of urban regions, DInSAR is suitable to estimate the subsidence in Bandung Basin for long time duration between two observations. 32 interferograms is generated from 21 ascending SAR images obtained from ALOS/PALSAR over a period from January 1, 2007 to March 3, 2011. In order to remove topographic phase, the 3-arc-second Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) is adopted. A detail DInSAR processing to estimate and describe the land subsidence history with time series of interferograms is explained in this chapter.

Assuming the displacements are stationary, the noises can be suppressed and the subsidence rate is obtained by averaging the interferograms which is the so-called interferogram stacking technique. However, several surface displacements may be not only linear but also nonlinear. In order to estimate the nonlinear displacement IPTA method is adopted. Using IPTA topographic phase, atmospheric phase and phase noise were estimated and suppressed from interferogram phase. Total displacement is the summation of the linear and nonlinear displacement. The displacement rate was also estimated from the linear displacement history. The maximum subsidence of about 12 cm per year which occurred in Cimahi city can successfully be identified by using both DInSAR and IPTA methods. The subsidence pattern and subsidence rate maps are not always correlated with the production well distribution and aquifer zoning maps due to geological structure of investigated area. The largest land subsidence has occurred in industrial regions and it can also be seen from the aquifer zoning map, which the region has experienced damage in the aquifer system. The seasonal characteristic of the land subsidence in Bandung has successfully been investigated based on the nonlinear component of displacement. Results show great potential of differential SAR interferometry to comprehensively monitor the process in developing groundwater in Bandung Basin.

In Chapter 4, the surface heave rate at oil sands field due to steam assisted gravity drainage (SAGD) has also been estimated by stacking unwrapped differential SAR interferometry. For the case of Hangingstone area in the lookup table creation for geocoding, the refinement of the lookup table was different from that of

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Bandung Basin area. Commonly, InSAR processing for the refinement of lookup table is enough to make use of a simulated SAR intensity image in order to obtain positioning accuracies at sub-pixel level in the automatic registration with the actual SAR image. For Bandung Basin area, the simulated SAR intensity was reasonably used to obtain at the sub-pixel accuracy. However, the topography of Hangingstone area is poor. It can make the simulated SAR intensity generated from a SRTM DEM not well working used to improve the accuracy up to sub-pixel due to a high decorrelation between both images (SAR intensity from PALSAR and simulated SAR intensity from SRTM DEM). A comparison of three adaptive filtering methods has been further conducted to choose the suitable method for optimally reducing noises over differential interferograms. Once quadratic phase is removed from unwrapped differential interferogram, the stacking is performed to estimate the surface heave rate which the stacking at the same time also removes atmospheric effects. Finally, the surface heave rate estimate is validated with the result of the network of 54 leveling surveys. Our result is in good agreement with the network surveys.

In Chapter 5, the surface heave induced by SAGD process has valuable information about the dynamic reservoir. We have therefore made use of the heave map to estimate distribution of reservoir deformations and reservoir volume change in the oil sand reservoir by means of an inversion technique. As a geomechanical inversion, the two-step inversion scheme is proposed based on a tensional rectangular dislocation model. In the first step of the inversion, the genetic algorithm is adopted to estimate the depth and rough deformation of the reservoir. The depth of the oil sand reservoir estimated from the inversion is well consistent with depth of steam injected depth (297 m). Secondly, the least square inversion with the penalty function and smoothing factor is used to efficiently invert the distribution of reservoir deformation and volume change from the surface uplift data. These results demonstrate that the InSAR technology is useful to provide ground surface deformations and accurately monitor reservoir deformation using inversion techniques

In Chapter 6, the general conclusions of the study is described, especially achievements, advantages and disadvantages of investigated results in this dissertation.

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（論文審査の結果の要旨）

本論文は、人工衛星によって取得された合成開口レーダーに対して、干渉処理を適応し、インドネシア国バンドン市における地盤沈下量を推定し、その地質学的な問題について検討した。さらにカナダ国のオイルサンド地域での地表面隆起量の推定を行い、それが SAGD(Steam Assisted Gravity Dgainage)法によるオイルサンド生産に伴う水蒸気圧入に起因することを明らかにし､隆起量に対して逆問題を解くことにより貯留層の変形量を推定した。得られた主な成果は次のとおりである。

1. インドネシア国バンドン盆地における過度の地下水の取水による地盤沈下を、合成開口レーダーの干渉解析（InSAR 解析）を用いて推定した。最大の沈下量は、2007 年 3 月 1 日以来、4 年の期間で 45cm 以上であり、地盤沈下の最大速度は、約 12 cm /年と推定された。大規模な地盤沈下を引き起こしている地域は、工業地域と家屋の密集した都市部であり、この地盤沈下の原因としては、都市地域での商業活動のための地下水の過度の消費であると想定される。
2. バンドン盆地での地盤沈下は、沖積層と湖沼堆積物からなる盆地の中央部で発生しており､沈降地域のほとんどは地下水の生産井が多い地域と一致している。しかし、堅い基盤岩を有する地域では、帯水層は取水のダメージを受けているが、地盤沈下は生じていないことが示された。
3. InSAR 解析ではフィルタリングによってノイズの除去が必要になる。カナダ国のオイルサンド地域で取得されたデータに対して、3 種類のフィルタリング手法を適用し、3 つの評価関数を用いてノイズ除去の効果を検討した。その結果、水蒸気注入により、3.6 cm /年の地表面隆起が観測された。この隆起のパターンは、GPS によって推定された同地域での隆起量分布と良い一致を示し、InSAR 手法の有用性を示した。
4. オイルサンド貯留層の変形と体積変化量を推定するために、2 段階の逆問題解法を提案した。最初のステップで、隆起データに対して遺伝的アルゴリズムを適用し、平均的な貯留層変形を推定し、第二段階で、平滑化最小二乗法を適用し、分割面毎での変形量を推定した。これにより水蒸気チャンバーの成長に対応した貯留層の総体積変化率が推定できた。

以上､本論文は､InSAR 解析によって地表面の微少な変形量の推定が可能であること、解析時にノイズが引き起こす問題点とその解決法の提案､および地表面変動結果の地質学的な検討について議論した。本論文で検討されている手法や知見は、これからの地表変形モニタリングへの応用が期待されることから、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、平成２４年２月２１日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。