京都大学教育研究振興財団助成事業
成　果　報　告　書

平成26年11月9日

公益財団法人京都大学教育研究振興財団
会 長　辻　井　昭　雄　様

所属部局: Graduate School of Engineering

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助成の種類	平成26年度 ・若手研究者在外研究支援 ・ 国際研究集会発表助成		
事業内容	IGARSS 2014		
開催期間	平成26年7月13日～平成26年7月18日		
開催場所	The Québec City Convention Centre, Québec, Canada		
参加者	総 数: Over 300	内 訳: America, Austria, Australia, Canada, China et al.	
成果の概要	タイトルは「成果の概要／報告者名」として、A4版2000字程度・和文で作成し、添付して下さい。「成果の概要」以外に添付する資料 ☑ 無 ☐ 有( )		
会計報告	事業に要した経費総額	300,575 円	
	うち当財団からの助成額	250,000 円	
	その他の資金の出所	(機関や資金の名称)	
	経費の内訳と助成金の使途について		
	費目	金額 (円)	財団助成充当額 (円)
	Registration Fee	21,528	21,528
	Air Ticket	163,513	163,513
	Transportation (Airport to Hotel)	12,000	12,000
	Accommodation	81,400	52,959
	Insurance	4,520	0
	VISA Application	17,614	0
	Total	300,575	250,000
	(*Foreign Exchange Rates is based on 2014.07.1)		
当財団の助成について	(今回の助成に対する感想、今後の助成に望むこと等お書き下さい。助成事業の参考にさせていただきます。)		

Report on the International Geoscience and Remote Sensing Symposium (IGARSS 2014)

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First of all, I would like to express my gratitude to Education and Research Revitalization Consortium of Kyoto University (京都大学教育研究振興財団) for giving me the opportunity to attend the IGARSS 2014 Symposium.

Introduction

This is a comprehensive report on the IGARSS 2014 event. This report aims to identify the main features and contributions of this event.

Event description

The International Geoscience and Remote Sensing Symposium (IGARSS 2014) / 35th Canadian Symposium on Remote Sensing (35th CSRS).
The symposium theme is "Energy and our Changing Planet". The development of new and renewable sources of energy in the context of a changing planet is a critical issue throughout the world.
This partnership between the IEEE Geoscience and Remote Sensing Society (GRSS) and the Canadian Remote Sensing Society / Société canadienne de télédétection (CRSS-SCT) builds on a fine tradition of collaboration that began over 25 years ago.
http://www.igarss2014.org/default.asp

Conference Venue

The Québec City Convention Centre, which won the 2006 Apex Award for the World's Best Congress Centre bestowed by the prestigious International Association of Congress Centers (IACC) was selected to host IGARSS 2014/35th CSRS.

Our contribution

An oral presentation was successfully delivered at the conference on Tuesday, July 15, 2014

Session Chairs:

Clemence Dubois, Karlsruhe Institute of Technology
Michael Henschel , MDA Corporation

Paper Detail

Paper:	TU4.01.4
Session:	INSAR Applications III
Time:	Tuesday, July 15, 16:40 - 17:00
Presentation:	Oral
Topic:	Analysis Techniques: InSAR and High Resolution SAR
Title:	**SURFACE DEFORMATION MONITORING USING SAR INTERFEROGRAMS AND GPS OBSERVABLES: APPLICATION TO TOKYO, JAPAN**
Authors:	Tamer Elgharbawi; *Kyoto University*
	Masayuki Tamura; *Kyoto University*

To watch a recording of the presentation please visit
http://www.igarss2014.org/ShowRecording.asp?C=C38C47A6

A copy of the published paper is also included in this report

SURFACE DEFORMATION MONITORING USING SAR INTERFEROGRAMS AND GPS OBSERVABLES: APPLICATION TO TOKYO, JAPAN

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ABSTRACT

This paper presents a method to monitor surface deformations using SAR interferometry and GPS observables. In this analysis we used least squares to reduce the errors presented in InSAR deformation maps temporally then we used a GPS based spatial phase filtering to spatially filter the estimated deformation maps. This method can generate crustal deformation time series with geodetic accuracy using only 10 interferograms and few operational GPS stations. The proposed method was tested on Tokyo bay area, Japan which has been affected by the 2011 Tohoku earthquake. The results were verified against deformations detected by GPS stations showing a mean standard deviation of 7.9 millimeters.

Index Terms— InSAR, GPS, Deformation Monitoring, 2011 Tohoku Earthquake

1. INTRODUCTION

Surface deformation monitoring using differential SAR interferometry has been established and used successfully to measure and study terrain deformations due to several phenomena by numerous researchers. Because of the errors presented in InSAR deformation maps several researchers have presented valuable methods for InSAR stacking and time series analysis that can produce an accurate deformation time series. Berardino et al. [1] have presented Small Baseline (SBAS) approach which uses the singular value decomposition (SVD) to link independent SAR acquisition datasets. They validated their approach using 70 differential interferograms of southern Italy with a maximum normal baseline of 130 m., Schmidt and Burgmann [2] have used least squares inversion of differential interferograms to estimate the incremental range change between SAR acquisitions. They processed 115 differential interferograms of Santa Clara valley, California, with a maximum normal baseline of 200 m. They stated that a minimum number of 30 interferograms are required to produce a reasonable time series.

The main target of this paper is estimating the co-seismic crustal deformations in Tokyo bay area which has been affected by the 2011 Tohoku earthquake using InSAR time series least squares analysis combined with GPS based supervised spatial phase filtering. This method is presented to overcome some of the limitations that prevent an adequate application of the existing methods. In this analysis we didn't have the luxury of choosing a normal baseline threshold other than the critical one. With the aid of least squares analysis and GPS based spatial filtering we managed to estimate crustal deformation time series with accuracy of millimeters level using only 10 interferograms. The differential unwrapped phase maps were analyzed using least squares method to obtain the most probable deformation values for each epoch of the study time frame. After estimating the deformation maps we used the GNSS Earth Observation Network System's (GEONET) GPS stations for supervised spatial phase filtering, this method was presented by ElGharbawi and Tamura [3].

ElGharbawi and Tamura [3] used more than 30 GPS stations to model and correct the tropospheric delay and introduced the application of GPS based supervised spatial phase filtering. Using GPS tropospheric delay to correct the InSAR deformation maps will generate interpolation errors between GPS stations even when using a dense GPS network like GEONET. In addition, the availability of more than 30 operational GPS station within and around the SAR scene can be very challenging for many sites around the world. That's why we used the least squares analysis as a temporal filter to reduce the tropospheric effect among other errors and we used GPS stations in supervised spatial phase filtering which will reduce the number of needed GPS stations down to four or five operational stations with in the SAR scene.

The use of GPS stations observables in spatial phase filtering was necessary because of the special nature of deformations occurred due to the 2011 Tohoku Earthquake. Because of that earthquake the whole Tohoku Island was shifted and the deformation signal was presented as long interferometric wave pattern dominating the entire deformation maps leaving no stable area that can be identified to facilitate the differentiation between actual deformations and other imposed biases.

2. METHODOLOGY

2.1. InSAR Stacking

Let's consider the number of available SAR images for the same area equal N and ordered in a time series [t_1: t_N]. Then the number of the unknown deformations for each pixel will equal $n = N\text{-}1$ and can be identified by [d_1: d_n]. The maximum number of differential interferograms that can be calculated is $M = N!/\big((N-2)!\,2!\big)$.

For clarification let's consider that we have N = 5 SAR images, then the unknown deformations will equal n=4 deformation segments [d_1, d_2, d_3, d_4] and the maximum number of interferograms M = 10. Figure 1 illustrates the interferogram structure for this example. Every horizontal bar represent an interferogram starting at the master image (left side) and ending at slave image (right side) and containing the unknown deformation components that represented by that interferogram. It is clear that every unknown deformation in this example is presented in at least 4 interferogram. It is important that every unknown deformation should be presented by as many as possible interferograms. After the generation of interferograms; flatting, topography removal, filtering and phase unwrapping should be carried out using suitable methods.

2.2. Problem Formulation

After phase unwrapping the unknown deformations **d** = {d_1 : d_n} can be estimated by minimizing the squared error function (***E***) (1). We had to take the topography error into consideration (3) because we are using interferograms with large normal baselines.

$$\boldsymbol{E} = \sum_{i=1}^{M}(LOS_i - \mathrm{D}_i - \Delta\,Topo)^2 \;\Rightarrow minimum \qquad (1)$$

$$\mathrm{D}_i = \sum_{j=\mathrm{t}(Master)}^{\mathrm{t}(Slave)} \mathrm{d}_j \qquad (2)$$

$$\Delta\,Topo = (B_{\perp i} \cdot \Delta h)/(r \cdot sin\,\vartheta) \qquad (3)$$

Where, LOS_i is the i^{th} InSAR LOS deformation, D_i is the unknown deformation components for the i^{th} interferogram, $\Delta\,Topo$ is the topography error, d_j is the unknown deformation of time segment j, $B_{\perp i}$ is the normal baseline of the i^{th} Interferogram, Δh is the DEM error, r is the sensor target distance and ϑ is the incident angle.

The minimum value of the squared error function ***E*** is reached when the first derivatives with respect to each component of the unknown surface deformations (d_i**)** are zero. This gives rise to the linear equation (4). Where **A** is design matrix with dimensions $M \times (n+1)$, **d** is the unknown deformation vector with dimensions $(n+1) \times 1$ and **L** is the observed LOS deformation vector with dimensions $M \times 1$.

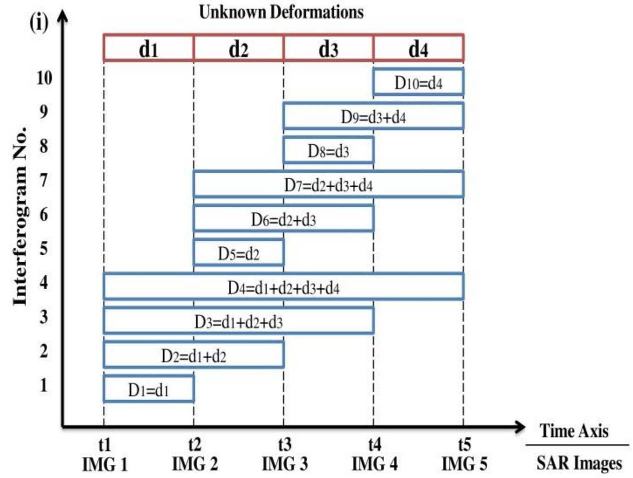

Fig. 1. InSAR Stacking Structure.

The matrix ($\mathbf{A^T \cdot A}$) is non-singular matrix; therefore inverting this linear system should be simple. Considering the example illustrated by Figure 1, the design matrix $\mathbf{A} = [\boldsymbol{B}, \boldsymbol{c}]$ (5) and unknown deformation vector of the system $\mathbf{d}^{\boldsymbol{T}} = [\mathrm{d}_1, \cdots, \mathrm{d}_n, \Delta h]$**.** It should be noted that the estimated deformations are discrete epoch to epoch values and to generate a deformation time series a successive summation of the deformation values should be done first as shown in (2).

$$\mathbf{d} = (\mathbf{A^T} \cdot \mathbf{A})^{-1} \cdot (\mathbf{A^T} \cdot \mathbf{L}) \qquad (4)$$

$$\boldsymbol{B} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \;\&\; \boldsymbol{c} = \begin{bmatrix} (B_{\perp 1})/(r \cdot sin\,\vartheta) \\ \vdots \\ (B_{\perp M})/(r \cdot sin\,\vartheta) \end{bmatrix} \qquad (5)$$

2.3. Supervised Spatial Filtering

ElGharbawi and Tamura [2] have presented a methodology for spatial phase filtering using GPS derived products. This methodology can be briefly described as follows. First, calculate the LOS deformation using the GPS stations' coordinates, radar incident and azimuth angles for each pixel. Second, identify the phase values corresponding to GPS stations in the deformation map and subtract the GPS derived LOS deformations from it. The residuals are the spatially correlated component of the imposed errors in deformation measurements at GPS stations positions in addition to the ambiguity value of the unwrapped phase. These residuals were used to fit a two dimensional surface of the first degree in range and azimuth directions. Finally this surface is subtracted from the deformation map. This method should be applied to the deformation maps estimated using the least squares method described in the previous section.

3. APPLICATION

The proposed method was tested using 5 ALOS-PALSAR images for Tokyo bay, Japan which was struck by an M9.0 megathrust earthquake on March 11, 2011. Tokyo has suffered from large deformations that affected the entire area. All the images are in ascending orbit and Fine Beam Single polarization (FBS) mode, additional details are in Table 1.

By using 5 SAR images the example illustrated in Figure 1 and the linear equations system in (4) and (5) are valid in our study; therefore interferograms were generated and structured as illustrated in Figure 1. The effect of topography was removed using SRTM-3 DEM. Goldstein method was used for filtering and Minimum Cost Flow (MCF) method was used for phase unwrapping with coherence threshold equals 0.2. To reduce the effect of phase decorrelation we used multilooking of 3 looks in range and 8 looks in azimuth. The unwrapped phase maps for all the interferograms were calibrated with respect to a reference GPS station (Figure 1).

Using least squares method to solve the system in (4) we estimated the unknown deformation values for the entire scene. For spatial filtering, 10 GPS stations were identified with in the study area with coherence value higher than 0.2 for the study time frame. We used 6 stations for spatial filtering as described in section 2.3 and reserved 4 GPS stations for verification. Figure 2 shows deformation map (d4) which represents the effect of the 2011 Tohoku Earthquake on Tokyo bay area, in addition to the locations of GPS stations.

Master	Slave	$B_\perp$ (m.)	Δ t (days)
3-4-2010	19-8-2010	593	138
	4-1-2011	1285	276
	19-2-2011	2328	322
	6-4-2011	2690	368
19-8-2010	4-1-2011	761	138
	19-2-2011	1849	184
	6-4-2011	2185	230
4-1-2011	19-2-2011	1850	46
	6-4-2011	2082	92
19-2-2011	6-4-2011	396	46

Table 1. Details of SAR images and interferograms

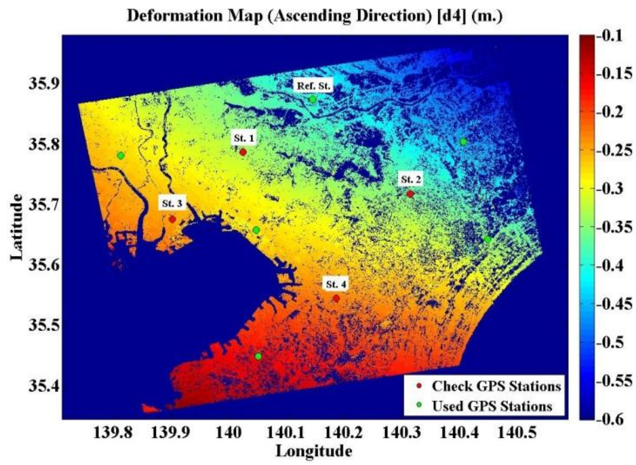

Fig. 2. Deformation map (d_4) of Tokyo bay area (19 Feb 2011 : 6 Apr 2011), with GPS stations locations.

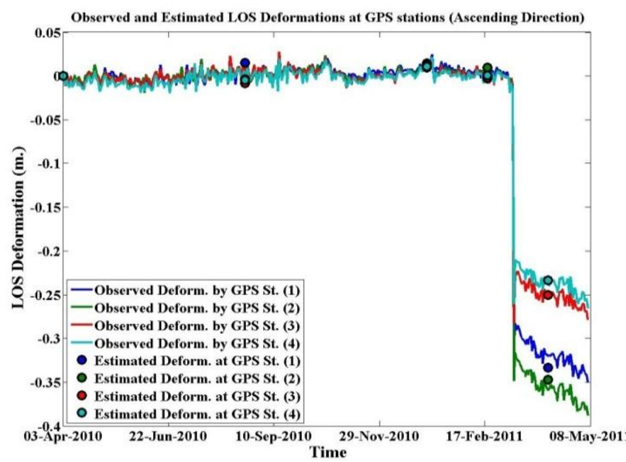

Fig. 3. Observed and estimated deformation time series of GPS stations.

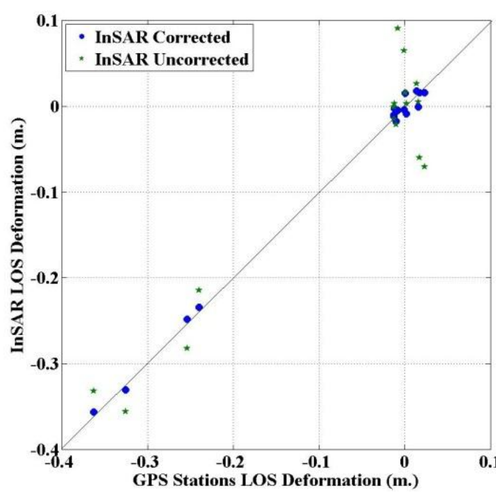

Fig. 4. LOS deformations obtained by GPS and InSAR before and after applying the supervised spatial filtering, positive values means motion towards the satellite.

GPS Station ID	Error Standard Deviation (± m.)		Improvement %
	Without GPS based Filter	With GPS based Filter	
1	0.0191	0.0133	30.5
2	0.0609	0.0056	90.7
3	0.0176	0.0071	59.4
4	0.0792	0.0056	92.9
Mean	0.0442	0.0079	68.4

Table 2. Statistical analysis for GPS stations time series.

After estimating the deformation maps for Tokyo bay area we extracted the deformation values for the reserved GPS stations and estimated the deformation time series (2), then compared the estimated deformations time series with the LOS deformations obtained by GPS (Figure 3). Also, we compared the estimated discrete deformations with the LOS deformations obtained by GPS before and after applying the supervised spatial phase filtering (Figure 4). The errors in the estimated deformation values were in sub centimeter level showing a mean standard deviation of 7.9 millimeters and the use of supervised spatial phase filtering has reduced the errors inherited in deformation time series showing a mean improvement of 68.4 % (Table 2).

4. CONCLUSION

In this paper we present a methodology to estimate surface deformation time series using small number of interferograms. This method uses the unwrapped phase maps and least squares analysis to estimate a series of deformation maps for the study area. Then by using the availability of continuous GPS network observations a supervised spatial phase filtering was conducted to produce the final deformation map series. This method was tested using 10 interferograms of Tokyo bay area, Japan which was affected by 2011 Tohoku Earthquake. The final deformation time series were compared against GPS stations observations and the mean standard deviation of the residuals after using the GPS based supervised spatial phase filtering was 7.9 millimeters showing a mean improvement of the deformation time series accuracy equals 68.4%, these results demonstrate the accuracy and usability of the proposed methodology.

5. REFERENCES

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