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Ground Deformation Tracking over Mt. Baekdu: A Pre-evaluation of Possible Magma Recharge by D-InSAR Analysis

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Abstract

Mt. Baekdu, located in the northeastern Korean peninsula close to the Korea-China border, has been documented to have had a few destructive eruptions in history. Even though it has been dormant since the major eruption in 1702 A.D, the seismic activity in Mt. Baekdu has increased over the last few years. Together with the small-scale but constant earthquakes, other precursors, such as increasing geothermal activity in hot springs and emission of gaseous components, have also been identified. Since the reactivation of the volcano is suspected, we applied the Pifferential Inter Ferometric Synthetic Aperture Radar (D-InSAR) processing over Mt. Baekdu to detect possible topographic deformation caused by magma activities. To address the harsh environmental factors, such as water vapor, heavy vegetation canopy and steep slope around summit, for D-InSAR processing, the SBAS approach was applied to ENVISAT Advanced Synthetic Aperture Radar (ASAR) data together with ALOS PALSAR two pass D-InSAR analysis for the comparison and a clear deformation signal over the monitoring area was detected. In spite of the absence of direct measurements, the deformation in Small Baseline Subsets (SBAS) interpretation can be taken as the evidence for possible volcanic activity and employed as part of a warning system. Based on the findings revealed in this paper, it is strongly proposed that an intensive observation network covering the extent of Mt. Baekdu, together with international collaboration, is urgently required.

Keywords: *Mt. Baekdu, surface deformation, magma activity, differential interferometry, SBAS, ENVISAT ASAR*

1. Introduction

Mt. Baekdu (also known as Changbai in Chinese) is a volcanic mountain located on the border between North Korea and China. It made one of the most destructive eruptions in the recorded history around 1000 A.D. This eruption was estimated to produce explosive Volcanic Explosivity Index (VEI) 7 eruption (Yin *et al.,* 2012) which was comparable to Mt. Tambora's eruption. Since making minor eruption in 1702 A.D. as clearly stated in the Korean history, the Mt. Baekduh has been dormant.

With continuous monitoring over Mt. Baekdu, it is evident that the frequencies of earthquakes and gas emission were increasing (Gao, 2004; Liu *et al.*, 2006). Based on the observation performed by Yun and Lee (2012), the sudden increment in seismic activities began in 2002 and made annual peak up to 2100 in only 2003. In addition, Xu *et al.* (2012) conducted a series of seismic, gas detection, GPS and precise leveling observation on the Chinese side of summit. The results showed important precursors of volcanic activation, including: (1) Strong seismic activities especially from 2002 to 2006 with the peak number of 243 in November 2003, following a period of seismic inactivity from 2006 to 2011; (2) Abnormal gas emissions in three hot springs around the summit from 2002 to 2006; (3) Strong vertical uplift during 2002 to 2005 and horizontal displacement away from Caldera Lake observed using GPS data; (4) A number of abnormal thermal activities in hot springs; (5) Surface deflation indicating new magma activities at the western and northern slopes from 2009. Therefore, it is realized that periodic magma activities are underway beneath Mt. Baekdu from the ground observations.

In addition to such short-term campaigns applied on discrete observation stations, a comprehensive monitoring covering overall extent of Mt. Baekdu was further proposed. The Differential Interferometric Synthetic Aperture Radar (D-InSAR) technique employing a series of remote sensed SAR phase angle difference was applied to address the difficulty for direct access to the border area due to political situation in this study. Although there are some alternative remote sensing methods to monitor the potential volcanic activities, such as thermal anomalies observation (Vaughan and Hoot, 2002) and gas emission detection (Eisinger and Burrows, 1998), D-InSAR has been considered as one of the most effective methods. For example, Zebkar and Goldstein

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(1986) monitor volcanoes using SAR data. Massonnet et al. (1995) applied spaceborne radar interferometry to observe Mt. Etna. Borgia *et al.* (2005) and Dzurisin *et al.* (2006) showed the methodology to establish the model of volcanic activity using D-InSAR analysis together with ground observations. Agustan *et al.* (2012)'s work is interesting due to its novel approach to model the Krakatau volcano using L-band D-InSAR and seismic data.

In this study, in order to deal with the harsh environmental conditions which might limit a successful D-InSAR processing over Mt. Baekdu, e.g., water vapor, vegetation canopy and steep slope around summit, a Small Baseline Subsets (SBAS) approach for detecting time series deformation (Berardino *et al*., 2002) employing ENVISAT ASAR images was further employed. Subsequently, the SBAS processing results from Mt. Baekdu were analyzed and interpreted together with the two-pass D-InSAR result using Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) data.

2. Characteristics of Target Area

Mt. Baekdu is covered by highly dense vegetation canopy except small portion near the summit (Fig. 1). Such vegetated land cover results in weak phase coherence in SAR processing and further lead to unstable phase angle processing and inaccurate estimation of surface deformation. Even in sparse vegetated area around the Candela Lake called Cheonji, the accuracy of InSAR results may be limited as the steep slope causes the loss of phase coherence (Lee and Liu, 2001). Furthermore, the snow cover around the Candela Lake normally exists up to early summer and also decreases the phase coherence. As described above, the environmental factors for attaining high phase coherences in SAR processing are generally absent in Mt. Baekdu.

The next issue relating to the successful D-InSAR processing at Mt. Baekdu is the effect of topographic and atmospheric

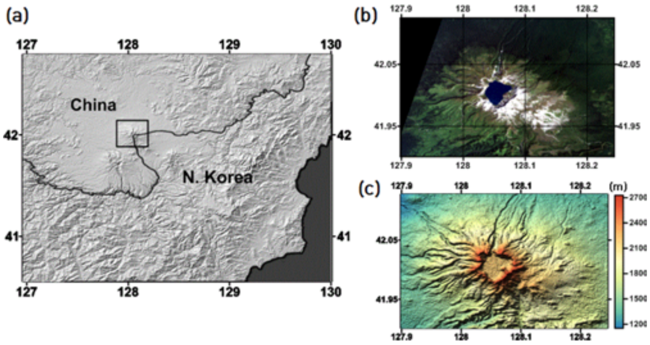

Fig.1. (a) The Location of Mt. Baekdu is Indicated by Black Box, (b) The EO-1 Advanced Land Imager (ALI) Space-borne Image Taken in June, 2008, (c) The Corresponding Zoomed-in View of DEM. The Snow Cover and Steep Slopes Around the Cheonji Candela Lake are Observed in (b) and (c)

outliers. Firstly, the ground and aerial surveying campaign is not feasible to cover large part of Mt. Baekdu. This results in the degradation of base DEM and contributes errors in D-InSAR products. Secondly, due to localized water vapor component, atmospheric contamination, in particular by vertical stratification and tropospheric anomaly, is significant in such high relief topography over Mt. Baekdu. Zebker *et al.* (1996) identified that the 20% change of tropospheric humidity could produce 10 to 14 cm ground deformation error. Considering the high altitude of Mt. Baekdu (2740 m) and the unstable weather condition where the annual temperature range is more than 30 K, the daily temperature range is up to 20 K in April and temperature lapse rate is varying from 0.3K/100 m to 0.6K/100 m (Nan, 2013), surface deformation observed in D-InSAR could not be correctly interpreted without any atmospheric correction process. Therefore, SBAS analysis capable of estimating topographic and atmospheric error components was introduced.

3. Data Sets and Processing Strategy

In this study, we focused on tracing minor movements occurring from 2007 to 2010. Regarding the selection of SAR image, considering the environmental conditions of the Mt. Baekdu, it was realized that the ALOS PALSAR image was an appropriate source in theory as the data with L-band wavelength was capable of producing relatively high phase coherence even in vegetated area. However, it was found that both the temporal and spatial PALSAR image coverage over Mt. Baekdu were not ideal to form interferograms. Instead, ENVISAT ASAR image data with comprehensive coverage during 2007-2010 was employed as the primary imagery for the D-InSAR analysis. A total of 19 ENVISAT ASAR C-band descending mode images captured in the testing period were introduced in this study (Table 1).

The C-band ASAR pairs over Mt. Baekdu occasionally produced noisy phase difference and weak coherence due to the environmental conditions, such as vegetation canopy, snow cover, steep slopes, erroneous phase angle caused by water vapor anomaly and long temporal gap between successive image acquisitions. To address the issues, the interferogram time series approach was employed in this study. There are two interferogram time series analysis algorithms commonly applied, including Persistent Scatterers (PS) and Small Baseline Subset (SBAS) approach. The PS method (Ferretti *et al*., 2000) allows identification of permanently strong scatterers in time-series interferograms with a common master image and sufficient number of slave images. Compared with the PS approach, the SBAS technique (Berardino *et al*., 2002) determines all the appropriate D-InSAR pair subsets possessing a small baseline. After the stacked differential interferogram is constructed, a linear system consisting of a small baseline combination matrix, phase values, and mean phase velocities are established. Singular Value Decomposition (SVD) together with Low Pass (LP) and High Pass (HP) filters are exploited to reduce the spatial and the temporal components of the noise, and subsequently the error reduced deformation

Table 1. ENVISAT ASAR Images over Mt. Baekdu during 2007-2010 Period

	Orbit	Track	Pass
2007-02-02 01:44:47.53	25751	146	Descending
2007-03-09 01:44:48.84	26252	146	Descending
2007-04-13 01:44:47.23	26753	146	Descending
2007-05-18 01:44:50.34	27254	146	Descending
2007-07-27 01:44:52.77	28256	146	Descending
2007-08-31 01:44:51.35	28757	146	Descending
2007-12-14 01:44:44.71	30260	146	Descending
2008-01-18 01:44:45.79	30761	146	Descending
2008-03-28 01:44:46.06	31763	146	Descending
2008-05-02 01:44:44.21	32264	146	Descending
2008-08-15 01:44:46.07	33767	146	Descending
2008-10-24 01:44:44.65	34769	146	Descending
2009-06-26 01:44:45.26	38276	146	Descending
2009-07-31 01:44:44.86	38777	146	Descending
2009-09-04 01:44:43.53	39278	146	Descending
2010-01-22 01:44:38.78	41282	146	Descending
2010-02-26 01:44:36.34	41783	146	Descending
2010-04-02 01:44:36.99	42284	146	Descending
2010-06-11 01:44:35.17	43286	146	Descending

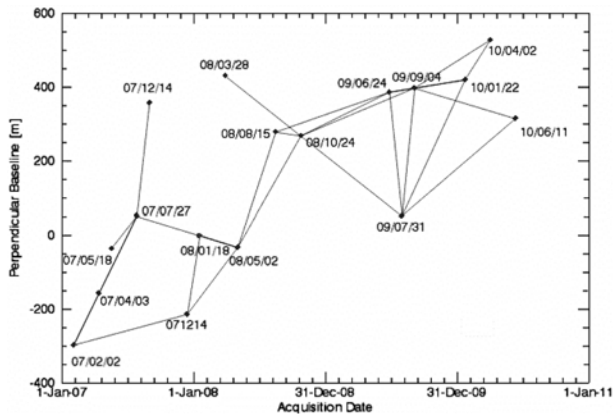

Fig. 2. Baseline Plot of ENVISAT ASAR Data during 2007-2010. The Dots Represent the Images and Lines Represent the Interferograms Formed.

velocities can be extracted. As a result,the atmospheric, orbital and base DEM artefacts are estimated and corrected in the procedure.

Considering the environmental conditions over Mt. Baekdu and also the number of ENVISAT ASAR images available in this study, SBAS was applied as the solution to address the effects of error and de-correlation elements. The commercial SARscape (Sarmap, 2012) interferogram analysis routine was employed to execute SBAS processing. Among all possible InSAR pairs to form interferogram, 25 pairs were established based on the baseline length, temporal gap (< 220 days) and actual phase coherences. Fig. 2 shows the baseline and temporal combination of formed ENVISAT ASAR pairs. The Shuttle Radar Topography Mission (SRTM) 90 m DEM was used as the base DEM for SBAS processing. Interferograms were then processed with the minimum cost flow unwrapping method (Costantini *et al*., 1998). The surface deformation was assumed as constant linear deformation in the SBAS modeling processor because the time span was relatively short and would cover the inactive period between 2007 to 2010. In addition to the ENVISAT ASAR images, a pair of ALOS PALSAR Fine Beam Double Polarization (FBD) images acquired in June 2010 and October 2010 was processed for comparison. For processing the ALOS PALSAR InSAR pair, Jet Propulsion Laboratory (JPL)'s Repeat Orbit Interferometry PACkage (ROI-PAC, Rosen *et al.*, 2004) was used.

4. Processing Results and Interpretation

The resultant deformation velocity map derived from SBAS processing is shown in Fig. 3. First of all, it is revealed that the relatively clear deflations occurred over the northern (R1) and southern part (R2) of Cheonji. In contrast to the minor and probably spurious deformations over the other parts of the summit, the areas of R1 and R2 might represent the true abnormality in surface movement in the northern portion and a small part of the southern slope. Compared with the on-site GPS and leveling survey of Mt. Baekdu conducted by Xu *et al.* (2012), it was evident that these were residual movements after the long inflation during the 2002-2005 period. The two-year time gap from 2005 to 2007 was the transition period between the active and inactive seasons. Thus, the temporal coverage of SBAS was able to obtain the residuals of active magma intrusion beneath Cheonji in these areas. The result is in good agreement with the theory of periodic magma activity beneath Mt. Baekdu. On the other hand, it was observed that there are alternative minor inflation and deflation patterns populated around the summit. However, those did not strongly coincide with the GPS and leveling survey results demonstrated in Xu *et al.* (2012). This was partially due to the lack of ground observation data.

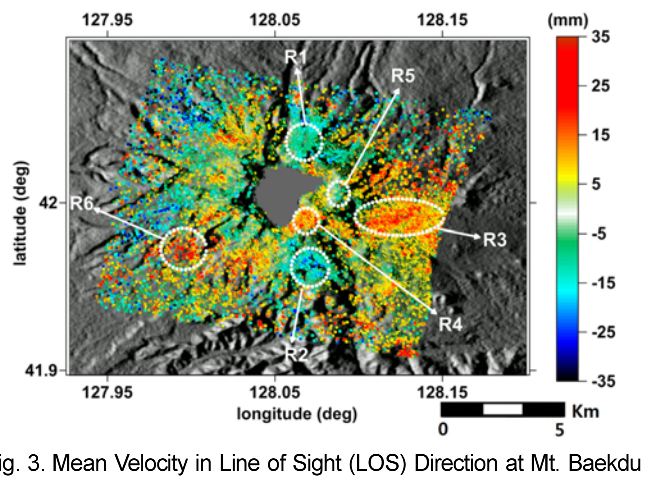

Fig. 3. Mean Velocity in Line of Sight (LOS) Direction at Mt. Baekdu during 01/2007–07/2008. Note the Significant Deflation Occurring in the Eastern Slope.

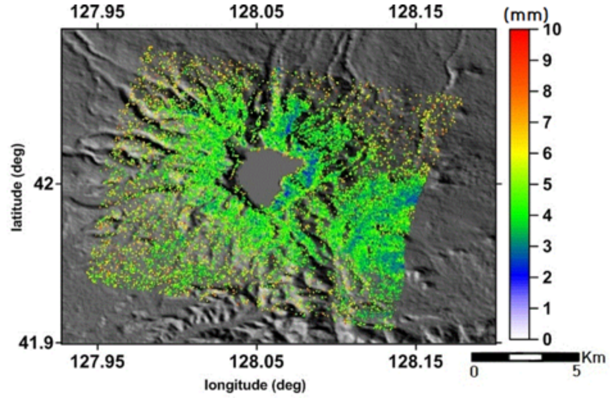

Fig. 4. The Precision of Mean Velocity Shown in Fig. 3. Lower Number Represents Better Estimated Precision.

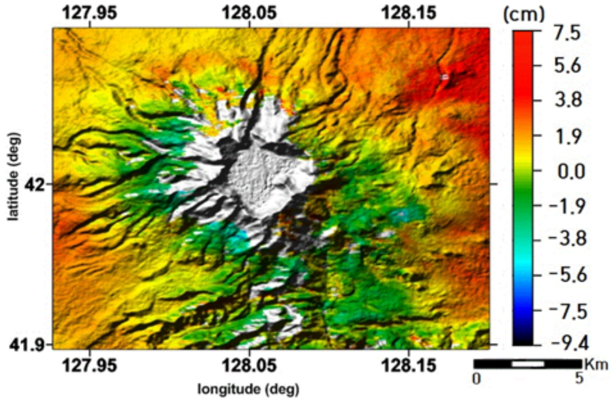

Fig. 5. The Two-pass D-InSAR Processing using ALOS PALSAR Pair Obtained on 06/06/2010 and 10/22/2012.

Therefore an appropriate explanation of the relationship between the observed phenomenon and the magma activities remained unsolved, even though the circumscribed patterns well suited with the epicenters of minor seismic moments around Candela Lake (Wu *et al*., 2005). It was noted that the most significant surface deformation in the SBAS processing results shown in Fig. 3 is the inflation over eastern flanks (R3). It was the strongest inflation in D-InSAR-based analysis and has not yet been published by any other in-situ or remote sensing observations. The extent and the magnitude (up to 15 mm) in the eastern deformation were highly obvious and thus ruled out the possibility of outlier originated from erroneous factors, such as co-registration issue and atmospheric artifacts.

The reliability of the deformation extracted from SBAS processing was evaluated using the standard deviation of coherence (Rodriguez and Martin, 1992) expressed as:

$$Precision = \frac{\lambda}{4\pi}\sqrt{(1-coh^2)/2coh^2} \qquad (1)$$

where *coh* is the phase coherence and and λ is the SAR wavelength. Resulting high values in (1) mean low reliability of surface deformation measurement.

The resultant velocity precision map is shown in Fig. 4. Due to the gentle-sloped non-vegetated terrain, it is observed that the reliability is high over the eastern candela rim and the eastern flank. On the contrary, relatively low reliability in deformation velocity was noticed over the western flank. As stated earlier, it was difficult to address the de-correlation problem originating from the vegetation canopy populated in high altitude, snow coverage or steep slope in D-InSAR processing, hence the relatively low reliability was inferred as the effects of such natural environmental factors. The atmospheric error frequently accounted for an incorrect interpretation of surface deformation could be excluded in this study because SBAS processing was capable of reducing the atmospheric anomaly to some extent.

Figure 5 presents LOS directional deformation over the same target area using two-pass D-InSAR analysis of the ALOS PALSAR pair acquired on 06/06/2010 and 10/22/2012 for the comparison of ENVISAT ASAR SBAS processing. The phase delay caused by the stratified atmospheric effect during SAR image acquisition makes the range of deformation from -4 cm in surrounding summit to +5 cm in base. It should be noted that the large deformation up to 9 cm per year during 1992-1998 period was also reported by Kim *et al.* (2001) using ERS C-band and JERS L-band image over Mt. Baekdu. Since such high eformations in D-InSAR analyse using both two pass ALOS PALSAR and ERS of 1992-1998 period are not shown in the mean deformation velocity map in Fig. 3, it is demonstrated that the stratified atmospheric effect was quite well addressed in the SBAS processing. Therefore, the interpretation of surface subsidence and uplift using our SBAS processing result was mostly reliable as the surface change was based on the magmatic activity rather than the atmospheric error effects.

The detailed time series analyses of deformation areas provided more information for the migration in surface as shown in Fig. 6. The systematic deflation is observed in Fig. 6(a) which is corresponding to R1 area in velocity map of Fig. 3. During the 2007-2010 period, it has been progressively deflated so that the assumption of the residual of magma intrusion is to be proven again in the time series analysis. The subsidence in R2 is less obvious in Fig. 6(b) but can be approximated as linear downward motions. Regarding to the clear inflation in eastern flank (R3) and southern caldera rim (R4), the time series analyses (refer to Figs. 6(c) and (d) respectively) show well-defined deformation in LOS direction, even though the pattern in R3 has the deviation which is probably originated by temporal de-correlation in lingering snow coverage. However, the other deformation patterns surrounding caldera rims and western flanks (R5 and R6) are very suspicious as shown in Figs. 6(e) and (f). Rather than deviation pattern of LOS directional movement, the trends are not identified as the systematic deformation. The phenomenon should be interpreted as the composition of the stationary surface and random noises.

5. Conclusions

Mt. Baekdu is recently under debate whether the volcanic

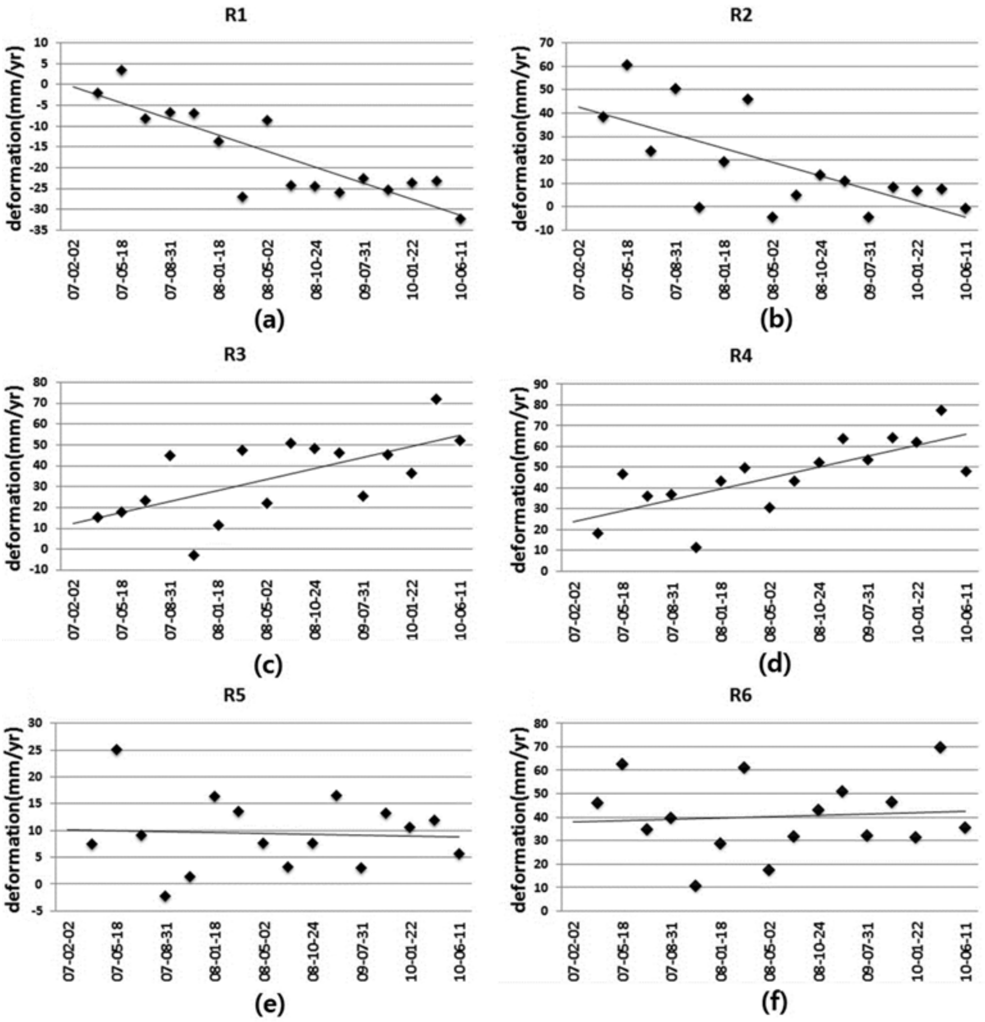

Fig. 6. Time Series Analyses of LOS Directional Deformation of Regions: (a) R1, (b) R2, (c) R3, (d) R4, (e) R5, (f) R6

activity, which may cause disastrous effect in eastern Asia, is initiated again. Considering the dreadful magnitude of the eruption in 10th century A.D and the huge population in this region, it is necessary to re-evaluate the potential volcanic risk of Mt. Baekdu. Compared with the recent direct measurement using GPS and leveling, SBAS processing with ENVISAT ASAR in this study showed negative surface deformations over the northern and southern Crater Lake during 2007-2010. These negative deformations during 2007-2010 were relatively clear, and the most reasonable explanation for this is the residual of surface uplift magma of 2002-2005 active period. On the contrary, there are some strong inflations in the eastern flank and summit. These results may indicate partial and periodic activation of magma incision under Mt. Baekdu. Conclusively, our SBAS processing supports the ground survey of Xu et al. (2012) and the increasing volcanic risks.

Based on the findings, we will continuously focus on the monitoring after 2010, which is assumed to be the next cycle of surface activation. If D-InSAR processing in this period reveals clear overall deformation, the periodic volcanic activation model can be verified. Meanwhile, the D-InSAR survey during 2002-2005 period where ERS image coverage is available will be re-evaluated using the relaxation techniques for water vapor effects.

In conclusion, it is understood that the dispute about Mt. Baekdu's volcanic activities can be suitably examined when long-term observation is achieved. Even if periodic magma activation during the first decade of 21st century is fully identified, it is not certain whether such activations are just temporal episodes or an event that may result in an eruption in the future. Since the effectiveness of D-InSAR analysis has been proven in this study, it is clearly necessary to exploit all possible space-borne SAR assets to monitor Mt. Baekdu. Unfortunately, the recent failure and the dismissal of space-borne SAR sensors, such as ENVISAT ASAR, ERS, and ALOS PALSAR, have largely impaired this capability. For the next few years, a new SAR satellite fleet, including the C-band Sentinel-1 of ESA, X-band Korean hi-resolution SAR, and L-band ALOS PALSAR-2, will be in operation. Therefore, it will be possible to carry out long-term InSAR monitoring using data with various wavelengths. Considering the huge impact that Mt. Baekdu's potential eruption would have on all eastern Asian countries, international collaboration to exploit all advanced sensor capabilities, together with ground truth, should be established.

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References

Agustan, F., Kimata, Y., Pamitro, E., and Abidin, H. Z. (2012). "Understanding the 2007-2008 eruption of Anak Krakatau Volcano by combining remote sensing technique and seismic data." *International Journal of Applied Earth Observation and Geoinformation*, Vol. 14, No. 1, pp. 73-82.

Berardino, P., Fornaro, G., Lanari, R., and Sansosti, E. (2002). "A new algorithm for surface deformation monitoring based on small baseline differential interferograms." *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 40, No. 11, pp. 2375-2383.

Borgia, A., Bignami, C., Stramondo, S., and Bustos, E. (2005). "Volcanic spreading of Vesuvius, a new paradigm for interpreting its volcanic activity." *Geophysical Research Letters*, Vol. 32, No. 3.

Costantini, M. (1998). "A novel phase unwrapping method based on network programming." *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 36, No. 3, pp. 813-821.

Dzurisin, D., Lisowski, M., Wicks, C. W., Poland, M. P., and Endo, E. T. (2006). "Geodetic observations and modeling of magmatic inflation at the Three Sisters volcanic center, central Oregon Cascade Range, USA." *Journal of Volcanology and Geothermal Research*, Vol. 150, No. 1, pp. 35-54.

Eisinger, M. and Burrows, J. P. (1998). "Tropospheric sulfur dioxide observed by the ERS-2 GOME instrument." *Geophysical Research Letters*, Vol. 25, No. 20, pp. 4177-4180.

Ferretti, A., Prati, C., and Rocca, F. (2000). "Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry." *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 38, No. 5, pp. 2375-2383.

Gao, Q. (2004). "Volcanic hydrothermal activities and gas-releasing characteristics of the Tianchi lake region, Changbaimountains." *Acta Geoscientica Sinica*, Vol. 25, No. 3, pp. 345-350.

Kim, S. W., Won, J. S., Kim, J. W., Moon, W. M., and Min, K. D. (2001). "Multi temporal JERS-1 SAR investigation of Mt. Baekdustratovolcano using differential interferometry." *Geoscience Journal*, Vol. 5, No. 4, pp. 301-312.

Lee, H. and Liu, J. G. (2001). "Analysis of topographic decorrelation in sar interferometry using ratio coherence imagery." *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 39, No. 2, pp. 223-232.

Liu, G., Zhang, H., and Kong, Q. (2006). "Analysis of the seismic activity at the Changbaishan Tianchi volcano." *Seismology and Geology*, Vol. 28, No. 3, pp. 503-508.

Massonnet, D., Boriole, P., and Arnaud, A. (1995). "Deflation of Mount Etna monitored by spaceborne radar interferometry." *Nature*, Vol. 375, No. 6532, pp. 567-570.

Nan, Y. (2013). *Metrological data over Mt. Baekdu by the ground observation in China*, Private Communication.

Rodriguez, E. and Martin, J. M. (1992). "Theory and design of interferometric synthetic aperture radars." *IEE Proceedings Part F*, Vol. 1392, No. 2, pp. 147-159.

Rosen, P. A., Henley, S., Peltzer, G., and Simons, M. (2004). "Updated repeat orbit interferometry package released." *Eos Transaction American Geophysical Union*, Vol. 85, No. 5, p. 47.

Sarmap (2012). SARscape <http://www.sarmap.ch/page.php?page=sarscape> (accessed 29th July 2012).

Vaughan, R. G. and Hook, S. J. (2006). "Using satellite data to characterize the temporal thermal behavior of an active volcano: Mount St. Helens, WA." *Geophysical Research Letters*, Vol. 33, No. 20, L20303.

Wu, J., Ming, Y., and Zhang, H. (2005). "Seismic activity at the Changbaishan Tianchi volcano in the summer of 2002." *Chinese Journal of Geophysics*,Vol. 48, No. 3, pp. 621-628.

Xu, J., Liu, G., Wu, J., Ming, Y., Wang, Q., Cui, D., Shangguan, Z., Pan, B., Lin, X., and Liu, J. (2012). "Recent unrest of Changbaishan volcano, northeast China: A precursor of a future eruption." *Geophysical Research Letter*, Vol. 39, No. 16, L16305.

Yin, Y., TimothyJull, A. J., Burr, G. S., and Zheng, Y. (2012). "A wiggle match age for the millennium eruption of tianchi volcano at Changbaishan northeastern China Yonggang Zheng." *Quaternary Science Rev*iew, Vol. 47, No. 1, pp. 150-159.

Yun, S. H. and Lee, J. H. (2012). "Analysis of unrest signs of activity at the Baegdusan volcano." *Journal of Petrological Society Korea*, Vol. 21, No. 1, pp. 1-12.

Zebker, H. A. and Goldstein, R. M. (1986). "Topographic mapping from interferometric synthetic aperture radar observations." *Journal of Geophysical Research: Solid Earth*, Vol. 91, No. B5, pp. 4993-4999.

Zebker, H. A., Rosen, P. A., and Hensley, S. (1996). "Atmospheric effects in interferometric synthetic aperture radar surface deformation and topographic maps." *J. Geophys. Res*., Vol. 102, No. B4, pp. 7547-7563.