SAR Measurements of Surface Displacements at Augustine Volcano, Alaska, Associated with the 1986 and 2006 Eruption

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Abstract—Augustine volcano is an active stratovolcano located at the southwest of Anchorage, Alaska. Augustine volcano had experienced seven significantly explosive eruptions in 1812, 1883, 1908, 1935, 1963, 1976, and 1986, and a minor eruption in January 2006. We measured the surface displacements of the volcano by radar interferometry and GPS before and after the eruption in 2006. ERS-1/2, RADARSAT-1 and ENVISAT SAR data were used for the study. Multiple interferograms were stacked to reduce artifacts caused by different atmospheric conditions. Least square (LS) method was used to reduce atmospheric artifacts. Singular value decomposition (SVD) method was applied for retrieval of time sequential deformations. The observed surface displacements from satellite radar interferometry were compared with GPS data. Satellite radar interferometry helps to understand the surface displacements system of Augustine volcano.

Keywords; suface displacements, Interferometry, GPS data.

I. INTRODUCTION

To study of volcano activities and interaction with the surface movements is important for understanding eruption cycle of a volcano. This process makes up as a series of events from deep magma generation to surface eruption, and includes such stages as partial melting, initial ascent through the upper mantle and lower crust, crustal assimilation, magma mixing, degassing, shallow storage, and finally ascent to the surface [1]. In advance of volcano eruption, some symptoms are preceded by surface displacements in response to increasing pressure from magma chambers or the upward intrusion of magma [2]. Accordingly, it is important to monitor surface displacements around volcano for protecting public welfare from volcano eruption.

Aleutian arc in Alaska has many active volcanoes in the world. In spite of the frequency of eruptions, these volcanoes remain poorly studied due to their remote location and expensive cost to keep monitoring volcanoes' activities. One of more effective tools to overcome this limitation is remote sensing studies of these regions. Moreover, measurements of surface displacements for radar interferometry [3], [4], [5] provide a comprehensive method aiding study of volcanoes. Radar interferometry has been used to investigate the surface deformation of active volcanoes [6], [7]. Augustine volcano is a 1260 m high and 90 km^2 size dacitic stratovolcano in southwestern Cook Inlet, about 275 km southwest of Anchorage, Alaska (Fig. 1). This island was formed on Jurassic and Cretaceous sedimentary strata and overlain by granitoid glacial erratics and volcanic hyaloclastites [8]. This volcano is one of the youngest and most active volcanoes in Cook Inlet [9], having experienced significant explosive six eruptions and recently in January 2006.

In this study, we process all of available SAR data for Augustine volcano between 1992 and 2006, using synthetic aperture radar (SAR) images acquired by ERS-1/2, ENVISAT and RADARSAT-1 satellite. We investigate the surface displacements associated with 1986 and 2006 eruptions at Augustine volcano in Alaska by June 1992 to October 2006 SAR images.

II. SPACEBORNE RADAR INTERFEROMETRY

A. *Radar images and DEM*

We made interferograms spanning the period from June 1992 to October 2005 using ERS-1/2 C-band radar satellites data from 5 tracks, ENVISAT C-band radar satellites data from June 2003 to October 2006. RADARSAT C-band satellites data were used to make interferograms from 2004 to October 2006 as well. We used the 30m Shuttle Radar Topography Mission (SRTM) DEM.

B. *Surface displacements (1992 – 2005)*

As a result of applying two-pass InSAR method using ERS-1 and ERS-2 SAR data, we constructed 15 interferograms (Fig. 2) that cover approximately one year span the period from 1992 to 2005 with good quality. Unfortunately, the Augustine volcano is covered by snow and ice during 6 or 7 months of the year, therefore we can make interferograms from SAR images acquired by around 4 months (from June to October). On the

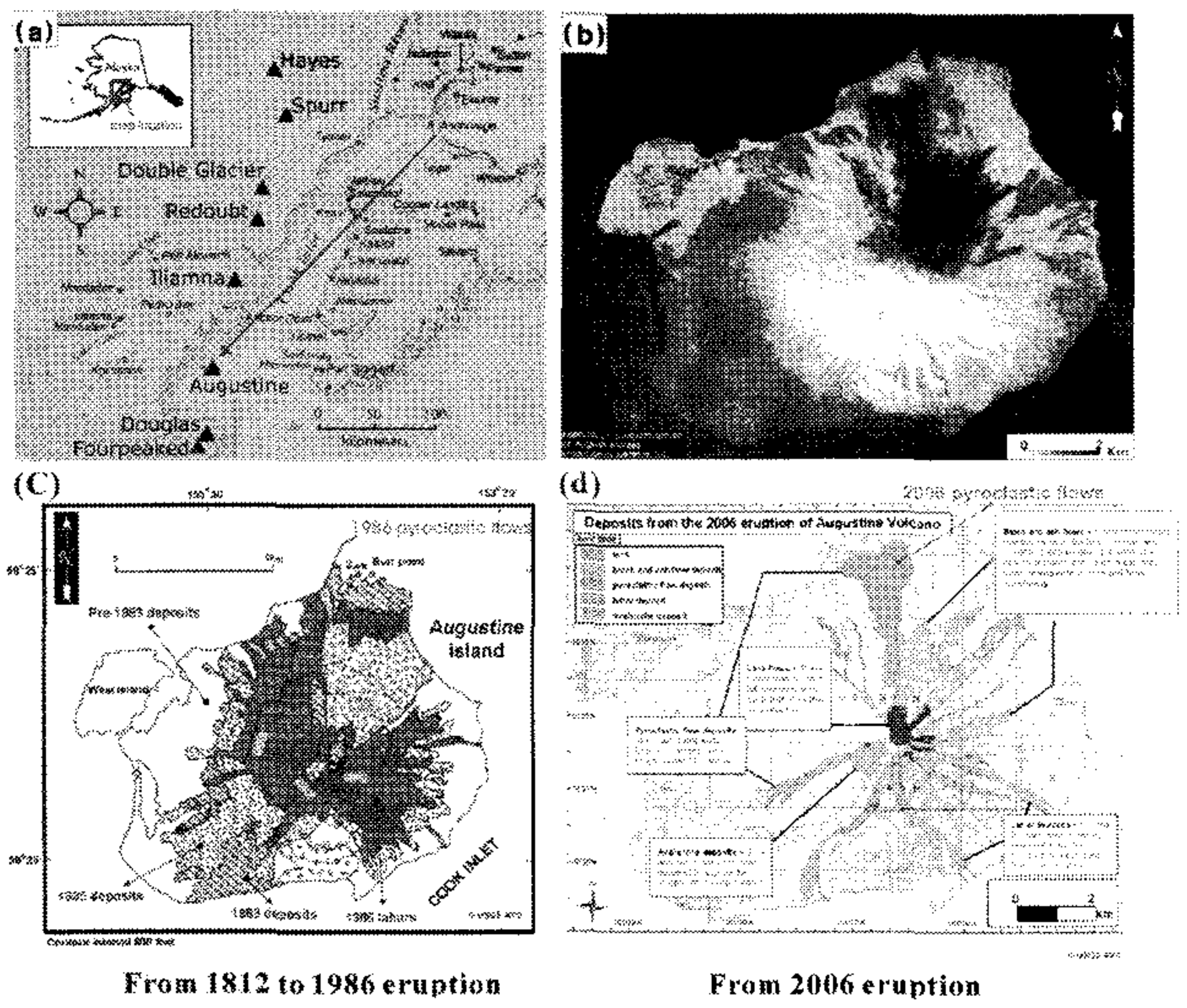

Figure 2. Study area (Augustine Island) is located in the southwestern portion of the Cook Inlet, Alaska. Picture(a) shows Augustine Island in southwestern Cook Inlet about 290kms southwest of Anchorage, Alaska. Picture(b) displays an aero-map over Augustine island by an airplane. (c) and (d) show historic pyroclastic flows deposits. (c) represents pyroclastic flow deposits for six events from 1812 to 1986 eruption. (d) shows not only pyroclastic flows deposits but also other deposits by 2006 eruption.

northern area of Augustine Island, 1 or 2 fringes are visible in the every interferogram. This deformation is probably due to the thermoelastic contraction of pyroclastic flow deposits from 1986's eruption over time. As with ERS-1 and ERS-2 interferograms, we constructed ENVISAT interferograms. (Fig. 3) has the good quality of all the ENVISAT interferograms covering the period from 2003 to 2005. They have a term of around 1-year and as with the ERS interferograms we can count 1 or 2 fringes in the northern portion of Augustine Island.

C. *Time series method (1992 – 2005)*

An individual interferogram has atmospheric artifacts, baseline decorrelation and unwrapping errors. These terms will be converted into errors in the calculated deformation at each pixel. Among of these errors, greatest source of error on the interferograms is often plagued by atmospheric artifacts [10], [11]. Usually atmospheric artifacts are related with particular epochs and not spatially correlated through time [12]. Phase delay by atmospheric artifacts could be estimated and removed from the interferograms using meteorological data or continuous GPS data [13]. Unfortunately, we did not get meteorological data or GPS data for this study area, so adopted least square inversion solution [14] to reduce the effects of atmospheric artifacts.

$$Gm = d \tag{1}$$

$$m = [G^T G]^{-1} G^T d = \begin{bmatrix} N & \sum Z_i \\ \sum Z_i & \sum Z_i^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum d_i \\ \sum Z_i d_i \end{bmatrix} \tag{2}$$

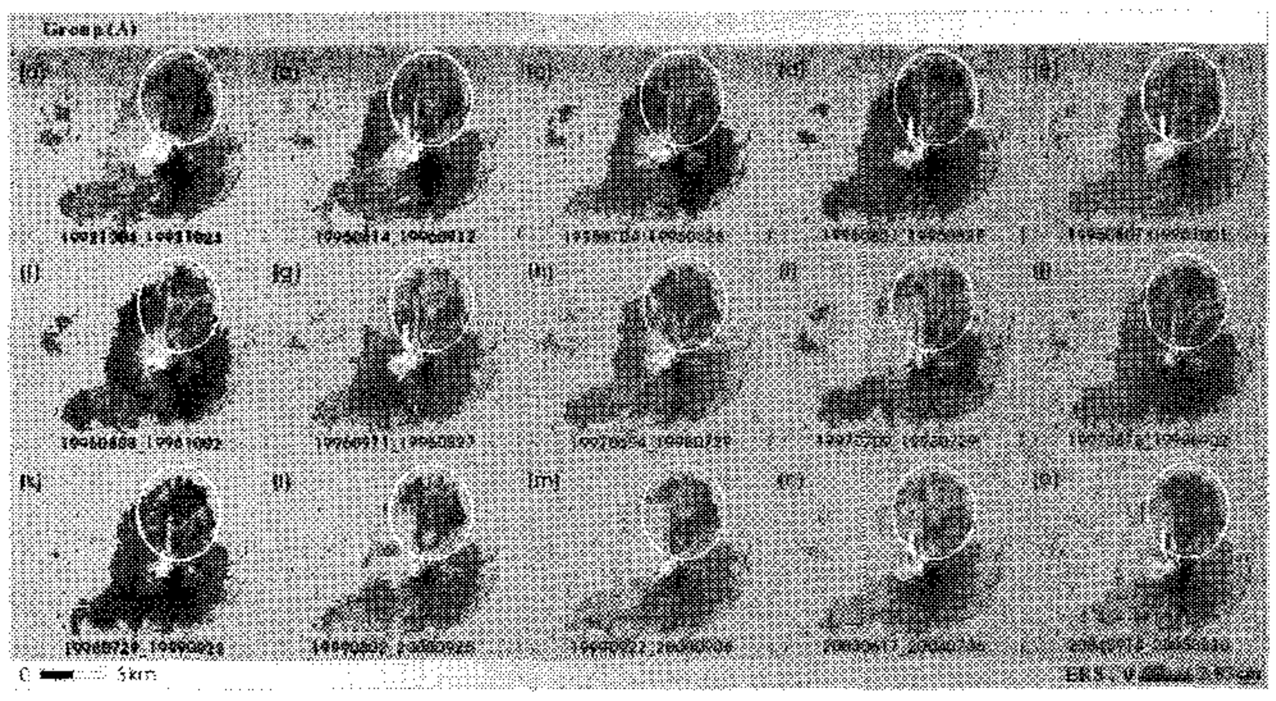

Figure 3. These interferograms (ERS-1/2 data) show surface displacements on the northern portion of Augustine Island from 1992 to 2005.

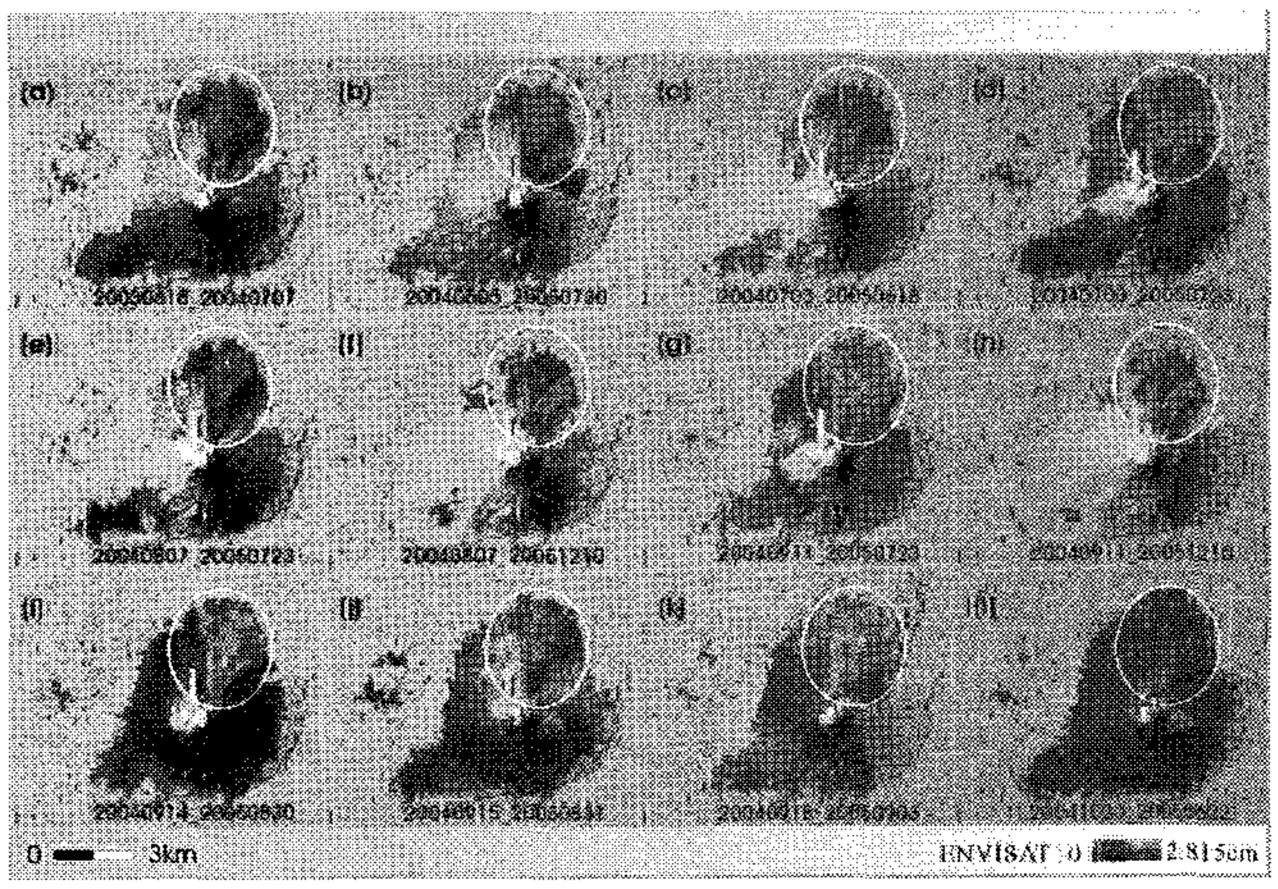

Figure 1. These 12-ENVISAT interferograms represent surface displacements at the north area of Augustine Island from June 2003 to September 2005

Where $G = [Z_1, Z_2, ..., Z_n]$ is a system matrix, each row correspond to an interferogram, while rows represent from start date to end date of each interferogram. In the case of $G_k = G_{d_i} - G_{d_j}$ interferogram, the values of columns i and j are +1 and -1, respectively, and other values are all zero. $d = [d_1, d_2, ..., d_n]$ is known incremental range change value for differential interferogram and $m = [m_1, m_2]$ is unknown deformation value. For the retrieval of a temporal deformation sequence, we used singular value decomposition.

$$G = USV^T \tag{3}$$

Where G is design matrix, U is orthogonal matrix containing the left-singular vectors of G, V is an orthogonal matrix containing the right-singular vectors of G and S is a square matrix whose diagonal values are the singular values of G. The inverse of G represents (4).

$$G^{-1} = VS^{-1}U^T \quad (4)$$

After singular value decomposition, we applied the optimum weighting factor for smoothed time series by Generalized cross validation (GCV) method [15]. It can be solved to find the correlation coefficient between the input deformation model and the calculated value.

D. DInSAR measurements by time series method

Augustine volcano has been detected terrain displacements at north portion of island by pyroclastic flow deposits (Fig. 1 (d)) since 1986's eruption. We invert differential interferograms derived from ERS-1, ERS-2 (track 229) and ENVISAT (track 2229) satellite data for a time-dependent deformation signal in the Augustine Island from June 1992 to August 2005. The time-dependent deformation is calculated by performing a linear inversion that solves for the incremental range change between SAR scene acquisitions. We selected coherent points from all interferograms (track 229 and track 2229) for applying least square inversion for reduce atmospheric artifacts and singular value decomposition for the retrieval of a temporal deformation sequence. (Fig. 4) shows 40 selected coherent points (P1 to P40) at Augustine Island. G1, G2 and G3 represent Global Positioning System (GPS), among these points, G1 is most stable GPS point and we choose G1 for reference point to measure surface displacements over Augustine Island. Image of center of (Fig. 4) was created by averaging all the unwrapped interferograms (track 164, 207, 229, 436 and 501 of ERS-1 and ERS-2 data) spanning one year during the period from June 1992 to November 2005. The graphs on the right of (Fig. 4) show the deformation history for points 6, 14 and 19 after applying least square inversion and singular value decomposition methods. These three points exhibit the most deformation with around 20.7cm, 36.5cm and 18.8cm (LOS direction) per each point for approximately 13 years, respectively. Black lines represent real values of temporal deformation while blue lines represent values produced by deformation history the optimum weighting factor for smoothed time series by Generalized cross validation (GCV) method. This deformation might be caused by thermalelastic contraction of 1986's pyroclastic flow deposits that was occur to terrain subsidence at north part of Augustine Island. The reason of total subsidence's difference according to each point dues to the thickness distribution of pyroclastic flow deposits [16].

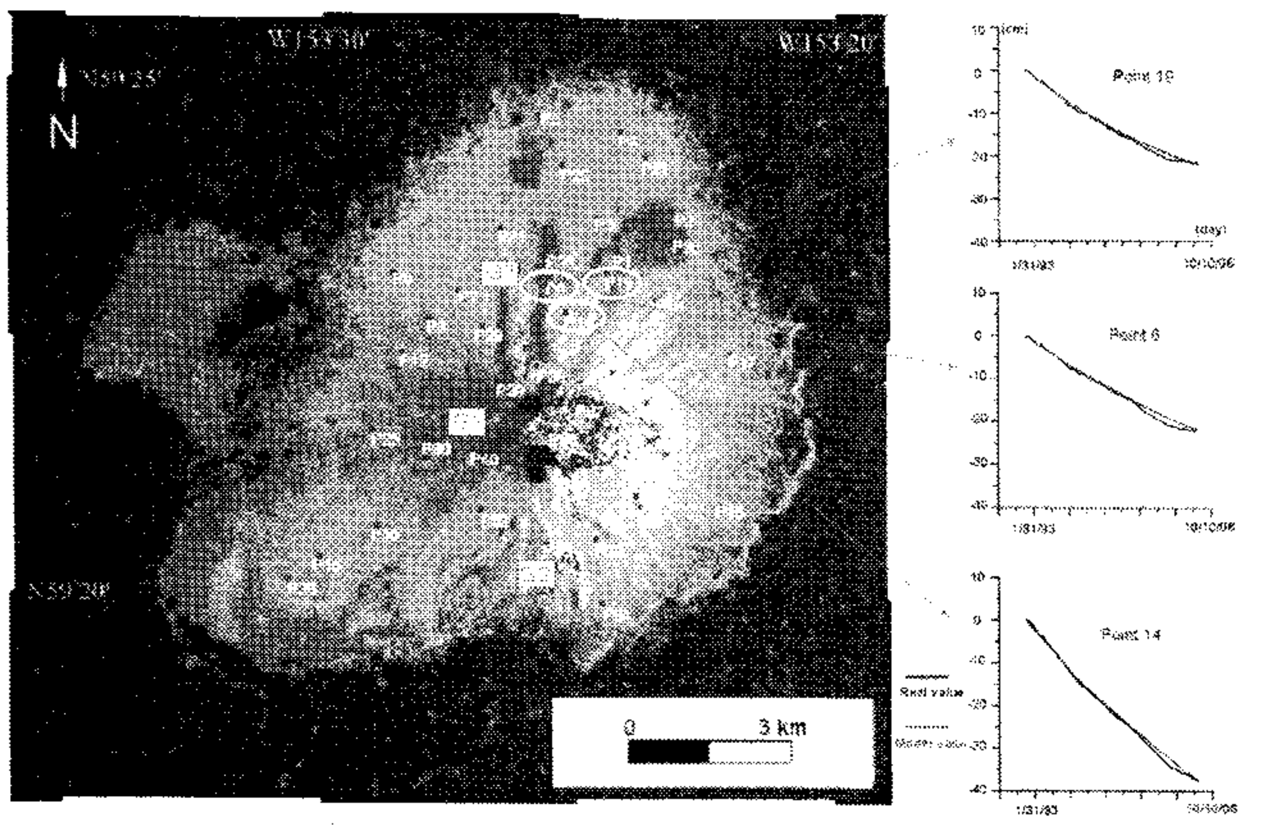

Figure 5. This image shows averaging the unwrapped interferograms spanning one year from 1992 to 2005. the graphs on the right represent total surface displacements each point.

E. Compare DInSAR to GPS data

Geodetic measurements of Augustine volcano began in 1986, and a Continuous Global Positioning System CGPS receiver was placed on the volcano in 2000. UNAVCO Plate Boundary Observatory (PBO) installed five additional dual-frequency CGPS receivers [17] named AV01 to AV05. We used CGPS data in order to compare with DInSAR measurements from September 2004 to September 2005. CGPS data were compared to DInSAR measurements with relative value, which is the difference value between one point and another point (Fig. 5). It is because DInSAR measurements cannot display absolute value unlike GPS data on each point. On the left side of (Fig. 5), blue points represent relative values of GPS point (G1) of (Fig. 4) and GPS point (G2) of (Fig. 4) and red line is DInSAR measurements with relative values of (G1) and (G2). To compare with DInSAR measurements, we modeled blue line using blue points on the graph by second order polynomial equation. There are maximum difference values of 0.4 cm between GPS data and DInSAR measurements on the left graph. The middle and the right side graph on the (Fig. 5) represent relative values of ((G1) and (G3)) and of ((G2) and (G3)), respectively. Maximum difference values are about 0.5 and 0.6 cm at the middle and the right side graphs between GPS data and DInSAR measurements from September 2004 to September 2005.

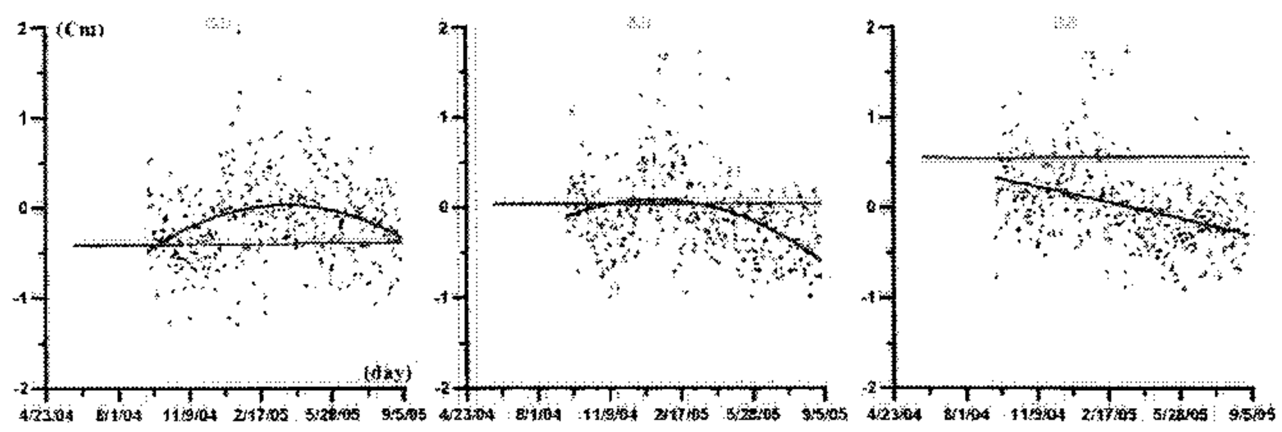

Figure 4. Compare DInSAR measurements to GPS data with relative values of two points. Blue points show GPS data and red line display DInSAR measureaments.

F. Inflation of pyroclastic flow deposits area by magma expansion

According to GPS data (G2 and G3), Augustine volcano had volume inflation from early summer 2005 to 2006 eruption [17] (Fig. 6 (a)). GPS data represent about 2 - 3 cm volume inflation from early summer 2005 to early January 2006 at G2 and G3 (Fig. 6 (a)). Unfortunately, we could not use SAR image from November 2005 to January 2006 by decorrelation according to weather condition. For analysis of this volume inflation with DInSAR measurements, we adopted another scheme using subsidence speed reducing of pyroclastic flow deposits. (Fig. 6 (b)) shows total subsidence from 1992 to 2005 at P14 (Fig. 4). Red dotted line represents modeling value using DInSAR measurements from 1992 to 2001 by second order polynomial equation. On the other hand, blue line

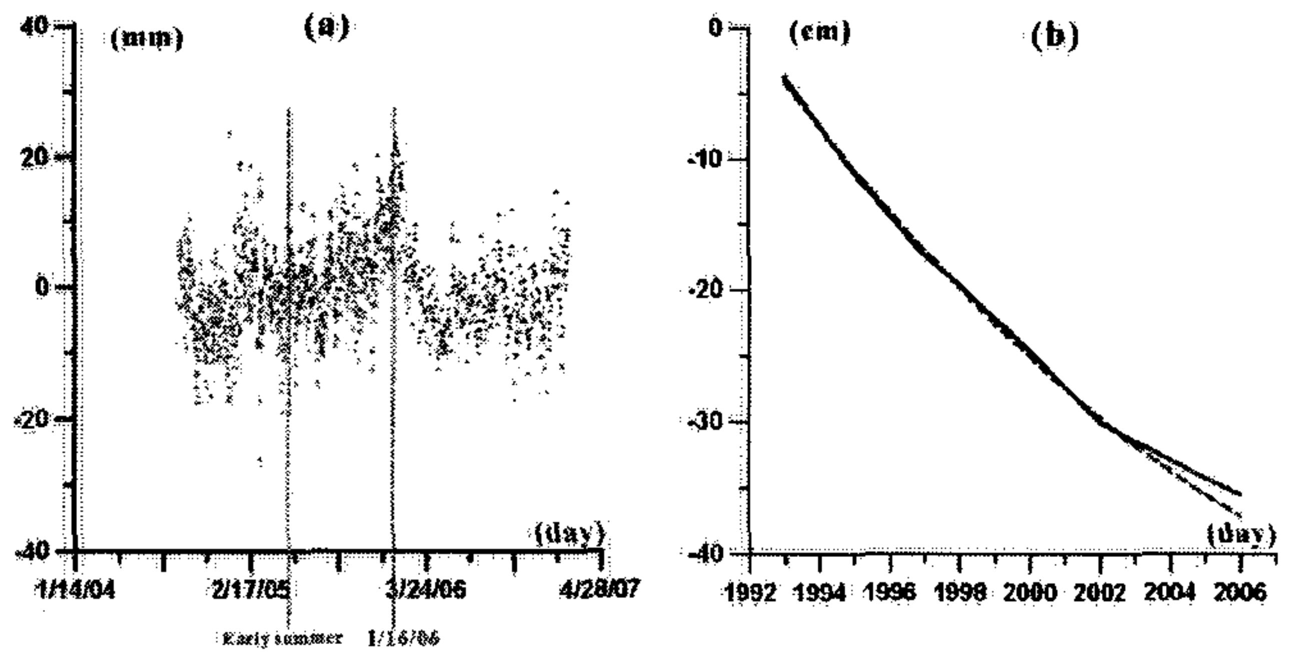

Figure 6. Graph (a) is GPS data on station G2 (blue triangle) and G3 (pink triangle). Graph (b) shows DInSAR measusrement (blue line) at P14 (Fig. 4) and DInSAR modeling by second order polynomial equation (red dotted line).

displays DInSAR measurements value at P14 from 1992 to 2005. As a result of subsidence speed reducing method, we can assume diminution of subsidence rate by magma volume expansion below the pyroclastic flow deposits area from 2003 to 2005. The graph (b) of (Fig. 6) shows 2 cm differences in total subsidence between 2003 and the end of 2005.

G. DInSAR result (2006 -)

(Fig. 7) shows subsidence at the northern portion by pyroclastic flow deposits after 2006 eruption. Even though the first ENVISAT interferogram has around 4 month's period from April 29, 2006 to August 12, 2006, it represents about 2 fringes. This subsidence can be explained to sum of poroelastic deformation by gravity load during short term.

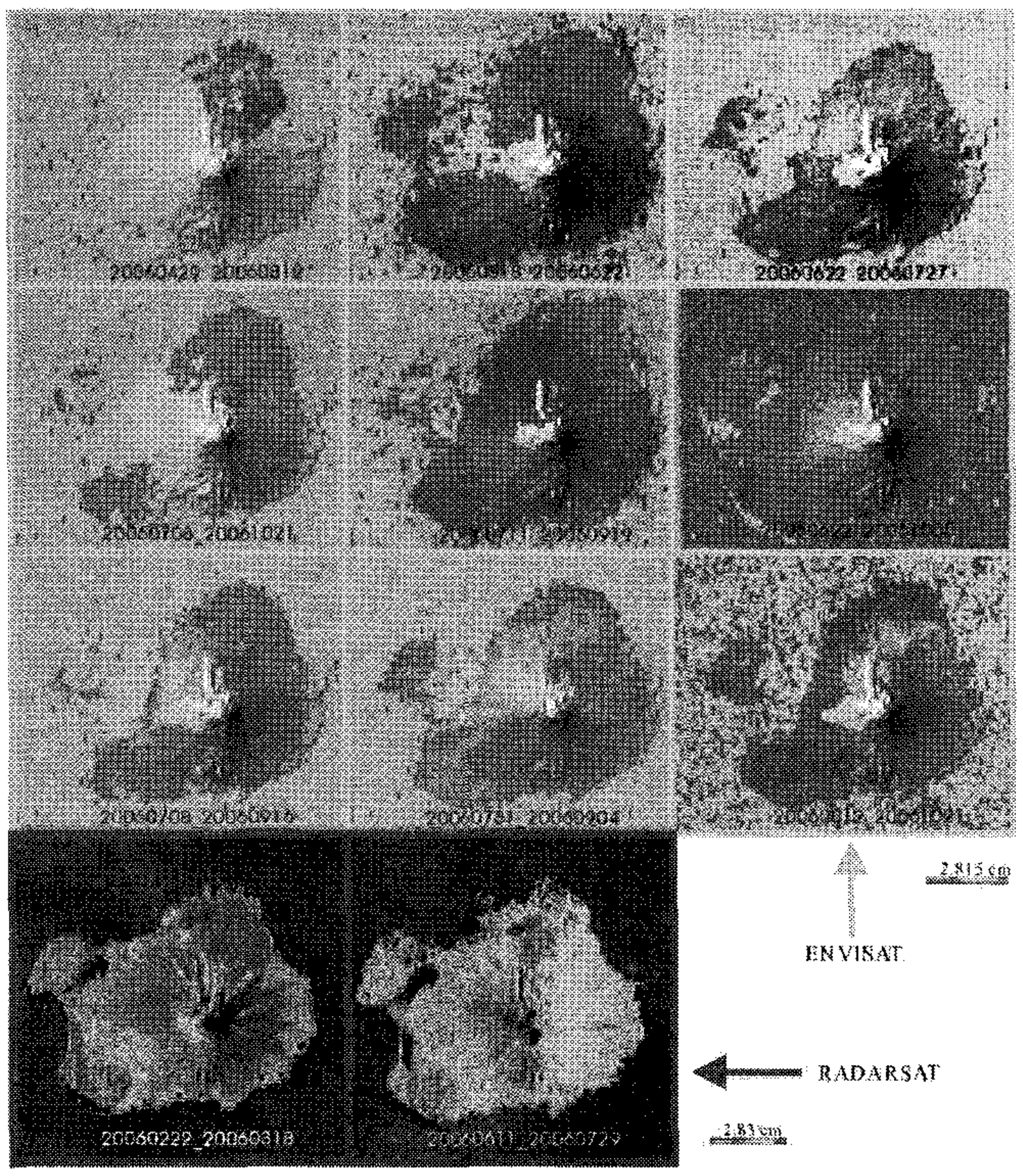

Figure 7. These 11 interferograms show ENVISAT and RADARSAT interferograms after 2006 eruption at Augustine volcano.

III. CONCLUSIONS

We measured surface deformation of Augustine Volcanic Island, Alaska, using ERS and ENVISAT data the period from June 1992 to December 2005. We used least square (LS) and singular value decomposition (SVD) method for reduces atmospheric artifacts and the retrieval of a temporal deformation sequence. The 1986 pyroclastic flow deposits of Augustine Volcano had experienced the most significant deformation. Subsidence rates were about 0.9-2.8 cm per a year and subsidence distribution according to region due to difference of pyroclastic flow deposits' thickness. The reason of subsidence prefers viscoelastic and thermoelastic deformation by constant deformation to poroelastic deformation by gravity load during short term. DInSAR measurements represent difference with GPS data about maximum 0.4 – 0.6 cm from 2004 to 2006.

Inflation of Augustine volcano before 2006 eruption was about 2 – 3 cm by GPS data from 2004 to January 2006, meanwhile DInSAR measurements by subsidence speed reducing method were calculated about 2 cm differences between 2003 and the end of 2005 at pyroclastic flow deposits area. This method seems highly related with volume inflation of Augustine volcano.

After 2006 eruption, northern part of Augustine Volcano had subsidence for pyroclastic flow deposits again with poroelastic deformation by gravity load during short term.

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