ANALYSIS OF LOCAL VELOCITY ANOMALIES OF DAVID GLACIER, EAST ANTARCTICA, BY USING DOUBLE-DIFFERENTIAL INSAR

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ABSTRACT: David Glacier in East Antarctica is an outlet glacier that forms Drygalski Ice Tongue to the Ross Sea, which has a profound effect on the ice mass change of East Antarctica. In this study, we applied the DDInSAR (Double-Differential Interferometric SAR) technique using Sentinel-1A SAR images and found local velocity anomalies. DInSAR processing was performed for about a year at an interval of 12 days from March 2017 to February 2018. The 20180615_20180627 DInSAR image was selected as a master and the remaining images were subtracted for DDInSAR operation to find the change in ice velocity. The time series DDInSAR images show a circular shaped anomalies approaching toward the radar LOS direction (swelling ice). A rough look at the time-series velocity of circular anomaly shows to decelerate significantly in Antarctic winter. Using both ascending and descending images, we obtained three components (north, east, and vertical) of circular anomaly, assuming that the velocity anomaly vector lies on a plane defined by the glacier flow direction and vertical direction. As a result, we can separate the velocity anomaly into 3 cm in flow-direction component and 5 cm of rise in the vertical component. Investigation of bed topography under ice using Bedmap2 data indicates that the surface elevation changes of glacier are likely to be caused by the hydrological change an uncharted subglacial lake and channels. It is found that the DDInSAR technique can be used to monitor the changes of glacier velocity and possible ice surface elevation changes caused by the hydrological activities of subglacial lakes and network of channels.

KEYWORDS: DDInSAR, Sentinel-1A, David Glacier, Subglacial lake

1. INTRODUCTION

Antarctic glacier's flow rates are sensitive to climate change. Ice loss in Antarctica could be a major cause of sea level rise worldwide. Therefore, continuous observation of the ice flow rate is required. The flow velocity of glacier is changed by the gradient of mass balance due to accumulation, ablation and melting, englacial and subglacial deformations, and basal sliding. Among them, basal sliding occurs when the basal shear stress is reduced. If there is water at the base, lubrication reduces friction between ice and bedrock which greatly reduces shear stress and increases glacier flow rate (Zwally *et al.*, 2002; Macgregor *et al.*, 2005). Subglacial water, which forms subglacial lakes, is an important factor of glacier flow because it greatly affects the behaviour of glaciers. The first subglacial lake found in Antarctica was Lake Vostok (77°30′S, 106°00′E), which was discovered by Radio Echo Sounding (RES) during the inland exploration of Antarctica in the 1960s. Since the discovery of Lake Vostok, many subglacial lakes have been discovered by using RES and satellite altimetry. In RES, the reflection from the surface of the subglacial lake is stronger than the reflection from the ice/bedrock interface or englacial layers so the signal appears bright and flat. In satellite altimetry data, subglacial lakes can be detected by the flat ice surface. RES data is acquired by airborne survey and subglacial lakes may not have been detected due to lack of exploration lines. The flat ice surface can also occur when the underlying shear stress is small. Therefore, the surface of small subglacial lakes may not be flat, making the detection of subglacial lakes limited. In a research by Smith *et al*. (2009), 124 subglacial lakes were found in Antarctica using ICESat Altimetry, where they found several subglacial lakes in our study area, David Glacier.

Antarctica is less accessible due to environmental factors, making research by using satellite images effective. Synthetic Aperture Radar (SAR) images can be taken in all weather conditions, making them particularly effective for the study of Antarctica. In this study, the Double Differential Interferometric SAR (DDInSAR) technique was used to observe changes in the flow velocity of the David glacier. DDInSAR technique was used to observe the tide effects of ice and to study the grounding line (Rignot, 1996; Rignot *et al.*, 2000; Han and Lee, 2014). This study uses DDInSAR to detect regions with changes in flow velocity at two different times.

2. RESEARCH AREA AND DATA

The research area is the David Glacier in the Northern Victoria Land, East Antarctica (Fig. 1). This glacier is an outlet glacier that forms the Drygalski Ice Tongue, the largest ice tongue in the East Antarctica, towards the Ross Sea. This glacier begins from Dome C and Talos Dome and forms a drainage basin of approximately 250,000 km^2 (Frezzotti, 1993).

Sentinel-1A satellite images were used for this research, which are produced by the European Space Agency (ESA) (Table 1). This satellite is equipped with a C-band SAR, which can obtain three sub-swaths in Interferometric Wide Swath Mode (IW) that covers the swath of 250 km. As the revisit cycle is 12 days, fast-flowing glacial regions more than 1 m/day is difficult to interferometrically observe because of its low coherence. In that case, only the upstream region with relatively low velocity can be observed. For David Glacier, it was possible to get ascending and descending images on the same day to retrieve displacement vector assuming horizontal flow only. The data were mainly processed by ESA's SNAP (SeNtinel Application Platform) software. We also used the Bedmap2 data to interpret the bed topography.

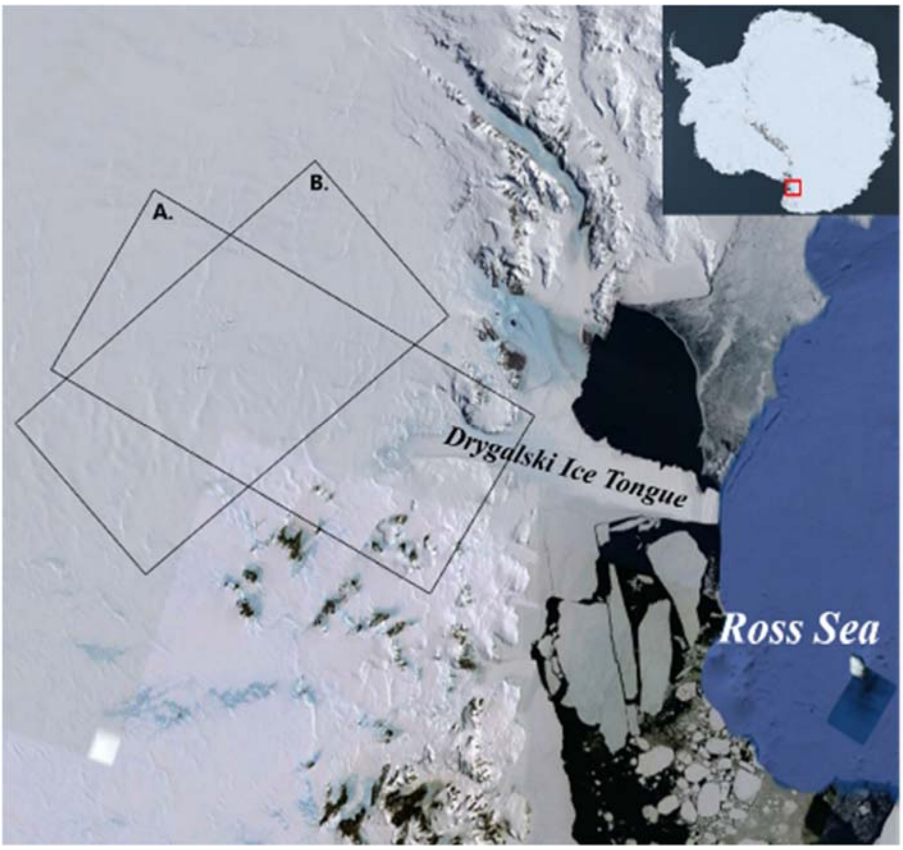

Fig. 1 The research area is marked with a red box in the attached Antarctic map. A is the outline of ascending IW2 image and B is that of descending IW1 image.

Table 1. Sentinel-1A DInSAR pair used in this study. DDInSAR images were acquired by subtracting the images from the master DInSAR image (red border). The bold DInSAR pairs were used to calculate true displacement.

Sentinel-1A / Ascending / HH polarization		
2017/03/04_2017/03/16	2017/07/02_2017/07/14	2017/10/30_2017/11/11
2017/03/16_2017/03/28	2017/07/14_2017/07/26	2017/11/11/_2017/11/23
2017/03/28_2017/04/09	2017/07/26_2017/08/07	2017/11/23_2017/12/05
2017/04/09_2017/04/21	2017/08/07_2017/08/19	2017/12/05_2017/12/17
2017/04/21_2017/05/03	2017/08/19_2017/08/31	2017/12/17_2017/12/29
2017/05/03_2017/05/15	2017/08/31_2017/09/12	2017/12/29_2018/01/10
2017/05/15_2017/05/27	2017/09/12_2017/09/24	2018/01/10_2018/01/22
2017/05/27_2017/06/08	2017/09/24_2017/10/06	2018/01/22_2018/02/03
2017/06/08_2017/06/20	2017/10/06_2017/10/18	2018/02/03_2018/02/15
2017/06/20_2017/07/02	2017/10/18_2017/10/30	**2018/06/15_2018/06/27 (master)**

Sentinel-1A / Descending / HH polarization	
2017/05/03_2017/05/15	**2018/06/15_2018/06/27 (master)**

3. METHODS

Firstly, DInSAR image is obtained by removing the terrain effect using a reference DEM. Phase unwrapping is performed using the SNAPHU program produced by Stanford University (Chen and Zebker, 2002). The two unwrapped DInSAR images were subtracted to obtain a DDInSAR image and then rewrapped by 2π for visual inspection. Any constant flow between the two DInSAR images is removed from the image, and only the change in flow rate will appear in DDInSAR image. In the David Glacier, a circular anomaly is found at the same location of the DDInSAR both in the ascending and the descending paths with a LOS angle difference of about 60 degrees. It is considered to be mostly of a vertical displacement because it shows a circular shape even though the displacements are in different LOS directions. The displacements of this circular anomaly in ascending and descending paths were merged into vertical and horizontal displacements. We assumed that horizontal direction follows the flow direction and is not changed, so that the true displacement vector in DDInSAR signal lies on a plane of vertical direction and the ice flow direction. The LOS vector is represented by the following equation using the incidence angle (i) and the satellite heading angle (h) measured clockwise from the north.

$$\hat{l} = (\sin i \cos h\,, -\sin i \sin h\,, -\cos i) \tag{1}$$

The horizontal flow vector, $\vec{d} = (d_x, d_y, d_z)$ is calculated as follows using the displacements obtained from the two DInSAR Images, d_a and d_d for the ascending and descending, respectively, and the LOS vector of each ascending, descending path, assuming that the vertical component is close to zero and most of them are horizontal components.

$$\begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} = \begin{bmatrix} \hat{l}_a \\ \hat{l}_d \\ \hat{z} \end{bmatrix}^{-1} \begin{bmatrix} d_a \\ d_d \\ 0 \end{bmatrix}, \tag{2}$$

where $\hat{l}_a$ is the ascending path LOS unit vector, $\hat{l}_d$ is the descending path LOS unit vector, $\hat{z}$ is the vertical unit vector, d_a is the DInSAR displacement from ascending path, and d_d is that from descending path. The normal vector of a plane defined by the horizontal flow vector and the vertical unit vector, can be obtained as

$$\hat{n} = \hat{z} \times \hat{d}, \tag{3}$$

where $\hat{d}$ is the unit vector of $\vec{d}$. Using this normal vector, LOS vector of ascending and descending path, and displacement of DDInSAR (dd_a and dd_d for the ascending and the descending, respectively), the true displacement vector of the DDInSAR $\overrightarrow{dd} = (dd_x, dd_y, dd_z)$ can be separated as below.

$$\begin{bmatrix} dd_x \\ dd_y \\ dd_z \end{bmatrix} = \begin{bmatrix} \hat{l}_a \\ \hat{l}_d \\ \hat{n} \end{bmatrix}^{-1} \begin{bmatrix} dd_a \\ dd_d \\ 0 \end{bmatrix} \tag{4}$$

As used herein, x, y, and z mean east, north and vertical, respectively.

4. RESULTS

As a result of applying the DDInSAR technique in the research area, circular anomaly and multiple channel shape signals were shown (Fig. 2). The circular anomaly signal appears in the same spot in the ascending path and descending path. In the ascending image, the signal of the channel type connected to the circular signal was also shown. DInSAR was performed every 12 days from 2017/03/04 (in yyyy/mm/dd format) to the 2018/02/15, and obtained all the DDInSAR images by subtracting other DInSAR images from the master DInSAR image (2018/06/15_2018/06/27). For the quality of DDInSAR images, the master image was selected as Antarctic winter image with high coherence. As a result, the circular anomalies in all images showed swelling ice in the LOS direction (in case of vertical motion) (Fig. 2). However, this value is relative because it represents a difference from the master DInSAR image. The annual trend appears that the anomaly tends to slow down significantly in Antarctic winter. When using the ascending and descending 2017/05/03_2017/05/15, 2018/06/15_2018/06/27 DDInSAR pair, the horizontal flow displacement shown by $\sqrt{dd_x^2 + dd_y^2}$ was identified with displacement of about 3 cm in the direction of the glacier flow, and the vertical displacement (dd_z) was found to rise about 5 cm (Fig. 3). From this, circular anomaly in glacier can be thought of not only as a result of flow velocity but also as a signal in which vertical and horizontal displacements are combined. After comparing with the bedmap2 data of the circular anomaly region (Fig. 4), we believe that a subglacial lake and channel system exist between ice and bedrock interface. The subglacial water flowing through the channel is stored below the glacier in the region where the circular anomaly appears.

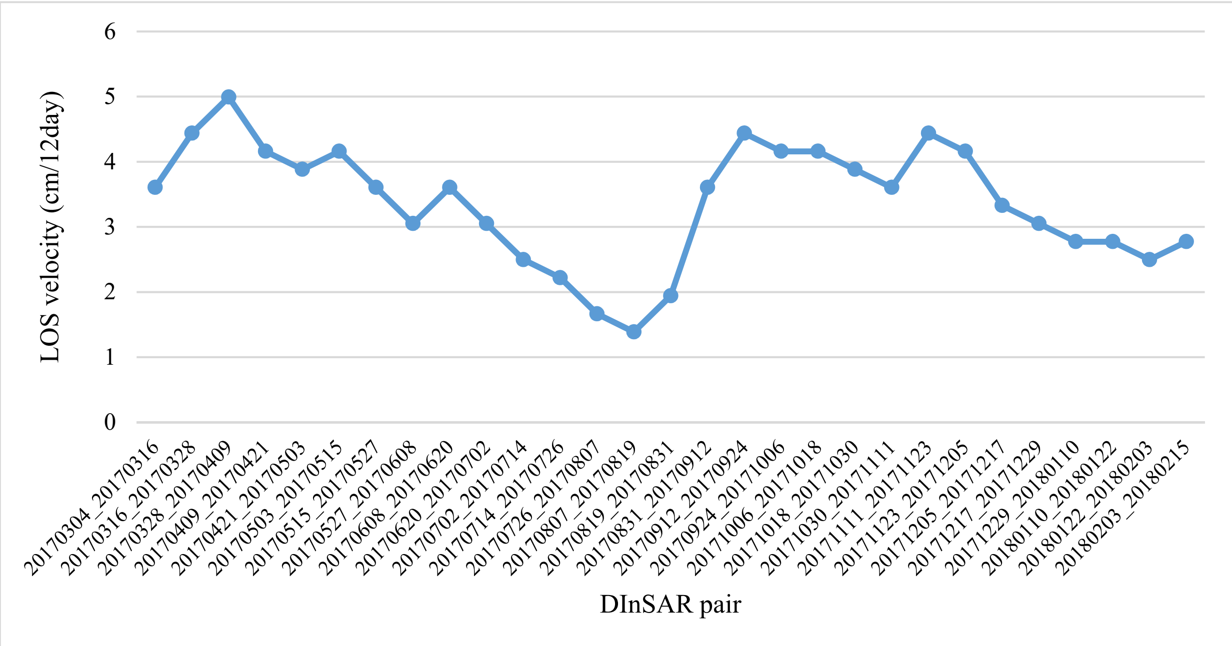

Fig. 2 Time-series graph of LOS velocity in circular anomaly in the ascending path DDInSAR image. It is a relative value to the master DInSAR image.

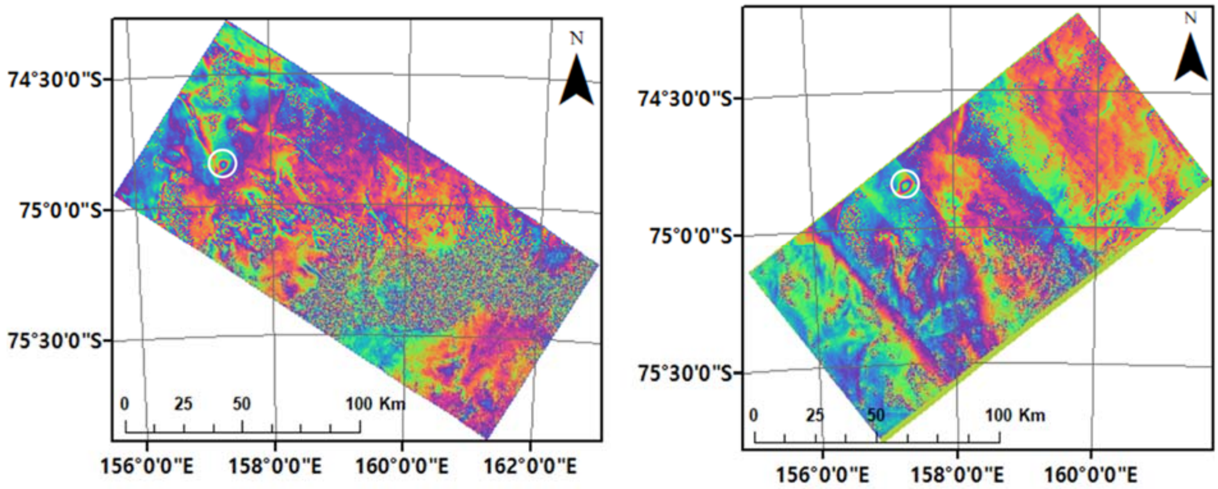

Fig. 3 The ascending (left) and descending (right) DDInSAR images. White circles in both images are the same position that show circular shaped anomaly. A channel pattern is also seen from north leading to the circular anomaly.

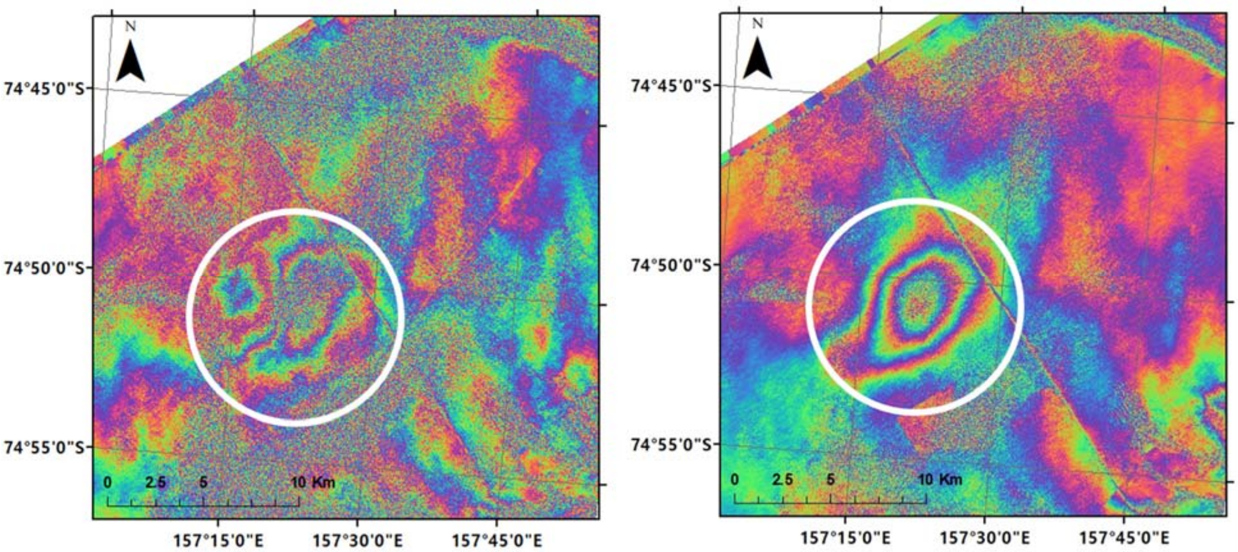

Fig. 4 The horizontal component of displacement change (left) and the vertical component (right) by combining the ascending and the descending DDInSAR images. The white circles are the same as marked in Fig 2. The displacement is re-wrapped so that one color cycle indicates a displacement change of 2 cm. Maximum 3 cm of velocity anomaly was shown in the direction of ice flow in SSE direction (left) while maximum 5 cm of vertical swelling is observed (right).

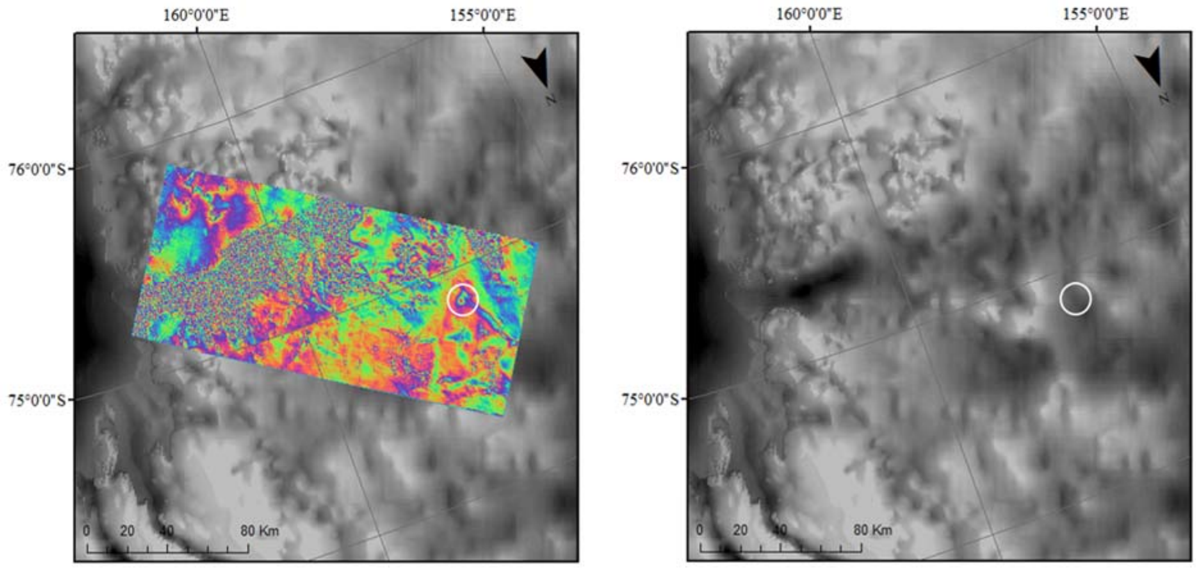

Fig. 5 Shaded relief map of the bedrock topography map near David Glacier. The circular anomaly appears in region marked with white circle.

5. CONCLUSION

DDInSAR images were analysed using Sentinel-1A SAR data from David glacier. In both the ascending and the descending path image, the circular anomalies were identified. The LOS velocity anomaly obtained from DDInSAR tends to slow down significantly in Antarctic winter. As a result of analysing the true displacement direction over this circular shape, it was confirmed that the horizontal flow displacement (~ 3 cm) and the vertical displacement (~5 cm) appeared together. Thus, the circular anomalies appearing in the flow glacier region are not simply caused by the acceleration or deceleration of the glacier flow rate, but by the synthesis of the vertical displacement. As a result of examining bed topography in this area, it is considered that there is a possibility of formation of drainage channel and subglacial lake. Long term observation of satellite data and a possible field work using GPR or RES is required to confirm the existence of the subglacial lake in this region (Fricker *et al.*, 2007; Smith *et al.*, 2017).

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