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Article

Grounding Line Change of Ronne Ice Shelf, West Antarctica, from 1996 to 2015 Observed by using DDInSAR

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Abstract : Grounding line of a glacier or ice shelf where ice bottom meets the ocean is sensitive to changes in the polar environment. Recent rapid changes of grounding lines have been observed especially in southwestern Antarctica due to global warming. In this study, ERS-1/2 and Sentinel-1A Synthetic Aperture Radar (SAR) image were interferometrically acquired in 1996 and 2015, respectively, to monitor the movement of the grounding line in the western part of Ronne Ice Shelf near the Antarctic peninsula. Double-Differential Interferometric SAR (DDInSAR) technique was applied to remove gravitational flow signal to detect grounding line from the interferometric phase due to the vertical displacement of the tide. The result showed that ERS-1/2 grounding lines are almost consistent with those from Rignot *et al.* (2011) which used the similar dataset, confirming the credibility of the data processing. The comparison of ERS-1/2 and Sentinle-1A DDInSAR images showed a grounding line retreat of 1.0 ± 0.1 km from 1996 to 2015. It is also proved that the grounding lines based on the 2004 MODIS Mosaic of Antarctica (MOA) images and digital elevation model searching for ice plain near coastal area (Scambos *et al.*, 2017), is not accurate enough especially where there is a ice plain with no tidal motion.

Key Words : Grounding line, DDInSAR, ERS-1/2, Sentinel-1A, 2004 MOA

1. Introduction

When an Antarctic ice sheet expands into the sea, it forms an ice body floating on the sea surface which is called an ice shelf. The line where the free floating ice shelf is in contact with bedrock is called a grounding line. The vertical movement of the tide or environmental change melts or freezes the base of the ice shelf, and the grounding line retreats or advances toward the sea (Thomas *et al*., 2004; Rignot *et al*., 2011). Tidal deformation of the ice shelf can cause ice breakdown (Von der Osten-Woldenburg, 1990; Bromirski and Stephen, 2012; Han and Lee, 2013). Thus, the ground line of an ice shelf is a sensitive

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indicator of polar environment change.

Rapid grounding line shift has been observed due to global warming in the southwestern Antarctica. The volume of the West Antarctic ice shelf is decreasing by 65 km^3 annually (Scheuchl *et al*., 2016; Thomas *et al*., 2004). West Antarctica Ice Sheet (WAIS) may increase global sea level from 3-5 m depending on its loss volume (Mimura, 2013). Therefore, changes in the West Antarctic have a major impact on global environment and need to be monitored continuously.

Antarctic coasts are subject to large restrictions on optical remote sensing because of the large amount of cloudiness and insufficient light intensity. Since the grounding line is defined at the base of the glacier, it is very difficult to observe in the field. Therefore, Synthetic Aperture Radar (SAR) has been widely used as it is not affected by the sun altitude and weather conditions. Especially, by acquiring two or more SAR images in the same study area and by applying a Differential Interferometric SAR (DInSAR) technique, the surface displacement can be measured with the accuracy of centimeter even when the atmospheric error is taken into consideration.

In an ice shelf, the horizontal flow due to gravity and the vertical motion due to tide are all seen in a single DInSAR image. If the horizontal flow of the ice shelf is assumed constant, it can be removed by differentiating the two DInSAR images (Han and Lee, 2013). This technique is called Double-Differential InSAR (DDInSAR), which allows precise analysis of glacier tidal deformations and locating of grounding line at high resolution (Rignot, 1996; Rignot *et al*., 2011). The first dataset that can be applied to the DDInSAR technique for the Antarctic ice shelves with relatively fast flow rates are the tandem InSAR images obtained from the ERS-1/2 satellites in the 1990s with one day temporal baseline. Given that the accuracy is 2-3 pixels when defining the grounding line by an operator, there is an error of less than 120 m (Li *et al*., 2015). Recently, Sentinel-1A/B satellites acquire images of the Antarctic ice shelf periodically at the shortest intervals of 6 days, and the error of the grounding line defined by DDInSAR image is about 100 m considering 2-3 pixel errors with 25m resolution of IW (Intereferometric Wide-swath) mode (Scheuchl *et al*., 2016).

Rignot and MacAyeal (1998) monitored the grounding line migration of the Antarctic Pine Ice Island glacier from 1992 to 1996 by applying the DDInSAR technique to the ERS-1/2 SAR image and found a 1.2 km retreat. In addition to DDInSAR method, various studies have been conducted as a method for extracting the grounding line. Fricker and Padman (2006) obtained elevation data of the Ronne ice shelves from the Geoscience Laser Altimeter System (GLAS) of the Ice, Cloud, and Land Elevation Satellite (ICEsat) to estimate the position of the grounding lines. Scambos *et al*. (2007) and Brunt *et al*. (2010) have used MODIS-based 2004 Mosaic of Antarctica (MOA) images, and found that the errors of grounding line on the Filchner-Ronne Ice shelf was within 2 km when comparing the ICES at result, especially in the ice plane north of Bungenstockrucken.

In this study, the change of the grounding line at the Ronne Ice Shelf in the West Antarctica was monitored by comparing the DDInSAR images from ERS-1/2 obtained in 1996 and those of Sentinel-1A in 2015. We also evaluated the results with those of Rignot *et al*. (2011) and the optically derived grounding lines by 2004 MOA.

2. Study Area and Materials

1) Study Area

Ronne Ice Shelf located in the West Antarctic near Weddell Sea has ice thickness over 150 m occupying area of 242,420 km^2, which is the second largest ice shelf after the Ross Ice Shelf (Brunt *et al*., 2011). It is bordered by the Filchner Ice Shelf located on the eastern Berkner Island. The two ice shelves have the same origins, so they are called Filchner-Ronne Ice Shelf.

The mean flow velocity of the ice shelves is relatively low at 300 m/year (Le Brocq *et al*., 2013), and it is easy to observe the hinge zone and tidal deformation by the DDInSAR technique with relatively large temporal baseline. In this study, the grounding line of an western part of Ronne Ice shelf was observed (75.1°S, 64.2°W), which is located near Antarctic Peninsula (Fig. 1).

2) Dataset

Both ERS-1/2 and Sentinel-1A satellites used to monitor the movement of the grounding line of the Ronne ice shelf are equipped with a C-band SAR with a center frequency of 5.3 GHz and 5.4 GHz, respectively. All images were downloaded as a Single Look Complex (SLC) format (ESA, 2018).

ERS-1/2 SAR images were acquired on 15 and 16, January 1996, and 19 and 20, February 1996 (Table 1). They were all acquired in descending orbit with VV polarization and a temporal baseline of one day.

Sentinel-1A satellite's Interferometric Wide (IW)

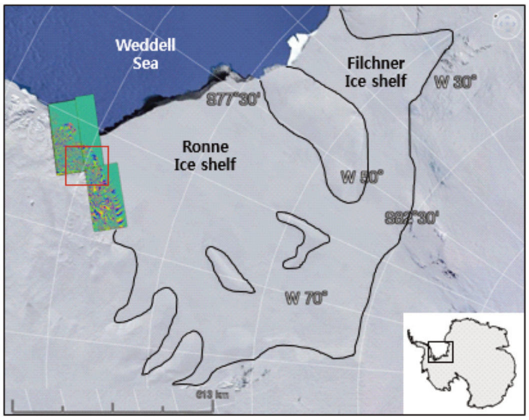

Fig. 1. The study area depicted by a Sentinel-1A DDInSAR image in the western part of Ronne Ice shelf, West Antarctica (edited from the Google Earth image). The red box is the region of interest for grounding line change.

Table 1. ERS-1/2 and Sentinel-1A data used in this study

	Acquisition Date (yyyy/mm/dd)	Perpendicular baseline (m)	Height ambiguity (m)
ERS-1/2	1996/01/15 1996/01/16	231.90	42.48
	1996/02/19 1996/02/20	221.43	44.49
Sentinel-1A	2015/06/12 2015/06/24	47.75	320.19
	2015/06/24 2015/07/06	40.61	378.27

Swath mode can acquire images with 250 km swath owing to the Terrain Observation with Progressive Scans (TOPS) technique. The IW mode consists of a total of three sub-swath images (IW1, IW2, IW3). Sentinel-1A images used in this study were acquired on 12 and 24 June, and 6 July 2015, all in descending orbit in HH polarization mode (Table 1).

The grounding lines of 2004 MOA (Scambos *et al*., 2007) can deviate from those extracted by DDInSAR technique due to the differences in methods. MODIS sensors are equipped with Aqua satellite for marine observation and Terra satellite for terrestrial and atmospheric observation, and it is mosaicked throughout the Antarctica with 260 MODIS images acquired from 20 November 2003 to 29 February 2004. A total of 260 MODIS images used to create the 2004 MOA Surface Morphology Image and Grain Size image map. The entire Antarctica was measured at 125 m resolution. The area where surface slope changes rapidly in the ice sheet or ice shelf were defined as the grounding line. The 2004 MOA grounding line is provided by the National Snow and Ice Data Center (NSIDC).

Rignot *et al*. (2011) have also defined the grounding line from the ERS-1/2, RADARSAT-1/2, and ALOS PALSAR satellites acquired at 50 m intervals throughout the Antarctic for 15 years from 1994 to 2009 with a nominal error of 100 m. They found that there exists up to 100 km difference between MOA-based and DDInSAR-based grounding lines especially where the glacier flow rate is fast. We will use this data to validate the data processing of ERS-1/2 as they used the similar dataset.

3. Methods

The ice shelf experiences both the horizontal flow due to gravity and the vertical motion from the tide. Assuming that the glacier flow rate is constant over the time period of SAR data acquisition, the DDInSAR operation of subtracting two DInSAR images removes the horizontal displacement and extracts only the vertical tidal motion (Rignot, 1996; Han and Lee, 2014). This makes it possible to clearly distinguish the grounding line between the ice sheet and the ice shelf, and the hinge zone.

For ERS-1/2, we generated two DInSAR images. Topographic fringes were removed by using Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) (Fujisada *et al*., 2005). For Sentinel-1A, we also created the two DInSAR images by using GETASSE30 DEM with a spatial resolution of 1 km. The use of different DEMs for ERS-1/2 and Sentinel-1A is due to different processing software, but it does not affect the result owing to relatively large height ambiguities (Table 1).

After phase unwrapping on each DInSAR image, DDInSAR images were generated by subtracting the two DInSAR images from each other. In the ERS-1/2 DDInSAR image (Fig. 2A) and the Sentinel-1A DDInSAR image (Fig. 2B), horizontal flow signals were not observed and only vertical tidal motion can be observed. The double-differential tide at the time of four SAR acquisitions were represented in the DDInSAR phase images. Therefore, the position of the grounding line can be estimated by the line of abrupt changes of tidal motion at the boundary between the ice sheet and the tide-modulated ice shelf.

In a similar way, Rignot *et al*. (2011) obtained the ERS-1/2 tandem pair images from January 18 to 19, 1996 and February 22 to 23, 1996, and then defined the grounding line by applying the DDInSAR technique. The topographic fringe was removed by using a DEM

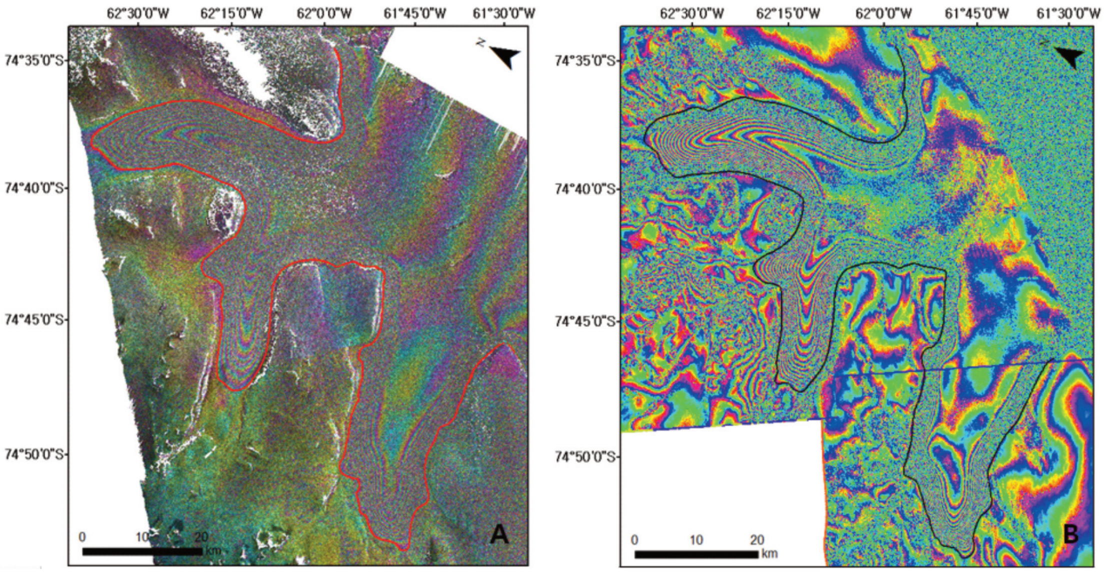

Fig. 2. Examples of grounding line extraction from (A) ERS-1/2 DDInSAR image (red line) and (B) Sentinel-1A DDInSAR image (black line).

measured with a 1 km grid through the altimeter of the ICESat satellite and the ERS-1 satellite. On the other hand, the grounding line extracted from 2004 MOA, which is an Antarctica surface morphology images were based on the break-in-slope change which has the location precision of ±250 m (Scambos *et al*., 2007).

In this study, the grounding line extracted by DDInSAR technique and the 2004 MOA grounding line were compared. The error of the two grounding line with different extraction methods was quantitatively evaluated. In addition, the DDInSAR technique was used to evaluate the change of grounding line during 20 years between 1996 and 2015.

4. Results and Discussion

In the western part of Ronne Ice Shelf near the Antarctic Peninsula, we defined the grounding line in various ways using satellite images and monitored the changes for 20 years. Fig. 3 shows grounding lines extracted from DDInSAR image of ERS-1/2 (black line) and Sentinel-1A (blue line). The ERS-1/2 DDInSAR-based grounding lines of Rignot *et al*. (2011) were in yellow dotted line while those of the 2004 MOA is in red dotted line.

The results show that the difference between grounding lines from our ERS-1/2 DDInSAR and those

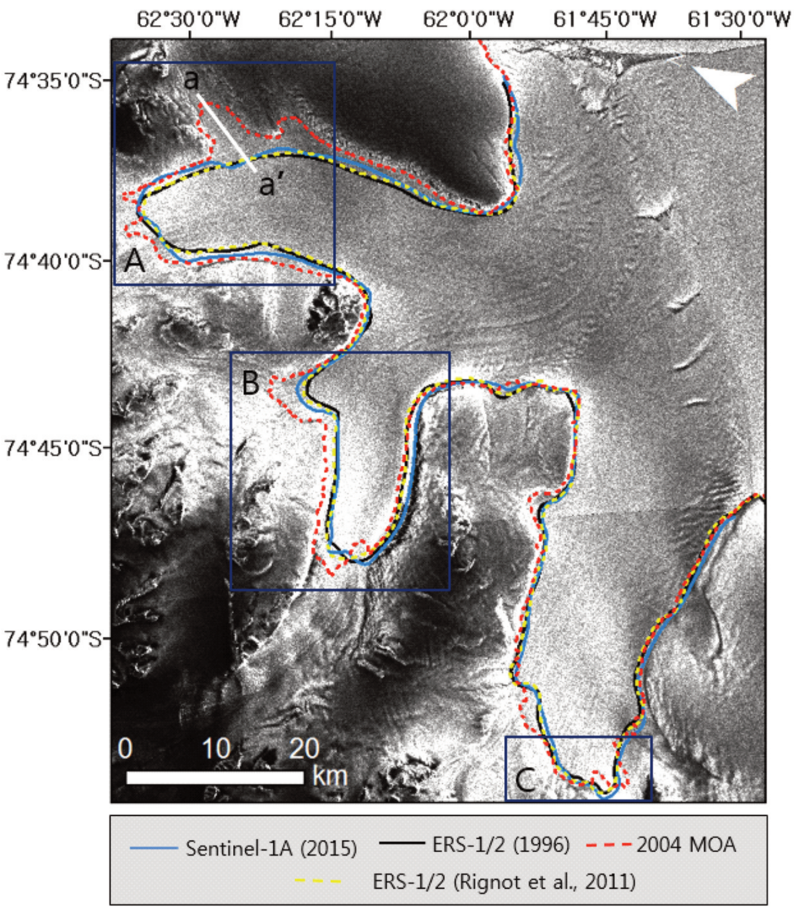

Fig. 3. The grounding lines obtained by ERS-1/2 DDInSAR image (black line) and Sentinel-1A DDInSAR image (blue line), 2004 MOA (red dotted line), and those from Rignot *et al.* (2011) (yellow dotted line). The background is the Sentinel-1A SAR amplitude image obtained on 12 June 2015.

of Rignot *et al*. (2011) is within ±100 m of nominal error range. This proves that the DDInSAR-based grounding line extraction is a reliable method.

To see the change of grounding line extracted from the ERS-1/2 DDInSAR image acquired in 1996 and the Sentinel-1A DDInSAR image acquired in 2015, we divided the study area into three regions as A, B and C. Region A did not show any motion of the grounding line within the error range of 100 m while Region B and C showed grounding line retreat of 1.0 km and 600 m, respectively.

Comparison of grounding lines extracted by 2004 MOA and DDInSAR showed large deviation in some areas. Region A shows deviations of up to 7 km in the northeast area and overall 2.0 ~ 2.3 km. Region B also showed difference of 3 ~ 3.6 km, as well as 2.1 to 2.7 km in Region C. Large deviation occurs especially in bay inward which is less likely to happen. It is difficult to precisely define the grounding line from optical sensors or DEM because it uses contrast effect of the optical image at the break-in-slope change between the ice shelf and the ice sheet. Therefore, MOA-based definition of grounding line does not contain information on the physical motion of glacier by tidal deformation. It is considered that there is a fundamental limitation of the 2004 MOA grounding line. Fig. 4 shows the schematic cross-section of a-a′ of Region A, explaining possible differences in grounding lines by MOA-based and DDInSAR-based methods. The 2004 MOA grounding line was extracted from the flattened area after the break-in-slope change of the Ice sheet while DDInSAR-based grounding line is defined at the beginning of the free-floating of the Ice shelf.

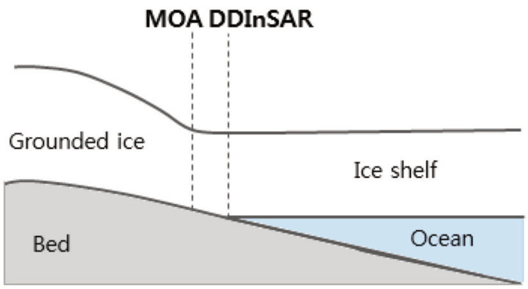

Fig. 4. Schematic representation of a-a′ cross section in Fig. 3 showing the differences in MOA- and DDInSAR-based grounding lines.

It is also an unrealistic hypothesis that the grounding lines would have retreated considerably from 1995 (ERS-1/2 DDInSAR) to 2004 (MOA), and then advanced back to the 1995's almost exactly in 2015 (Sentinel-1 DDInSAR). This is the main reason we think the MOA-derived grounding line has a technical error especially in the grounded ice plain.

As a conclusion, the DDInSAR-based grounding line extraction is a reliable and accurate method while optical or DEM-based methods may contain significant limitations. It is expected that more precise monitoring of grounding line change will be possible if SAR image with shorter temporal baseline is continuously acquired and the DDInSAR image of high resolution is generated at least once every year.

5. Conclusion

The change of the grounding line was monitored for 20 years through the grounding lines extracted by DDInSAR techniques and those from 2004 MOA in the western part of Ronne Ice shelf.

Similarity of grounding lines obtained by using slightly different dates of ERS-1/2 DDInSAR images have confirmed the reliability of the DDInSAR-based method. Quantitative monitoring of ERS-1/2 and Sentinel-1A DDInSAR images showed that the grounding line have possibly retreated 1.0 ± 0.1 km between 1996 and 2015 in the study area. Large difference of grounding lines from 2004 MOA when compared with DDInSAR-based ones indicates a fundamental limitations of the grounding line extraction by optical images or DEM.

It is expected that Sentinel-1A/B DDInSAR image is suitable for mapping the grounding line and its possible drift over the entire Antarctic coast where glacial flow is relatively slow.

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