EXTRACTION OF ICE FLOW VELOCITY BY COMBINATION OF DINSAR AND OFFSET TRACKING METHODS FOR PINE GLACIER, WEST ANTARCTICA

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ABSTRACT:

West Antarctica is the main contributor to global sea level rise at present and in the coming decades, since it occupies 80% of mass loss in Antarctica. In this paper, a combination of Differential Interferometric Synthetic Aperture Radar (DInSAR) and offset tracking technology is used to extract the ice flow velocity of the Pine Island Glacier (PIG), a typical glacier in West Antarctica. Due to the large deformation gradients in PIG, DInSAR technology is used to extract ice flow velocity in bare rock and mountains, then offset tracking technology is used to extract ice flow velocity in areas where glaciers collapse frequently. Finally, the above two results are mosaiced into a new image of the interannual ice flow velocity of PIG in 2017. Through qualitative and quantitative evaluation, it is found that the ice flow velocity extracted by the combination has high accuracy in both high and low velocity areas. In summary, we concluded that the combination of DInSAR and Offset tracking can obtain reliable ice velocity products in glaciers that change rapidly. This combination is of scientific significance for monitoring the movement and evolution of glaciers in the West Antarctica.

1. INTRODUCTION

As the largest ice sheet in the world, the movement and evolution of Antarctica will have a chain effect, affecting global sea-level rise and fall, climate change and ocean current movement. Under the background of global warming, the indicative effect and amplification effect of glaciers on climate change are becoming more and more obvious. Therefore, Antarctica is also a natural study area for global climate change (Eavrs et al., 2021). Over the past three decades, global warming has led to the large-scale disintegration of the ice shelf. The Antarctic ice sheet has lost $2,725 \pm 1,400$ Gt of ice, of which West Antarctica accounts for 80% of the disintegration activity (Rignot et al., 2011). The ice shelves of West Antarctica are along the sea basin and with great instability. In particular, the rapid disintegration of the ice shelf along Pine Island Glacier (PIG) and adjacent glaciers has led to a large amount of melt water flowing into the ocean, raising the sea level. It will have a great impact on the rise of global sea level in the coming decades.

Studying the mass balance of glacier is an important entry point for global sea level change (Shepherd et al., 2018). Ice flow velocity is closely related to the mass balance of ice sheet and ice shelf, and also an important input parameter for calculating ice flux and an index for describing the state and characteristics of ice flow (Thakur et al., 2021). Employment of remote sensing to detect the ice flow movement characteristics of ice sheet and ice shelf is an important method in the study of ice flow velocity (Baumhoer et al., 2018). This method can be divided into optical remote sensing and microwave remote sensing. The core of optical remote sensing measurement is to determine the corresponding points of the master-slave image and calculate the real displacement through the scale (Dirscherl et al., 2020). For the features of Antarctic glaciers that are easy to identify and exist stably all year round, such as cracks, these features can be used to extract ice flow velocity from Landsat MSS images (Cheng et al., 2019). With the development of image processing technology, a series of automatic matching algorithms are proposed. For example, the normalized cross correlation (NCC) method is used to automatically extract ice flow velocity (Li et al., 2017). Subsequently, other feature matching algorithms have been proposed and applied. Such as, least squares matching method (Li et al., 2021), phase correlation method (Li et al., 2018) and orientation correlation method (Han et al., 2018). Optical remote sensing measurement method has the advantages of high degree of automation and easy to extract ice flow velocity in a large-scale range (Alley et al., 2018). However, due to the limitations of optical image spatial resolution and feature matching algorithm, the accuracy of optical method is relatively low. Moreover, the surface velocity monitoring method based on optical image is easy to be affected by cloud and rain.

The limitation of optical remote sensing has prompted people to use microwave remote sensing to monitor the Antarctica. Microwave radar can obtain Antarctic surface information allday and all-weather. Moreover, it is very sensitive to the change of terrain information of ice shelf (Johnson et al., 2020). The proposal of DInSAR principle lays a theoretical foundation for extracting ice flow velocity by synthetic aperture radar data. DInSAR uses radar phase difference, satellite orbit parameters and other information to calculate the surface deformation information, so as to calculate the ice flow velocity in line of sight of radar (Yu et al., 2020). Since the interferometric phase

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of DInSAR includes the topographic phase caused by elevation fluctuation, this method is only applicable to the area with short baseline and small elevation fluctuation (Han et al., 2017). Using SAR data assisted with DEM of the study area for DInSAR, the ice flow velocity of most low velocity glaciers in Antarctica can be roughly extracted (Samsonov et al., 2019). In the early days, scholars mostly used ERS satellite images to extract range and azimuth glacier deformation (Tong et al., 2018). With the launch of Sentinel satellite, it has become an important data source in DInSAR processing. DInSAR technology has been employed to map almost the entire West Antarctica ice flow velocity product based on Sentinel images (Mouginot et al., 2017). DInSAR method is very sensitive to the coherence of master-slave images. For fast moving regions, phase incoherence will occur (Han et al., 2016). SAR data has high resolution and can also record the texture characteristics of glaciers. Therefore, the method applied to optical remote sensing is also suitable for SAR data. Tomo et al. (2021) used the offset tracking method to study the spatial distribution of ice flow velocity of glaciers with fast-flow velocity in East Antarctica. In the Antarctic Peninsula where disintegration is frequent, offset tracking can also perform well (Seehaus et al., 2018). Therefore, using offset tracking to monitor the ice shelves with a great number of deformations in West Antarctica has become a trend (Samsonov et al., 2021).

In this paper, we combined the DInSAR and offset tracking methods to map the surface ice velocity with both fast-flow and low-flow in PIG, West Antarctica. DInSAR technology was used to extract the small deformation in low-flow velocity areas, and the offset tracking technology was employed to supplement the large deformation regions. The first part of this paper reviews the existing research on ice flow velocity extraction. The second part introduces the study area and data, and then, presents the principle and implementation of this combination in detail. The third part introduces the experimental results of extracting the ice velocity of PIG. Finally, we summarize the study.

2. DATA AND METHOD

2.1 Study area

The location of PIG in West Antarctica is shown in Figure 1. PIG is one of the largest glaciers in West Antarctica, and its total ice shelf area is about 17.5*10-4 km2, accounting for 10% of the ice sheet area of West Antarctica. It is composed of the upstream ice sheet and the downstream ice shelf, and it eventually merges into the Amundsen Sea. PIG has undergone many large-scale disintegration events, and its velocity and front position are constantly changing, so it has become a hot spot for glacier research. PIG has a highly variable elevation with a fluctuation of 150 m from the entrance to the sea to the grounding line. There is even a drop of nearly 700 m from the inland upstream in PIG (Shean et al., 2016). The main ice shelf of PIG consists of three parts: the fast-moving central ice shelf, and the slow-moving northern and southern ice shelves located on both sides of the central ice shelf. The images selected in this paper cover these three areas.



Figure 1. The location of study area. These two layers are overlaid on the Landsat Image Mosaic of Antarctica (LIMA, (Bindschadler et al., 2008)).

2.2 Data

PIG has a wide range of ice flow velocity, up to about 4,300 m/yr, and only the data with short-time baseline can be used for DInSAR processing in the high-flow-velocity region, leaving very little image data that meets the requirement. Launched by ESA on April 3, 2014 and April 25, 2016 respectively (Potanet al., 2019), Sentinel-1 A/B satellites are designed for monitoring land, coastal zone, sea ice and polar regions on a global scale. The revisit cycle period of a single satellite is 12 days, and the orbital phase difference between satellites A and B is 180°. The revisit cycle period of the two satellites can be shortened to 6 days, which reduces the impact of time decorrelation on the accuracy of results, and provides an advantageous radar data source for the study of ice flow velocity. Sentinel satellite has four imaging modes (Table 1), in which the resolution of IW mode is 10 m * 10 m and its width is 250 km. In this paper, we use 24 scenes (two scenes per month) IW SLC to extract the ice flow velocity of PIG in 2017. Compared with the existing velocity products, the accuracy of this method is verified.

Parameter	Sentinel-1A/B
Resolution/m	5*20
Repeat cycle/day	6 12
Band	C band
Polarization	VV HH VH HV
Data type	Single Look Complex (SLC)
Imaging mode	Interferometric Wide swath (IW)

Table 1. Selected parameters of Sentinel satellite in this study.

2.3 DInSAR method

DInSAR method mainly uses the phase information of SAR images to extract surface deformation (Nela et al., 2019). The basic principle is to carry out complex conjugate multiplication for each pixel in two SAR images with the same area and different periods. Then, the generated phase is processed to obtain the complex interferogram. The topographic and flat

phase are simulated by external DEM data for differential interference to remove the redundant information, and only the deformation phase information in the interferogram is retained, Finally, the phase information is converted into deformation to obtain the velocity during the image time interval (Chen et al., 2013). In the process of DInSAR, there are three factors affecting its accuracy. First, the temporal incoherence: the ground feature changes between the two images. Second, the spatial incoherence: this situation will occur when the spatial baseline exceeds the critical baseline. Finally, the atmospheric phase disturbance. When using DInSAR to detect ice flow velocity in West Antarctica, the biggest influencing factor is that the deformation gradient is too large. When the surface deformation of two adjacent pixels exceeds half a wavelength (is the wavelength of satellite signal), we cannot accurately unwrap the interferometric phase (Pepe et al., 2012).

DInSAR method is implemented in the process shown in Figure 2(a). DEM assisted co-registration is performed on the interferogram pairs by the cross-correlation algorithm. The azimuth and range errors are controlled within 0.2 pixels so that sub-pixel accuracy georeferencing is achieved. After the slave image is perfectly matched with the master image, it begins to generate interferogram phase. The differential phase of the interferogram is composed of displacement phase, topographic phase, atmospheric phase and phase noise. It is generally believed that the atmospheric phase will not affect the deformation of the glacier. The topographic phase can be eliminated by introducing an external DEM, then the phase noise can be eliminated by adaptive filtering (adf) algorithm, and the rest is displacement phase. This phase can be unwrapped into displacement information through the minimum cost flow (mcf).

2.4 Offset tracking method

Offset tracking method mainly uses the intensity information of two SAR images covering the same area for sub-pixel level coregistration (Gomez et al., 2019). It will obtain a large number of sub-pixel level offsets of corresponding points, and then decompose the offset into offset in range direction (along satellite line of sight direction) and offset in azimuth direction (along orbital flight direction) (Figure 2(b)). This technology needs to analyze the corresponding points like DInSAR, but it doesn't need phase unwrapping. It is suitable for high flow velocity glaciers with large gradient deformation (Choe et al., There are two implementation methods of offset 2021). tracking, intensity tracking algorithm and coherence tracking algorithm respectively. The applicable conditions of the two methods are different. The coherence tracking algorithm uses interferometric phase for cross-correlation calculation. It will also be affected by temporal, spatial incoherence, atmospheric phase disturbance like DInSAR. The intensity tracking algorithm mainly uses the intensity information of SAR image, so it can be effectively used to monitor areas with a little change in ground object and ground object scattering characteristics. Therefore, this method requires a short time interval between two images. The coherence of SAR image in the high flow velocity area of PIG is often low, so the offset tracking based on intensity tracking algorithm is more suitable. The intensity tracking algorithm is to calculate the normalized crosscorrelation (NCC) of the intensity information of the two SAR images, and to find the peak of the intensity cross-correlation coefficient of the feature pixels. It is considered that the offset with the maximum cross-correlation coefficient is the offset of corresponding points (Yan et al., 2019).

Similarly, co-registration is also required before offset tracking. When the feature elements of corresponding points are highly correlated, high accuracy can be obtained through a small search window. If the distribution of feature elements corresponding points is discrete, it is necessary to resample the image by multi-look. It ensures the continuity of surface features at the cost of reducing image resolution. Therefore, multi-look is performed by ratio of 8:2 at range and azimuth, and then matching window of 256 * 256 pixels is used to collect the displacement. Offset tracking has the advantage in detecting large deformation gradients at the scale of 10 cm to 10 m. However, DInSAR is limited to a relatively small deformation range of centimeter level.



Figure 2. Technical flow charts of DInSAR (a) and offset tracking (b) employed in this study.

3. RESULT

3.1 Ice flow velocity of PIG

Using the combination of DInSAR and offset tracking, the deformation in the line of sight direction in this area within 6 days is extracted. The result includes two parts: small deformation (0 - 1 m) extracted by DInSAR and large deformation (1 m - 80 m) extracted by offset tracking. After conversion, we obtain the velocity (about 0 - 60 m/yr) in the low velocity area and the velocity (about 60 m/yr - 4,500 m/yr) in the high velocity area. Based on the boundary of two ice flow velocity results, we build a 100 m buffer, respectively. Then, the two results were fused into a mosaic with both low and high flow velocities. In addition, we fuse the overlapped parts of the buffer with the mean value in the fusion process. Finally, the mosaic is projected to the coordinate system of WGS_1984_Antarctic_Polar_Stereographic. The ice flow velocity map of PIG in 2017 is completed (Figure 3 (a)). It can be seen that the high velocity of PIG is mainly concentrated in the middle ice shelf, up to 4,500 m/yr, and the velocity of ice shelves on both sides is low. Our combination can well distinguish between high velocity and low velocity, and there is a good smooth at the boundary of high and low velocities. Because of the high resolution of Sentinel image, the final ice flow velocity map has high quality.

3.2 Accuracy analysis

In order to verify the accuracy of the combination, we introduced the Antarctic ice velocity map (MEaSUREs InSAR-Based Antarctica Ice Velocity Map, Version 2) produced by Rignot's team for accuracy analysis (Mouginot et al., 2017). First, we analyze the overall accuracy. We construct the fishnet

with a sampling interval of 10 m, extract the velocity value of our product and Rignot's product to the fishnet points. Then, we take our product's velocity value as the x-axis and Rignot's velocity value as the y-axis, draw all fishnet points on the coordinate axis (Figure 4). It can be seen that most of the points are concentrated near the blue line with slope of 1, which can prove that our velocity is close to that of Rignot. In addition, we subtract Rignot's velocity value from mine to obtain the difference map (Figure 5). After statistics, The difference, and the difference between 100 m/yr accounts for 86.9%. Therefore, the overall difference between our product and Rignot's is between 100 m/yr, which is proved that our combination performs well in PIG.



Figure 3. Comparison of ice flow velocity: SAR product of this study (a) and Rignot's product from MEaSURES InSAR-Based Antarctica Ice Velocity Map (Mouginot et al., 2017) (b).



Figure 4. Scatter diagram of our product and Rignot's (Mouginot et al., 2017). The x-axis is the velocity of our product, the y-axis is the velocity of Rignot's. The slope of the blue line is 1, indicating the position when our velocity is equal to that of Rignot.



Figure 5. Ice flow velocity difference between our result and Rignot's (Mouginot et al., 2017).

Next, we perform a detailed accuracy analysis including low velocity and high velocity analysis. We quoted a rock outcrop map (Burton-Johnson et al., 2016) to analyze the accuracy of low ice flow velocity. Theoretically, the annual average velocity of rock outcrop should be 0. By counting the average velocity of rock outcrop, the velocity accuracy in low velocity area can be verified. The distribution of rock outcrops in the PIG is shown in the black circle in Figure 6. According to statistics, the annual average velocity of these rock outcrops of our product is 4.2 m/yr; The standard deviation (Std.) of velocity is 2.9 m/yr. Similarly, we also count the average velocity and Std. of Rignot's rock outcrop, which are 2.3 m/yr and 1.3 m/yr, respectively. It can be seen that they are close to our product, both of which are approximately 0. In summary, there is a high accuracy in the low ice flow velocity generated by the combination approach.



Figure 6. Distribution and parameter statistics of rock outcrop in PIG. The black circle represents the distribution of rock outcrop. The table at the top right counts the annual average velocity and standard deviation of rock outcrop of our product and Rignot's (Mouginot et al., 2017).

Finally, we introduced the ice flowline data (Liu, 2015) of Beijing Normal University for accuracy analysis of high ice flow velocity. Four representative ice flowlines in the main ice flow are selected (Figure 7). We generate isometric points along each flowline at an interval of 1km, extract our velocity and Rignot's velocity to these equidistant points, and compare the values of these points respectively (Figure 7). It can be found that the two curves in each chart have a high degree of similarity and are relatively smooth. The difference of the two data on the ice flowline is also mostly concentrated within 100 m/yr, which is very rare in high velocity area. To sum up, the maximum deviation between our product and Rignot's is concentrated within 100 m/yr, which proves that our product has good accuracy in high flow velocity area.



Figure 7. Velocity comparison diagram of two products on four ice flowlines. The black lines in the figure at the top right represent the distribution of the four flowlines (Liu, 2015), respectively.

4. CONCLUSION

Antarctica is sensitive to global climate and environment change, so it is an amplifier and indicator for sensing global change. Ice flow velocity is one of the important parameters of the Antarctic, which can help to understand the spatial distribution characteristics of ice shelf, quantitatively analyze the output quality of ice shelf, and fully forecast the dynamic changes of ice shelf.

This paper shows the advantages of combination of DInSAR and offset tracking methods in detecting ice flow velocity areas with large gradient deformation range. Through this combination, the technical limitation of a single method is solved, which not only ensures the flow velocity accuracy in the area with fine deformation, but also makes the extraction of large deformation possible. We used this combination to make the ice flow velocity map of PIG in 2017 successfully. Through qualitative evaluation, our product has high resolution. It can well distinguish between high velocity and low velocity, and has a better smoothness at the boundary between them. We carried out quantitative evaluation by introducing a lot of published products. It can be verified that our products have high accuracy in both high and low velocity areas, which further shows that our combination has high applicability in PIG.

Monitoring the ice flow velocity is of significance to the study of ice shelf disintegration, ice sheet mass balance, global climate change and sea level change. The combination proposed in this paper can better extract the ice flow velocity in rapidly changing areas and provide constructive suggestions for the movement monitoring of typical glaciers in West Antarctica.

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