COSMO-SKYMED AO PROJECTS - TIDAL DEFLECTION CHARACTERISTICS OF CAMPBELL GLACIER, EAST ANTARCTICA, OBSERVED BY DOUBLE DIFFERENTIAL SAR INTERFEROMETRY

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ABSTRACT

In this paper, we suggest a method of estimating flexural parameters of glacier responding to tide height. During 2010 to 2011, we obtained 16 COSMO-SkyMed one-day interferometric tandem pairs over Campbell Glacier, East Antarctica, in every 16 days and extracted signal from vertical tidal motion by applying Double-Differential Interferometric SAR (DDInSAR) technique. To find the tidal flexural parameters for Campbell Glacier, we used several tide models (TPXO7.1, FES2004, CATS2008a and Ross_Inv) and an elastic beam model. The result showed that the inverse barometric effect-corrected Ross_Inv showed best correlation with the tidal motion from DDInSAR. The deflection constant of Campbell Glacier was determined to be 0.926 with R^2 of 0.964. The elastic damping factor of a stream line, as an example, was derived as 0.827±0.099 km^{-1}, from which the glacier thickness was estimated to be 406±52 m.

Index Terms— Campbell Glacier, tidal deflection, COSMO-SkyMed, one-day tandem, DDInSAR

1. INTRODUCTION

Glacier flow rate, ice discharge and mass balance of glaciers are important factors in polar research. Satellite synthetic aperture radar (SAR) has provided high quality images over polar region where cloudy days and dark nights limit the usability of optical images. Differential Interferometric SAR (DInSAR) technique has been widely used to extract surface displacement of glaciers by removing topographic signals from the interferogram. However, DInSAR signals of floating glacier contain the displacements from both horizontal creep flow and vertical tidal motion [1]. To calculate glacier mass balance and to estimate tidal response of glacier, two signals should be separated.

Assuming that the glacier flow rate is steady over time, the horizontal motion can be cancelled out by differencing the two DInSAR signals. The remaining signal would be the difference of tidal motion between two differential interferograms [2]. This technique is called as Double-Differential Interferometric SAR (DDInSAR). DDInSAR has been used to assess the accuracy of tide models in Antarctic Ocean [3], to define the grounding line and hinge zone of glaciers [2], and to estimate the retreat of hinge line of glaciers [1]. However, most of the studies used limited number of DInSAR pairs with temporal baseline of at least 3-days and more, except for a few one-day tandem pairs. A series of DInSAR observations with shorter temporal baseline is necessary to accurately analyze the fast-flowing glaciers. COSMO-SkyMed, a constellation of four satellites with X-band SAR onboard, have recently provided the capabilities of obtaining one-day tandem InSAR pairs in every 16 days.

In this paper, we extract the vertical tidal displacement of Campbell Glacier, one of the fastest flowing glaciers in East Antarctica, by applying DDInSAR to a series of 16 COSMO-SkyMed one-day tandem DInSAR pairs obtained from the year 2010 to 2011. We then compare the DDInSAR signals with several tide models before and after inverse barometer effect (IBE)-correction [4]. Finally, we determine the elastic parameters of Campbell Glacier by using an elastic beam model.

2. STUDY AREA AND DATA

Campbell Glacier is located in northern Victoria Land, East Antarctica (Fig. 1). Campbell Glacier forms an ice tongue and flows into Terra Nova Bay in Ross Sea where Jangbogo Antarctic Research Station, a new Korean research station, will be constructed by 2014. Campbell Glacier tongue is composed of two ice streams: a thick main stream in steady motion and a branch stream having rotational motion. Floating height of the main stream of Campbell Glacier tongue is higher than that of the broken branch stream. The tidal flexural characteristics of Campbell Glacier were analyzed from the main stream of glacier tongue only.

We obtained a total 16 COSMO-SkyMed one-day tandem InSAR pairs with short perpendicular baseline from 5.7 m to 181.7 m from June 2010 to November 2011 (Table 1). All of the COSMO-SkyMed SAR images were acquired in Stripmap mode, VV polarization and descending orbits at a resolution of 3 m. We used the ASTER GDEM to remove

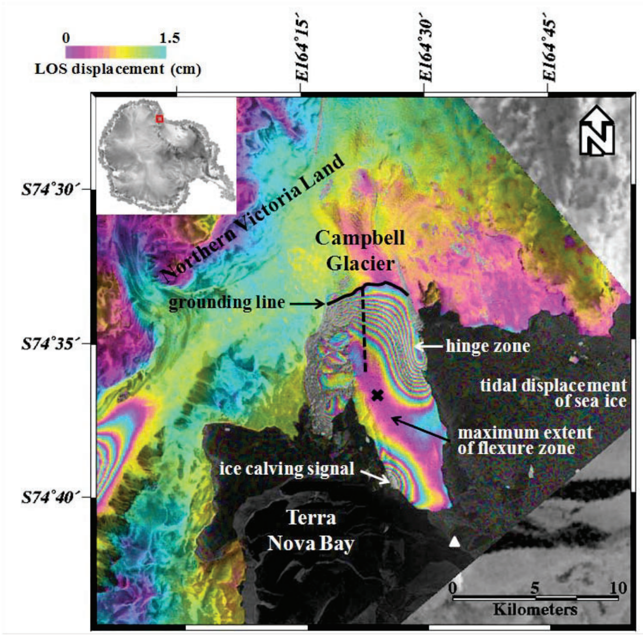

Fig. 1. An example of DDInSAR image over Campbell Glacier, East Antarctica, derived from COSMO-SkyMed DInSAR pairs obtained on 2, 3 July 2010 and 31 March, 1 April 2011. Each fringe represents the component of tidal displacement of 1.5 cm in the direction of radar line of sight (LOS).

the topographic phases from the one-day interferograms. In the snow and ice covered area, the GDEM was inaccurate due to whiteout effect during stereo matching. Erroneous pixels of GDEM were removed and interpolated.

Four tide models were used to compare tide height with the vertical displacement of Campbell Glacier tongue: TPXO7.1, FES2004, CATS2008a and Ross_Inv. TPXO7.1 and FES2004 are global tide models, while CATS2008a and Ross_Inv are the Antarctic regional tide models. These models predict tide height under the barotropic conditions so that they do not consider the IBE. It is known that root mean square error (RMSE) of those models are 10~20 cm in the whole Antarctic Ocean [5], which may not be accurate enough for comparison with the cm-accuracy of DDInSAR.

To access the accuracy of tide models in terms of their compatibility with DDInSAR, we compared the predicted tide data with *in situ* data. Tide height was measured by a water pressure gauge installed at Terra Nova Bay for 11 days from 2 to 13 February, 2011. We also used atmospheric pressure data from February 2010 to January 2012, measured in every hour by an automatic weather system installed at Terra Nova Bay, for the IBE-correction (~1 cm per 1 mbar).

Table 1. The 16 COSMO-SkyMed one-day tandem DInSAR pairs used in this study.

Dates (master, slave)	perpendicular baseline (m)
2010/06/16, 2010/06/17	31.6
2010/07/02, 2010/07/03	-46.3
2011/01/26, 2011/01/27	18.9
2011/02/27, 2011/02/28	5.7
2011/03/15, 2011/03/16	-44.4
2011/03/31, 2011/04/01	-39.2
2011/05/02, 2011/05/03	-89.6
2011/05/18, 2011/05/19	75.9
2011/06/03, 2011/06/04	-36.5
2011/06/19, 2011/06/20	-47.5
2011/08/22, 2011/08/23	181.7
2011/09/07, 2011/09/08	37.3
2011/10/09, 2011/10/10	-44.4
2011/10/25, 2011/10/26	-110.9
2011/11/10, 2011/11/11	-91.7
2011/11/26, 2011/11/27	-23.4

3. METHOD

The vertical tidal deflection of glacier tongue, Z, is a function of the distance from a grounding line of glacier (x) and time (t), which can have the following solution of an elastic beam model [6].

$$Z(x,t) = Z_0(t)\left[1 - e^{-\beta x}(\cos\beta x + \sin\beta x)\right], \qquad (1)$$

where Z_0 is the tidal deflection beyond the hinge zone ($x \to \infty$). β is the elastic damping factor of glacier given by

$$\beta^4 = 3\rho_s g \frac{1-\nu^2}{Eh^3}, \qquad (2)$$

where ρ is the density of sea water (=1030 kg m^{-3}), g is the acceleration of gravity (=9.81 m s^{-2}), ν is the Poisson's ratio for the glacier (=0.3), E is the Young's modulus for the glacier (=0.88±0.35 GPa) [6], and h is glacier thickness. In equation (1), we assumed that $Z_0(t)$ is a function of tide height (T) multiplied by a deflection constant α at $x \to \infty$. The deflection constant represents the flexural property of a tidal glacier in response to tide, having the value range of [0, 1]. The difference of Z contained in a one-day DInSAR signal, $\dot{Z}$, can be related to the one-day difference of tide height ($\dot{T}$). However, we cannot measure $\dot{Z}$ directly from the DInSAR signal as the horizontal creep flow is also included. Assuming a constant horizontal creep flow during the observation time, the vertical tide motion of glacier can be solely measured by the DDInSAR signal, $\Delta\dot{Z}$, between two one-day DInSAR images as

$$\Delta\dot{Z}(x,t) = \alpha\Delta\dot{T}(t)\left[1 - e^{-\beta x}(\cos\beta x + \sin\beta x)\right], \qquad (3)$$

where $\Delta\dot{T}$ is the difference of $\dot{T}$. We can now derive α and β, the elastic flexural characteristics of glacier by tide, once we have accurate tide height data.

From TPXO7.1, CATS2008a and Ross_Inv, we extract tide height $T_{predict}$ beyond the hinge zone of Campbell Glacier (a black cross in Fig. 1) at time of the COSMO-SkyMed SAR image acquisition. The $T_{predict}$ of FES2004 is extracted at the front of Campbell Glacier tongue (a white triangle in Fig. 1) because FES2004 regards the glacier tongue as inland and no data is available. We derived the one-day difference of $T_{predict}$, $\dot{T}_{predict}$, and the difference of $\dot{T}_{predict}$ ($\Delta\dot{T}_{predict}$) between two DInSAR acquisitions. To find the representative value of α, we perform linear regression between $\Delta\dot{T}_{predict}$ and the vertical displacement beyond the hinge zone of Campbell Glacier ($\Delta\dot{Z}_0$) extracted from the double-differential interferograms.

The accuracy of tide models is assessed by using *in situ* measured tide height (T_{in_situ}), the one-day difference of T_{in_situ} ($\dot{T}_{in\_situ}$) and the difference of $\dot{T}_{in\_situ}$ ($\Delta\dot{T}_{in\_situ}$). We also assess the accuracy of the IBE-corrected $T_{predict}$ ($T^{IBE}_{predict}$), $\dot{T}_{predict}$ ($\dot{T}^{IBE}_{predict}$) and $\Delta\dot{T}_{predict}$ ($\Delta\dot{T}^{IBE}_{predict}$).

Recognizing the necessity of IBE-correction, we then reanalyze linear regressions between $\Delta\dot{T}^{IBE}_{predict}$ and $\Delta\dot{Z}_0$ to calculate more accurate α value. We also estimate β by fitting the elastic model to 120 DDInSAR signals, $\Delta\dot{Z}$, along the dotted line shown in Fig. 1.

4. RESULT AND DISCUSSION

Total 120 DDInSAR images over Campbell Glacier were generated out of 16 one-day tandem COSMO-SkyMed DInSAR images. Fig. 1 is one of them, as an example, generated from the two InSAR pairs obtained on 2-3 July 2010 and 31 March-1 April 2011. Although the two InSAR pairs were obtained in summer and winter season, the double-differential interferometric phases by horizontal glacier flow disappeared completely over the grounded part of Campbell Glacier. We therefore confirmed that the assumption of steady ice flow of the grounded glacier is valid. Fig. 1 also shows the grounding line of the glacier, ice calving signal at the end of the ice tongue, and tidal signal over sea ice.

Fig. 2(a) shows linear regression between $\Delta\dot{T}_{predict}$ from Ross_Inv tide model (before IBE-correction) and $\Delta\dot{Z}_0$, representing the α of 1.518. From the regressions based on other tide models, the α was also estimated as much higher than 1, which were hardly acceptable values stating that the tidal deflection of Campbell Glacier is bigger than the actual change in tide height.

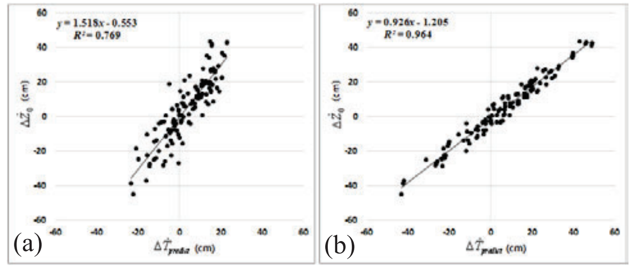

Fig. 2. (a) Linear regression between $\Delta\dot{T}_{predict}$ predicted from Ross_Inv_2002 and $\Delta\dot{Z}_0$. (b) Linear regression between $\dot{T}^{IBE}_{predict}$ predicted from Ross_Inv_2002 and $\Delta\dot{Z}_0$.

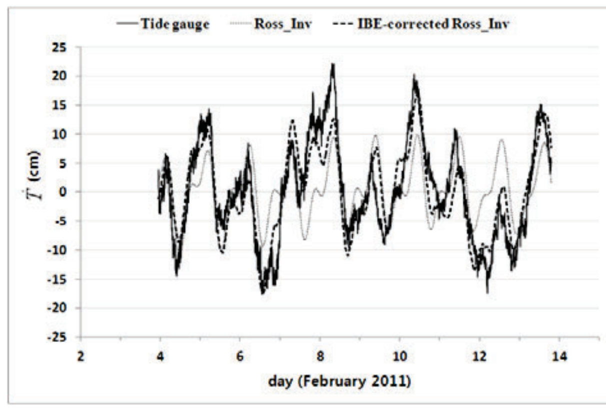

Fig. 3. One-day difference of tide height ($\dot{T}$) in every 5 minute calculated from the *in situ* tide height (thick line), the predicted from Ross_Inv model (thin dotted line) and the IBE-corrected Ross_Inv model (thick dotted line).

To assess the accuracy of the tide models, we compared $T_{predict}$ with T_{in_situ} obtained just for 11 days. The RMSE of $T_{predict}$, one–day difference $\dot{T}_{predict}$, and $\Delta\dot{T}_{predict}$ were as high as 8~10 cm, which were not accurate enough to analyze tidal motion of glacier by DDInSAR. The RMSE of $T^{IBE}_{predict}$, after IBE-correction, showed no improvement due to low frequency errors. However, the RMSE $\dot{T}^{IBE}_{predict}$ and $\Delta\dot{T}^{IBE}_{predict}$ showed improvement (4~6 cm) as shown in Fig. 3. Linear regressions between $\Delta\dot{T}^{IBE}_{predict}$ predicted by all tide models and $\Delta\dot{T}_{in\_situ}$ showed that the slope and intercept were 1.06 to 1.14 and -1.98 to -0.13, respectively with high R^2. This confirms that the IBE-corrected tide models are useful to predict the change in tide height with time.

The values of α were less than 1 in the regressions between $\Delta\dot{T}^{IBE}_{predict}$ and $\Delta\dot{Z}_0$, except for the regression based on FES2004, with the R^2 higher than 0.9. The regression based on Ross_Inv showed the highest R^2 of 0.964, representing the α of 0.926 (Fig. 2b). Ross_Inv is known to have outstanding ability in the prediction of tide height over Ross Ice Shelf (RIS) because it assimilates the tide height measured by *in situ* tide gauge on the RIS and uses the accurate grounding line extracted from SAR data [7]. Considering only R^2 of the regression, FES2004 showed the second best regression, however, α was higher than 1. The accuracy of FES2004 over the RIS seems to be less than other tide models [7] because of its erroneous grounding line for the RIS. The grounding line of FES2004 is also problematic for Campbell Glacier, which might have caused an erroneous α. The regression based on CATS2008a also showed high R^2. However, CATS2008a and its previous version are known to have larger error of the prediction of tide height in ice shelf region than other tide models [5]. TPXO7.1 and its previous version predicted relatively accurate tide height around the Antarctic Ocean [5]. However, R^2 of the regression was the lowest in this study. From this research, we can conclude that IBE-corrected Ross_Inv is the best tide model to predict tide height in Terra Nova Bay. The representative value of α for the Campbell Glacier is 0.926±0.017. Based on the high R^2 and the fact that the intercept of the regression was close to 0, we confirmed the assumption of steady ice creep is correct and the deflection constant α is independent of tide height.

We also estimated the elastic damping factor β from 120 double-differential interferograms. The average of β is 0.827 km^{-1} with a standard deviation of 0.099 km^{-1}. Using the value of β and the equation (2), the thickness of Campbell Glacier tongue along the dotted line in Fig. 1 was estimated to be 406±52 m. Previous estimate of ice thickness estimated from the assumption of hydrostatic equilibrium at the grounding line of Campbell Glacier was 456 m, leaving the difference of 50 m with our estimation. As the error of ice thickness estimation from the hydrostatic equilibrium is known to be ±100 m [8], the elastic damping factor and the glacier thickness estimated in this paper is considered reasonable.

The α and β of Campbell Glacier suggested in this study may still include the errors either from the double-differential interferograms or the IBE-corrected Ross_Inv. A total error of the vertical displacement extracted from the double-differential interferograms was estimated to be 2.0 cm by using the error assessment method described in [3]. The RMSE of $\Delta\dot{T}^{IBE}_{predict}$ predicted by Ross_Inv was 5.8 cm by comparing that with $\Delta\dot{T}_{in\_situ}$ for 11 days. These errors contributed to the uncertainty of the values of α and β of Campbell Glacier which was estimated at 1.8% and 12.0%, respectively.

5. CONCLUSION

The double-differential interferograms generated from the COSMO-SkyMed one-day tandem DInSAR pairs provided very precise measurement of tidal displacement of Campbell Glacier. After the IBE correction, Ross_Inv tide model well predicted the changes in tide height over time in Terra Nova Bay. The deflection constant and the elastic damping factor of Campbell Glacier were estimated to be 0.926±0.017 and 0.827±0.099 km^{-1}, respectively. The ice thickness along a streamline of Campbell Glacier was estimated at 406±52 m. Such tidal flexure parameters suggested in this study can be useful to estimate the tidal displacement of Campbell Glacier if accurate tide height is provided by a combination of the existing tide model and atmospheric pressure data from AWS. It is worth noting that continuous one-day tandem DInSAR observations of glacial flow by using COSMO-SkyMed constellation in every 16 days are critically important to this study. Together with atmospheric pressure data and tide model, DDInSAR is a useful and unique way to define the flexural characteristics of tide water glaciers and ice shelves in Antarctica even in the absence of tide gauge data.

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REFERENCES

[1] Rignot, E., “Evidence for rapid retreat and mass loss of Thwaites Glacier, West Antarctica,” *J. Glaciol.*, vol. 47, no. 157, pp. 213-222, 2001.

[2] Rignot, E., “Tidal motion, ice velocity and melt rate of Petermann Gletscher, Greenland, measured from radar interferometry,” *J. Glaciol.*, vo. 42, no. 142, pp. 476-485, 1996.

[3] McMillan, M., A. Shepherd, P. Nienow, and A. Leeson, “Tide model accuracy in the Amundsen Sea, Antarctica, from radar interferometry observations of ice shelf motion,” *J. Geophys. Res.*, vol. 116, C11008, doi:10.1029/2011JC007294, 2011.

[4] Padman, L., M. King, D. Goring, H. Corr, and R. Coleman, “Ice-shelf elevation changes due to atmospheric pressure variations,” *J. Glaciol.*, vo. 49, no. 167, pp. 512-526, 2003.

[5] King, M. A., and L. Padman, “Accuracy assessment of ocean tide models around Antarctica,” *Geophys. Res. Lett.*, vol. 32, L23608, doi:10.10292005GL023901, 2005.

[6] Vaughan, D. G., “Tidal flexure at ice shelf margins,” *J. Geophys. Res.*, vol. 100, no. B4, pp. 6213-6224, 1995.

[7] Padman, L., and H. A. Fricker, “Tides on the Ross Ice Shelf observed with ICESat,” *Geophys. Res. Lett.*, vol. 32, L14503, doi:10.1029/2005GL023214, 2005.

[8] Rignot, E., J. Mouginot, and B. Scheuchl, “Antarctic grounding line mapping from differential satellite radar interferometry,” *Geophys. Res. Lett.*, vol. 38, L10504, doi:10.1029/2011GL047109, 2011.